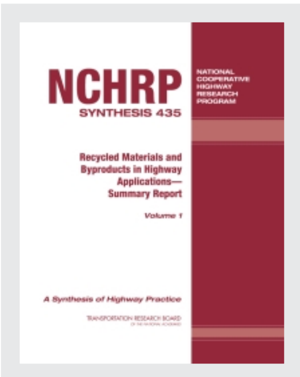


# Recycled Materials and Byproducts in Highway þÿApplications Summary Report, Volume 1

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## AUTHORS

Stroup-Gardiner, Mary; and Wattenberg-Komas, Tanya

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

# NCHRP SYNTHESIS 435

# Recycled Materials and Byproducts in Highway Applications—Summary Report

## *Volume 1*

## *A Synthesis of Highway Practice*

CONSULTANTS
Mary Stroup-Gardiner
Gardiner Technical Services LLC
Chico, California
and
Tanya Wattenberg-Komas
Concrete Industry Management Program
California State University
Chico, California

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## FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

## PREFACE

*By Jon M. Williams*
*Program Director*
*Transportation Research Board*

Recycled materials and industrial byproducts are being used in transportation applications with increasing frequency. There is a growing body of experience showing that these materials work well in highway applications. This study gathers the experiences of transportation agencies in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. Information for this study was acquired through a literature review, and surveys and interviews with state department of transportation staff. The report will serve as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts, and should, thereby, assist producers and users in "leveling the playing field" for a wide range of dissimilar materials.

Mary Stroup-Gardiner, Gardiner Technical Services LLC, Chico, California, and Tanya Wattenberg-Komas, Concrete Industry Management Program, California State University, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The report is presented in eight volumes, the first of which is available in hard copy and on the Internet. The next seven volumes are available through the Internet only and can be accessed at http://www.trb.org/Publications/NCHRPSyn435.aspx. The eight volumes are:

Volume 1 *Recycled Materials and Byproducts in Highway Applications—Summary Report*
Volume 2 *Coal Combustion Byproducts*
Volume 3 *Non-Coal Combustion Byproducts*
Volume 4 *Mineral and Quarry Byproducts*
Volume 5 *Slag Byproducts*
Volume 6 *Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*
Volume 7 *Scrap Tire Byproducts*
Volume 8 *Manufacturing and Construction Byproducts*

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

# RECYCLED MATERIALS AND BYPRODUCTS IN HIGHWAY APPLICATIONS—SUMMARY REPORT

## SUMMARY

Recycled materials and industrial byproducts are being used in highway applications with increasing frequency. Although there is a growing body of experience showing that these materials work well in a number of highway applications, the related information and experience are not synthesized in a coherent body. This study gathered the recent experiences of state agencies, both foreign and domestic, in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. It includes strengths and weaknesses of material applications. The synthesis serves as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts and can assist producers and users in "leveling the playing field" for a wide range of dissimilar materials.

This report is presented in eight volumes, the first of which, *Recycled Materials and Byproducts in Highway Applications—Summary Report* is available in hard copy and on the Internet. Volumes 2–8 are available on the Internet only and present comprehensive information on the following: (Volume 2: *Coal Combustion Byproducts*; Volume 3: *Non-Coal Combustion Byproducts*; Volume 4: *Mineral and Quarry Byproducts*; Volume 5: *Slag Byproducts*; Volume 6: *Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*; Volume 7: *Scrap Tire Byproducts;* and Volume 8: *Manufacturing and Construction Byproducts*). Volumes 2–8 can be accessed at http://www.trb.org/Publications/NCHRPSyn435.aspx.

The original 1994 survey by Collins and Ciesielski focused on identifying research on waste products in a limited number of highway applications. In fewer than 20 years, a number of these waste products are now considered recycled materials and byproducts that are routinely used in a range of highway applications. In 1994, waste products were generally classified by the main source of the waste stream. The byproducts, identified as waste products in the 1994 survey, were used to prepare a second agency survey, which was administered in the summer of 2009. The results from the agency survey and the literature review of each of the byproducts were used to meet the objectives outlined in the original synthesis scope of work:

- **Byproducts:** Develop a comprehensive list of current candidate materials and uses in a matrix format.
- **Test methods:** Identify and review available test procedures for assessing physical and chemical characterization, compaction, geomechanical properties, long-term durability, and environmental performance, including suitability and risks.
- **Material preparation:** Summarize best material preparation and quality control techniques (including stockpiling).
- **Transformation:** Review possible modifications to transform marginal materials into suitable materials. This includes mechanical, chemical, or environmental strategies.
- **Handling:** Address material handling issues associated with the use of recycled materials.
- **Design:** Explain design adaptations that may be required for successful use.
- **Construction:** Identify site construction practices that have proven effective.
- **Lessons learned:** Identify failures, causes, and lessons learned.

- **Barriers:** Identify the major scientific, contractual, and perceptual barriers to adoption of suitable alternative materials by states and steps used to overcome these barriers.
- **Costs:** Identify cost savings from use of recycling, including energy and materials.
- **Gaps:** Summarize gaps in knowledge.
- **Roadmap:** Develop a research roadmap to address these findings.

Highway applications included in the survey and literature review included hot mix asphalt (HMA) pavement (asphalt binder and HMA mix), portland cement concrete (PCC) pavement (cement manufacture, mortar, mix), drainage, embankment, granular base, stabilized base, flowable fill, and surface treatments. Each application category has a wide range of variations that may or may not be suitable for a particular type of byproduct.

Each byproduct section starts with a summary of the types of byproducts and a description of the process that produces each type. Historically reported physical, chemical, and environmentally related properties, uses, production quantities, and cost representative data are assembled for research and projects reported prior to about 1998. The literature review focused on information contained in research and documentation published from about 1998 through 2009.

## BYPRODUCTS

Currently, a number of the waste streams reviewed in 1994 have been redefined and somewhat separated into individual types of byproducts, each with its own advantages and disadvantages, when used in a given application. The main waste streams and currently identified types of byproducts in each category included in this synthesis are:

- ***Coal combustion byproducts*:** coal boiler ash, coal bottom ash, fly ash (Types C and F), flue gas desulfurization (FGD), and fluidized bed combustion (FBC).
- ***Non-coal combustion byproducts*:** municipal solid waste (MSW) bottom ash, MSW combined ash (bottom ash and exhaust fines), and sewage sludge ash.
- ***Slags*:**
  - *Iron blast furnace slags*: blast furnace slag (BFS), air-cooled BFS, granulated ground BFS, expanded BFS, and vitrified pelletized BFS.
  - *Steel slags*: basic oxygen furnace (BOF), electric arc furnace (EAF), open hearth (OH) furnace, and ladle slag.
  - *Non-ferrous slags*: copper, nickel, lead, zinc, and phosphorous.
- ***Mineral and quarry byproducts*:** baghouse fines, coal refuse, mill tailings, spent oil shale, pond fines, screenings, and waste rock.
- ***Reclaimed asphalt pavements* (*RAP*):** baghouse fines (asphalt concrete mixture), unused plant mix, unmilled RAP [pavement removal where flexible pavement layer remains in large sizes (i.e. chunks)], as-milled RAP, and separated and stockpiled RAP.
- ***Recycled concrete aggregate* (*RCA*):** concrete plant end of day waste and water; recycled concrete material (RCM); hardened, crushed, and washed RCM; and returned fresh concrete in a new batch.
- ***Construction demolition waste recycled concrete aggregate* (*CDW RCA*):** recycled concrete aggregate from general construction demolition projects.
- ***Scrap tire rubber*:** whole tires, slit tires, ground tires, shredded or chipped tires, ground rubber, crumb rubber aggregate (dry process), crumb rubber modifier (wet process), and tire buffing.
- ***Kiln dusts*:** cement and a combination of cement and lime kiln dust.
- ***Roofing shingles*:** paper backed, fiberglass backed, tear-offs, and built-up roofing.
- ***Paper manufacturing*:** pulp and lime mud, manufacture, and post-consumer.
- ***Spent foundry sand*:** green sands and core sands.
- ***Sulfur and sulfates*:** sulfur, fluorogypsum, and phosphogypsum.
- ***Waste glass*:** processed glass aggregate (amber, green, flint colors), and powdered glass.

## TEST METHODS

In some cases, standard test methods may need to adjust certain handling and mixing methods such as how long to dry a material to a constant weight or when and how to add the byproduct during mixing. Highly water-absorptive byproducts may need further adjustments to laboratory drying times so that an accurate measure of moisture at the time of construction can be obtained. Byproducts that can be degraded by handling may need to have specific requirements for sampling and handling of samples taken for quality control.

## MATERIAL PREPARATION

Optimum byproduct preparation and quality control considers the differences between each type of byproduct and the byproduct variability when developing stockpiling, quality control, and quality assurance programs. Although each category and type of byproduct has a range of best practices for handling, production, and placement, a general list of information needed to identify the most economical and beneficial practices has been assembled.

The best material post-processing and stockpiling practices are typically the most economical as well. A regional recycling facility can provide the best means of controlling byproduct separation, any required post-processing, and quality control. Post-processing of industry byproducts may be needed to broaden the acceptance of a byproduct to meet the required application specifications. A highway application that uses a particular byproduct needs to be identified so that the waste materials can be post-processed based on the specified application properties for improved usage.

As technological changes are made to the industry producing the byproducts, the physical and chemical properties of the byproducts can change. This may require altering the disposal practices of the industry producing the byproduct. When industries producing various types of a given category of byproduct provide separate disposal sites or stockpiles, improved consistency of the byproduct properties can be achieved. Improvements in key properties of each byproduct should be periodically determined and documented.

If the byproduct is post-processed at the plant site, environmental and noise regulations are addressed by the contractor. In the case of on-site crushers, regulations for fugitive dust and the noise from crushing in an urban environment are considered.

## HANDLING

Optimum storage of byproducts to be used in highway application provides proper drainage to minimize runoff and fugitive dust for fine, dry byproducts. Good locations for stockpiles are within the environmentally permitted area with good drainage. In some cases, byproduct properties can be enhanced with weathering, whereas others can solidify when in contact with water so that dry storage may be needed, depending on the byproduct. Finer ash byproducts are added by using a separate storage silo at ready-mix plants and metering technology for adding mineral filler during HMA production. Consideration by plant managers of size differences between the byproduct and virgin materials can improve the efficiency of the plant particulate emissions removal system. Byproducts, as with all other construction materials, require proper on-site storage facilities, material stockpiling best practices, potential handling degradation owing to possible environmental impacts, and worker safety.

## DESIGNS

The majority of the agencies interviewed for their experience with byproducts in highway applications reported that simple changes are needed, such as adjustments to mix volumetrics and pavement thickness. Changes to volumetric mix designs for either HMA or PCC applications consider differences in specific gravities and moisture absorption. PCC applications are adjusted for specific gravities, inclusion of cementitious materials (i.e., pozzolans), and the water demand for the mix. In the case of HMA applications, volumetric adjustments are used to obtain the desired in-place air voids, voids in mineral aggregate, and voids filled with asphalt cement. The in-place HMA mat thickness is commonly specified in units of pounds per square yard and byproducts that will be influenced by the changes in specific gravities. High specific gravities result in thinner mat thicknesses if the unit weights for the project are not adjusted.

When byproducts are used in unbound applications, in-place density and ground water contamination are considerations for optimal performance. Density is commonly determined using the sand cone method or a nuclear density gauge. In some cases, adjustments to the test method procedures can be made to conventional procedures to provide more accurate measurements; for example, byproducts with high hydrogen contents resulted in higher nuclear density measurements compared with laboratory density testing. Correlations between gauge and lab results for each project can be used to overcome these differences. Byproducts with the potential for ground water contamination are located above the water table, both for the project and for the production storage areas. It is important that unusual factors such as the fire potential of shredded tires be considered when defining the layer heights of the byproduct in an embankment or fill design.

## CONSTRUCTION

The most successful PCC construction processes factor in changes in set times and slump (workability) in the work schedule and the time at which finishing can be started or forms stripped. In the case of HMA applications, the contractor assesses the need to establish a nonstandard rolling pattern or equipment sequencing to achieve optimum density and ride quality. As with conventional materials used in embankments, fills, and stabilized bases, testing and monitoring of the optimum moisture and density are needed. Some production quality control programs increase the numbers of samples tested to account for increased application product variability.

Agencies routinely using a given byproduct in highway application(s) reported no or only limited changes in construction processes.

## COSTS

From the financial point of view, it is beneficial for byproducts to be located close to the project location to provide a cost savings. Suggested distances were fewer than 30 to 50 miles from the project. Alternatively, a regional recycling facility can be used to economically produce a post-processed byproduct that can be packaged, bagged, or shipped longer distances. Byproduct generators without their own captive landfills have a higher economic incentive to find markets for byproducts; for example, typical power plant landfill costs range from $3 to $15/ton for plants with their own landfills, which increases to $10 to $35/ton for those without landfills. The lower the market value of the byproduct, the less likely a plant owner will be to spend money on improving the quality and consistency of its byproduct. Transportation costs may limit the use of byproducts to local projects.

Agencies routinely using byproducts in highway applications almost always reported cost savings as one of the primary reasons for using recycled materials. However, financial costs can increase for agencies and contractors because of the increased efforts needed for additional post-processing, increased requirements for quality control/quality assurance (QC/QA) testing, and additional environmental monitoring over time. The variability in the byproducts may require additional preconstruction and construction quality control testing to design and monitor the uniformity of the project. Additional testing can increase both the design and construction costs. Monitoring wells for tracking changes in water quality may be needed when byproducts are used in unbound or semi-bound applications.

Some byproducts with high specific gravities can make it more costly to haul, because tonnage is needed for the same volume. Higher absorbed water percentages in the byproducts can result in increased drying costs during production of the highway application products. These high liquid absorption capacities will increase the binder demand, and therefore the cost, because binders (portland cement or asphalt cement) are the most expensive component in the mixes.

Highway applications routinely monitor and pay on units of mass and/or volume. Some byproducts require plant adjustments to account for different specific gravities (e.g., fly ash vs. cement-specific gravities) or to account for higher unit weights when calculating haul costs for the same volume of materials (e.g., steel slag in HMA).

## LESSONS LEARNED

Regardless of byproduct type or application, agencies routinely using a specific byproduct identified improved performance as a benefit compared with traditional materials. However, these respondents also noted that data and proper documentation is still needed to confirm the perceived improvement in performance with the use of recycled materials and byproducts. Training for the field and laboratory staff is needed to achieve the optimum benefits and performance improvements resulting from the sometimes steep learning curve for possible production and construction process changes. Agencies generally noted that byproduct variability increased the need to monitor QC/QA testing and/or increase the testing frequency.

The availability of storage and/or stockpiling space for the byproduct at the plant can influence whether or not the contractor uses the byproduct. Environmental and noise regulations may limit additional post-processing such as crushing at the plant.

A total of 85 telephone interviews revealed that very few agencies had poor performance with the byproducts and applications commonly used in their state. However, there were some differences between agencies using the same byproduct in similar applications. For example, agency experience with roofing shingles in HMA applications ranged from good to poor. The reasons for the difference in experiences need to be more rigorously defined so that best practices guidelines can be developed for specific types of byproducts in specific applications.

## GAPS

### Environmentally Related Gaps

First and foremost, communications between environmental and materials engineers need to be improved. Each group of agency engineers must appreciate the needs, regulations, and requirements that another group is required to meet. Improved communication is required to help streamline the best use for each byproduct type in each application. Education and communication is essential between byproduct suppliers and users so that each group of stakeholders understands the importance of byproduct properties, availability, and quantities on application uses. Education and communication is also needed to help identify and minimize differing and/or conflicting federal, state, and local regulations. Regulations may have different impacts on different stakeholders.

Consistent environmental guidelines are needed before increased use of byproducts can be achieved. Estimates of the recyclability at the end of the service life of the application (i.e., sustainability) are also needed.

Environmental testing programs along with environmental cost information are needed to assess the environmental costs and benefits of applications that use byproducts. Life-cycle environmental assessments require information on anticipated changes in energy and heat for both the traditional raw materials and byproducts in the application process. There are a number of software programs available to assist with environmental impacts such as leaching or emissions potential. Examples include:

- **CalTOx:** This program is a risk assessment model that calculates emissions of a chemical, the concentration of the chemical in the soil, and the risk of adverse health effects.
- **IWEM** (Industrial Waste Management Evaluation Model): Software is designed to minimize or avoid adverse ground-water impacts by evaluating types of liners, hydrogeological site conditions, and the toxicity and expected leachate concentrations from the recycled material.
- **PaLATE** (Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects): This is an Excel-based program designed to record inputs on design, initial construction, maintenance, equipment, costs, and output cost and environmental results.
- **STUWMPP** (Screening Tool for Using Waste Materials in Paving Projects): Uses dilution-attenuation factors obtained from the seasonal soil compartment (SESOIL) model and relates leaching concentrations from byproducts and soils to concentrations in underlying ground water.
- **WiscLEACH:** This model is based on a three-analytical solution using the advection-dispersion-reaction equation to describe transport in the vadose zone and ground water. The development of the model was calibrated to results from HYDRUS-2D (Lin et al. 2005).

There are two other programs that can also be used; however, these are marketed (i.e., purchase required) software programs:

- **IMPACT™:** Provides methods for conducting analyses for the transport and accumulation of contaminates, and for calculating the dose or risk to humans.
- **HYDRUS-2D:** This software is a finite-element program for simulating the movement of water, heat, and multiple solutes in variably saturated media.

## Application Gaps

The most readily identifiable missing information in the literature and agency responses includes a lack of training and education programs for all stakeholders with regard to byproducts, potential uses, and how to evaluate the environmental and financial advantages and disadvantages. There is a consistent lack of understanding of regulations, processes, and specification requirements that must be met by each stakeholder group. For example, byproduct producers are unaware of highway application aggregate properties that influence an application's performance.

The number and variation of byproduct descriptions limit the development of material specifications for byproducts. The lack of specifications for key material properties for each type of byproduct appears to be a factor in an inappropriate selection of a byproduct to be used in a particular application. The lack of specifications makes it difficult for the byproduct suppliers to efficiently post-process and/or stockpile byproducts so that they can be more readily used in highway applications.

The identification of spatial location and potential quantities of byproduct sources is needed before an agency engages in a recycling program. Alternatively, the same information is needed by the byproduct producer for local highway projects before an optimal and economical use for the byproduct can be identified.

Mineralogical, chemical, and mechanical properties for each source of byproduct need to be developed so that changes in key properties over time and between sources can be defined; this will help in the development of byproduct specifications for physical and chemical properties.

Standard test method adjustments are required to properly evaluate byproduct and highway application product properties and performance. For example, a correlation between laboratory and nuclear field density test results is needed so that accurate in-place densities can be made when the byproduct contains a significant amount of hydrogen constituents. Mix design test methods define the order of addition of application components during sample preparation so that samples are fabricated that represent construction processes. Precision statements for test methods could be redeveloped or expanded when using byproducts since the original statistics were likely developed using variations in traditional materials. This is important because testing variability must be considered in the development of quality control and specification limits.

Best practices guidelines for stockpiling, handling, and placement are essential. These guidelines may or may not vary by the type of byproduct and application. Contractor and crew training are needed to successfully construct for the best performance the modified application.

Post-construction evaluations involving on-site environmental impact assessment should be a part of implementing the use of byproducts in highway applications. This is particularly important when using byproducts in unbound applications without a history of use.

Life-cycle cost analyses require additional information about the financial costs associated with preparing the byproducts. Cost information on additional testing and inspection requirements are needed as well as changes in construction processes so that potential changes in cost can be estimated.

Agencies reported that when permitting is based on environmental issues using environmentally friendly byproducts processes can result in significant carbon dioxide ($CO_2$) reduction credits. However, more work is required to fully document the environmental benefits.

## BARRIERS

Byproducts in highway applications need to be economically advantageous when compared with traditional materials and processes. A byproduct with little difference in cost but resulting in improved performance can overcome the financial barrier. However, there is limited information on either the economic or performance improvement for most byproducts in highway applications. Limited sources or quantities of byproducts in a region of the country prevent a few agencies from using potentially beneficial byproducts. In some cases, there may be a local requirement to use more of a byproduct in highway applications when the supplier has a greater financial incentive for an alternate use.

Byproduct variability is a consistent agency concern. However, byproduct suppliers are not always motivated to provide their byproducts in a form that is useful or best for highway applications. Producers may not separate stockpiles of different byproducts from the same process (e.g., power plants). This is possibly a financial or site consideration with available square footage. It is also possible that the byproduct supplier is not aware of the specific needs for each highway application. Suppliers may also resist additional post-processing of the byproduct such as crushing the material to a specific range of sizes or instituting a drying process for byproducts in slurry form. Some byproducts may need time in the stockpile to weather, which may require more storage capacity at the process site. Alternatively, some byproducts would be prepared as-needed to prevent long-term storage deterioration.

Key byproduct properties that relate to the application product properties and constructability must be conveyed to the byproduct supplier. It is important that agencies and contractors understand the original materials and processes that produce the byproduct. Byproduct suppliers need to be aware that the size, size distribution, particle shape, specific gravity, absorption capacity (water), toughness, and durability are primary concerns for highway applications. Byproducts that have a high water absorption capacity may generate problems with frost heave in unbound applications in cold, wet climates. Byproducts with primarily one-sized fine particles (e.g., spent foundry sand) have a desirable quality for casting operations but may create gradation problems when used as fine aggregates in PCC or HMA applications. Some byproduct reactions with other components result in destructive expansive reactions or a loss of ultimate application product strengths. In some applications, appearance is also a consideration so any influence of the chemistry, color, or texture of the byproduct can be important.

Byproduct suppliers, contractors, and agencies must be aware of the chemistry of the byproducts as well as their potential for air and ground-water contamination, and potential chemical interactions with other application materials. Leaching of heavy metals is a major consideration when using nontraditional materials in highway applications. The ultimate recyclability of the application product at the end of life is to be assessed so that agencies can evaluate the long-term environmental impact. This information can be used to evaluate the impact of cradle-to-grave life-cycle costs and environmental assessments.

Environmentally related barriers include additional sets of environmental regulations when using byproducts, lack of federal guidance, lack of state environmental guidance, increasingly rigorous air and water quality standards, and difficulty in finding and using environmental software by engineers and contractors.

Other barriers include arbitrary limits on material properties (e.g., a maximum specific gravity for aggregates) and maximum or minimum limits on use as a replacement (e.g., fly ash and ground granulated blast furnace slag), inadequate contractor experience, lack of agency experience, lack of test data to support the use in a given application, cost information, performance history, and needed adjustments to traditional empirical relationships (e.g., PCC compressive strength used to estimate flexural strength).

“Stove piping” by byproduct generators and users of the byproducts in highway applications also restrict increased use. Stove piping refers to the lack of generators and users understanding of each other’s needs and limitations. Each stakeholder group is limited to an understanding of the processes of their own industries.

CHAPTER ONE

# RESEARCH ROADMAP

The best method of increasing the beneficial use of byproducts in highway applications is to focus on local and regional uses, because byproduct use will be highly dependent on the near-source parameters such as local competition with natural materials suppliers, transportation costs, byproduct availability, product production facilities (e.g., concrete and HMA plants), quantities available for use, regional environmental conditions, and traffic volumes. The general concept for matching byproducts with applications for beneficial use with optimal application use was demonstrated in a research document by Petavratzi and Barton (2006). This concept addresses the collection of the information needed as noted in the preceding gaps and barriers sections. Byproduct producers and byproduct users are to develop and assemble information prior to joint producer–user collaboration on the most beneficial byproduct usages.

## BYPRODUCT PRODUCER

Byproduct generator information is needed to describe, as best possible, the specific type of a given category of byproduct used in previously constructed or to-be constructed projects. At a minimum, the location of the point source(s) of byproducts within the process generating the byproduct (e.g., bottom ash and pollution control system), the technology used to generate the byproduct (e.g., precaliner kiln, wet cement kiln, and dry cement kiln), quantities of each type of byproduct, stockpiling practices, geographical location of byproduct sources, and current disposal costs (e.g., tipping fees and on-site landfill containment facilities), and identification of any environmental regulations that apply to the classification and reuse of the byproduct is necessary.

Some industries have undertaken byproduct risk assessment testing programs that will likely contain chemical properties of the byproducts associated with environmental impacts. These data may be useful, if available, in the development of anticipated chemical variability of the byproducts by region of the country and process technology as well as material safety data sheets. Data for the mechanical and physical properties of these sources are needed so that byproduct material specifications for highway applications can be developed.

The current methods for byproduct disposal, stockpiling, and any post-processing of the byproducts need to be identified. At this point, an assessment of individual plant post-processing or the establishment of regional recycling centers for byproduct usage should be considered.

## BYPRODUCT USER

Agencies assemble material physical and chemical properties that are to be evaluated for each potential use of byproducts, which was described by Petavratzi and Barton (2006) as “fitness for use” characteristics. Both agencies and contractors are to identify any environmental regulations that apply to the classification and reuse of byproducts in a particular application.

The Recycled Materials Resource Center website (RMRC 2010) provides a list of test methods used to assess a wide range of highway application products. This website includes general information on values primarily associated with testing historically used natural materials. These test methods need to be more closely evaluated so that nontraditional properties are accurately reflected in the test results (e.g., optimum drying times and temperatures).

The fiscal tipping point for using a given type of byproduct in a specific application product is to be estimated. For example, a byproduct to be used as a portland cement substitute at a given percent by weight for a specific number of cubic yards of concrete required each year needs to be calculated then compared with the locally available supply so that the capital cost for an additional material storage silo can be estimated. The impact of requested production changes on agency and contractor sampling, testing, and training also would be considered. Information on the cost and availability of currently used raw materials is to be collected so that the impact of substituting or adding recycled materials can be assessed. Potential concerns with the cost of recycling could be estimated.

## MATCHING BYPRODUCT PRODUCER WITH BYPRODUCT USER

A match between each type of byproduct and each specific highway application is essential. Agencies require guidance for identifying enhanced performance possibilities that can be obtained from using byproducts in their projects. It is important that the guidance consider the various types of byproducts that may be provided by the byproduct supplier. Currently, the most well-defined type of byproduct is fly ash, which has specifications for Type C and Type F. However, each byproduct type yields application products with differences in the performance of individual applications. That is, the type of fly ash has different impacts on PCC versus stabilized base performance characteristics. Any regulations governing the byproducts must be addressed by both the byproduct producer and the user so that the most beneficial and economical paring can be achieved.

Another example of the necessity for guidance when using a byproduct is the use of steel slag in HMA applications. Several agencies reported using steel slag in surface treatments to improve pavement friction, while one state used steel slag to construct an entire lift of HMA pavement with numerous construction problems and poor performance results. The states using the byproduct for a surface treatment noted excellent results, whereas the agency placing the full lift of steel slag HMA reported major problems with density achieved during construction, durability of the in-service pavement, and the cost of recycling. Specific specifications could be developed for byproduct properties as well as their use in specific applications. Performance data of these applications need to be documented.

Test methods require careful selection and review for byproduct material properties, mix designs, application characterization for performance (e.g., compressive strength), and construction QC/QA testing such as density measurements. Test methods for the byproduct material property testing need to be assessed for ruggedness. For example, ASTM E1169-07 Standard Practice for Conducting Ruggedness Tests can be used to identify any test method preparation or procedure factors that require adjustment when testing byproducts. It is likely that sample sizes, drying times, reagents, and the number of measurements needed per lot will require adjustment. The precision of the test methods form the basis for allowable material QC/QA specification limits, which may warrant adjustment when using recycled materials.

Two components are to be considered when fully assessing the cost of using byproducts in highway applications: economical impact(s) and environmental impact(s). The financial life-cycle cost inputs require information on the cost of raw materials, application, production, transportation, placement, testing, expected life of the application product, and salvage values and costs associated with using the different types of byproducts. The performance and salvage values and costs will be the most difficult to collect and/or estimate.

The environmental evaluation requires energy and emissions data for each type of byproduct, application usage, product placement, and potential recycling process. Information is needed for particulate emission, gaseous emissions, energy, and heat. The assessment of the environmental impacts depends on the characteristics of a particular geographical area that is to be defined for each analysis. A standard level of evaluation should be established for consistency in reported information.

Education and training are to be addressed at this point. Both byproduct producers and users must engage in technology transfer; field and lab technicians are to introduce any required testing changes or additions. Public awareness programs are essential to improve environmental stewardship perceptions of agency practices and policies.

CHAPTER TWO

# INTRODUCTION

Waste recycling in the early 1990s began to focus on high-volume discarded materials with potential recyclable value (Collins and Ciesielski 1994). Over the last two decades, a number of streams previously considered as waste have become valuable byproducts in highway applications. Increasing public awareness of green house gas generation, diminishing non-renewable natural resources, and the need for environmentally responsible and resource-efficient (sustainable) construction is focusing more attention on increasing the use of recycled materials. Local, state, and federal programs are encouraging the use of current waste streams as value-added byproducts.

At the same time, agencies and legislative bodies are restricting byproduct use with often conflicting environmental regulations, lack of standards for byproducts in specific highway applications, and arbitrary legislative efforts. Highway applications are perceived by the public as useful means of disposal for a wide range of waste streams because of the large volume of materials used for these projects. However, agencies need to consider any addition to a highway application as a construction material, which should enhance the performance and/or lower the cost of the final application. In some cases, such as the use of fly ash in PCC, both of these goals are met. Hence, there are a number of agencies using this former waste stream as an additive to improve concrete durability and as an economical replacement for portland cement.

Some agencies differ significantly in their experiences with the use of other byproducts in highway applications. Differences in cost savings, availability, reported byproduct properties, environmental issues, constructability, and performance are common. Increased use of byproducts is complicated by the range of final applications that can use one or more of these byproducts. Information is needed that can determine the reasons for the differences and more consistently assess the viability of using a given byproduct in a specific application.

Although there is a growing body of experience showing that these materials can work well in specific highway applications, the related information and experience is not synthesized in a coherent body.

## OBJECTIVES

The objectives of this synthesis of highway applications using byproducts were to:

- Develop a comprehensive list of current candidate materials and uses in a matrix format.
- Identify and review available test procedures for assessing physical and chemical characterization, compaction, geomechanical properties, and long-term durability, and environmental performance, including suitability and risks.
- Summarize best material preparation and quality control techniques (including stockpiling).
- Review possible modifications to transform marginal materials into suitable materials.
- Address material handling issues associated with the use of recycled materials.
- Explain design adaptations that may be required for successful use.
- Identify site construction practices that have proven effective.
- Identify failures, causes, and lessons learned.
- Identify the major scientific, contractual, and perceptual barriers to the adoption of suitable alternative materials by states and steps used to overcome these barriers.
- Identify cost savings from the use of recycling, including energy and materials.
- Assess gaps in knowledge.
- Suggest a research roadmap to address these findings.

## SCOPE AND SYNTHESIS APPROACH

The objectives of this synthesis were met by collecting information from an on-line survey of state engineers, telephone interviews of agency staff with experience using byproducts, and a literature review. The agency survey was developed with one group of questions for each major byproduct category. The full survey can be found in Appendix A. The first question in each group was designed to capture the range of individual types of byproducts used in various highway applications (e.g., concrete and geotechnical) using a matrix that limited the respondent's options to predetermined choices. The matrix was followed by three open-ended questions to capture the respondent's experiences with performance, barriers, and identification of contacts with information of projects that demonstrated performance (good or bad). This request yielded contacts for 85 separate telephone interviews that collected information on cost savings, design changes, material testing, construction adjustments, environmental benefits, and application performance. A 90% return rate on the survey was obtained.

Categories of byproducts included in the agency survey and the literature review included:

- Coal combustion products
- Non-coal combustion byproducts
- Mineral and quarry byproducts
- Slag byproducts
- Reclaimed asphalt pavement (RAP)
- Recycled concrete aggregate (RCA)
- Construction and demolition waste (CDW)
- Scrap tire byproducts
- Cement kiln dust (CKD)
- Roofing materials (shingles, built-up roofing)
- Sulfur and sulfates
- Foundry sands
- Glass byproducts.

Highway applications included in the survey and literature review were:

- Bound applications
  – Asphalt binder and HMA
  – Portland cement and PCC
  – Surface treatments
  – Flowable fill.
- Unbound applications
  – Embankments
  – Granular base
  – Stabilized base.

Although stabilized bases are technically a bound material, they are discussed in the unbound section based on their primary use as base material and the low chance of binding byproduct compounds and metals owing to the low binding material content.

The literature review collected additional information for materials characterizations, byproduct preparation, byproduct control, material handling guidance, design adaptations, construction, transformation of marginal materials, failures (causes, lessons learned), barriers, costs, and gaps in the information. Academic, industry, and state agency papers, presentations, and reports were used to document work completed from about 2000 through 2008; information before 1999 has been reported in other documents (Collins and Ciesielski 1994; RMRC 2008).

## SYNTHESIS ORGANIZATION

Volume one provides a stand-alone document that summarizes:

- Byproduct background information.
- Highlights of information collected from the extensive literature reviews for each byproduct category.
- Agency survey results on current use of byproducts in highway applications from the 45 states that responded to the survey.
- Performance comments submitted to the on-line agency survey.
- Advantages and disadvantages to using byproducts in highway applications collected during 85 telephone interviews.
- Information that addresses the major synthesis objectives and is generally applicable to all of the byproducts.
- Recommendations for future research programs to increase the use of recycled materials in highway applications.

Volumes 2–8 are available on the web only at http://www.trb.org/Publications/NCHRPSyn435.aspx.

Chapter two is the introduction.

Chapters three through nine contain reported data on byproduct properties (physical and chemical), environmentally related properties, and the production and use of the byproducts. Each chapter also contains annotated bibliographies for research and state agency documents that document the use of the byproducts in highway applications. Key information and reported data is included. The agency survey information is repeated in each chapter to provide a single complete document for each byproduct.

- Chapter three—Coal combustion byproducts
- Chapter four—Non-coal combustion byproducts
- Chapter five—Mineral and quarry byproducts
- Chapter six—Slags
- Chapter seven—Asphalt concrete pavements
- Chapter eight—Scrap tire byproducts
- Chapter nine—Manufacturing and construction byproducts
- Chapter ten—Summary of performance comments on survey
- Chapter eleven—Agency interviews
- Chapter twelve—Conclusions and recommendations

Chapter nine includes information for CKD, roofing materials, paper manufacturing waste, foundry sand, waste glass, and sulfate waste byproducts.

CHAPTER THREE

# COAL COMBUSTION BYPRODUCTS

## BACKGROUND

Coal combustion byproducts are generated from the fossil fuel used in electric power generation, which produce about 50% of the electricity demand in the United States. At this time, there are a number of coal combustion byproducts that are marketed for various uses. These include bottom ash, fly ash, boiler slag, and flue gas desulfurization (FGD) materials (Kalyoncu 2000; EPA 2005). Each type of byproduct is obtained from a different location in the typical steam generating system (Figure 1). There are various options for storage of these byproducts (Figure 2). Coal combustion byproducts have traditionally included:

- **Boiler slag:** Obtained from molten ash collected in wet-bottom boilers where the molten ash is water cooled. The molten ash shatters into black angular pieces that range in size from coarse sand to fine gravel and have a smooth appearance. The material is collected in wet-bottom boilers or cyclone units. The major components are silica, aluminum, iron, and calcium (Butalia and Wolfe 2000; EPA 2008).
- **Bottom ash:** Collected from the bottom of dry-bottom boilers and range in size from fine gravel to fine sand. The material is heavier than fly ash. The major components are similar to the boiler slag (Butalia and Wolfe 2000; EPA 2008).
- **Fly ash:** Entrained particles in the exhaust gases leaving the combustion chamber. This consists of the finest particles collected from coal burning processes. The major components are also similar to those found in boiler slag and bottom ash.
- **Flue Gas Desulfurization (FGD):** FGD is a mixture of gypsum ($CaSO_4$), calcium sulfite ($CaSO_3$), fly ash, and unreacted lime or limestone that results from the removal of sulfur dioxide ($SO_2$) from the exhaust (Kalyoncu 2000). This is also referred to as synthetic gypsum. The major components are calcium, sulfur, silica, iron, and aluminum.

FBC ash is a new byproduct, the result of new boiler technology within the conventional coal burning power plant. Figure 3 shows where the new technology fits within the coal combustion process. FBC is a process of burning coal in which the coal is inserted in a bed of particles that are suspended in the air and that react with the coal to more cleanly heat the furnace. With the FBC technology, coal is burned at a slightly lower temperature, which helps prevent some nitrogen oxide gases from forming (ACAA 2009). Coal combustion is accomplished by combining the coal with a sorbent such as limestone or other bed material. The fuel and bed material mixture is fluidized during the combustion process so that complete combustion can be accomplished along with the removal of sulfur gases. FBC materials are a combination of unburned coal, ash, and spent bed material used for sulfur control. The spent bed material, removed as bottom ash, contains reaction products from the absorption of gaseous sulfur oxides such as $SO_2$ and $SO_3$ (EERC 2009). FBC can also contain some amount of free lime. Atmospheric FBC (AFBC) systems may be either bubbling (BFBC) or circulating (CFBC). Pressurized FBC (PFBC) is a new combustion technology.

The chemistry of types of coal combustion byproducts is dependent on components in the raw coal fuel source and technological changes. There are four types, or ranks, of coal that can be used as a fuel source in power plants: anthracite, bituminous, sub-bituminous, and lignite. A limited amount of anthracite coal is burned; therefore, the primary composition of coal combustion byproducts is controlled by the differences between bituminous, sub-bituminous, and lignite coal. The common components found in all types of coal are silica, alumina, iron oxide, and calcium oxide with varying amounts of unburned carbon. Sub-bituminous and lignite coals have higher concentrations of calcium and magnesium oxide, but reduced percentages of silica and iron oxide, and a lower unburned carbon content (i.e., loss on ignition) compared with bituminous coal. Changes in power plant equipment, such as the new FBC systems, not only produces a fifth coal combustion byproduct but can change the chemistry of the other byproducts that are collected after passing through the FBC process. The influence of new processes on traditional properties of fly ashes should be monitored for chemistry changes that may affect highway application placement or performance.

## LITERATURE REVIEW SUMMARY

A total of 144 documents were located, reviewed, and summarized to provide information about material preparation, handling practices, construction processes, and costs. A summary

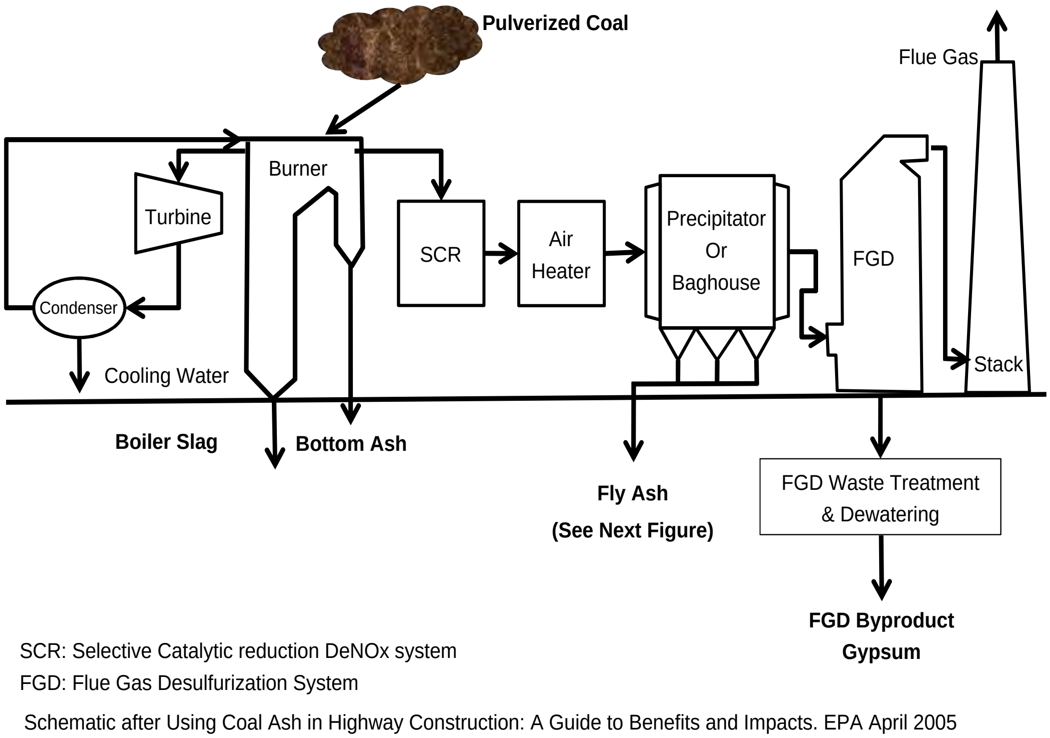


FIGURE 1 Typical coal burning power plant schematic (after EPA 2005).

of material preparation and quality control considerations found in the literature included:

- Increased variability in the physical and chemical properties of the byproducts elevated the need for additional quality control testing.
- Few byproduct quality control procedures were uncovered, although the need for verification of physical and chemical properties was found throughout the literature because of the dependency of the byproducts on coal source and power plant equipment configurations.
- There was a lack of byproduct specifications for purchasing material. This limited the ability of the agency to evaluate QC/QA programs.

A summary of materials handling practices for coal combustion byproducts included:

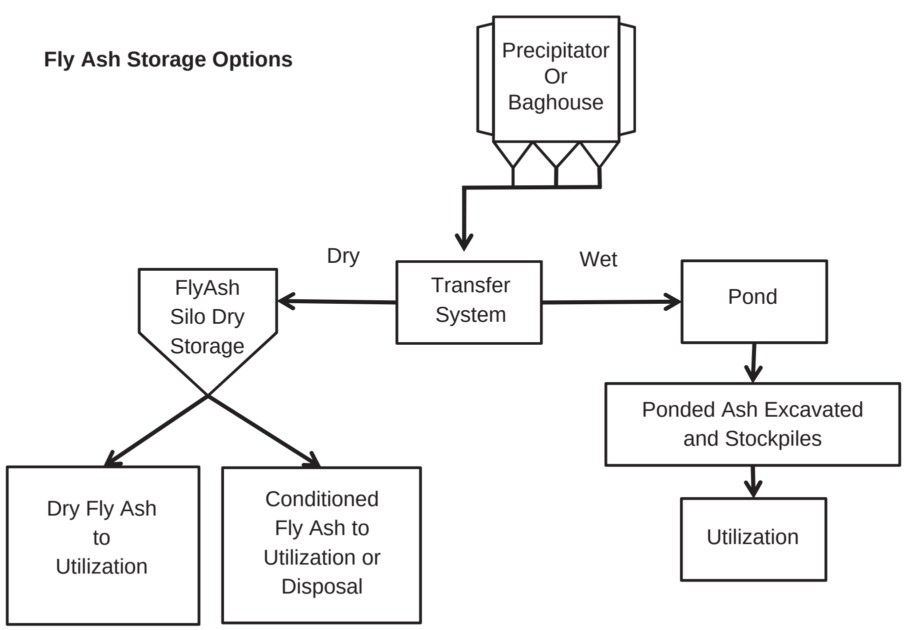


FIGURE 2 Fly ash storage options (continued from previous figure) (after FHWA 2005).

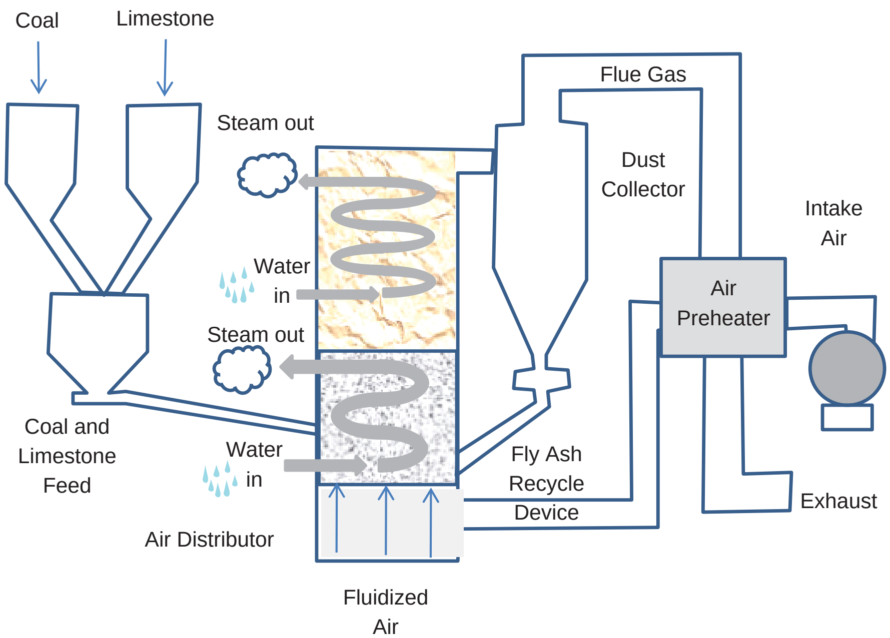


FIGURE 3 Schematic of a fluidized bed combustion (FBC) boiler (EERC 2009).

- Byproducts from different sources needed to be kept separate, because the physical and chemical properties are dependent on the coal source and technology used by each power plant.
- Leaching was a concern and the byproducts needed to be stockpiled so that ground-water contamination was prevented.
- FBC solidified when water was added. This will be a material stockpiling concern that needs to be addressed if this byproduct is to be used in highway applications. It is possible that some highway applications would require a covered storage area.
- Depending on the highway application, an extra storage silo was necessary for the byproduct.
- Fugitive dust control needs to be considered when handling the byproducts.

The main focus of research and applications to date has been to use these byproducts as substitutes for virgin materials, using the existing materials, design, and construction specifications. Alternatively, options that may be less restrictive were used with the byproducts. For example, bottom ash was more likely to be used in cold mix emulsifiers, which have less restrictive requirements for gradation and durability than conventional HMA (Kalyoncu 2000). When using coal combustion byproducts in embankments, the slope stability of blends met requirements when heights were less than 20 m with a horizontal to vertical ratio of 2:1 or flatter with a factor of safety higher than 1.3. Compaction was important to achieving the design requirements (Kim et al. 2005).

Construction differences that might be considered included:

- Monitoring wells for water quality when using byproducts in fill applications.
- HMA QC/QA likely to deal with a larger variability in in-place density when using these byproducts.
- Extra testing and monitoring of the optimum moisture content when using byproducts in stabilized soils.

No specific failures were identified in either the literature review or the survey responses; however, several comments were made that indicated difficulty in testing and material properties:

- Additional testing was needed to account for byproduct variability in such specified properties as HMA density and achieving needed support from stabilized soils as a result of inconsistent optimum moisture contents.
- Nonuniformity of the physical and chemical byproduct properties was a problem when achieving the desired application properties.
- Type C fly ash in PCC applications resulted in problems with durability of the concrete (Estakhri et al. 2006).

Only limited cost information was found in the literature, and this included:

- Power plant owners approached lower value byproducts with a "cost avoidance" philosophy. The lower the market value of the byproduct, the less likely the plant owner was to spend money on improving quality and consistency.
- Power plants without their own landfills had a higher economic incentive to find markets for byproducts. Typical plant landfill costs range from \$3 to \$15/ton for plants with their own landfills. Landfilling using another company increased costs from \$10 to \$35/ton.

TABLE 1
2009 AGENCY SURVEY RESPONSES FOR USE OF COAL COMBUSTION BYPRODUCTS IN HIGHWAY APPLICATIONS

| Byproducts | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
| Coal Bottom Ash | 1 | 1 | 1 | 7 | 7 | 3 | 2 | 4 | 1 |
| Boiler Slag | 0 | 1 | 1 | 4 | 1 | 8 | 5 | 2 | 0 |
| Type C Fly Ash | 0 | 0 | 1 | 5 | 19 | 5 | 0 | 33 | 15 |
| Type F Fly Ash | 0 | 0 | 0 | 3 | 19 | 4 | 0 | 41 | 7 |
| FGD Scrubber Ash | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Combustion Ash, Unknown Type | 4 | 2 | 1 | 4 | 2 | 2 | 3 | 1 | 3 |

- Transportation costs limited the use of byproducts to local projects.
- Agencies and contractors had increased testing costs because of the extra efforts needed for QC/QA.

Limited laboratory research investigated transforming byproducts into more acceptable highway applications. Researchers used a combination of fly ash and FGD (synthetic gypsum), combined by disk pelletization using moderate temperatures to cure the resulting pellets, to form aggregates. Additional background and research information can be found at the following websites:

- American Coal Ash Association trade organization: www.acaa-usa.org
- Energy and Environmental Research Center, University of North Dakota: http://www.undeerc.org/
- Recycled Materials Resource Center: www.rmrc.unh.edu/
- Turner–Fairbank Highway Research Center: http://www.fhwa.dot.gov/research/tfhrc/

## AGENCY SURVEY RESULTS FOR COAL COMBUSTION BYPRODUCTS

The results showed the main use for Types C and F fly ash is in PCC applications, followed by flowable fill and soil stabilization (Table 1). A limited number of states used coal ash, boiler slag, and combustion ash (unknown type). No states were using FGD in highway applications. Table 2 and Figure 4 indicate the states that reported using coal combustion ash byproducts in multiple highway applications.

TABLE 2
STATES USING COAL COMBUSTION BYPRODUCTS IN HIGHWAY APPLICATIONS FROM SURVEY

| Number of Applications | States | | | | | |
|---|---|---|---|---|---|---|
| | Coal Bottom Ash | Boiler Slag | Type C Fly Ash | Type F Fly Ash | FGD | Combination or Unknown |
| 8 | — | — | — | — | — | ID |
| 7 | VA | — | — | — | — | — |
| 6 | — | — | — | — | — | — |
| 5 | — | — | — | — | — | — |
| 4 | — | — | IA, KS, KY, MO, MS, VA | IA, MS, VA | — | — |
| 3 | MD, MO, NC | IL, WV | CO, DE, OH, OR, TX, WA | CO, DE, KY, ND, WA | — | FL, NC, UT |
| 2 | VT | KY, MO | AL, DC, FL, GA, LA, MN, ND, NY, SC, UT, WV | AL, CT, DC, MN, NY, OH, PA, SC, TX, UT, VT, WV | — | KS |
| 1 | AL, GA, IN, NH, NJ, NY, OH, PA, WI | AL, FL, IN, KS, MA, MS, NJ, OH, TX, VT, WI | AK, AR, AZ, CT, IL, IN, NE, NJ, NM, OK, WI | AR, AZ, GA, ID, IL, IN, KS, LA, MA, ME, MO, NC, NE, NH, NJ, NM, NV, OR, OK, WI | — | AL, PA |

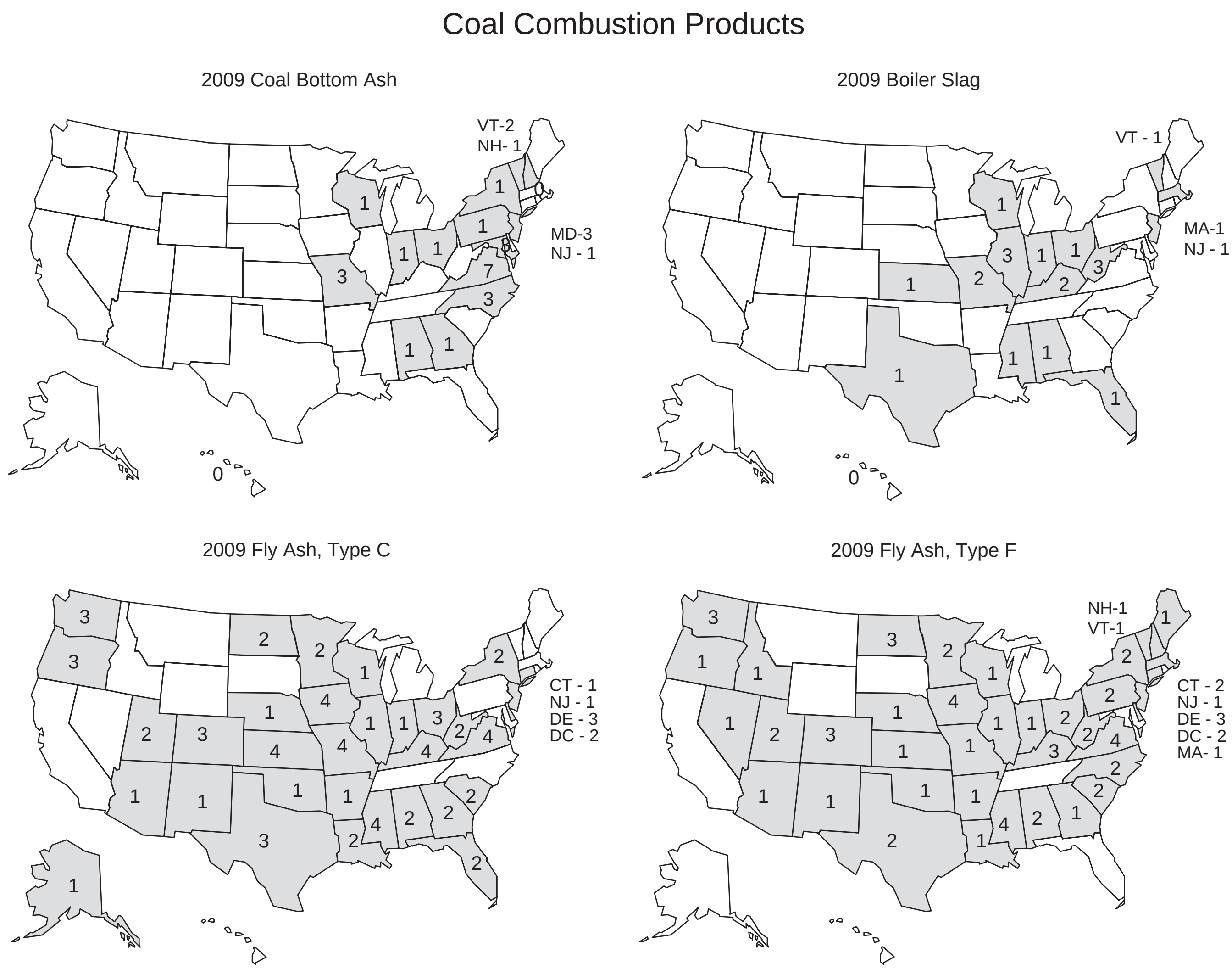


FIGURE 4 Agency survey results for coal combustion byproducts (numbers indicate the number of applications that use the byproduct).

CHAPTER FOUR

# NON-COAL COMBUSTION BYPRODUCTS

The types of municipal solid waste (MSW) and sewage sludge byproducts can be classified as:

- MSW
  - Bottom ash
  - Boiler ash
- Combined ash (most common in the United States)
- Sewage sludge combustion ash.

For clarification, the use of combinations of byproducts in the United States versus the separation of byproducts in Europe might be included in any discussion of these byproducts.

## MUNICIPAL SOLID WASTE

### Background

Minnesota defines MSW as any garbage, refuse, and other solid waste from residential, commercial, industrial, and community activities that the generator of the waste aggregates for collection, but does not include auto hulks, street sweepings, ash, construction debris, mining waste, sludges, tree and agricultural wastes, tires, lead-acid batteries, motor and vehicle fluids and filters, and other materials collected, processed, and disposed of as separate waste streams (Minnesota Statutes § 115A.03, Subd. 21). MSW combustion ash is the end result of burning this waste material in solid waste combustion facilities. Figure 5 shows a general schematic of a typical solid waste combustion facility and indicates the MSW byproduct collection locations within the facility. MSW fly ash, as with coal combustion fly ash, is ash removed from the air pollution control system, which consists of the scrubber and fine particle removal system.

In the United States, most facilities combine the air pollution control system ash byproducts into the combined ash collection location (RMRC 2008). In Europe, most facilities separate and separately manage the MSW bottom ash and MSW fly ash streams.

The two basic types of MSW combustion facilities in the United States are mass burn and refuse-derived fuel (RMRC 2008). The mass burn facilities combust unsorted solid waste, whereas the refuse-derived fuel facilities burn preprocessed waste. The preprocessing consists of shredding solid waste and removing ferrous metal and certain non-ferrous metals prior to burning. Currently, about 15% of the total ash fraction is recovered metal material and only about 5% of all non-ferrous metal is recovered from the pre-combustion MSW. Because of the difference in the waste streams being burned, the byproduct composition and characteristics will be dependent on the type of combustion facility producing the MSW byproducts.

Other MSW byproduct differences are associated with the age of the various combustion facilities. The newer facilities incorporate more advanced furnace designs and emissions controls. For example, newer facilities will add lime or lime-based reagents into the pollution control system to remove the acid gases from the gas stream. This results in both reacted and unreacted lime in the MSW fly ash. Newer emissions control systems are also more efficient at capturing finer particles in the exhaust gases, which result in changes in the physical and chemical composition of the MSW fly ashes.

### Literature Review Summary

The only MSW information found for material handling was related to separating the raw MSW prior to use as a refuse-derived fuel. The only reference to material preparation of sewage sludge was found in the research that used this byproduct to burn with clay to produce lightweight aggregates. For this usage, the sewage sludge was dried and crushed to 0.15-mm sieve size before sintering (burning) with the clay.

A Korean study used dried and crushed sewage sludge and combined it with various percentages of clay in a rotary kiln to produce a synthetic lightweight aggregate. It was interesting to note that the chemical composition of the dried sewage sludge was found to be similar to that of clay. The toughness of the synthetic aggregate was as good, or better, than that of commercially available European lightweight aggregate. Most of the trace metals of concern were not detectable in leachate testing of the synthetic aggregates. Other testing of MSW focused on the evaluation of heavy metals and increased pH.

### Agency Survey Responses for Municipal Solid Waste

Of the 30 states with a potential source for MSW combustion ash byproducts, only Kentucky, North Dakota, and Wisconsin indicated they had experience with using MSW byproducts in highway applications in 2009 (Table 3). Both Kentucky and

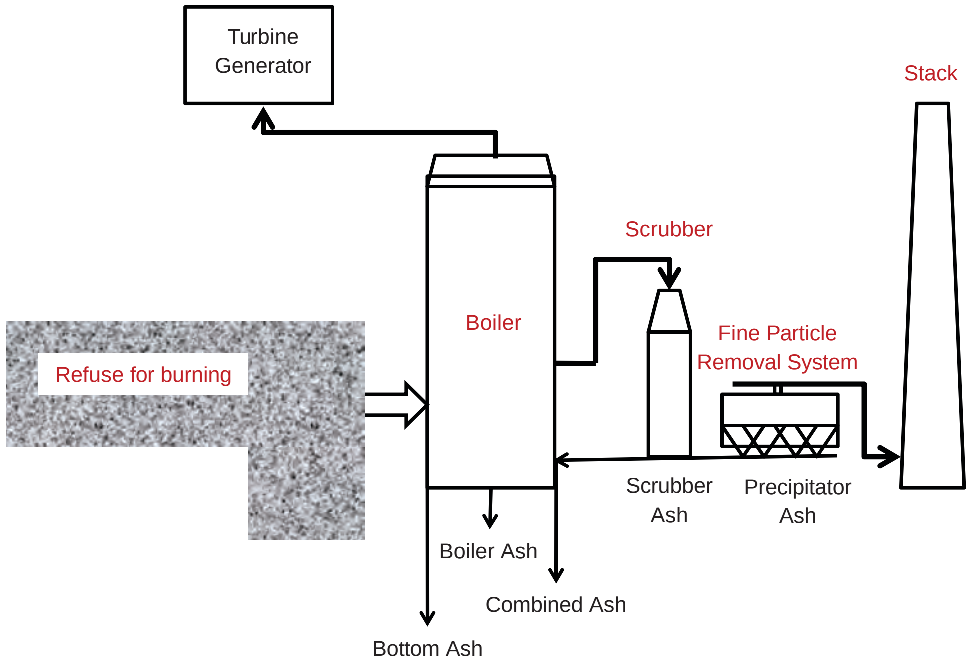


FIGURE 5 Schematic for MSW combustion process (after RMRC 2008).

TABLE 3
SUMMARY OF NUMBER OF STATES USING MSW BYPRODUCTS IN HIGHWAY APPLICATIONS

| | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Byproducts | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Surface Treatment | PCC | Soil Stability |
| MSW Bottom Ash | 0 | 0 | 0 | 2 (KY, ND) | 1 (WI) | 0 | 0 | 0 | 0 |
| MSW Combination Ash | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Combustion Ash, Unknown Type | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Embank. = embankment.

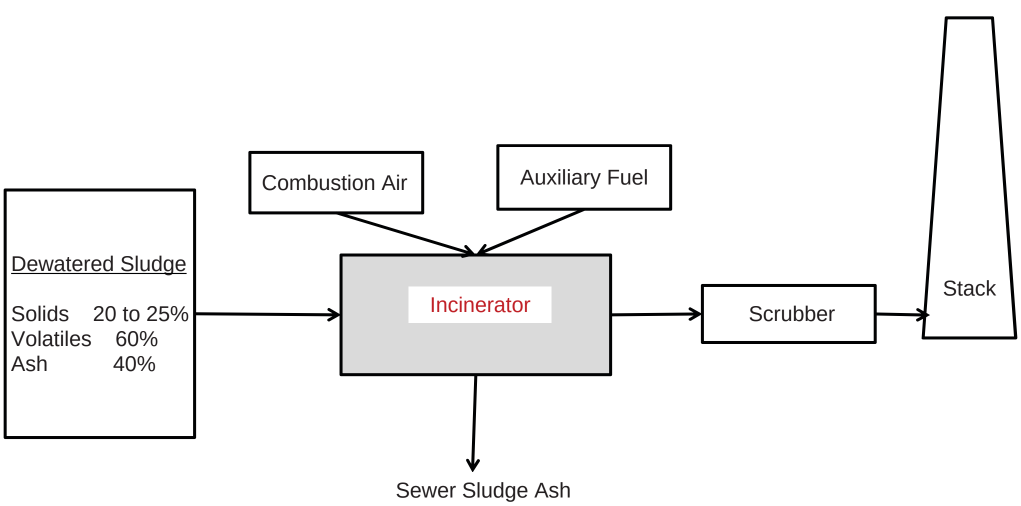


FIGURE 6 Schematic of sewage sludge combustion process (RMRC 2008).

North Dakota used the byproduct in embankment applications and Wisconsin used it in flowable fill.

## SEWAGE SLUDGE

### Background

Sewage sludge ash is the byproduct generated by the combustion of dewatered water treatment plant sewage sludge in one of two types of incinerator facilities. One type of facility is the multiple hearth, and approximately 80% of the systems in the United States are this type. The second type of system, which is less frequently used in the United States, is a fluidized bed configuration (RMRC 2008). The multiple hearth facility is typically comprised of a circular steel furnace with a number of solid refractory hearths and a central rotating shaft. The dewatered sludge, usually with about 20% solids, is introduced into the furnace. Cooling air is used to prevent overheating; spent air is recirculated (i.e., combustion air; Figure 6). The flue gases are scrubbed as a part of the air pollution control system that removed the particles in the air flow. The fluidized bed facility configuration consists of a vertical cylindrical vessel with a grid in the lower portion to support a bed of sand. The dewatered sludge is introduced into the vessel above the sand bed and combustion air flows upward and fluidizes the mixture of hot sand and sludge (RMRC 2008).

### Agency Survey Responses for Sewage Sludge

Minnesota was the only agency that reported having explored sewage sludge ash in flowable fill.

CHAPTER FIVE

# MINERAL AND QUARRY BYPRODUCTS

## MINERAL BYPRODUCTS

### Background

Types of mineral byproducts include waste rock, mill tailings, coal refuse, wash slimes, and spent oil shale (RMRC 2008; TFHRC 2009).

- *Waste rock* is material removed along with overburden from surface mining operations that, by itself, has little or no useful mineral content.
- *Mill tailings* are very fine particles that are rejected from the grinding, screening, or raw material processing.
- *Coal refuse* is rejected material from the processing and washing of coal.
- *Wash slime* byproducts are derived from phosphate and aluminum production that use water to clean the parent material.
- *Spent oil shale* is what is left over after oil shale is processed for oil content; the industry developed in the 1970s during the oil embargo era.

Additional information can be found at the following websites:

- Recycled Materials Resource Center website: www.rmrc.unh.edu/
- Turner–Fairbank Highway Research Center website: http://www.fhwa.dot.gov/research/tfhrc/

### Literature Review Summary

Material preparation of mining byproducts included:

- Removing overburden and deleterious materials from waste rock before using in highway applications;
- Removing plastic fines;
- Resizing by crushing or sieving to obtain desired application gradations;
- Testing for leaching potential, which was important for byproducts with known sources of sulfur compounds and radioactive elements; and
- More environmental testing prior to using some sources of mineral processing byproducts.

Increased cost considerations found in the literature or indicated in the agency responses included:

- Trucking costs associated with long-haul distances,
- Additional byproduct preparation such as overburden and plastic fines removal, and
- Additional testing requirements to satisfy EPA requirements.

### Agency Survey Results for Mineral Byproducts

Embankments were the most-used highway application for incorporating waste rock (11 agencies) and mill tailings (3 agencies). HMA was the next most-used application that used mineral byproducts (Table 4). Seven agencies used waste rock in more than one application (Table 5, Figure 7). None of the agencies reported using coal refuse, wash slimes, or spent oil shale byproducts.

## QUARRY BYPRODUCTS

### Background

Quarry byproducts are the result of quarrying activities that include extraction, rock preparation, and additional processing procedures such as screening and treatment (Figure 8). Most excess material can be reused in restoration of the quarry; however, there are significant amounts of quarry byproducts remaining that need to be managed. Quarrying limestone and dolomite usually produces 20% to 25% fines and sandstones/gritstone up to 25%. Quarry scalping is considered to be the coarse, clay-contaminated material from the pre-screening extracted rock (before the primary crusher).

The RMRC and Turner–Fairbank Highway Research Center (TFHRC) websites (RMRC 2008; TFHRC 2009) identified three quarry byproducts:

- Screenings
- Settling pond fines
- Baghouse fines.

Screenings are defined as the finer fraction of crushed stone that accumulates after primary and secondary crushing and separating on the 4.75-mm screen. Settling pond fines (often referred to as simply “pond fines”) are defined as the fine material collected after washing aggregates and recovering the aggregates retained on the 0.60-mm screen. The combination

TABLE 4
NUMBER OF AGENCIES USING MINERAL BYPRODUCTS IN HIGHWAY APPLICATIONS

| Byproducts | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Coal Refuse | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mill Tailings | 0 | 0 | 0 | 3 | 1 | 5 | 1 | 0 | 0 |
| Waste Rock | 0 | 0 | 2 | 11 | 1 | 7 | 2 | 2 | 0 |

Embank. = embankment.

TABLE 5
STATES USING MINERAL BYPRODUCTS IN HIGHWAY APPLICATIONS
IN 2009

| Number of Applications | States | |
|---|---|---|
| | Mill Tailings | Waste Rock |
| 4 | — | ND |
| 3 | — | WI |
| 2 | KY, MN, NY | IL, MN, MO, NY, VA |
| 1 | KS, MO, MS, WI | AL, CT, GA, KY, MD, NM, OK, PA, VT, WA |

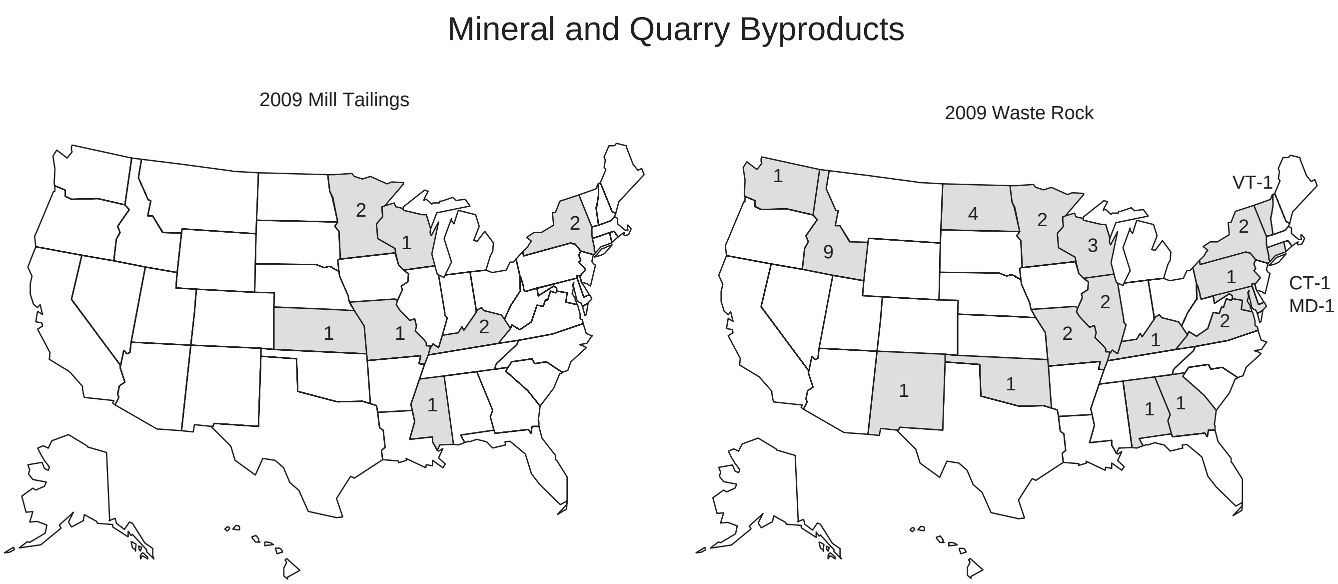


FIGURE 7 Agency survey results for mineral byproducts (numbers indicate the number of applications that use the byproduct).

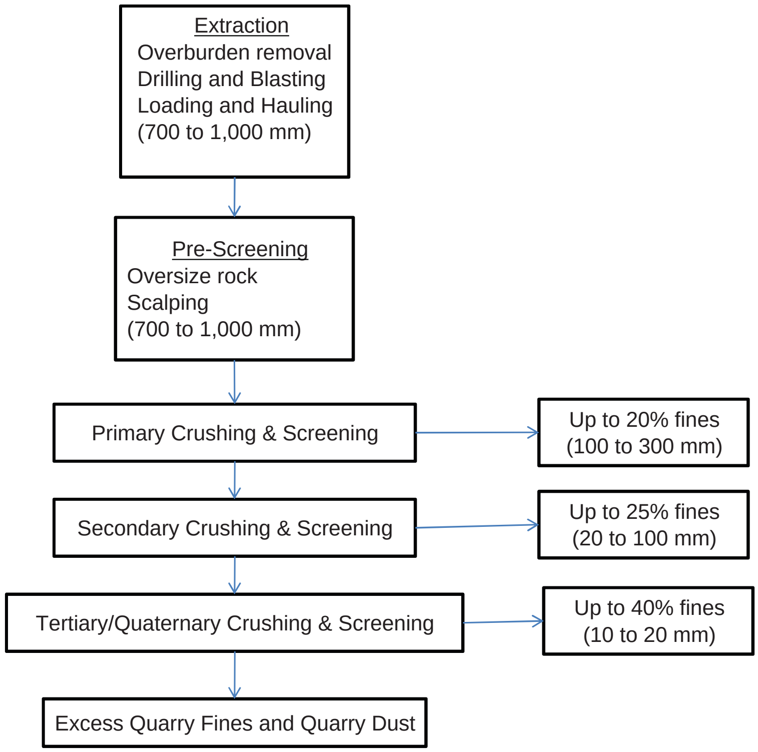


FIGURE 8 Flowchart for a typical quarry operation (RMRC 2008).

of water and minus 0.60-mm fines are discharged into settling ponds or basins where the fines are left to settle out (gravity). Another term, pond clay, has been used to identify material collected from washed natural sands and gravels. Baghouse fines represent the material collected by dry processing plant dust collection systems (i.e., air quality technology).

Several definitions and/or descriptions of material properties for each category were found in the literature. Both United Kingdom and Australian researchers indicated that clear definitions of types of quarry byproducts are needed.

Additional information can be found at the following websites:

- National Stone, Sand, and Gravel Association: www.nssga.org
- Aggregate and Quarry Association (NAPA) of New Zealand: www.aqa.org.nz
- Recycled Materials Resource Center (RMRC): www.rmrc.unh.edu/
- Turner–Fairbank Highway Research Center (TFHRC): http://www.fhwa.dot.gov/research/tfhrc/

#### Literature Review Summary

Information on byproduct handling, processing, and transformation of marginal materials was found in the literature. Recommended materials preparation activities included the removal of plastic fines, potentially needing to re-sieve to obtain desired application gradations, and the dewatering of byproduct slurries prior to use in most highway applications.

Several instances of manufacturing synthetic aggregates were found in the literature. Florida researchers adapted existing agricultural technologies for producing synthetic aggregates manufactured from limestone fines (passing the 0.075 sieve) and binder (e.g., cement). The results showed a good match between the binder and limestone materials that has the potential to be used in PCC applications (McClellan and Eades 2002). Cresswell (2007) used a combination of crushed rock fines with paper sludge (binder) to produce synthetic aggregates with some initial success.

No specific requirements for structural or construction adaptations were found in the literature or noted in the agency responses. It appears that existing specifications for material and application properties were used with or without the inclusion of byproducts.

#### Agency Survey Results for Quarry Byproducts

The majority of the states indicated they used quarry byproducts in either HMA or pavement surface treatment applications (Table 6). These byproducts were also being used in PCC, flowable fills, and embankment applications,

TABLE 6
RESULTS FOR AGENCY SURVEY FOR QUARRY BYPRODUCTS USED IN HIGHWAY APPLICATIONS

| Byproduct | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Baghouse Fines (aggregate production) | 1 | 0 | 0 | 0 | 0 | 17 | 2 | 1 | 0 |
| Pond Fines | 0 | 0 | 0 | 1 | 1 | 4 | 2 | 1 | 0 |
| Screenings | 0 | 0 | 6 | 5 | 8 | 25 | 11 | 7 | 1 |
| Mineral or Quarry Byproduct, Unknown Type | 1 | 1 | 2 | 3 | 3 | 5 | 1 | 2 | 2 |

Embank. = embankment.

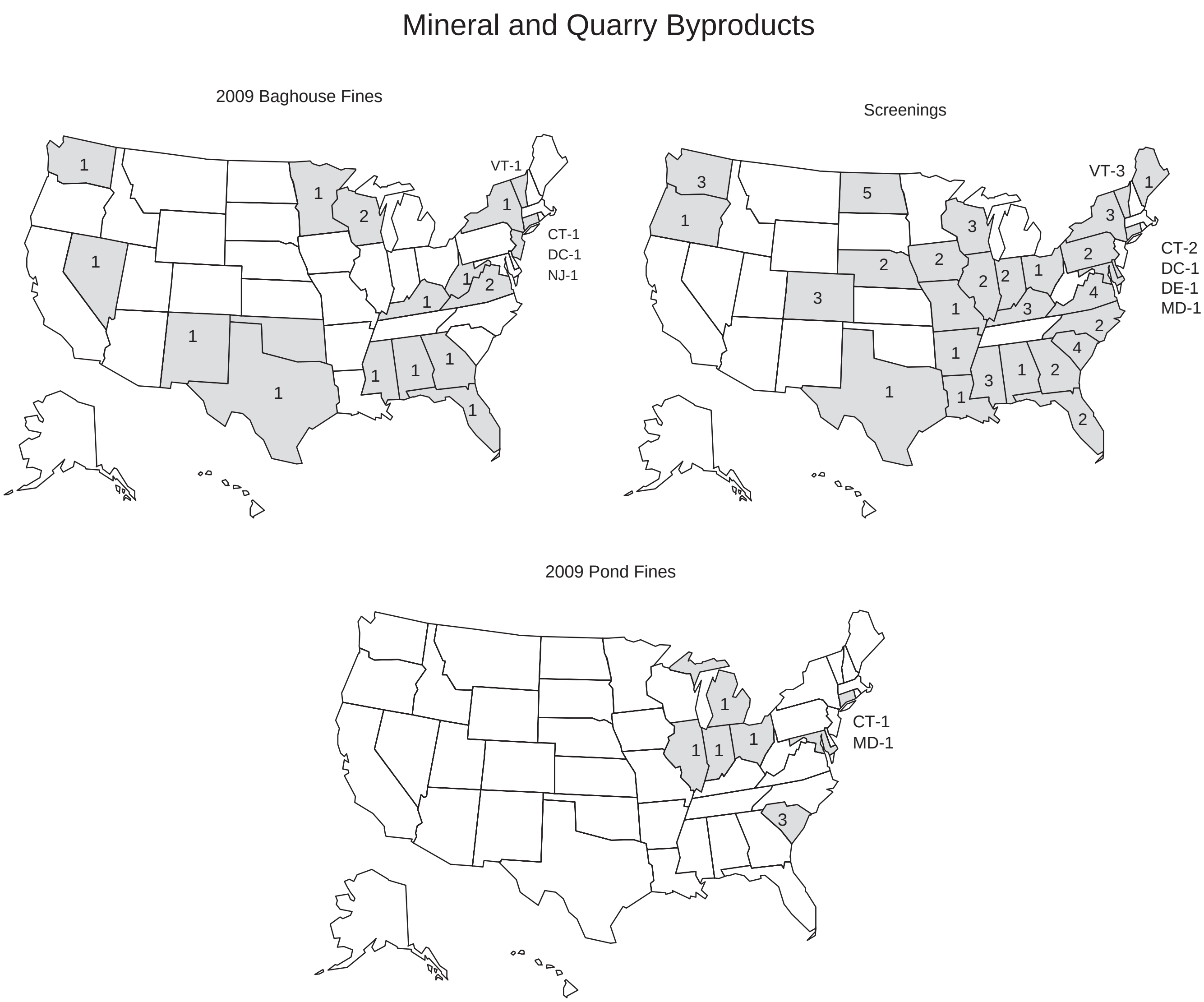


FIGURE 9 Agency survey results for quarry byproducts (numbers indicate the number of applications that use the byproduct).

TABLE 7
STATES USING QUARRY BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

| Number of Applications | States | | | |
|---|---|---|---|---|
| | Baghouse Fines | Pond Fines | Screenings | Unknown Type |
| 9 | — | — | — | ID |
| 6 | — | — | — | GA |
| 5 | — | — | ND | — |
| 4 | — | — | SC, VA | — |
| 3 | — | SC | CO, KY, MS, NY, VT, WA, WI | — |
| 2 | VA, WI | — | CT, FL, GA, IL, IN, IA, NC, NE, PA | NY |
| 1 | AL, CT, DC, FL, GA, KY, MN, MS, NJ, NM, NV, NY, OK, TX, VT, WA, WV | CT, IL, IN, MD, OH, WI | AL, AR, DC, DE, LA, MD, ME, MO, OH, OR, TX | CT, IL, NM |

but much less frequently. Given the selection of "unknown type" by some respondents, it appears there was no distinction of fines based on the source of fine aggregates. States having experience with pond fines or screenings in highway applications tended to be concentrated in the eastern part of the country (Figure 9). Table 7 shows the most commonly used quarry byproducts were screenings and baghouse fines.

CHAPTER SIX

# SLAGS

## FERROUS SLAG BYPRODUCTS

### Background

Ferrous slags are the byproducts of the iron, produced by the first furnace and steel, produced with a second furnace process. Iron is obtained by combining iron ore, iron scrap, and fluxes (limestone and/or dolomite) in the first blast furnace. The product from this furnace is pig iron, which can be used to fabricate products (e.g., cast iron) or as input for steel making. The byproduct from the this furnace is blast furnace slag (BFS), which is defined by ASTM as the nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other alkaline materials that are developed in a molten condition simultaneously with iron in a blast furnace.

Different cooling processes of the slag result in different BFS byproducts. Air-cooled BFS (ACBFS) is obtained when the BFS is poured into beds and slowly cooled under ambient conditions. A crystalline structure is formed and a hard, lump slag is the result. Cooling is accelerated by adding controlled amounts of water, air, or steam, which produces a byproduct with increased cellular structure. This byproduct is expanded or foamed BFS and is lightweight with high porosity. BFS cooled and solidified with water and air quenched in a spinning drum produces a pelletized BFS byproduct. Adjustments of the cooling process are used to increase or decrease the crystalline structure or to alter the glassy (vitrified) characteristics. Crystalline structures are desirable for use of the slag as an aggregate replacement; more vitrification (more glass content; amorphous) is needed for reactive cementitious applications. BFS that is cooled and solidified rapidly in water has little or no crystalline structure and has sand-sized particles. This byproduct is then crushed or milled into fine, cement-sized particles to produce granulated ground BFS (GGBFS).

A second furnace is needed to produce steel (Figure 10). This furnace uses the liquid blast furnace metal, scrap, and fluxes (lime, dolomitic lime) and high-pressure oxygen injection to produce a wide range of steel products. Steel furnace slag (SFS) can be obtained from any one of three types of furnaces: basic oxygen furnace (BOF), electric arc furnace (EAF), or open hearth (OH) furnace. Figure 10 indicates the different points in the process where steel slag is produced. As with iron manufacturing, the steel making byproduct characteristics will depend on the type of technologies and the composition of the raw materials. The most common types of steel slag byproducts are BOF slag, EAF slag, and ladle slag. Additional information can be found at the following websites:

- National Slag Association: www.nationalslag.org
- Slag Cement Association: www.slagcement.org
- Recycled Materials Resource Center: www.rmrc.unh.edu/
- Turner–Fairbank Highway Research Center: http://www.fhwa.dot.gov/research/tfhrc/

### Literature Review Summary

The list of the most commonly researched and used iron slag byproducts included BFS, GGBFS, and ACBFS. Other iron slag byproducts expand the list to include expanded or foamed BFS, pelletized BFS, and vitrified BFS; however, little was found in the literature for research or use of these byproducts.

Steel slag byproducts were used much less frequently than iron slag byproducts. As with the iron slag byproducts, steel slag byproduct material properties depend strongly on the type of furnace and point in the process from which the byproduct was obtained. The steel slag byproducts identified in the literature included steel furnace slag, EAF slag, BOF slag, OH furnace, and ladle slag.

The generic term, steel slag, was used in a number of the articles found in the literature review. When the specific type of steel slag was determined, the EAF byproduct was the most frequently identified followed by the BOF slag.

The following recommendations were identified for handling and stockpiling slag byproducts:

- Slags had better material properties after weathering in a stockpile.
- Using freshly produced BFS should be avoided to minimize the reactivity of slags.
- A method statement for storing, handling, and measures for protecting water quality was needed.
- Using BFS in wet, poorly drained soils or in areas below the water table should be avoided to limit the potential for ground-water contamination.
- Good compaction was needed and ponded water should be avoided in unbound applications in the construction of heavily trafficked areas.

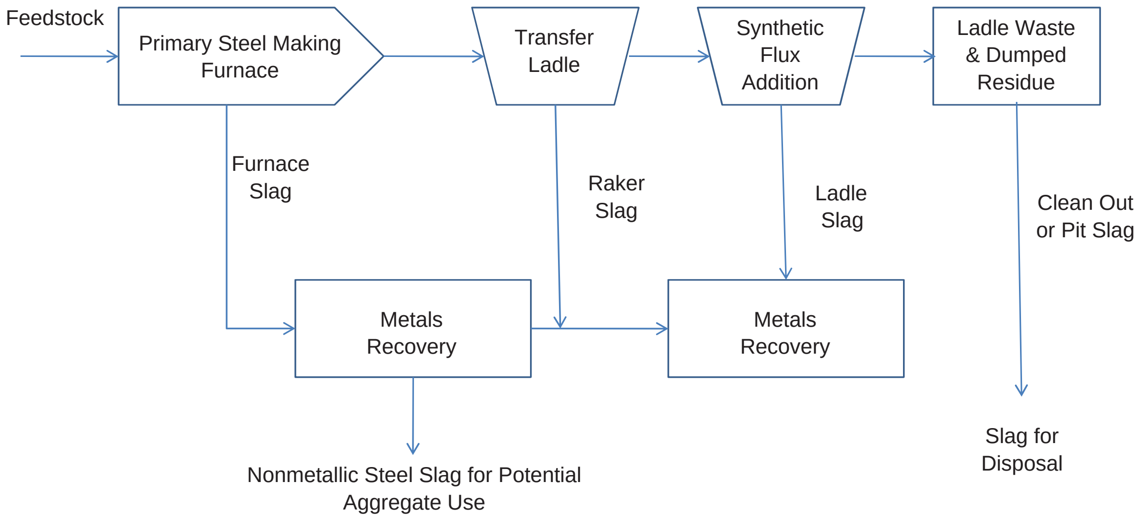


FIGURE 10 Slag production from steel making plant (after RMRC 2008).

The following plant adjustments need to be considered:

- Increased silo storage at plants to handle additional materials.
- Plant adjustments (e.g., air flow) to account for the different specific gravities and dust contents.
- Changes to the order of addition or rate of addition of individual components.

Volumetric mix designs for either HMA or PCC need to consider the different specific gravities of the slag byproducts. In the case of HMA applications, the mat thickness is commonly specified in units of pounds per square yard. When mixes contained byproducts with high specific gravities, the resulting mat thickness was reduced because the unit weights for the project were not initially adjusted to account for the change in unit weights.

Standard QC/QA programs were used, although in some cases limits on the amount of byproduct in an application were occasionally necessary. One agency required a preconstruction trial mix program. A second agency implemented a requirement for a contractor to develop a self-test program.

Skid resistance was improved with steel slags in the HMA surface course, but decreased when some non-ferrous slags were used. Contradictory skid resistance experiences were found in both the literature and agency responses.

When permitting was based on environmental issues, using GGBFS in particular resulted in significant $CO_2$ reduction credits.

From the financial standpoint, byproducts situated close to the project location minimized the haul distance and improved cost savings. The high specific gravity of steel slag made it more costly to haul because more tonnage was needed to produce the same volume. Higher water absorption capacities of some slags increased the demand for cements (portland or asphalt) and therefore the cost of the application products. The variability in the byproducts required additional preconstruction and construction quality control testing to design and monitor the uniformity of the project. The additional testing increased both the design and construction costs.

One application for producing synthetic aggregates was found using GGBFS treated with carbon dioxide at ambient temperatures and pressures to manufacture lightweight aggregates with aggregate impact values of between 14% and 17% loss after impact.

Three methods of treatments for marginal steel slag materials were found. One method used wet grinding of EAF and argon oxygen decarbonization steel slags to reduce problems with harmful expansive reactions when used with aluminum or galvanized metals. A second approach improved the strength-related reactivity of EAF slag by re-melting and rapidly cooling the steel slag to increase the glass content. This process showed potential for increasing the slag reactivity. The third method combined BOF steel slag with gypsum waste and cement bypass dust to form a binder without the use of cement.

#### Agency Survey Results for Ferrous Slag Byproducts

The most commonly used iron slag byproduct was GGBFS in PCC applications (Table 8). Steel slag was used primarily in HMA applications and pavement surface treatments. ACBFS was used in bound applications by some states in HMA, surface treatment, and PCC applications. Unbound usage of ACBFS

TABLE 8
RESULTS FOR AGENCY SURVEY FOR IRON AND STEEL SLAG BYPRODUCTS USED IN HIGHWAY APPLICATIONS

| Byproducts | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Blast Furnace Slag | 0 | 1 | 1 | 6 | 1 | 5 | 3 | 3 | 2 |
| ACBFS | 0 | 0 | 3 | 4 | 0 | 6 | 6 | 4 | 0 |
| GGBFS | 0 | 1 | 1 | 1 | 6 | 2 | 0 | 30 | 2 |
| Expanded BFS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Vitrified, Pelletized BFS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Steel Slag | 0 | 1 | 0 | 3 | 0 | 13 | 4 | 2 | 0 |
| Unknown Type | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 |

Embank. = embankment.

included embankment and drainage applications. A number of states indicated a generic use of blast furnace slags in a range of applications, with embankments being the most common. Table 9 and Figure 11 show the states using the iron and steel byproducts.

## NON-FERROUS SLAG BYPRODUCTS

### Background

Non-ferrous slags are produced during the recovery and processing of non-ferrous metals from natural ores (RMRC 2008). As with steel slag, non-ferrous slag byproduct ends up as either a rock-like or granular material. Three groups of non-ferrous byproducts were listed on the RMRC (2008) website: (1) copper and nickel slags, (2) lead/zinc slags, and (3) phosphorous slags.

There are three basic steps in copper, nickel, and lead/zinc processing:

- Roasting, which is heating below the melting point;
- Smelting, which melts the roasted material; and
- Converting, where the metal from the process is separated from impurities.

Phosphorous, copper, nickel, and zinc slags can be air-cooled or granulated (RMRC 2008; TFHRC 2009). Often, molten slag is dumped into a pit and allowed to cool. When the slag is cooled rapidly by quenching with water, a vitrified frit-like granulated slag is obtained. The result is a more uniformly shaped small particle that is more reactive than air-cooled. Air quenching results in the solidification of larger masses. Copper slag produced by smelting the copper concentrates in a reverberatory furnace is referred to as reverberatory copper slag. The cooling rate strongly influences the internal grain structure of the slags and mineralogy that, in turn, influences the physical properties.

### Literature Review Summary

Research and pilot projects that indicated some non-ferrous slags, when used in asphalt concrete pavements, showed improved friction resistance, while others had poor friction properties. Both zinc and phosphorous slags were reported to improve friction properties but were limited in their use by

TABLE 9
STATES USING IRON AND STEEL BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

| No. of Applications | States | | | | | |
|---|---|---|---|---|---|---|
| | BFS (General) | ACBFS | GGBFS | Expanded BFS | Steel Slag | Unknown Type of Slag |
| 6 | — | — | — | — | — | — |
| 5 | WV | IL, IN | — | — | — | ID |
| 4 | UT, VA | OH | — | — | — | — |
| 3 | — | — | AL, PA | — | IN | — |
| 2 | KY, WI | KY, PA, VA | KS, KY, MS, NJ, OH, TX, WA | — | MO, OH, SC, WI | AK |
| 1 | AL, MD, NJ, NY, VT | FL, MO, NJ | AR, CT, DC, DE, FL, ID, IL, IA, LA, ME, MN, MO, NC, NE, NH, NY, OK, OR, SC, VA, VT, WI, WV | IL | AL, CO, CT, DC, IL, IA, KY, MN, OR, PA, VA, WV | DC, FL, MA |

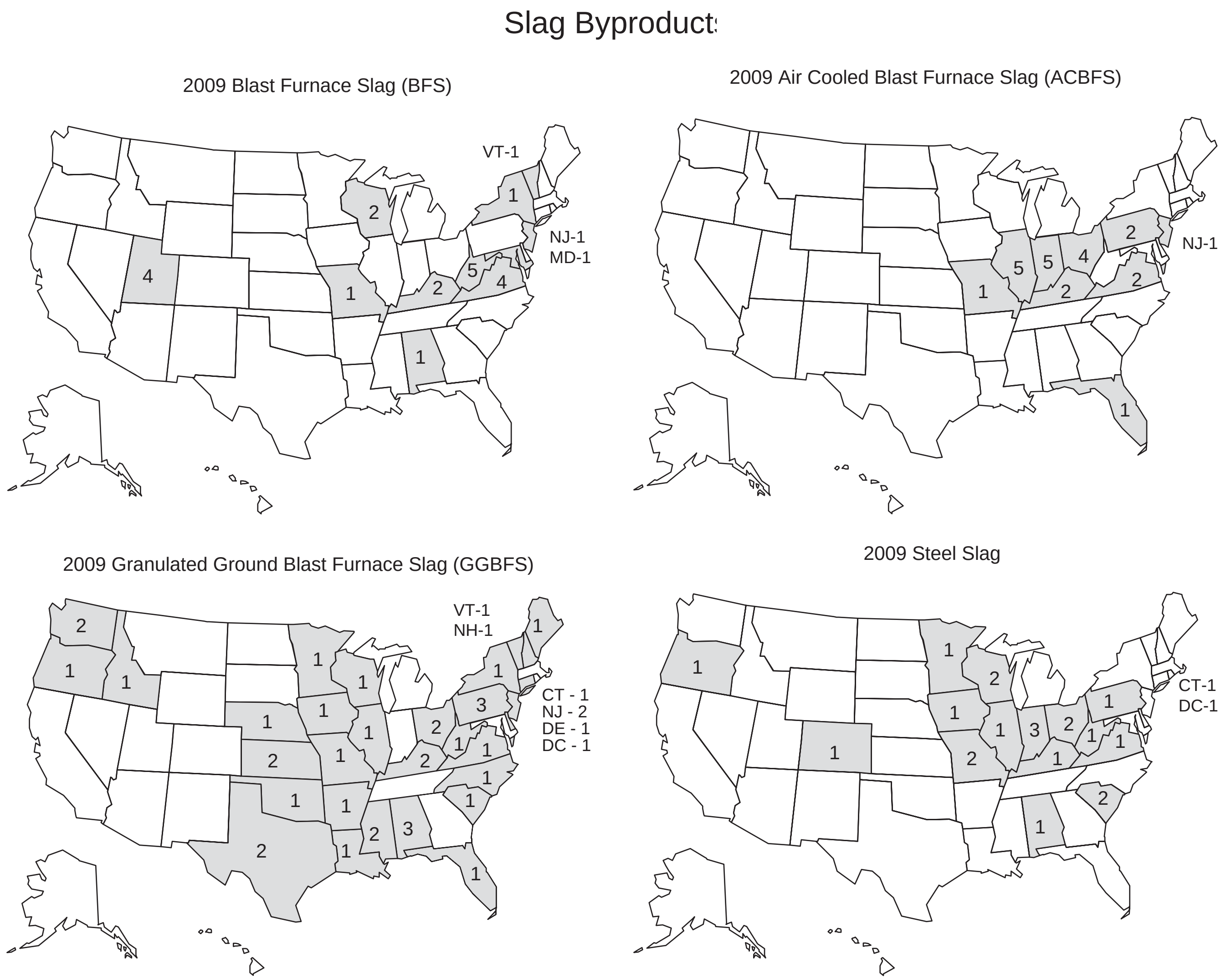


FIGURE 11 Agency survey results for iron and steel slag byproducts (numbers indicate the number of applications that use the byproduct).

TABLE 10
RESULTS FOR AGENCY SURVEY FOR NON-FERROUS SLAG BYPRODUCTS USED IN HIGHWAY APPLICATIONS

| Byproduct | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Copper and Nickel | None Reported | | | | | | | | |
| Lead, Lead-Zinc, and Zinc | None Reported | | | | | | | | |
| Phosphorous | 0 | 0 | 0 | 0 | 0 | 1 (KY) | 0 | 0 | 0 |

Embank. = embankment.

the lack of availability, whereas nickel slags were reported to have poor friction characteristics as aggregates in pavement surface mixes.

Some asphalt concrete mixes with non-ferrous slags were reported to exhibit moisture sensitivity, which could be addressed with lime treatment of the surface. These slags when used as an aggregate are likely to have poor friction properties.

#### Agency Survey Results for Non-Ferrous Slag Byproducts

The agency survey question for non-ferrous slag usage in highway applications and agency responses are shown in Table 10. Only Kentucky indicated having used phosphorous slag in HMA applications.

CHAPTER SEVEN

# ASPHALT CONCRETE PAVEMENTS AND RECYCLED ASPHALT PAVEMENTS

## RECYCLED CONCRETE AGGREGATES

### Background

The types of PCC byproducts that were evaluated for use in highway applications included:

- RCA (FHWA definition)
- CDW RCM
- PCC manufacturing byproducts:
  - Fresh concrete reused in other loads of fresh concrete
  - End of day hardened PCC, fractured (washed or unwashed for fines control)
  - Washed fresh concrete to recover the original components (primarily aggregates).

FHWA (2004) limits the definition of RCA as PCC byproduct obtained from the removal of old PCC pavements. The specific definition is:

> Recycled concrete aggregate: is a granular material manufactured by removing, crushing, and processing hydraulic-cement concrete pavement for reuse with a hydraulic cementing medium to produce fresh paving concrete. The aggregate retained on the 4.75 mm sieve is called coarse aggregate and the material passing the 4.75 mm sieve is called fine aggregate.

Some states have expanded the definition to include bridge structures and decks, sidewalks, curbs, and gutters that have had the steel removed from the old concrete.

One of the main advantages to using these sources for RCA is that state projects historically used high-quality aggregates with consistent properties defined in state specifications. High-quality and durable old concrete may be useful in new structural PCC applications, whereas lower-quality old concrete may be more useful in subbase or fill applications (ACPA 2008).

RCA from old highway projects has five main steps:

1. Removal of as many potential contaminates as possible prior to demolition of PCC
2. Demolition of structure
3. Crushing and sizing RCA
4. Secondary removal of contaminates
5. Removal of dust and fines (air blowing or washing).

An alternate source of RCA is from commercial construction debris. However, state agencies prefer to reuse material recovered from either state projects or known sources of supply because general CDW RCA can have contaminates such as bricks, wood, steel, ceramics, and glass. RCA from the demolition of other structures is not currently allowed in the United States; however, international research has explored methods for obtaining construction demolition debris for use in highway applications.

Suppliers of fresh PCC have other potentially useful PCC byproducts. At the end of the day, leftover unused PCC mix is off-loaded. This mix can be dumped into a solid mass that can then be broken up and used as RCA at a later time. Alternatively, it can be washed to recover the aggregates for future use. There has been some experimentation with using the leftover mix to form an irregular block of PCC to be used as rip-rap. This is time-consuming and not currently a common practice. Once the trucks are unloaded, they need to be cleaned. This process uses water to rinse out the trucks and produces water with an elevated pH. The reuse of both the water and the solids (usually aggregates) has to be considered. Unused fresh PCC mix may occasionally be remixed with a fresh batch of PCC.

These recycled materials, while potentially useful in highway applications, will have different physical and chemical properties than those of old recycled concretes.

### Literature Review Summary

When RCA was used in PCC mixes, the water-to-cement, or cementitious materials, ratio may require adjustment to maximize workability. Alternatively, water reducers or superplasticizer was used to maintain strength requirements while achieving a workable mix. The PCC mix design testing included evaluations of freeze/thaw and alkali silica reactivity (ASR) resistivity, as well as volume changes, as a result of drying, and thermal contractions and expansions. High shrinkage characteristics are to be considered carefully so that early cracking failures are avoided. The use of fly ash with the RCA will improve the ASR resistivity and decrease the volume changes in RCA PCC. If the water demand-related workability issue was adequately addressed during the mix design then construction processes were not changed.

The best way to control the variability within and between stockpiles of RCA was to maintain constant moisture content.

Sprinkling systems were recommended along with increased testing for stockpile moisture contents. Stockpiles of RCA should be constructed so that nearby water sources are not affected by alkali. Washing of the RCA was used to improve the fines content of the RCA byproducts. Another good practice for improving quality and minimizing RCA variability was to keep stockpiles of RCA from different sources separate if at all possible.

Structural design was occasionally influenced by the lower specific gravities, compressive and tensile strengths, and resilient moduli values. RCA PCC typically had higher water demands, creep, drying shrinkage, permeability, coefficients of thermal contraction/expansion, corrosion rate, and carbonization.

When RCA was used in drainage systems, it was to be used below the drainage lines to minimize altering the ground-water properties. Filter fabrics could be selected to prevent clogging by the fines and carbonation byproducts.

The costs of recycling PCC byproducts varied by source, region of country, and the quality needed for a given highway application. It was economically desirable to use RCA when the tipping fees were less than the charges for landfilling PCC waste. Use of RCA was also promoted when the cost could compete with the cost of purchasing new aggregates. In some cases, the contractor achieved cost savings when using RCA because of the reduced number of haul trucks and reduced fuel consumption. Agencies reduced project costs because of reduced needs to alter existing highway features such as curbs, gutter, and overhead clearances.

### Construction and Demolition Waste Concrete

The FHWA definition of recycled concrete aggregate narrowly limits the sources of old PCC to reclaimed highway pavements; however, some states have expanded the definition to include reclaimed bridge PCC. Little work has been done until very recently in the United States on the use of construction demolition byproducts in highway applications. Most of the information found on this byproduct was located in international research publications.

The three separate steps needed to recover CDW concrete byproducts are the demolition of the original structure, processing of the mixed waste stream, and sorting of the individual byproducts for recycling. The efficiency in recovering the byproducts can be enhanced by using organized demolition of specific structural components, initial processing, and sorting of each byproduct (Lauritzen 2004). Optimal sorting of materials starts with the development of the demolition process and technologies (selective demolition) and correct handling of the recyclable materials. This takes more time and planning than traditional demolition and until recently demolition has been considered a low tech process, with rapid removal and disposal being the main focus. Quality standards for CDW recycled materials are needed along with education and technology transfer.

Additional information can be found at the following website: Construction Materials Recycling Association (CMRA): www.cdrecycling.org.

### Agency Survey Responses for Recycled Concrete Aggregate Byproducts

The survey contained questions about the use of all of the identified types of byproducts except the CDW RCA. The most commonly used highway application for RCA was as embankment and drainage material followed by use in PCC applications (Table 11). Most states used RCA washed or unwashed (Table 12). Six states recycle the end of day waste and water. Only one state indicated it allowed fresh PCC to be added to a new batch. The states with experience using recycled concrete in highway applications are shown in Figure 12.

TABLE 11
NUMBER OF STATES USING RCA BYPRODUCTS IN HIGHWAY APPLICATIONS

| Byproducts | Number of States Using Byproduct in Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stability |
| Concrete, Plant, End of Day Waste, and Water | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 3 | 0 |
| Returned Fresh Mix Added to New Batch | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| RCA, Crushed and Washed | 0 | 0 | 8 | 12 | 1 | 2 | 1 | 9 | 0 |
| RCA, Crushed but Unwashed | 0 | 0 | 7 | 18 | 0 | 0 | 1 | 6 | 2 |
| RCA, Unknown Type | 1 | 1 | 2 | 4 | 1 | 1 | 2 | 1 | 1 |

Embank. = embankment.

TABLE 12
STATES USING RCA BYPRODUCTS IN HIGHWAY APPLICATIONS

| Number of Applications | States | | | | |
|---|---|---|---|---|---|
| | Concrete, Plant, End of Day Waste and Water | Returned Fresh Mix Added to New Batch | RCA, Crushed and Washed | RCA, Crushed but Unwashed | RCA, Unknown Type |
| 9 | — | — | — | — | ID |
| 4 | — | — | IL | — | — |
| 3 | — | — | CO, ND | FL, GA | — |
| 2 | IL | — | LA, MD, NC, VA, VT, WA | IL, KY, MN, ND, WA, WI | — |
| 1 | MO, NC, NE, VA,TX | NC | AL, DE, FL, MN, MS, NJ, OR, OK, SC, WI | AZ, CO, CT, DC, HI, IN, ME, MO, NC, NE, NH, NJ, NY, OH, OK, PA, TX, VA | GA, MO, ND, NV, VT |

## Reclaimed Concrete Materials

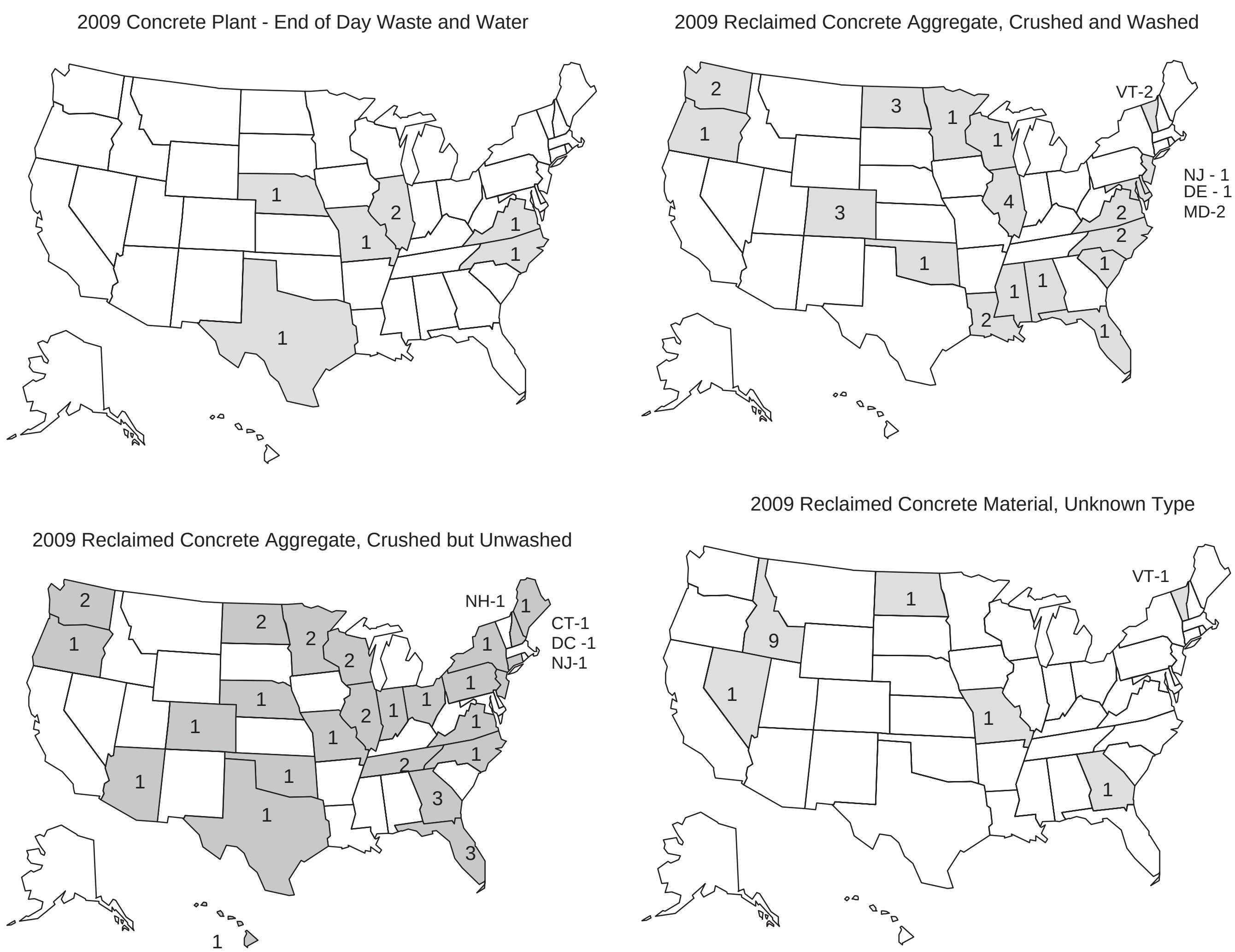


FIGURE 12 Agency survey results for recycled concrete aggregate byproducts (numbers indicate the number of applications that use the byproduct).

## RECLAIMED ASPHALT PAVEMENT

### Background

Asphalt concrete is removed during maintenance or rehabilitation activities by grinding (milling) the surface, pulverizing the old pavement along with a portion of the base or subgrade, or ripping up the old pavement. Milled or post-processed old asphalt concrete pavement is referred as reclaimed asphalt pavement, or RAP. RAP can be processed on-site using in-place recycling technologies or it can be removed from the job site and stockpiled at a contractor's plant site (central plant recycling). In-place recycling includes hot in-place, cold in-place, and full-depth reclamation and is covered in a separate NCHRP synthesis. Central plants can be either HMA or cold mix asphalt (CMA) plants. Regardless of whether in-place or central plant recycling is used, it is advisable that preconstruction testing include an evaluation of moisture susceptibility (Scullion et al. 1997, 2003).

Hot central plant recycling combines RAP with new aggregates and fresh asphalt in the presence of heat and is the most common method used by contractors (Santucci 2007). The amount of RAP used in the new mix varies between agencies with the layer of the pavement being constructed. The use of RAP by agencies varies between 0% and 30% in the upper layers to up to 50% in shoulders and stabilized bases (TFHRC 2009). RAP can be added to HMA at either batch or drum mix plants. Cold mix central plant recycling combines RAP with new aggregate (if needed) and emulsified asphalt or an emulsified recycling agent without the use of heat in a central plant. Other additives can be used to help regulate the emulsion rate of set, early strength gain or improved moisture resistance.

In-place recycling includes hot in-place, cold in-place, or full-depth reclamation. Both hot and cold in-place recycling only addressed the top 1 to 4 in. of the old pavement surface. Asphalt concrete pavements pulverized in-place along with a portion of the unbound materials (i.e., full-depth reclamation) provides a stabilized base material that is covered with a wearing surface. In-place recycling of asphalt concrete pavements is covered in a separate NCHRP synthesis currently in production.

RAP can be used as backfill material (TFHRC 2010); however, most RAP is reused in the production of fresh HMA either in-place or stockpiled and added during central plant production processes. Another smaller source of recycled asphalt concrete material is the rejected or leftover fresh mix at the end of a day's production. Additional information can be found at the following websites:

- National Asphalt Pavement Association (NAPA) www.hotmix.org
- American Recycling and Reclaiming Association (ARRA) www.arra.org

### Literature Review Summary

Guidance was found in the literature for minimizing embrittlement of the mix binder when using high levels of RAP, improving consistency of mix properties with stockpiling practices, using RAP in mechanically stabilized earth (MSE), and cost considerations. The use of rejuvenators had the potential for allowing for a higher RAP content in an HMA mix while still achieving the desired combined binder properties needed for good long-term performance. In addition, using crumb rubber and RAP in HMA had some potential for mitigating increased brittle behavior of the mix. Material preparation included fractionation of the RAP to make it easier to control the final mix gradation. RAP stockpiles were commonly tested to determine the asphalt content, aggregate gradation, and other aggregate properties as required by specifications. The use of warm mix asphalt technologies improved the workability of RAP HMA.

Cold mixes with the proper moisture contents were placed with conventional paving equipment and operations. Mix property variability tended to increase with increased RAP content; therefore, adjustments to sampling frequency needed to be increased so that the design properties were achieved during construction. Care needs to be taken during the mixing of cold RAP mixes so that overmixing is avoided.

Density measurements of RAP backfill were accomplished with standard nuclear gauges as long as the readings were correlated with a standard laboratory compaction measurement. However, the nuclear gauge readings tended to report higher than actual densities. It is important that correlation curves be established for each project. When RAP was used as backfill in an MSE, it was well-compacted so that deformation was minimized and adequate contact with the reinforcement was obtained. The lower angle of internal friction is to be considered when calculating the pullout capacity of the reinforcement.

Fuel costs are a major component in producing and placing asphalt concrete mixes. When warm mix technologies were used to produce HMA the energy consumption decreased by 4%. Increasing the use of RAP to 10% resulted in a 6% reduction in energy consumption. At 50%, RAP reduced energy consumption to an equivalent of energy needed to produce CMA. Increasing the amount of RAP in HMA increasingly reduced energy use.

Conflicting information with regard to cost savings was found in the literature. One study showed that increasing the allowable RAP content from 20% to 30% did not result in a statistically significant cost savings, and at least three bids were needed to notice cost savings in the bids. That is, competition was necessary to pass the savings on to the agency. More benefits were seen when higher RAP contents were considered as value engineering. Also, a minimum threshold of cost savings to the contractor was required before increased RAP content was considered economically attractive.

TABLE 13
NUMBER OF STATES USING RECYCLED ASPHALT PAVEMENTS IN HIGHWAY APPLICATIONS

| Byproducts | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Treatments (non-structural) | PCC | Soil Stability |
| Baghouse Fines (HMA plant) | 2 | 0 | 0 | 0 | 0 | 36 | 0 | 0 | 0 |
| HMA, Unmilled (chunks) | 0 | 0 | 2 | 11 | 0 | 3 | 0 | 0 | 2 |
| HMA, Plant/Project Fresh Left-Over Mix | 0 | 0 | 0 | 1 | 0 | 18 | 1 | 0 | 1 |
| RAP, as Milled and Stockpiled | 0 | 0 | 4 | 9 | 0 | 36 | 3 | 0 | 5 |
| RAP, Separated into Sized Stockpiles | 0 | 0 | 3 | 2 | 0 | 34 | 3 | 0 | 1 |
| RAP, Unknown Type | 1 | 0 | 1 | 3 | 0 | 13 | 0 | 0 | 3 |

Embank. = embankment.

**Agency Survey Results for Recycled Asphalt Pavements**

All agencies responding to the survey indicated they have used RAP byproducts in at least one application. The majority of the states reused HMA baghouse fines in the production of fresh HMA. The majority of the states also used either as-received or fractionated RAP in fresh HMA (Table 13; Figure 13). Fewer states reused fresh HMA left-over mix in fresh HMA. The most common use of unground RAP (i.e., chunks) was in the construction of embankments. A limited number of states used RAP in pavement surfaces, soil stabilization, or drainage materials. Only a few states used RAP in more than one highway application (Table 14). No distinction was made in this survey with regard to use in either in-place or central plant recycling.

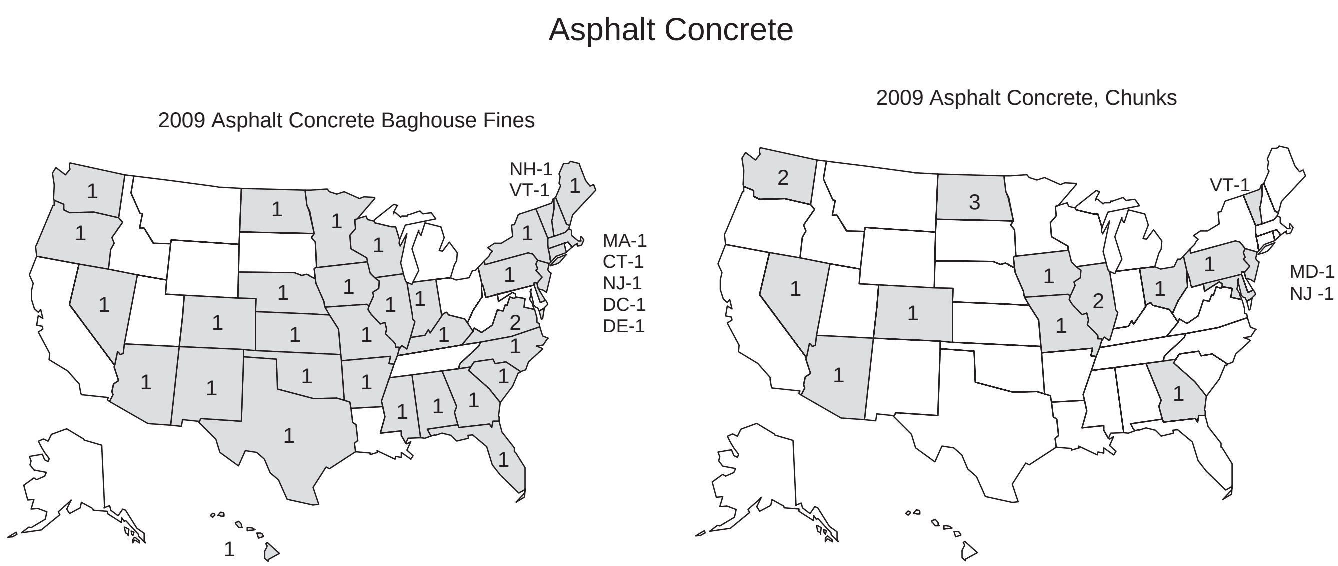


FIGURE 13. (*Figure continued on next page*)

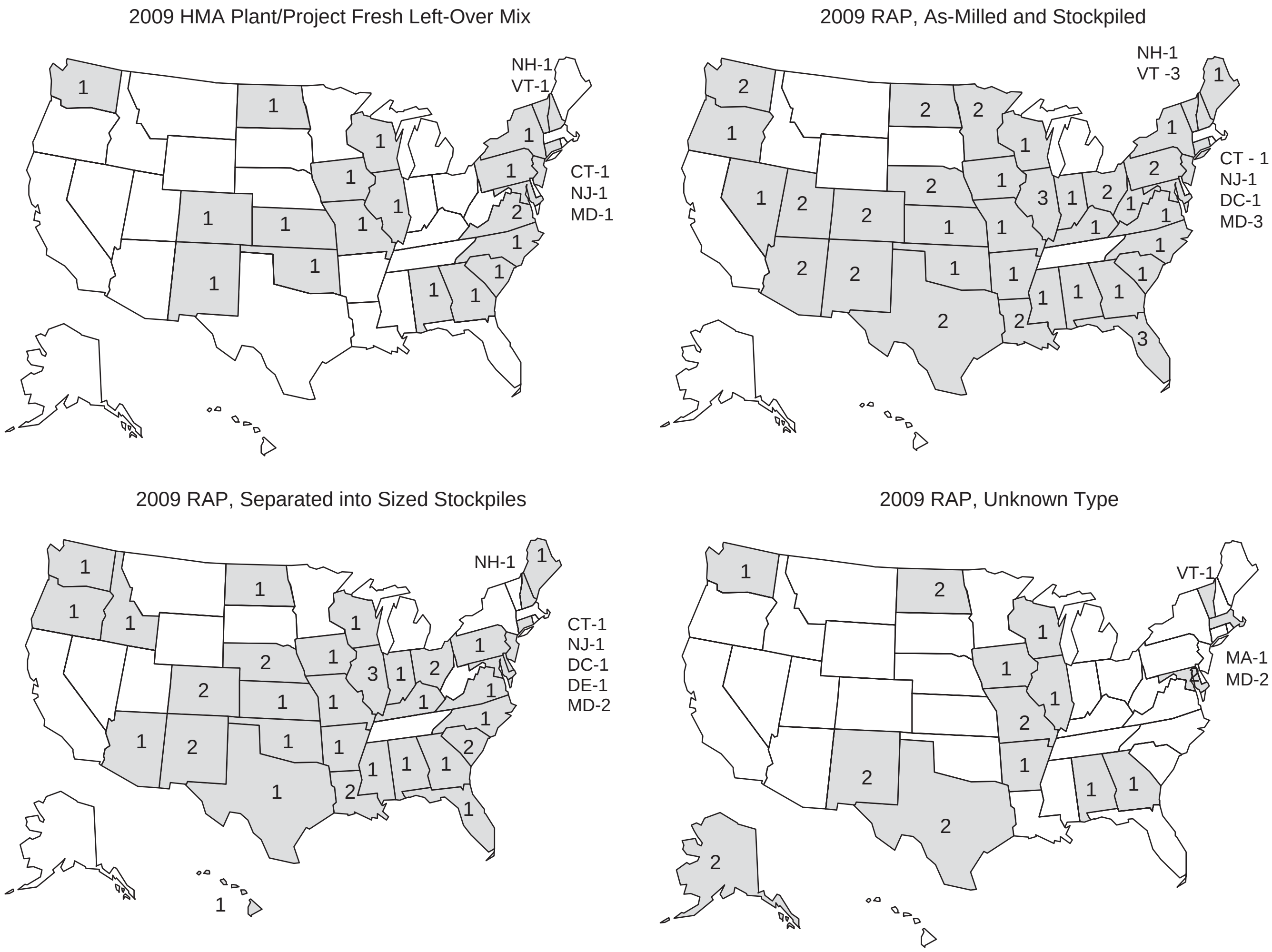


FIGURE 13 (*continued*) Agency survey results for recycled asphalt pavement byproducts (numbers indicate the number of applications that use the byproduct).

TABLE 14
STATES USING RECYCLED ASPHALT PAVEMENT IN HIGHWAY APPLICATIONS

| Number of Applications | States | | | | | |
|---|---|---|---|---|---|---|
| | Baghouse Fines (HMA plant) | HMA, Unmilled (chunks) | HMA, Plant/Project Fresh Left-Over Mix | RAP, As-Milled and Stockpiled | RAP, Separated into Sized Stockpiles | RAP, Unknown Type |
| 3 | — | ND | — | FL, IL, MD, VT | IL | — |
| 2 | VA | IL, WA | VA | AZ, CO, LA, MN, ND, NE, NM, OH, PA, TX, UT, WA | CO, LA, MD, NE, NM, OH, SC, VA | AK, MD, MO, ND, NM, TX |
| 1 | AL, AR, AZ, CO, CT, DC, DE, FL, GA, HI, IL, IN, IA, KS, KY, MA, ME, MN, MO, MS, NC, ND, NE, NH, NJ, NM, NV, NY, OK, OR, PA, SC, TX, VT, WA, WI | AZ, CO, GA, IA, MD, MO, NJ, NV, OH, PA, VT | AL, CO, CT, GA, IL, IA, KS, MD, MO, NC, ND, NH, NJ, NM, NY, OK, PA, SC, VT, WA, WI | AL, AR, CT, GA, IN, IA, KS, KY, ME, MO, MS, NC, NH, NJ, NV, NY, OR, OK, SC, VA, WI, WV | AL, AZ, CT, DC, DE, FL, GA, HI, ID, IN, IA, KS, KY, ME, MO, MS, NC, ND, NH, NJ, OR, OK, PA, TX, VA, WA, WI | AL, AR, GA, IL, IA, MA, VT, WA, WI |

CHAPTER EIGHT

# SCRAP TIRE BYPRODUCTS

## BACKGROUND

Approximately one scrap tire is generated per person in the United States every year (RMRC 2008). Approximately 30 million of these tires can be used for retreading, which leaves about 250 million scrap tires in need of alternative uses or disposal. The main scrap tire byproducts, as defined on the RMRC website, are:

- *Whole tires:* used as-is with no post-processing.
- *Slit tires:* cut in half or sidewalls separated from the tread.
- *Shredded or chipped tires:* 4 in. by 4 in. (100 by 100 mm) to as large as 9 in. by 18 in. (229 by 457 mm). (Note: there are no equivalent sieve sizes for these measurements; sizing is done by manual measurements or visual observations.)
- *Ground rubber:* ranging in sieve size from 3/4 inch to the No. 100 sieve (19 mm to 0.15 mm) and regular in shape.
- *Crumb rubber:* ranging in sieve size from No. 4 to the No. 200 sieves (4.75 mm to less than 0.075 mm).

ASTM D6270 Standard Practice for Use of Scrap Tires in Civil Engineering defines tire-derived aggregate (TDA), with different definitions for shredded, chipped, or ground rubber byproducts.

Further definitions for scrap tire byproducts are provided by the Rubber Manufacturers Association (RMA 2006). This reference notes that ground tire byproducts are generated by tire buffings (no specific size requirements), and processed whole tires that are sorted into four size-based categories:

- *Tire buffings:* byproduct of the retreading industry.
- *Coarse rubber:* No. 4 to 1 in. sieve sizes (4.75 to 25 mm).
- *Ground rubber:* No. 80 to No. 10 sieve sizes (0.177 to 2.0 mm).
- *Fine ground rubber:* No. 40 to No. 80 sieve sizes (0.037 to 0.177 mm).

Information found in the literature used these terms, sometimes interchangeably, with no clear indication of the size of the scrap tire byproduct actually used in the project. The lack of consistency in the use of terms and definitions made it difficult to compare results from various studies. Additional information can be found at the following websites:

- Rubber Manufacturer's Association: www.rma.org
- Rubber Pavement Association: www.rubberpavements.org

### Literature Review Summary

A number of highway applications were found for scrap tire byproducts. Information was collected for byproducts used in embankments, fills, PCC, HMA, and crack sealants. Several researchers reported soil improvements when combining TDA with soil. Laboratory study of soil–TDA combinations of embankment fill had higher strength and lower unit weight, greater resistance to lateral sliding of embankments on geotextile layers, low active earth pressure and higher interface resistance, and greater resistance to bearing failure because of lighter weight. Compacted TDA had a significantly lower thermal conductivity than conventional soils that can provide good insulation.

TDA base was used successfully when designed using the standard Boussineq's solution for embankment design. Field studies of soil–TDA combinations for an MSE wall showed that conventional design methods for the MSE wall can be used with soil–TDA backfill. Leachates were evaluated for TDA–soil mixtures. Drinking water standards were occasionally exceeded when the byproduct was submerged in water; however, the concentrations were not detectable a short distance away.

The advantages to using crumb rubber in PCC were decreased unit weight, porosity, thermal conductivity, and chloride penetration. The byproduct also increased toughness (the ability to exhibit large deformations prior to failure). Reported disadvantages were a loss of compressive and tensile strengths.

Combining crumb rubber with fly ash in PCC applications somewhat improved the compressive strength compared with crumb rubber without fly ash in PCC applications. Crumb rubber in PCC changed the damping characteristics used in seismic designs of structural concrete. One report noted that crumb rubber could be used in precast applications to produce light-weight low-strength panels with good insulation and noise damping properties. Larger-size scrap tire byproducts tended to separate during construction with PCC slurries and there was a maximum size that can be used without segregation. PCC slurries with larger scrap tire byproducts proved difficult to finish and were relegated to use in applications that were covered (e.g., soil cap).

## HOT MIX ASPHALT APPLICATIONS

In HMA applications, the performance-grade (PG) binder specification designation did not consistently change with the addition of the crumb rubber. Any changes in the asphalt cement grade were a function of the original binder actual temperature grading rather than the specification grading temperatures. When crumb rubber (continuous process) is added, the maximum summer temperature for which the binder could be used increased by about 1.2°C to 1.5°C of the true temperature grading for each 1% of crumb-rubber modified (CRM). The low winter temperature was decreased by about 0.2°C for each 1% of CRM.

Crumb rubber in HMA open- and gap-graded wearing surface significantly lowered the noise level of the tire–pavement interaction when compared with conventional dense-graded HMA. However, it was not clear if the reduction was a function of the crumb rubber or the gradation. It can be noted that the high film thickness and low draindown of the CRM binders facilitated the use of more open-graded HMA than could be achieved with an unmodified binder.

Combinations of CRM asphalt binders and RAP were used in the same mixes. The laboratory work showed that care was necessary in the design phase to make sure that the combined binder properties had acceptable high temperature rheology and were suitably crack resistant at cold temperatures.

National Institute for Occupational Safety and Health noted emissions for crumb rubber HMA were higher than for conventional HMA and the temperature needed to be kept as low as possible. The use of crumb rubber in HMA production occasionally produced eye, nose, and throat irritations for the paving crews, which was related to the total measured particulates. The use of warm mix asphalt technologies was shown to have the potential for keeping temperatures lower than standard temperatures while still maintaining workability. Applying a hot crumb rubber modified binder over paving fabric resulted in wrinkling of the fabric and a tendency for the fabric to stick to the pneumatic tire rollers.

## AGENCY SURVEY RESULTS FOR SCRAP TIRE BYPRODUCTS

Ground tires and crumb rubber (wet or dry process) were most frequently used in HMA applications, followed by emulsions and crack sealants (Table 15). The most commonly used application for shredded tires or chipped tires was in embankments. Table 16 summarizes which scrap tire byproducts were used by each state agency (Figure 14). Only Vermont used slit tires as drainage material and only Texas used whole tires in embankments. Three states reported having used scrap tire byproducts, but the type of byproduct used was unknown.

TABLE 15
NUMBER OF STATES USING SCRAP TIRE BYPRODUCTS IN HIGHWAY APPLICATIONS

| Byproducts | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stability |
| Ground Tires | 6 | 9 | 0 | 2 | 0 | 13 | 2 | 0 | 0 |
| Shredded or Chipped Tires | 1 | 1 | 1 | 14 | 0 | 3 | 1 | 0 | 0 |
| Slit Tires | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Whole Tires | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Crumb Rubber Aggregate (dry process) | 3 | 1 | 0 | 0 | 0 | 15 | 3 | 0 | 0 |
| Crumb Rubber Modifier (wet process) | 8 | 4 | 0 | 0 | 0 | 22 | 8 | 0 | 0 |
| Tires, Unknown Type or Size | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 2 |

Embank. = embankment.

TABLE 16
STATES USING SCRAP TIRE BYPRODUCTS IN HIGHWAY APPLICATIONS

| Number of Applications | States | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ground Tires | Shredded or Chipped Tires | Slit Tires | Whole Tires | Crumb Rubber (dry) | Crumb Rubber (wet) | Unknown Type |
| 9 | — | — | — | — | — | — | ID |
| 4 | AZ, TX, VA | — | — | — | — | PA, VA | — |
| 3 | — | — | — | — | — | AK, AZ, TX | MA |
| 2 | CT, IL, IA, MN, NE | CT, IA | — | TX | AK, CT, NE, PA | MO, NE, NY, OR | — |
| 1 | AL, CO, FL, ME, NC, OK, WI | CO, DE, IN, LA, ME, MN, NC, NH, NJ, NY, OK, PA, TX, VA, VT, WA | VT | — | IL, IA, KY, ME, MO, MS, NH, NJ, NV, NY, OK, OR, WI, WV | AL, DE, GA, IL, IA, KY, LA, ME, MN, MS, NJ, NV, OK, SC, VT, WA, WI | NJ |

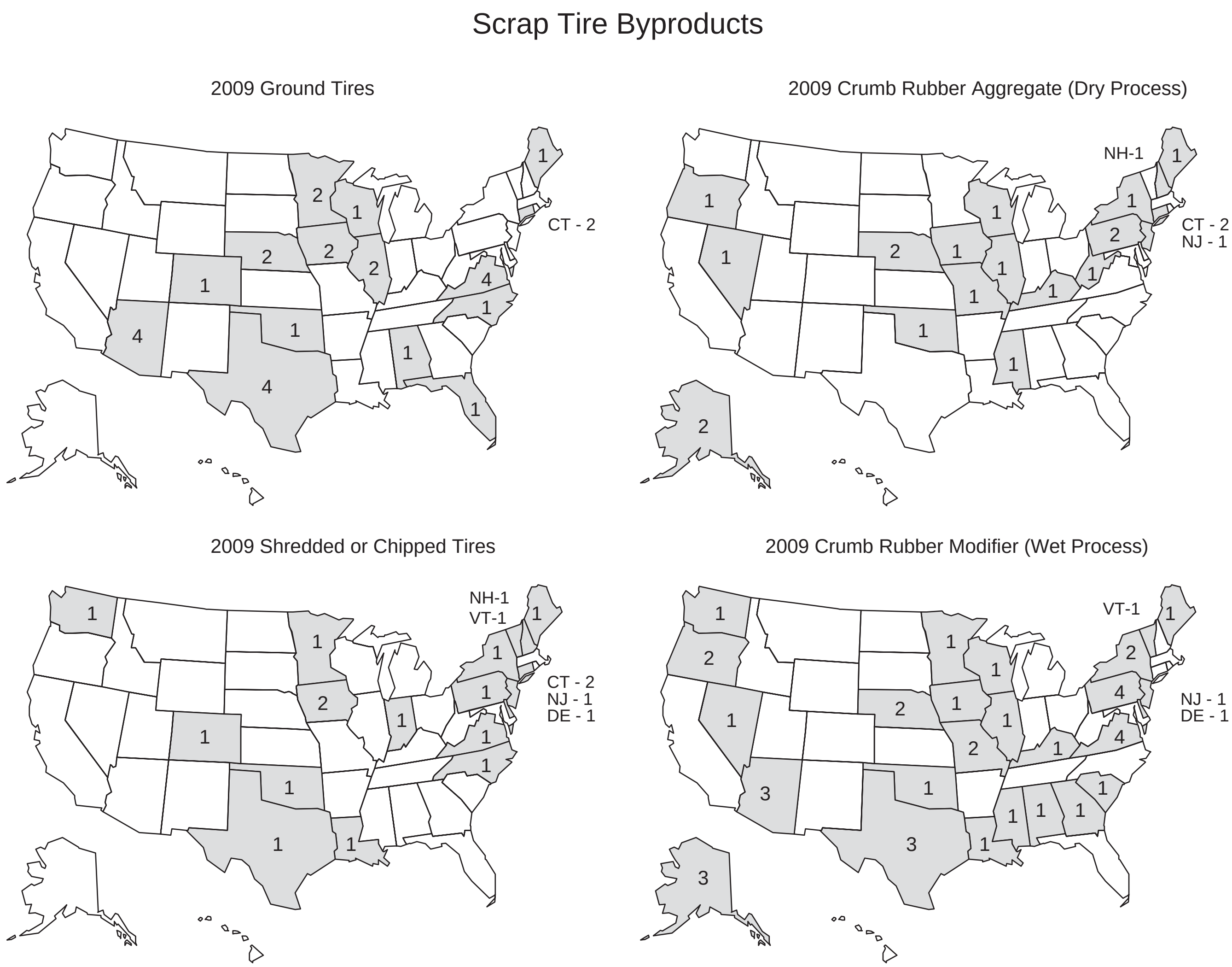


FIGURE 14 Agency survey results for scrap tire byproducts (numbers indicate the number of applications that use the byproduct).

CHAPTER NINE

# MANUFACTURING AND CONSTRUCTION BYPRODUCTS

## CEMENT KILN DUST

### Background

Cement kiln dust (CKD) is generated during the production of the cement clinker and is a dust particulate mixture of partially calcined and unreacted raw feed, clinker dust, and ash that is enriched with alkali sulfates, halides, and other volatiles (Adaska and Taubert 2008). According to EPA (2010), the definition of CKD is "a fine-grained, solid, highly alkaline material removed from the cement kiln exhaust gases by scrubbers (filtration baghouses and/or electrostatic precipitators)." The composition of CKD varies by plant and over time at a single plant. Much of the material comprising CKD is incompletely reacted raw material, including a raw mix at various stages of burning and particles of clinker.

Cement is produced using a rotary kiln to turn raw materials (limestone, clay, iron ore, silica) into a sintered product referred to as a clinker. Gypsum is added at the end of the process to manage the rate of hydration. A rotary kiln is fundamentally a long, slowly rotating cylinder tilted at a slight angle with the burner at the lower bottom end. The raw materials enter the top end of the cylinder, are heated, then exit and cool. The sintered material at the bottom end is referred to as "clinkers." Kilns were first introduced in the 1890s and became popular in the first part of the 1900s as improvements were made to provide continuous production and a more consistent final product in larger quantities ("Understanding Cement" 2010). There are three main types of kilns:

- Long-wet kiln
- Long-dry kiln
- Precalciner kiln.

The original kiln style was the long-wet kiln, which feeds in the raw material as slurry, and the cylinder can be up to 656 ft long and 20 ft in diameter. The length is required because the material needs sufficient time to dry out the slurry water, which until recently was difficult to blend and add dry ("Understanding Cement" 2010). Once in the kiln the materials are calcined then sintered to form the clinker. Some of these kilns are still in use.

Newer dry kiln configurations add the dry, blended raw materials after passing through a pre-heating tower using heat from recycling hot kiln gases (Figure 15). The heat exchange is accomplished by feeding the finely ground raw material, called raw meal, into the top of the pre-heater tower, then passing through a series of cyclones in the tower through which the hot gases are circulated ("Understanding Cement" 2010). The high surface area and small particle size provide efficient heat transfer and about 30% to 40% of the decarbonation of the raw meal before it enters the kiln. Because the material enters preheated, the length and the diameter of the cylinder can be smaller but still produce the same quantity of clinker per hour.

The precalciner kiln, the newest technology, is similar in concept to the dry kiln but with the addition of a second burner, or precalciner (Figure 16). With the additional heat, 85% to 95% of the material is decarbonated before entering the kiln ("Understanding Cement" 2010).

The particulates for all types of the cement kilns are captured from the exhaust gases using air pollution control devices such as cyclones, baghouses, and electrostatic precipitators (Adaska and Taubert 2008). The particles captured in this process are the CKD. The type of kiln that generates the dust can significantly influence the chemistry of the CKD byproduct.

### Literature Review Summary

The list of the most commonly researched and used CKD byproducts include CKD, long-wet or long-dry kiln, and CKD precalciner kiln.

CKD for PCC applications was most effective when there was a high concentration of calcium oxide (CaO) and a low loss on ignition. These properties were found to be a function of the type of cement kiln technology. Periodic byproduct testing was recommended to track historical changes in CKD byproduct over time, since changes in technology, burner fuel, and/or sources of raw materials can change the properties of the CKD. Post-processing of the CKD improved reactivity by the grinding of the CKD.

Fresh CKD was best if kept dry prior to use in a highway application. Keeping track of the age of the CKD on the information provided to the user could help decrease byproduct variability.

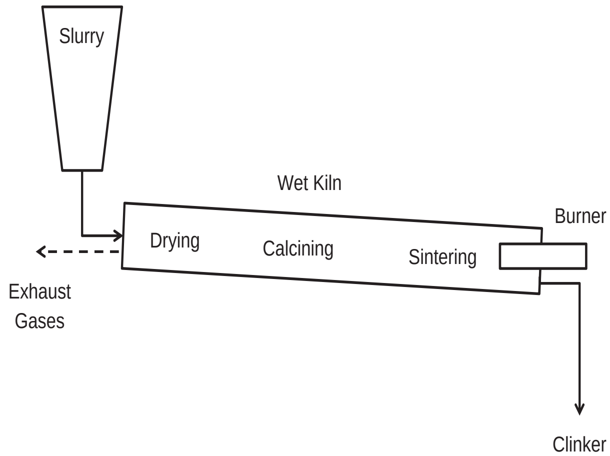


FIGURE 15 Typical long-wet kiln configurations (after "Understanding Cement" 2010).

Project and research data showed that using CKD in PCC applications generally reduced the compressive strength, but a combination of CKD and fly ash helped minimize the loss of strength. The best strengths were obtained when the CKD had a high CaO content and a low loss on ignition. CKD or CKD–fly ash decreased PCC workability and occasionally required the use of superplastizers in the PCC mix design.

CKD was also used to improve soil properties by decreasing plasticity and increasing strength. Adding fly ash with the CKD resulted in further property improvement. CKD increased in the pH of water, which needs to be considered during the project selection and design phases.

Reactivity of the CKD was improved with warmer and slowed by colder temperatures. The rate of improved strength owing to weather conditions and the increased strength of the soil should be considered in designing and constructing the applications.

One study evaluated the properties of landfilled CKD, which were relatively consistent throughout the 12 years of the operation, although there were noticeable differences in the composition owing to hydration over time. The aged CKD reactivity was lower than fresh CKD byproducts.

### Agency Survey Results

The most common use of CKD was in soil stabilization (Table 17). Eleven states indicated they have used CKD in highway applications (Table 18, Figure 17). Two of these states used a combination of cement and lime kiln dusts. No information was collected with this survey on the type of kiln used to produce the byproduct.

## ROOFING MATERIALS

### Background

From the late 1800s to the 1970s, roofing shingles were manufactured by saturating a thick organic mat such as cotton, asbestos, waste paper, or wood fibers with asphalt topped with protective stone coating (Figure 18; Seattle Roof Broker 2010). Although the shingles came with 15- to 20-year warranties, they were typically left in place from 30 to 35 years. In the 1970s, the conversion was made from organic to fiberglass

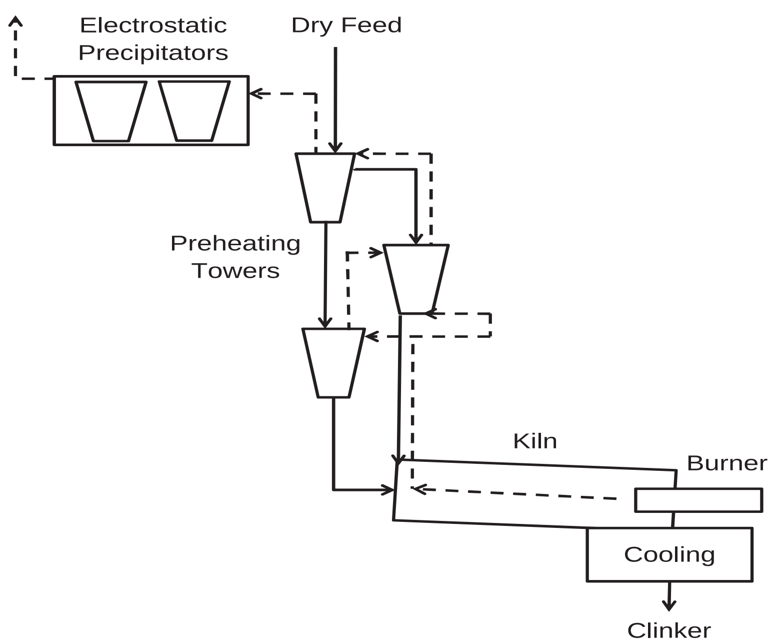


FIGURE 16 Precalciner kiln configuration (after "Understanding Cement" 2010).

TABLE 17
RESULTS FOR AGENCY SURVEY FOR CEMENT KILN DUST BYPRODUCTS USED IN HIGHWAY APPLICATIONS

| Byproduct | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Cement Kiln Dust | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 3 | 7 |
| Combination Kiln Dust | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |

Embank. = embankment.

TABLE 18
STATES USING CKD BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

| Number of Applications | States | |
|---|---|---|
| | Cement Kiln Dust | Combined Dust |
| 2 | OR | — |
| 1 | CO, IL, IN, IA, KY, MO, NE, NM, NY, TX | IA, MA, NY |

backing. However, the 1974 oil embargo and the economic recession in the 1980s compelled roofing shingle manufacturers to focus on cost savings, which led to a reduction in the fiberglass mat (expensive) and an increase in mineral filler content in the asphalt to extend the binder volume and save money. There was declining asphalt content in the newer shingle products compared with the older recycled asphalt shingles (RAS) materials.

There are several types of roofing materials that are asphalt-based products available for recycling, including:

- Roofing manufacturing byproducts (pre-consumer);
- Tear-offs (post-consumer); and
- Built-up roofing (BUR), which is an asphalt and roofing felt product constructed in-place.

No information was found on the research or use of BUR in highway applications.

Regardless of the source of the shingles, RAS needs to be post-processed by shredding, sizing, and cleaning to be used in highway applications. The steps in processing RAS for use in highway applications are:

- Grinding
- Sizing
- Contaminate removal (tear-offs)
- Stockpiling.

Brock (2007) described various methods of shredding RAS that have been tried over the years. Equipment needed for processing includes crushers, hammer mills, and rotary shredders, with variable success (Figure 19; Brock 2007). Brock (2007) noted that most shingles were shredded with large wood chippers with 500 hp engines that produced about

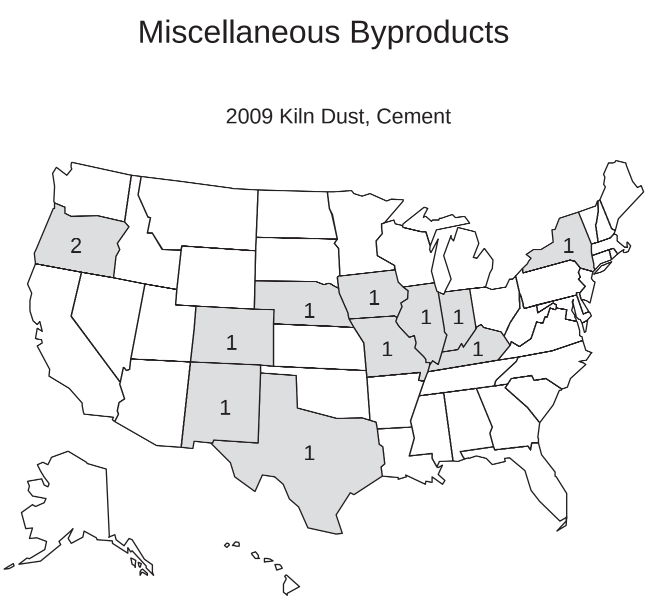


FIGURE 17 Agency survey results for cement kiln dust byproducts.

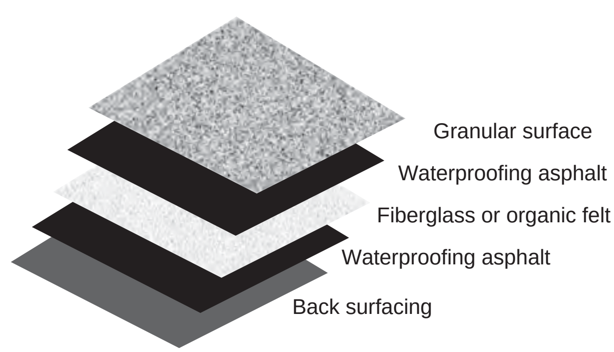


FIGURE 18 Typical composition of roofing shingles (after Gevrenov 2007).

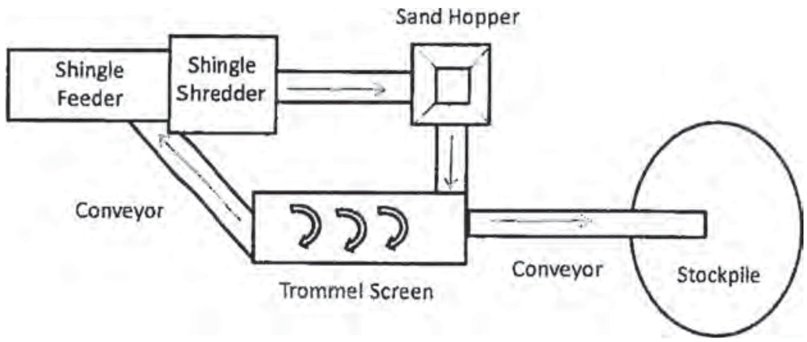


FIGURE 19 Typical grinding operation set up (after Brock 2007).

50 to 75 tons of RAS per hour. To ensure that the RAS meets the ½ inch minus particles size, the material needed to pass through the shredder a second time.

Grinding could be easier in the winter when the shingles are cold and more brittle, which helps minimize agglomeration. The oxidation of the roofing asphalt aided in reducing the agglomeration of the shredded material (VANR 1999). A Minnesota recycler found grinding manufacturing byproduct was easier if the material had weathered by being stored in a stockpile for a year before grinding. Manufacturing byproducts were reportedly more difficult to process than the aged roofing material, which had hardened with age and was less likely to agglomerate during grinding (VANR 1999). Some shredding processes used water to cool the cutting heads and limit dust production. It can be noted that aging may help the mechanical processing but could result in a harder asphalt byproduct that might accelerate pavement cracking resulting from embrittlement.

#### Literature Review Summary

The list of the most commonly researched and used byproducts include roofing manufacturer (pre-consumer) and tear-off shingles (post-consumer).

Post-processing (grinding) of RAS is needed to size the byproduct for HMA, soil improvements, and dust control applications. Some contractors added sand during the grinding process to minimize agglomeration. If sand was used, it needed to be considered in the overall application design. Others reported that grinding of the RAS in colder weather was easier and minimized agglomeration of particles.

Grinding processes that are used to cool the cutting heads need to evaluate the moisture contents of the stockpiles prior to use. Dust mitigation was required during RAS grinding operations. Any metals (tear-offs) were removed as the RAS was stockpiled. Recommendations were made for preparing individual stockpiles for each type of RAS byproduct. Some states required the stockpile to be tested for asbestos content (primary for tear-offs). This was not a concern for current manufacturing byproducts because asbestos is no longer used in roofing materials.

When RAS was used in HMA applications, the combined RAS-aged asphalt and fresh asphalt cement PG grade occasionally resulted in a higher PG grade upper temperature and occasionally a warmer PG grade lower temperature. Changes in the binder properties owing to the addition of 5% RAS were similar to changes observed when using 30% to 40% RAP only (Schultz 2010). The aged RAS asphalt increased the viscosity and stiffness of the binder and the final HMA. In some cases, the moisture content of RAS required longer dwell times in HMA plants. Higher moisture content RAS HMA showed an inclination to be tender during rolling, which had to be delayed to prevent movement of the mix under the rollers.

Recent research focused on the use of RAS as a means of improving the stability of poor soils or as a method of dust control. Soil stability improvements used 5% finely ground RAS to increase the California bearing ratio (CBR) values of soils with initially low values. Improvements were seen in CBR, compressive strengths, and especially tensile strengths of the modified soils. The most improvement was seen when the soil had high fines content. A combination of RAS and fly ash worked well with silty subgrade soils. RAS did not improve properties when used with base materials with initially higher CBR value (e.g., crushed limestone).

A dust control study used ground tear-offs, which were spread on a gravel base and mixed with a motor grader. The result was approximately 2.5 in. of surface mix, which was somewhat friable. An emulsion fog seal was used to preserve the surface. Three states have used similar applications to reduce dust and provide improved driving conditions.

Tipping fees varied widely across the country. Based on material values and operating costs in the early 2000s, the most commonly reported tipping fee was approximately $50/ton with cost grinding, sorting, testing, housing, regulator and administrative costs of about $40/ton. The cost of processing RAS was equivalent to 75% to 80% of the average tipping fees. Organic-backed manufacturer RAS and tear-offs provided a cost savings of approximately 5% per ton of HMA at

TABLE 19
USE OF ROOFING SHINGLE BYPRODUCTS IN HIGHWAY APPLICATIONS

| Byproduct | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stability |
| Roofing Shingles, Fiberglass-Backed | 1 | 0 | 0 | 0 | 0 | 14 | 0 | 0 | 0 |
| Roofing Shingles, Paper-Backed | 0 | 0 | 0 | 0 | 0 | 13 | 0 | 0 | 0 |
| Roofing Shingles, Tear-Offs | 1 | 0 | 0 | 0 | 1 | 12 | 0 | 0 | 1 |
| Roofing Shingles, Unknown Type | 1 | 0 | 0 | 0 | 4 | 1 | 0 | 0 | 0 |
| Roofing, Built-Up Roofing (BUR) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Embank. = embankment.

4% RAS content (Brock 2007). Fiberglass-backed RAS produced a savings of about 3% per ton of asphalt. The difference in cost savings was the result of the higher asphalt content used for the organic-(paper) backed shingles that were prevalent in the older shingle products. Recycling equipment maintenance costs could be a significant factor in the costs of operation owing to the presence of the granular component in the grinding mechanisms.

### Agency Survey Results for Roofing Shingle Byproducts

The primary use of recycled asphalt shingles was in HMA application, although several states indicated a use in fills, and one state reported experience with its use in soils (Table 19). No states were currently considering or using BUR byproducts in any highway applications. Those states using RAS in unbound applications were using tear-offs (Table 20, Figure 20).

## RECYCLED FOUNDRY SANDS

### Background

Foundry sand is a uniformly graded, high-quality sand byproduct from the ferrous and non-ferrous metal casting industry (FIRST 2004). The metal casting industry uses the foundry sand in two ways: The first is as a molding material to form the external shape of the cast part; the second as a core material to fill the internal void space in products such as engine blocks. Because sand grains do not naturally adhere to each other to hold the desired mold shape, binders are added to the sand. Recycled (spent) foundry sand (RFS) can include other materials from foundry processes such as cleaning and grinding operations, slag, and dust collector equipment (i.e., baghouses) (Partridge and Alleman 1998).

Most foundries have two sand systems: one for external modeling lines and one feeding the internal core lines. After the metal is poured and the cast product is cooled the green sand is shaken off of the part, recovered, and reconditioned for reuse in the molding process. Used cores are reclaimed during the cooling and shaking processes. The reclaimed core material is crushed and reintroduced into the green sand systems to replace a portion of the sand lost in the process. Broken and/or excess cores or those that do not break down when crushed are discarded. The flow chart for typical foundry processes is shown in Figure 21.

Binder systems can be either clay-bonded systems (green sand) or chemically bonded systems (resin sands) (FIRST 2004). Green sands are used to produce about 90% of the casting volume in the United States and consist of 85% to 95% silica, 4% to 10% bentonite clay, 2% to 10% carbonaceous additive (e.g., seacoal and gilsonite), and 2% to 5% water. The carbon content gives the sand a black color. Resin sands are used in core-making, where high strengths

TABLE 20
AGENCIES USING ROOFING SHINGLE BYPRODUCTS IN HIGHWAY APPLICATIONS

| Number of Applications | States | | | | |
|---|---|---|---|---|---|
| | Fiberglass-Backed | Paper-Backed | Tear-Offs | Unknown Type | Built-Up Roofing (BUR) |
| 2 | — | — | ME, VA | — | — |
| 1 | AK, AL, DC, FL, ID, IL, KY, LA, MO, NC, NV, NY, OH, OR, WV | AK, AZ, CT, DC, FL, KY, LA, MO, MS, NC, NY, OH, OK, VA | AK, AZ, CT, DC, DE, ID, KY, MO, NY, OH, OK | AL, MO, SC, VT, WI | — |

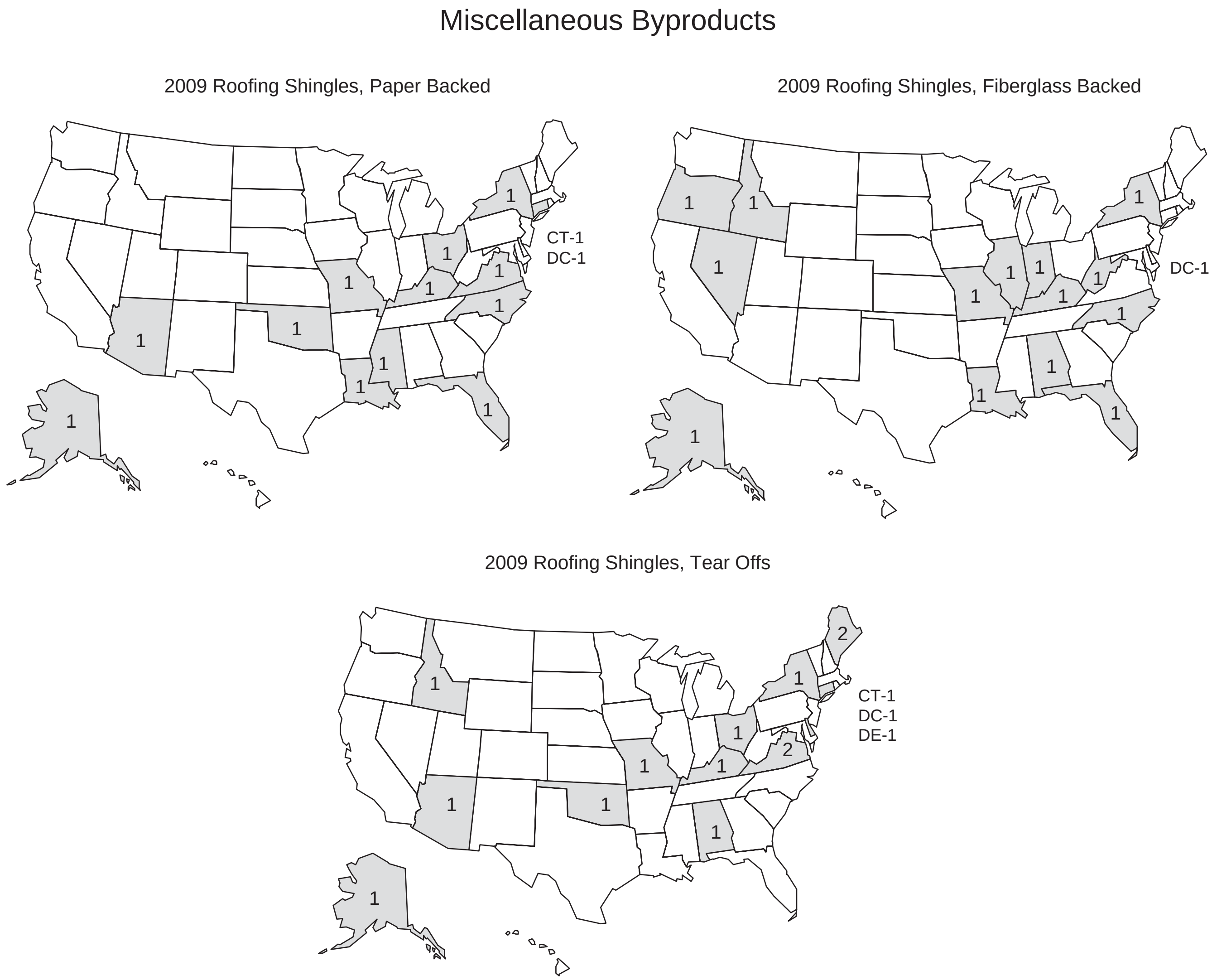


FIGURE 20 Agency survey results for roofing shingles byproducts (numbers indicate the number of applications that use the byproduct).

are needed to withstand the heat of the molten metal, and in mold making. Most of the chemical binders consist of an organic binder (e.g., oil, cereal, and wood proteins; Hughes 2002), which is activated by a catalyst, although some systems use an inorganic binder such as portland cement or sodium silicate (Hughes 2002). The most common chemical binder systems are phenolic-urethanes, epoxy-resins, furfyl alcohol, and sodium silicates (FIRST 2004). The resin sands tend to be somewhat coarser in texture than the green sands.

It may be important to separate the RFS byproduct streams at the foundry because of the different material characteristics of the external and core molding sands. Any metal contaminates in the recycled sands must be removed. Large chunks of burned cores, referred to as core butts, required further crushing, separation, and screening before recycling.

**Literature Review Summary**

The list of the most commonly researched and used byproducts include green sands and core sands.

The foundry sand byproducts are separated by their use in the casting process, which alters the physical and chemical properties. These differences are a function of the type of additive used with the original foundry sand, the type of metal being cast, and the specific casting process used. Green sands are used to form the external modeling lines and are reclaimed and reused by the foundry until they fail to meet foundry sand requirements.

The casting cores have been hardened by additives such as epoxies, resins, and organic binders (e.g., portland cement

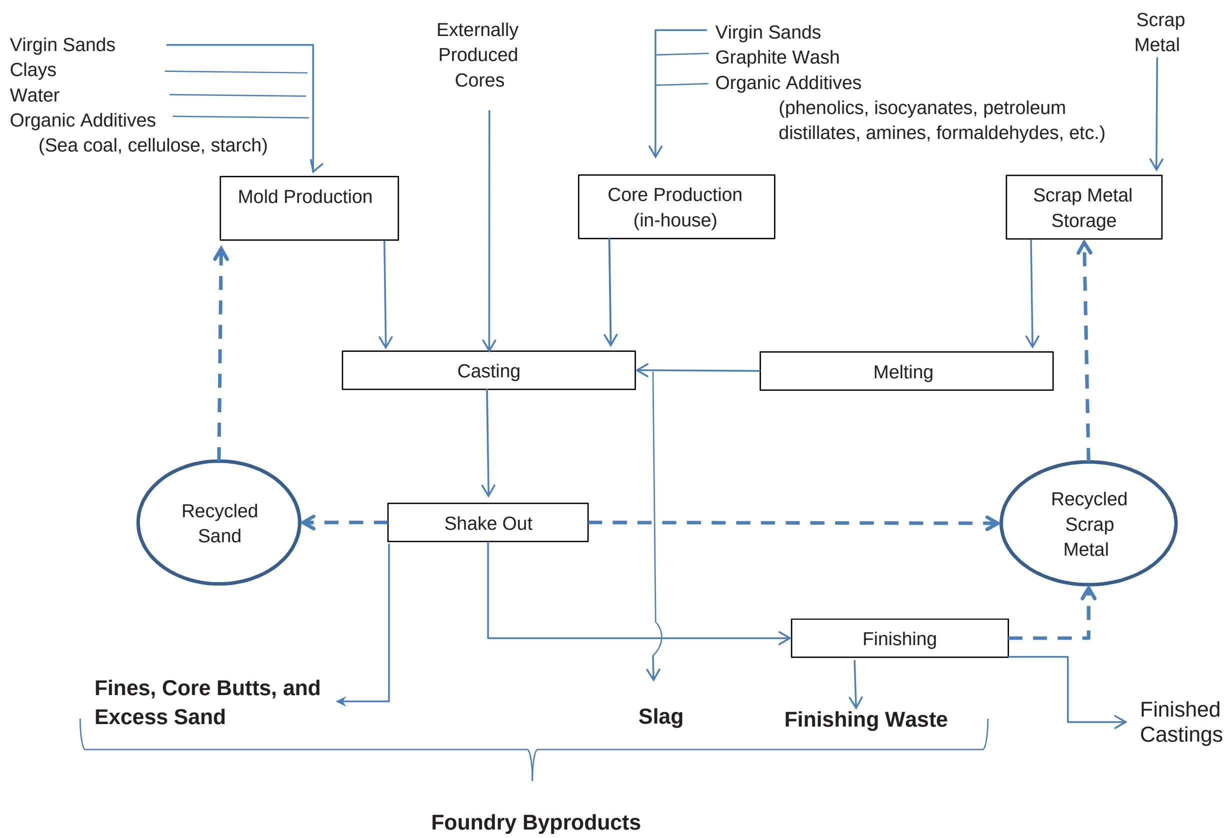


FIGURE 21 Flow chart for the generation of foundry sand byproducts (after Partridge and Alleman 1998).

and wood proteins) to form the inside of the part. This portion of the spent foundry sand required further crushing, separation, and screening before using in highway applications. Post-processing included the removal of general refuse and other contaminates, metals, and sizing.

Research and pilot projects only occasionally apply RFS separating green and core sands. PCC applications showed RFS PCC mixes typically required higher portland cement contents, which was addressed during the mix design phase. Fly ash was needed to compensate for a loss of workability owing to the RFS.

When RFS was used in embankments, base, or as fill the designs needed to account for a less freely draining material. Additional crushing and compaction efforts may be needed if the spent foundry sand cores are not crushed prior to use in base applications.

Specific recommendations for using RFS as a base material were to place the byproduct on a prepared foundation in horizontal loose lifts not to exceed 8 in., then compact the lifts to a stable, durable condition with at least eight passes of a vibratory steel wheel roller with a minimum weight of 10 tons or the centrifugal equivalent. The compaction of the lifts needs to achieve 98% of the maximum density proper moisture content to achieve the desired in-place density. A significant amount of water was occasionally required so that compaction was achieved on the first time around, as RFS was difficult to re-wet because of the clay additive.

If the sides and top of the RFS layer were exposed, recommendations included covering the sides and top with natural soil with a minimum vertical cover of 3 ft, measured from the subgrade elevation and a minimum horizontal cover of 8 ft.

Regional recycling facilities in one region were used to reduce the cost of post-processing byproducts. The benefits of using a recycling facility included a single disposal location for smaller foundry operations, post-processing operations for useable byproducts with consistent properties, and adequate quantities for a given application product.

### Agency Survey Results for Recycled Foundry Sand

Table 21 shows that only six states reported experience with RFS in highway applications. Only North Carolina noted experience with sands from sand blasting operations (Table 22; Figure 22). Five states used recycled foundry sand in unbound (drainage, embankment) or semi-bound (flowable fill) applications. No distinction was made between green sand and cores in the survey questions or responses.

TABLE 21
RESULTS OF AGENCY SURVEY FOR FOUNDRY SAND BYPRODUCTS
USED IN HIGHWAY APPLICATIONS

| Byproduct | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Sand Blasting Waste | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Sand, Foundry | 0 | 0 | 1 | 3 | 2 | 0 | 0 | 0 | 0 |

Embank. = embankment.

Utah was not currently using RFS in highway applications and the respondent provided information as to why, noting that the uniform size and round shape, which is a desirable property for casting metals, would make it difficult to meet the well-graded aggregate specifications and angular fines requirements for bases and HMA.

## WASTE GLASS BYPRODUCTS

### Background

Waste glass from material recovery facilities is referred to by several names: glass cullet, recycled glass, soda lime glass, crushed glass, or processed glass aggregate. The term "glass cullet" is the more commonly used. This byproduct is recovered from glass containers and from breakages and inferior products made during glass manufacturing. Glass cullet from the glass manufacturing process includes such materials as broken, obsolete, and/or off-specification glass from the manufacturing of plate, window, and analytical glassware (Wartman et al. 2004). Glass from automobiles, lead crystal, television monitors, lighting fixtures, and electronics applications are excluded because of their composition and coatings. The Northeast Resource Recovery Association identifies suitable sources of recycled crushed glass as glass or ceramic bottles, glass jars, ceramic tableware and cookware, vases, ceramic flowerpots, plate glass, mirror glass, and residential incandescent light bulbs.

Most post-consumer containers can be sorted into three categories based on color, which is achieved by different chemical compositions:

- Flint glass: colorless glass food, beverage, beer, liquor, and wine bottles
- Amber glass: brown beer and liquor bottles
- Green glass: green wine and beer bottles.

TABLE 22
STATES USING FOUNDRY SAND BYPRODUCTS
IN HIGHWAY APPLICATIONS IN 2009

| No. of Applications | States | |
|---|---|---|
| | Sand Blasting Waste | Sand, Foundry |
| 2 | — | WI |
| 1 | NC | IA, IN, OH, PA |

Glass cullet can be provided by the material recovery facilities as unwashed, larger, broken glass particles; unwashed but crushed glass cullet; and as washed glass cullet. Washing the byproduct removes most of the contaminates such as paper, plastics, and metals, which would also be considered contaminates in most highway applications.

### Literature Review Summary

The byproduct categories needed for glass cullet are processed glass aggregate (any color) and powdered glass.

Post-processing by washing and crushing produced acceptable physical properties and reduced material variability. For example, the specific gravity became more consistent when the glass cullet is washed, regardless of final gradation. Contamination by "gummy" substances such as labels on the glass cullet wash was removed during this process. Crushing operations were needed to produce a well-graded byproduct,

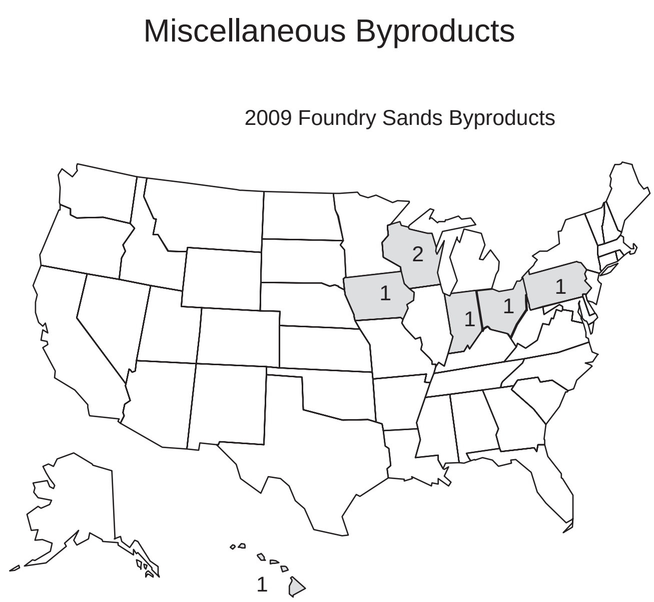


FIGURE 22 Agency survey results for foundry sand byproducts (numbers indicate the number of applications that use the byproduct).

TABLE 23
RESULTS FOR AGENCY SURVEY FOR GLASS PROCESSING BYPRODUCTS USED IN HIGHWAY APPLICATIONS

| Byproduct | Number of States Using Byproduct in a Given Highway Application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embank. | Flowable Fill | HMA | Pavement Surface Treatment (non-structural) | PCC | Soil Stability |
| Any Type | 2 | 1 | 4 | 9 | 2 | 8 | 2 | 3 | 1 |

Embank. = embankment.

which could then be combined with gravel to meet specification requirements. Glass cullet greater than about 3 mm in size were visibly identifiable as crushed glass and required heavy gloves to handle safely.

Glass cullet could be safely handled when it was sized to meet ASTM D448 No. 8 or finer. Handling concerns focused on the potential hazards associated with fugitive dust (eye contact and inhalation). Stockpile storage time sufficient to minimize leachable materials is important.

Reclaimed glass was typically limited to containing no more than 5% of contaminates (e.g., paper, foil, metal, corks, and wood debris). Contaminates were attributed to miscellaneous waste stream differences such as glass color, chemical content of label ink, specialty glass chemistries, and waste thermometers (i.e., mercury content).

Most of the design adaptations were focused on adjustments needed in the design of PCC mixes. It is important that mix designs consider expansive reactions that are a function of the percentage of the glass cullet. As the percentage of glass cullet increased, the water-to-cementitious material ratio was increased to maintain a consistent slump. The air content increased linearly with an increase in the percentage of glass aggregate and occasionally required adjustments to the mix design. High-range water reducers were needed to maintain adequate workability and desired slump. The amount of water reducers was similar to those necessary when using fly ash only. Expansive reactions were minimized by added fly ash or blast furnace slag to help because of the glass cullet. Workability was reduced somewhat, which resulted in more time and effort required to finish PCC surfaces. Segregation and bleeding were observed with glass cullet in PCC mixes.

Unbound applications were less frequently used. The low CBR and limestone bearing ratio limited the use of glass cullet as a base or subbase course. Washing the glass cullet to remove contaminates improved the drainage characteristics compared with unwashed glass cullet. The cleanliness of the glass cullet is to be considered when designing embankments and fill. Glass cullet used as a drainage material works best in combination with synthetic liners, geogrids, or geotextiles when it was not placed directly on the liner material. Recommendations were made to use glass cullet drainage material when there was a minimum depth of ground water or bedrock of 4 ft, and a minimum distance of 150 ft away from any surface water body.

The benefits were noted as the reduced cost of transporting glass to a landfill or distant disposal site, reduced use of landfill air space, reduced amount of virgin aggregate consumed, and improved environmental awareness and attitudes. The costs listed as associated with glass cullet use were the costs of curbside collection, crushing glass, and mixing with aggregate.

#### Agency Survey Results for Waste Glass

Table 23 shows that only six states indicated they used waste glass in more than one highway application. Fifteen states used this byproduct in a single application (Table 24). Figure 23 shows the geographical distribution of the states that indicated experience with this byproduct. The only western states with experience were Alaska, Hawaii, and Idaho.

## SULFUR AND SULFATE WASTE BYPRODUCTS

### Sulfur Byproducts

*Background*

A major byproduct from the oil and gas industries is brimstone, which is essentially elemental sulfur (Shell 2010a–e). Sulfur, in the form of sulfuric acid, is also a byproduct of ferrous and nonferrous metal smelting. The use of sulfur as a binder to produce a construction material has been explored for more than a century (McBee et al. 1985). These early efforts used the sulfur as the binder in mortars and con-

TABLE 24
STATES USING GLASS BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

| No. Applications | States |
|---|---|
| 9 | ID |
| 3 | PA |
| 2 | MA, MN, NY, VT |
| 1 | AK, CT, FL, HI, IA, ME, NC, NH, NJ, SC, VA, WI |

## Miscellaneous Byproducts

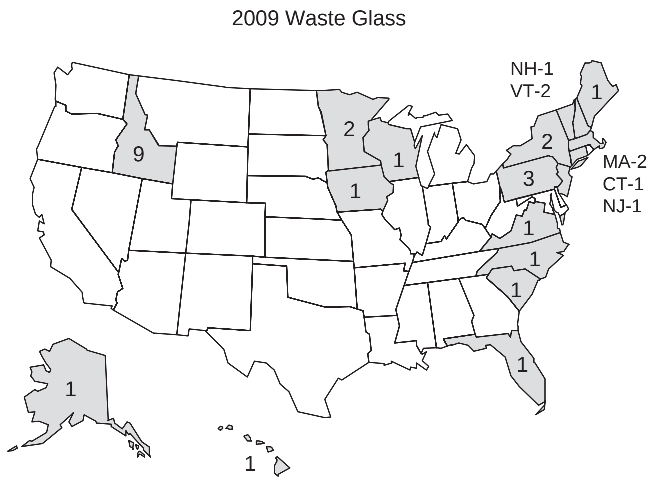


FIGURE 23 Agency survey results for glass byproducts (numbers indicate the number of applications that use the byproduct).

cretes to produce acid-resistance mixes with good strength. Research in the mid-1930s discovered that thermal properties of the sulfur mixes could be improved by adding an olefin polysulfide, marketed under the name of Thiokol. In the 1940s, sample preparation and specifications for sulfur polymer concrete were standardized by the American Society for Testing and Materials as ASTM C1312 and C1159.

Sulfur was first used in asphalt cements in the early 19th century as a product that was minimally sensitive to temperature changes and weathered well. The original use fell out of favor with the marketing of air-blown asphalts. The substitution of sulfur for a portion of the asphalt cement was investigated in the late 1930s, but additional development of sulfur-extended asphalts did not arrive until the mid-1970s when the oil embargo increased the cost of crude oil and limited the availability of asphalt cement.

Highway applications for sulfur include sulfur-extended asphalt and sulfur concrete. Sulfur, a naturally occurring component in asphalt, can be substituted for the more expensive portland or asphalt cement. Sulfur was most commonly combined with polymers and aggregates to produce sulfur polymer concrete starting in the early 1990s. The main uses were as a rapid repair mix and to encapsulate hazardous materials (Mattus and Mattus 1994).

*Literature Review*

Benefits to using sulfur in concrete were (Micropowder 2010):

- Sulfur polymer concrete (SPC)
  - Gained strength rapidly (about 80% within a few hours of placement)
  - Resistant to acids such as sulfuric, hydrochloric, and nitric acid
  - Durable in corrosive environments
  - High density
  - Resisted cracking
  - Resisted plastic deformation.

Benefits to using sulfur-extended asphalt in HMA mixes were (Mattus and Mattus 1994; Shell 2010a):

- Increased stiffness without becoming brittle at cold temperatures
- Allowed the use of softer, lower viscosity asphalt cements to be used in cold climates while minimizing rutting problems during hot summer seasons
- Better performance than conventional HMA in extremely hot or cold climates
- Improved the overall structural capacity of the pavement system
- Could be reheated since the hardening process is thermosetting
- Potential for reducing pavement thickness and therefore cost
- Performance appeared to be comparable to conventional HMA.

Disadvantages to using sulfur byproducts included:

- Required modifications to field mixer to provide heated material on-site (SPC)
- Worker safety concerns because of formation of hydrogen sulfide or sulfur dioxide gas if mixing temperature is too high
- Sulfur mix becomes difficult to work with at temperatures greater than 320°F owing to increased viscosity
- Although not flammable on its own, sulfur still meets the criteria of U.S.DOT of a hazardous material.

*Agency Survey*

Sulfur was not included in the agency survey as the resurgence of the use of sulfur in highway construction applications had not been observed before 2009.

### Sulfate Waste Byproducts

*Background*

Sulfate rich byproducts, fluorogypsum and phosphogypsum, are the result of the production of hydrofluoric and phosphoric acid. The *fluorogypsum* byproduct (RMRC 2008; TFHRC 2009) is the result of combining fluorspar and sulfuric acid and is discharged in slurry that solidifies over time in the holding ponds, and then must be crushed and separated if the byproduct is to be used. The resulting byproduct is sulfate-rich with a

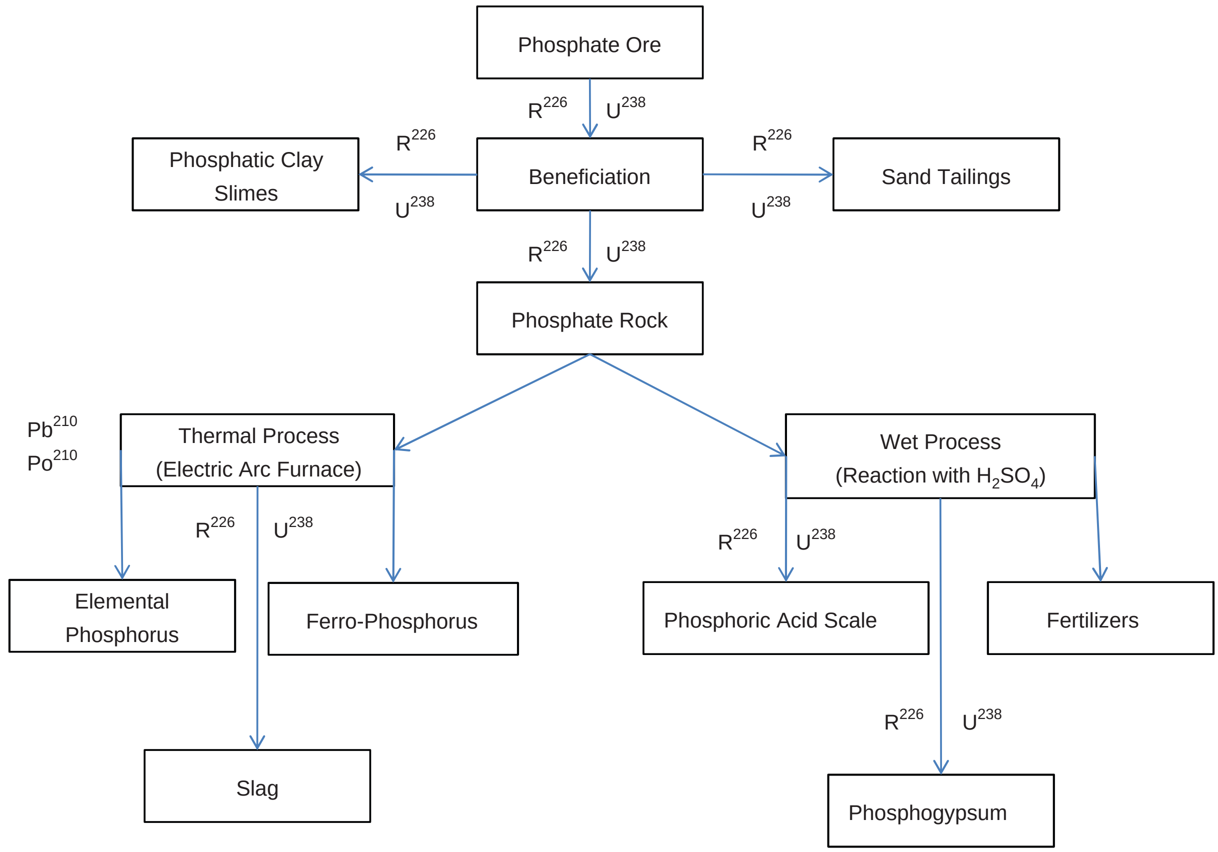


FIGURE 24 Schematic of phosphate process (after Deshpande 2003).

primarily well-graded sand silt particle size. *Phosphogypsum* (RMRC 2008) is a solid byproduct from phosphoric acid production and is a byproduct from a wet process that uses hydrochloric acid to treat phosphate rock. The process is outlined in Figure 24.

### *Literature Review Summary*

Sulfate and sulfur types of byproducts included fluorogypsum, phosphogypsum, and sulfur. Only a limited amount of information was found for these byproducts, no specific test methods were found in this information. Louisiana is the only state that has evaluated blended calcium sulfate, the fluorogypsum byproduct in cementitious blends, as a base material. These byproducts are to be bound to minimize undesirable leachates. No additional information was available with regard to materials handling, quality control, design changes, or construction guidelines.

### *Agency Survey Results for Sulfate Byproducts*

No states indicated they were currently using sulfate byproducts in highway application in this survey.

## WASTE PAPER MILL SLUDGE

### Background

Waste paper mill sludge is the byproduct of the paper production process. The major byproducts from the pulp and paper waste stream are as follows (Bird and Talberth 2008):

- Waste water treatment plant (WWTP) residuals
- Boiler and furnace ash
- Causticizing residuals.

The primary residuals, approximately 40% of the WWTP, including de-inking residuals (paper recycling operations), consist mostly of processed wood fiber and inorganic or mineral materials (e.g., kaolin clay, $CaCO_3$, and $TiO_2$). Secondary residual (activated waste sludge) is mostly bacterial biomass (nonpathogenic) and makes up about 1% of the WWTP. Dewatering the WWTP residual produces a byproduct with between 30% and 40% solids, and once dewatered the material is not considered hazardous as defined by RCRA. A few facilities can dry the WWTP to produce a byproduct with 70% to 95% solids. Chlorinated organic compounds tend to concentrate in the solids, which can be an environmental concern.

Boiler and furnace ash (energy recovery) is produced from wood, coal, or a combination of wood, coal, and other solid fuels (most common) used in the pulp and paper processes. Causticizing residues have three components: lime mud, green liquor dregs, and slaker grit. Lime mud (calcium carbonate and water) is burned in a lime kiln to regenerate the byproduct to lime (CaO). This byproduct may also contain unreacted calcium hydroxide and unslaked calcium oxide, magnesium, and sodium oxides. The lime mud is approximately 70% to 80% solids.

Green liquor dregs are composed of nonreactive and insoluble materials remaining after inorganic process chemicals (smelt) from the recovery furnace are mixed with water. The dregs are removed by gravity clarification, resulting in a byproduct with 45% to 55% solids. The major components are carbonaceous material along with calcium, sodium, magnesium, and sulfur.

Slaker grits are produced by mixing lime (burned or unburned) with the green liquor dregs, and contain between 70% and 80% solids. The solid portion is about 50% fibers and up to 50% minerals with a pH of about 12, which is neutralized before disposal. The solids can also contain titanium oxide and calcium sulfate.

#### Literature Review Summary

About 50% of these byproducts are used in land application, for energy production (incineration), or landfilled. Currently there has been little research for use in highway applications and only one agency indicted using this byproduct.

Potential use of these byproducts will likely focus on soil modification (lime mud), cement or concrete additives, or as an aggregate replacement (bottom ash).

#### Agency Survey Results for Pulp and Paper Byproducts

Only Kentucky indicated they had used paper pulp or lime mud in HMA applications.

CHAPTER TEN

# SUMMARY OF PERFORMANCE COMMENTS ON SURVEY

Open-ended questions were included in each byproduct category, which allowed the respondents to report their own experiences with the performance of application products that used each byproduct. The written comments were reviewed and categorized into general terms representing the comment content as excellent, good, fair, and poor qualities. Responses containing words such as “excellent,” “much improved,” and “superior” were counted as “excellent” performance. Comments such as “performed as good as conventional materials” and “no differences noticed” were cataloged as “good.” Wording such as “not as good as . . .” and “didn’t last as long as . . .” were classified as “fair.” Specific comments such as “will never try again” and “don’t recommend” are represented by the “poor” category. The ratings for each type of byproduct and highway applications are shown in Tables 25 through 28.

The results showed consistent rankings for some byproducts in application products (e.g., RAP in HMA), whereas others showed ratings ranging from excellent to poor performance for a single byproduct in a single application (e.g., scrap tire rubber in HMA applications). The wide differences in some byproducts can be explained by the specific type of byproduct in a single category and single application. For example, agencies using scrap tire rubber in HMA applications rated the performance as good to excellent when incorporating crumb rubber into the asphalt cement using the wet process. States reporting poor performance were using the crumb rubber in the dry process, which considers the rubber as an aggregate particle. It is likely other byproducts with a range of performance ratings may be linked to variations in the specific characteristics of a single type of byproduct or in the selection of the most appropriate process or highway application. This possibility might be more thoroughly explored in future research efforts.

TABLE 25
SUMMARY OF PERFORMANCE RESPONSES FROM AGENCY SURVEY FOR SHINGLES, KILN DUST, GLASS, AND FOUNDRY SAND

| Performance Characteristic | Roofing Shingles | | | | Kiln Dust | | | | Waste Glass | | | | Foundry Sand | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor |
| *HMA* | | | | | | | | | | | | | | | | |
| Rutting | | | | | | | | | | | | | | | | OH |
| Stripping | | | | | | | | | | | | HI, VA | | | | |
| Performance—General | | AL, KY, NC | NJ | FL | | | | | | | NJ | FL | | | OH | |
| *Unbound* | | | | | | | | | | | | | | | | |
| Base and Subbase | | | | | NV | | | CO | | | | | | AL | | |
| Performance—General | | | | | | KY (mixed) | | | | | | | | | | |

TABLE 26
SUMMARY OF PERFORMANCE RESPONSES FROM AGENCY SURVEY FOR MINERAL, QUARRY, AND FERROUS SLAG BYPRODUCTS

| Performance Characteristic | Mining Byproducts | | | | Quarry Byproducts | | | | Blast Furnace Slag (general) | | | | Steel Slag | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor |
| *HMA* | | | | | | | | | | | | | | | | |
| Stripping | | | | | | | | | | AL | | | | | | |
| Performance—General | | KS | | | | AR, CO, DE, FL, IA, IL, KY, LA, MO, NE PA, TX | | | AL | | | | | IN | | CO |
| Surface Treatments | | | | | | | | | KY, FL, WI, IL | OH | | | MO, IL | IA | | |
| *PCC* | | | | | | | | | | | | | | | | |
| Workability | | | | | | | | | FL | | | | | | | |
| Permeability | | | | | | | | | | MA, NJ | | | | | | |
| Scaling | | | | | | | | | | | | OH,VT | | | | |
| ASR | | | | | | | | | NJ | | | | | | | |
| Durability | | | | | | | | | FL | | | | | | | |
| Performance—General | | | | | | | | AR | MS, TX | AL, DC, DE, IA, IN, KS, LA, MO, OH, NY VA, VT, WA | | | | IN | | |
| *Unbound* | | | | | | | | | | | | | | | | |
| Fills and Embankments | UT | | | | | | | | | | | | UT | | | |
| Base and Subbase | | MD | | | | MD, ND, SC | | | | OH | | PA | | IN | | |
| Rip/RAP | | AL | | | | | | | | | | | | | | |

TABLE 27
SUMMARY OF PERFORMANCE RESPONSES FROM AGENCY INTERVIEWS FOR GGBFS, FLY ASH, AND BOTTOM ASH BYPRODUCTS

| Performance Characteristic | GGBFS | | | | Fly Ash | | | | Bottom Ash | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor | Excellent | Good | Fair | Poor |
| *HMA* | | | | | | | | | | | | |
| Rutting | | | | | | | | | | TX | | |
| Performance—General | | | | | | KY, AL | | KY | | TX | | |
| *PCC* | | | | | | | | | | | | |
| Workability | | | | | | WI | | | | | | |
| Permeability | | | | | | ME, TX | | | | | | |
| ASR | | | | | UT | ID, IL, PA, SC, TX, VT | | | | | | |
| Strength | | | | | | | DC | | | | | |
| Performance—General | | NY, WA | | | AZ, IN, MS, VA, TX | AL, AR, CO, IL, LA, MA, MO, ND, NH, NV NY, OH, WI, SC, VT, WA | | | | | NH[*] | |
| *Unbound* | | | | | | | | | | | | |
| Fills and Embankments | | | | | | MD, OH | NH[1] | | | | | |
| Base and Subbase | | | | | | KY, MD, NE, OH, PA, TX | | | | | MO | |

[*]Has not been used long enough to get information on long-term performance.
ASR = alkali silica reactivity.

TABLE 28
SUMMARY OF PERFORMANCE RESPONSES FROM AGENCY INTERVIEWS FOR TIRES, RCM, AND RAP BYPRODUCTS

| Performance Characteristic | Tires | | | | Recycled Concrete Material | | | | RAP Wearing Course (top layer of HMA) | | | | RAP (lower layers of HMA) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Excel | Good | Fair | Poor | Excel | Good | Fair | Poor | Excel | Good | Fair | Poor | Excel | Good | Fair | Poor |
| *HMA* | | | | | | | | | | | | | | | | |
| Raveling | | PA | | PA | | | | | | | | | | | | |
| Performance—General[1] | AZ | KY, ME, NJ, VA, TX | IA | IL, KY, ME, MS, MO, NJ, OR | | | | | | AL, AR, AZ, CO, CT, DE, FL, GA, HI, IA, IL, IN, LA, MA, ME, MN, MO, MS, NC, ND, NE, NH, NJ, NM, NY, OH, OK, OR, PA, SC, TX, UT, VT, WA, WV | | | | AK, AL, AR, AZ, CO, CT, DC, DE, IA, ID, FL, GA, HI, IL, IN, KS, LA, MA, ME, MN, MO, MS, NC, ND, NE, NJ, NH, NM, NY, OH, OK, OR, PA, SC, TX, UT, VT, WA, WV | | |
| Surface Treatment | | GA, NH, TX | | GA | | | | | | | | | | | | |
| Performance—General | | | | | | FL, ND, VA | | | | | | | | | | |
| Crack Sealant | | CO | | CO | | | | | | | | | | | | |
| *Unbound* | | | | | | | | | | | | | | | | |
| Fills and Embankments | | ME, NH | | | | IL, OH | | KY | | | | | | | | |
| Base and Subbase | | | | | | AL, LA, MD[2], ND, NJ, NE, NH, NV, PA, SC | IA | | | | | | | | | |
| Aesthetics | | | NH | | | | | | | | | | | | | |

[1] Good performance associated with crumb rubber wet process; poor performance associated with crumb rubber dry process (aggregate replacement).
[2] Has not been in use long enough to get information on long-term performance.
Excel = Excellent.

CHAPTER ELEVEN

# AGENCY INTERVIEWS

The initial survey requested that respondents identify contacts for projects using any of the byproducts in any of the highway applications. This request yielded 85 agency contacts for 92 combinations of byproducts and highway applications, which were used to conduct telephone interviews using the following questions:

1. What *types* of byproducts were used in your project(s)?
2. Project details such as project location, date of construction, size, etc. (when a specific project is being evaluated, just put "standard usage" if it is commonly used in the state).
3. Was the project a success or failure? Why?
4. Did you use any specific testing of the *byproducts?*
5. Did you have to alter your standard QC/QA testing program when constructing the projects?
6. Were there any specific materials handling concerns with the byproducts?
7. Did the application design need to be altered for the use of the byproducts (i.e., mix designs, structural support values, etc.)?
8. Were there any construction concerns or changes needed?
9. Were there any cost savings or additional costs associated with the use of byproducts?
10. Were there any environmental issues/concerns?
11. What did your agency learn from this project?

The numbers of interviews for each type of byproduct and highway application are summarized in Table 29.

The following sections summarize information obtained from the interviews. The responses to questions 1 and 2 were used to sort the information based on specific byproduct and highway application. Responses to questions 3 through 10 were summarized based on the percentage of the interviews that represented the terms indicating the desirable answer. The desirable answer reflects whether "yes" or "no" would be the most beneficial for the agency. The responses to the last question are collectively summarized at the end of this section.

## PORTLAND CEMENT CONCRETE APPLICATIONS

A total of 25 interviews were conducted to evaluate agency experiences with byproducts in PCC applications. Eighteen interviews covered coal combustion byproducts with five interviews addressing the use of Type C or F, seven the use of only Type F, and six only the use of Type C. Five agencies were interviewed regarding the use of slag; all five used only GGBFS.

Seven interviews were conducted for agencies using slags in PCC applications. One agency had experience with blast furnace slag (no specified type), five agencies specified GGBFS, and one agency used steel slag. Table 30 summarizes the responses to questions 3 through 10 for using coal combustion byproducts in PCC applications.

### Coal Combustion Byproducts in Portland Cement Concrete Applications

Most of the interviews indicated that agencies believed they did not need to change their project details, the use of the byproduct was saving money, and the application performance was good. The two major downsides to using byproducts were the need to adjust QA/QA programs and construction processes.

Only one state noted a lack of success, which was the result of the difficulty in finishing the PCC surface. Three other agencies indicated similar problems, but still considered their projects as successful. None of the states needed to alter their typical project design details when using the byproducts in the applications. Typical testing associated with the byproducts evaluated the chemical and physical properties of the cement, mortar, or concrete properties rather than the properties of the byproducts themselves. Agencies address byproduct properties by using existing AASHTO or ASTM standards for the properties of Type C and Type F fly ashes. Although it was not clear from the interview notes, it is likely those states using a chemical evaluation are evaluating the individual components (e.g., portland cement and coal combustion byproduct). In most cases, standard QC/QA programs were sufficient. In one case, the contractor was required to provide material certifications as a QC/QA measure.

The only handling comments noted in the interviews were dust control and inhalation concerns and the need for extra silos for storage at the plant. Design changes commonly needed when using coal combustion byproducts focused on adjustments to the mix design composition (e.g., volumetrics, water reducers, and air entrainment). Idaho required an independent assurance testing laboratory. Five states indicated construction concerns were related to delays in the set

TABLE 29
SUMMARY OF NUMBER OF STATES WITH EXPERIENCE USING BYPRODUCTS IN HIGHWAY APPLICATIONS

| Material | Applications | | |
|---|---|---|---|
| | PCC | HMA | Aggregate, Embankment, and Fill |
| *Coal Combustion Byproducts* | | | |
| Fly Ash (general) | 5 | 0 | 0 |
| Fly Ash, Type C | 6 | 0 | 0 |
| Fly Ash, Type F | 7 | 0 | 0 |
| Bottom Ash | 0 | 0 | 1 |
| Ponded Ash | 0 | 0 | 1 |
| Total | 18 | 0 | 2 |
| *Slags* | | | |
| BFS | 1 | 1 | 1 |
| GGBFS | 5 | 2 | 3 |
| Boiler Slag | 0 | 0 | 0 |
| Steel Slag | 1 | 3 | 1 |
| Copper Slag | 0 | 0 | 1 |
| Total | 7 | 6 | 6 |
| *Mineral and Quarry Byproducts* | | | |
| Baghouse Fines | 0 | 2 | 0 |
| Pond Fines | 0 | 1 | 0 |
| Screenings | 0 | 1 | 0 |
| Copper, Silver, and/or Gold Tailings | 0 | 1 | 0 |
| Total | 0 | 5 | 0 |
| *Tire Byproducts* | | | |
| Shredded Tires | 0 | 1 | 2 |
| Terminal Blend (wet process) | 0 | 2 | 0 |
| Crumb Rubber (wet process) | 0 | 7 | 0 |
| Chipped Tires | 0 | 0 | 1 |
| Total | 0 | 10 | 3 |
| *Miscellaneous Byproducts* | | | |
| Cement Kiln Dust | 0 | 2 | 0 |
| Shingles—Manufacture | 0 | 5 | 0 |
| Shingles—Tear Offs | 0 | 4 | 0 |
| *Recycled PCC and HMA Byproducts* | | | |
| RCA | 0 | 0 | 8 |
| RAP | 0 | 14 | 0 |

TABLE 30
INTERVIEW SUMMARY OF BYPRODUCTS IN PCC APPLICATIONS

| Question | Assumed Desirable Response | Percent of Agencies Interviewed with Response | |
|---|---|---|---|
| | | Coal Combustion Byproducts | Slag |
| Cost Savings? | Yes | 86 | 60 |
| Success? | Yes | 93 | 100 |
| Project Details Altered?[1] | No | 100 | 100 |
| Standard QC/QA Altered? | No | 57 | 100 |
| Handling Concerns? | No | 93 | 80 |
| Design Altered?[2] | No | 71 | 100 |
| Construction Changes? | No | 50 | 60 |
| Environmental Concerns? | No | 93 | 100 |
| No. of Interviews | | 18 | 7 |

[1]Project details refer to project location, size, type, etc.
[2]Design refers to mix design, structural design, etc.

time and difficulty in finishing the PCC surface. All of the respondents indicated a cost savings was achieved; however, several agencies noted that the savings may depend on the contractor. In one case, the cost savings were attributed to a lower life-cycle cost rather than an initial cost savings. Three states listed leachate testing as an additional consideration for projects when using these byproducts. One state noted that using silica fume along with the GGBFS generated inhalation concerns (i.e., microsilica).

The positive lessons learned when using coal combustion byproducts included low permeability (i.e., protection of reinforcing steel from corrosion) and good ASR resistance. Disadvantages include difficulty in finishing, delays in finishing times, slow initial strength gains, and material variability.

### Slag Byproducts in Portland Cement Concrete Applications

None of the agencies had a need to change project details, designs, or QC/QA programs, and none indicated concerns with environmental issues. Standard project details, testing, and QC/QA programs were used to produce consistently successful projects. Handling considerations included the need for extra silo storage capacity and cold weather concreting concerns owing to the reduced heat of hydration of the PCC. Slow set times resulted in construction delays and finishing issues. Three of the five states with experience in using GGBFS indicated a cost saving, whereas two states reported no change in the PCC application costs. Advantages included ASR and sulfate attack mitigation, and that a denser, less permeable concrete was achieved.

## HOT MIX ASPHALT APPLICATIONS

A total of 44 interviews were conducted covering agency use of byproducts in asphalt cement and asphalt cement concrete applications. Interviews were conducted for:

- Slag byproducts (six interviews)
- Mineral and/or quarry byproducts (five interviews)
- Scrap tire byproducts (ten interviews)
- Shingle byproducts (nine interviews)
- RAP byproduct (14 interviews).

Table 31 summarizes the responses to questions 3 through 10 for byproducts used in HMA applications. The slag byproducts used were steel slag (three interviews), GGBFS (two interviews), and boiler slag (one interview). The main mineral and/or quarry byproducts used in HMA applications were fine mineral or quarry byproducts (five interviews). Fourteen interviews were conducted to capture agency experiences using RAP. Ten interviews were conducted to evaluate state experiences with scrap tire rubber in HMA using either the dry process (aggregate replacement) or an asphalt cement modifier (wet process). Only two interviews covered agency experience with using CKD in HMA as mineral filler. Nine respondents answered questions concerning the use of shingles in HMA; four of the nine indicated they allowed either the use of manufactured or tear-offs.

### Slag Byproducts in Hot Mix Asphalt Applications

Five interviews were conducted with states using slag byproducts in HMA applications (see Table 31). Only about 57% of the agencies managed to place successful projects and only 29% believed there was an economic advantage to using slag in HMA applications. The majority (>50%) of the responses showed that changes were made to materials handling, designs, and construction processes. Less than 30% of the agencies changed QC/QA programs.

The steel slag byproduct had a high specific gravity and was the main point to consider in the necessary mix design changes. Increases in field sample sizes for additional testing were the most often noted changes. Construction processes needed changes in application rates when specifications were based on the weight of materials for a given area. Some agencies noted the difficulty in controlling the mix temperatures

TABLE 31
INTERVIEW SUMMARY OF BYPRODUCTS IN HMA APPLICATIONS

| Question | Assume Desirable Response | Percent of Agencies Interviewed with Response | | | | |
|---|---|---|---|---|---|---|
| | | Slag | Mineral/Quarry | Tires | Shingles | RAP |
| Successful? | Yes | 57 | 100 | 60[3] | 80 | 100 |
| Cost Savings? | Yes | 29 | 100 | 20 | 80 | 86 |
| Project Details Altered?[1] | No | 57 | 100 | 40 | 20 | 93 |
| Standard QC/QA Used? | Yes | 71 | 75 | 60 | 80 | 100 |
| Handling Concerns? | No | 43 | 75 | 60 | 20 | 57 |
| Design Altered?[2] | No | 43 | 100 | 10 | 40 | 43 |
| Construction Changes? | No | 14 | 75 | 50 | 80 | 64 |
| Environmental Concerns? | No | 71 | 75 | 50 | 40 | 79 |
| No. of Interviews | | 6 | 5 | 10 | 9 | 14 |

[1]Project details refer to project location, size, type, etc.
[2]Design refers to mix design, structural design, etc.
[3]Successes when using tires in HMA are limited to only the wet process; dry process was considered unsuccessful by interviewees.

and moisture content in the field samples. Additional costs were associated with using steel slag in HMA because the high specific gravity increased the haul costs for a given volume of mix. Colorado, Florida, and Virginia reported they would not use this combination of byproduct and HMA again because of construction problems and costs. Iowa was the only state that indicated a routine use of steel slag as a high-quality friction course.

### Mineral and Quarry Byproducts in Hot Mix Asphalt Applications

Five interviews were conducted with states using mineral or quarry byproducts in HMA applications. All five agencies said the projects were successful and resulted in cost savings. None of the states needed to alter their project details, mix designs, and/or structural designs. Only one of four responses indicated a need to change QC/QA programs, construction processes, or had environmental concerns.

Texas tests for wear when using copper, silver, and/or gold tailings and, depending on the fineness of the material, needed to require that the rolling patterns be adjusted by monitoring in-place density with a nuclear gauge. When using the copper, silver, and/or gold tailings, Texas noted training of the field crews was essential so that the staff was aware of any testing issues. Dust, an environmental concern, was associated with using baghouse fines and on general handling concerns associated with using the tailings. Lessons learned focus on the need for evaluating and analyzing the performance of the application products and the need for outreach education and technology transfer for local agencies and maintenance departments.

### Recycled Asphalt Pavements in Hot Mix Asphalt Applications

Fourteen interviews were conducted for agencies using RAP in fresh HMA (see Table 31). This survey was limited to central plant RAP use as there is a separate synthesis for in-place asphalt pavement recycling. All (100%) of the 14 interviews showed agencies considered their RAP projects successful; however, only 86% of the agencies noted a corresponding cost savings. Project details only needed to be altered by 7% of the agencies.

A number of states reported that they focused on changes in the mix designs that were related to adjustments of the quantities of binder in the final mix. Most of the laboratory testing change involved evaluating the asphalt content and gradation of the RAP, extraction and recovery of RAP binder, and addressing determination of PG specification grading of binders. Although the extent of the laboratory testing increased, none of the interviews mentioned a need to adjust their QC/QA programs.

Standard construction processes were used by 64% of the agencies. When changes were needed, they were related to slower production rates (Nebraska) or contractor familiarity with using RAP (Missouri).

About 57% of the agencies noted that conventional handling methods were applicable to handling RAP. When there were concerns, they were related to achieving aggregate specification values when post-processing the RAP (i.e., fractionating the RAP into a number of sizes).

The only performance considerations were related to rough longitudinal joints (New Jersey) and a higher cracking potential (New Mexico) owing to embrittlement of the binder by the old RAP asphalt cement.

The interviews revealed a number of lessons learned when using RAP in HMA applications. There appeared to be less difficulty in using RAP when the percentages are lower (about 15% RAP); however, several states were working on how to increase the allowable percentage of RAP. Both the gradation and binder quantities of the application product needed to be closely monitored. Limited use of RAP was based on the anticipated depletion of RAP availability and competing byproducts (e.g., RAP vs. tire rubber). Cost considerations discussed were how to credit the contractor for asphalt content in the RAP (New Mexico), which now credits 50% of the RAP binder instead of 100%. Virginia noted cost savings were tied to the handling and processing of the RAP prior to use in HMA.

### Scrap Tire Byproducts in Hot Mix Asphalt Applications

Ten interviews were conducted with agencies using scrap tires in HMA applications. Nine interviews were with agencies using the wet process of modifying asphalt with crumb rubber. Of these nine agencies, seven used the traditional field blend method for adding the crumb rubber to the asphalt. The two other agencies used the crumb rubber in terminal blends, which is a newer method of modifying the asphalt at the terminal rather than at the HMA contractor's plant. About 60% of the agencies had successful projects. Two states that reported unsuccessful projects (Alaska and Washington) had used scrap tire byproducts with the dry process that considers the rubber as an aggregate replacement. These projects had premature performance-based failures. Georgia and Texas routinely used crumb rubber in the wet process, whereas most of the other states interviewed indicated they were at various stages of and are approaching routine use.

Only 20% of the agencies reported that this byproduct reduced the cost of the projects. Georgia, New Hampshire, and Texas indicated that cost savings were the result of increased performance (i.e., better life-cycle costs).

The most frequently cited handling limitation was the availability of the equipment for HMA plant blending operations. This method of modifying the asphalt usually needed to move equipment. Adjustments were needed for mix design methods as well as the assessments of mix properties. Construction observations noted slower production rates and compaction difficulties with the crumb rubber modified asphalts. Smoking when using crumb rubber was noted as an environmental consideration. Lessons learned focused on the need to collect performance data.

### Roofing Shingles in Hot Mix Asphalt Applications

Interviews revealed that five states (Delaware, Iowa, Missouri, Texas, and Virginia) were using roofing shingle manufacturing byproducts in HMA applications and four of these states were also using tear-offs. Only Texas indicated the use of shingles in HMA applications was close to becoming a standard. About 80% of the interviews indicated successful projects were placed, cost savings were noticed, standard QC/QA programs were used, and conventional construction processes were applicable. At the same time, 80% of the interviews showed agencies needed to alter project designs and/or materials handling procedures. Approximately 60% of the agencies expressed environmental concerns (related to asbestos) and/or the need to change mix designs. Mix designs needed to consider volumetrics, binder content, additional fiber content, and in-place binder. HMA testing adjustments included chemical testing of the byproduct, checks for deleterious materials (e.g., asbestos), recovered binder properties, and performance testing.

Handling difficulties were related to the clumping or balling of the ground shingles. Delaware reported mixing the shingles with RAP to minimize the problems with balling of the shingles, and Iowa noted that modifications were needed to the plant feeder system when adding the shingles. Missouri contractors were using a finer grind of the shingles to minimize plant feeding problems.

The responses showed that the use of shingles was considered a viable use of the byproduct once the handling concerns are overcome. Texas noted that the use of byproducts should be based on performance and not legislatively driven.

Environmentally related comments included a concern with potential health problems from small particle sizes of the roofing byproduct components and the need to keep the shingles away from the flames in the HMA drum (i.e., smoking). All of the four states using tear-offs (a byproduct of construction debris) indicated environmental concerns with the possibility of asbestos in the shingle supply.

## UNBOUND HIGHWAY APPLICATIONS

Sixteen interviews were conducted with agencies with experience with byproducts used in various unbound applications (Table 32):

- Coal combustion byproducts (two interviews)
- Slag byproducts (six interviews)
- Tire byproducts (three interviews)
- CKD (two interviews)
- Reclaimed concrete aggregates (eight interviews).

The only use of coal combustion byproducts in an unbound highway application was bottom and ponded ash (Missouri). Six interviews were conducted with agencies using slag and three for the use of shredded tires. Of the six states with experience using slags in unbound applications, one used BFS, three used GGBFS, and two agencies had experience using non-ferrous slag. The most frequent contact information was provided for unbound applications using RCA.

### Coal Combustion Byproducts in Unbound Applications

Only Missouri uses coal combustion byproducts in embankments. The pilot projects were classified as successes using

TABLE 32
INTERVIEW SUMMARY OF BYPRODUCTS IN UNBOUND APPLICATIONS

| Question | Response | Percent of Agencies Interviewed with Response | | | | |
|---|---|---|---|---|---|---|
| | | Coal Combustion | Slag | Tires | CKD | RCA |
| Cost Savings? | Yes | 100 | 33 | 50 | 100 | 78 |
| Success? | Yes | 100 | 67 | 100 | 0 | 89 |
| Project Details Altered?[1] | No | 100 | 67 | 50 | 50 | 100 |
| Standard QC/QA Used? | Yes | 0 | 100 | 100 | 100 | 78 |
| Handling Concerns? | No | 0 | 100 | 0 | 100 | 56 |
| Design Altered?[2] | No | 100 | 33 | 50 | 100 | 89 |
| Construction Changes? | No | 100 | 100 | 100 | 100 | 56 |
| Environmental Concerns? | No | 100 | 67 | 0 | 100 | 89 |
| No. of Interviews | | 2 | 6 | 3 | 2 | 8 |

[1]Project details refer to project location, size, type, etc.
[2]Design refers to mix design, structural design, etc.
RCA = recycled concrete aggregates; CKD = cement kiln dust.

standard density testing for quality control. The only handling comments were that fugitive dust (also an environmental concern) needed to be controlled and the moisture content in the ponded ash be considered when mixing for soil remediation.

#### Slag Byproducts in Unbound Applications

Two states have used BFS in unbound highway applications (Utah and New York). Neither Utah nor New York needed to alter their project details to achieve successful projects with their standard QC/QA programs. Utah indicated both higher costs and material chemistry concerns with sulfate and chloride in the BFS byproducts. New York noted improved durability and a longer life span (i.e., lower life-cycle cost) were achieved when using BFS, and Utah noted the desire to promote further use of BFS. Illinois indicated previous experience using copper slag as an aggregate, but the project was not successful. The respondent was not sure of the reason(s) for the failure.

#### Scrap Tire Byproducts in Unbound Applications

New York, New Jersey, and Virginia were interviewed on their use of shredded or chipped tires in unbound applications such as embankments and backfill (see Table 32). Both New York and Virginia noted they originally placed embankments as a result of agency emphasis in the 1990s, but without dedicated funding incentives to use the material, little byproduct is currently being used. Both states indicated an increased need to conduct ground-water testing for undesirable leachates. Construction concerns were related to compaction and density.

Safety concerns were related to worker safety when handling the shredded steel belted tires (without the steel fibers being removed) and clumping of the tire shreds.

The cost could be defrayed by either free tires or state funding support for disposal. The general consensus was that the byproduct could be used in this application, but it is not yet cost-effective without funding incentives.

#### Cement Kiln Dust in Unbound Applications

Both agencies interviewed (Missouri and Texas) have used cement kiln dust (CKD), although neither indicated the use resulted in a cost savings. Testing adjustments included evaluating the support of the application for stabilized base with cone penetrometer testing and leachate testing for both stockpiled CKD and after use in applications. Neither state reported any handling concerns, alterations to designs, or construction concerns. Texas noted that CKD cost about half as much as using lime and fly ash, and also noted the performance of the application product was good but the politics could influence the availability of the byproduct.

#### Recycled Concrete Aggregates Byproducts in Unbound Applications

Nine states used RCA as an aggregate replacement in base applications (see Table 32). Most states (89%) indicated cost savings, and 78% of the agencies reported successful projects. Maryland indicated they tried this byproduct in 1977 but only had "just OK" success. Colorado, Delaware, Iowa, Mississippi, Nebraska, Missouri, Texas, and Virginia successfully use RCA and Mississippi is in the process of developing standard specifications for this byproduct.

A few of the respondents indicated that their QC/QA programs (22%) and construction processes (44%) needed some changes. QC/QA changes were usually a need for additional testing. The most important property to measure was identified as gradation. In-place density testing was difficult to measure for at least one agency (Maryland). The major difficulty was the inability to use a standard sand cone density test resulting from large void spaces. Nebraska used density testing based on establishing rolling patterns for each project.

Mix design changes were occasionally needed when using partial sand along with the RCM in the application. The liquid limit requirements needed to be adjusted or waived in the specification requirements. Comments related to handling focused on accounting for, or adjusting, moisture content, monitoring for gradation consistency, stockpile building practices, and room for the additional stockpiles of materials. Virginia noted that the stockpiles moisture content was stabilized by watering the stockpile. Workability was related to fines and moisture content with higher contents resulted in reduced workability. Mississippi occasionally had compaction concerns that were thought to be related to cold, wet weather. Lessons learned comments were very positive. One comment was "would use more if it were available."

#### Lessons Learned

This section presents a summary of the lessons learned by the agencies using byproducts in highway applications. In general, the advantages associated with using byproducts in highway applications are (Table 33):

- Byproducts usually provided better material properties than the natural material it replaces.
- Agency staff perceived a cost reduction was obtained when using the byproduct.
- Agency staff considered it a good use of a recycled byproduct.
- Performance characteristics such as alkali–silica reactivity, sulfate resistance, and reduced permeability needed to be addressed in the mix design phase.
- Improved pavement surface characteristics included better friction and lower vehicle–pavement noise.
- Generally better durability and performance of the highway application product was achieved.
- Longer service life of the application was achieved.

TABLE 33
SUMMARY OF LESSONS LEARNED ABOUT THE ADVANTAGES TO USING BYPRODUCTS IN HIGHWAY APPLICATIONS

| Application | Byproduct Category | Type of Byproduct | State | Better than Natural Material | Cost-Effective | Good Use of Recycled Byproduct | Improved Workability | ASR Resistance | Durability and/or Performance | Strength | Sulfate Resistance | Friction | Reduced Permeability | Noise Reduction | Longer Application Life |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BASE (unbound material) | Coal combustion | Bottom & ponded ash | MO | | | X | | | | | | | | | |
| | RCA | RCM | CO | X | X | | | | | X | | | | | |
| | | | DE | | X | | | | | | | | | | |
| | | | IA | | | X | | | | | | | | | |
| | | | MD | | | X | | | | | | | | | |
| | | | NE | | | X | | | | | | | | | |
| | | | MO | | | X | | | | | | | | | |
| | | | VA | | | X | | | X | | | | | | |
| | Slag | BFS slag | NY | | X | | | | X | | | | | | X |
| | | | UT | | | X | | | | | | | | | |
| | Tires | Shredded | NY | | | X | | | | | | | | | |
| | | | VA | | | | | | | | | | | | |
| HMA | Manufacturing and construction | CKD | MO | | | X | | | | | | | | | |
| | | | TX | | X | | | | X | | | | | | |
| | | Shingles, man. | DE | | | X | | | | | | | | | |
| | | Shingles, man., & tear-offs | MO | | | X | | | | | | | | | |
| | Mineral and quarry | Baghouse | TX | | | X | | | | | | | | | |
| | RAP | RAP | DE | | | | | | X | | | | | | |
| | | | ID | | | X | | | | | | | | | |
| | | | NE | | X | | | | | | | | | | |
| | Slag | Steel | IA | | | | | | | | | X | | | |
| | | Boiler | MO | | | X | | | | | | | | | |
| | | GGBFS | VA | X | | | | | X | | | | X | | |
| | Tires | Dry | MO | | | X | | | | | | | | | |
| | | Wet | NY | | | X | | | | | | | | | |
| | | | NH | | | | | | X | | | | | | |
| | | | NJ | | | | | | X | | | | | X | |
| | | | NY | | | X | | | | | | | | | |
| | | | TX | | | | | | | | | | | X | |
| PCC | Fly ash | General | AR | | | X | | | | | | | | | |
| | | | FL | | | X | | X | X | | | | | | |
| | | | NV | | | | | X | | | | | | | |
| | | | NY | | X | | | X | X | | | | | | |
| | | F | ID | | | X | | | | | | | | | |
| | | | VA | | | X | | | | X | | | | | |
| | | C,F | MS | | | | X | | | | | | X | | |
| | | | NJ | | | X | | X | X | | | | | | |
| | Slag | GGBFS | AK | | | X | | | | | | | | | |
| | | | DC | | | | | | | | | | X | | |
| | | | DE | | | | | X | | | | | | | |
| | | | MS | | | | | | | | X | | X | | |
| | | | NJ | | | X | | | | | | | | | |

Man. = manufactured; C = Type C fly ash; F = Type F fly ash.

Table 34 summarizes the lessons learned about barriers that need to be overcome to improve and advance the use of byproducts in highway applications. It can be noted that the initial agency written survey that requested agency contacts for the phone interviews yielded contacts for byproducts in primarily main stream usage and with a history of successful projects. In general, the barriers were:

- Lack of experience with the byproduct in a particular application
- Construction difficulties
- Poor experiences
- Lack of byproduct material properties
- Costs
- Needed mix design changes
- Local availability of byproduct
- Environmental concerns
- Numerous or conflicting environmental regulations
- Lack of training for agency and contractor field staff.

TABLE 34
SUMMARY OF LESSONS LEARNED ABOUT THE DISADVANTAGES TO USING BYPRODUCTS IN HIGHWAY APPLICATIONS

| Application | Byproduct Category | Type of Byproduct | State | Not Cost-Effective | Clogged Drainage Systems | Construction Difficulties | Lack of Availability | Poor Experience | Byproduct Material Properties | Climate Limitations | Lack of Experience | Mix Design Adjustments | Additional Training Needed for Inspectors and Field Staff | Contaminates in Byproduct | Regulations and Politics | Need to Restrict Source of Byproduct | Environmental Concerns |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BASE (unbound material) | RCA | — | VA | | X | | | | | | | | | | | | |
| | | | MS | | | | | | | | | | | X | | | |
| | | | TX | | | | | | | | | | | | | X | |
| | Slag | Copper slag | IL | | | | | X | | | | | | | | | |
| | Tires | Shredded | NY | X | | | | | | | | | | | | | X |
| | | | VA | | | | | | | | | | | | | | |
| HMA | Manufacturing and construction | Shingles, man., & tear-offs | IA | | | X | | | | | | | | | | | |
| | | | TX | | | | | | | | | | | | X | | |
| | | | VA | | | | | | | | X | | | | | | |
| | Mineral and Quarry | Baghouse | CO | | | | | | | | | X | | | | | |
| | | Copper, silver, & gold tailings | TX | | | | | | | | | | | | | | |
| | | Pond finds & screenings | GA | | | | | | | | | | X | | | | |
| | RAP | — | ID | | | | | | X | | | | | | | | |
| | | | CO | | | | | | | | X | | | | | | |
| | | | GA | | | | | | | | | | | | | | |
| | | | IA | | | | | | | | | | | | | | |
| | | | MS | | | | | | | | | | | | | | |
| | | | MO | | | | X | | | | | | | | | | |
| | | | NM | | | | | | X | | | | | | | | |
| | | | NJ | | | | | | | | | | | | | | |
| | | | NY | | | | | | | | | | | | | | |
| | | | TX | | | | | | | | | X | | | | | |
| | | | VA | | | | | | X | | | X | | | | | |
| | | | WA | | | | | | | | | X | | | | | |
| HMA | Slag | BFS | FL | | | | | X | | | | | | | | | |
| | | GGBFS | IA | | | | | | | | | | | | | | |
| | | Steel | IA | | | | | | X | | | | | | | | |
| | | | IA | | | | | | X | | | | | | | | |
| | | | CO | | | | | X | | | | | | | | | |
| | | | VA | X | | X | | | | | | | | | | | |
| | Tires | Dry | AK | | | X | | | | | X | | | | | | |
| | | | WA | X | | | | X | | | | | | | | | |
| | | Shredded tires | DE | | | | | | | | X | | | | | | |
| | | | NV | | | | | | | X | | | | | | | |
| | | Terminal, wet | NY | | | | | | | | X | | | | | | |
| | | Wet | NY | | | | | | | | | | | | | | X |
| | | | NY | X | | | | | | | | | | | | | X |
| | | | CO | | | | | | | | X | | | | | | |
| | | | GA | | | | | | | | X | | | | | | |
| | | | VA | | | | | | | | X | | | | | | |
| PCC | Fly ash | C | NE | | | X | | | | | | | | | | | |
| | | C, F | CO | | | | | | | | | | | | | | |
| | | | ND | | | | X | | | | | | | | | | |
| | | | TX | | | | X | | | | | | | | | | |
| | | F | ID | | | | | | | | | | | | | | |
| | | General | NV | | | | | | | | | | | | | | |
| | | | DE | | | X | | | | | | | | | | | |
| | | | WA | | | X | | | | | | | | | | | |

Man. = manufactured; C = Type C fly ash; F = Type F fly ash.

CHAPTER TWELVE

# CONCLUSIONS AND RECOMMENDATIONS

The recent use of byproducts in a range of highway applications found in the literature and agency surveys is summarized in Table 35. Although various byproducts are indicated as being used with specific highway applications, some of the information was only found in research publications that reported only initial laboratory experimentation. The reader is referred to the individual byproduct chapters for a more in-depth summary of the particular uses.

## TEST METHODS

Testing of the byproducts and application products used existing testing and specification standards, regardless of the country reporting the research. Table 36 lists the AASHTO test methods found in the literature, while Table 37 lists ASTM standards. The use of standard test methods evaluates material properties of byproducts as either partial or full replacements for virgin materials. The major drawback to this approach is that these byproducts were not considered in the test method development. Mixing protocols, test method parameters, particle sizes and distribution, as well as precision statements were developed using virgin materials and may not be applicable to individual byproducts or the resulting application products produced with recycled byproducts. Standards organizations such as AASHTO and ASTM could assess individual test methods to determine if the procedures and precision statements are applicable. EPA test methods identified are listed in Table 38.

## BYPRODUCT PREPARATION AND QUALITY CONTROL

Although each category and type of byproduct had a range of best practices for handling, production, and placement, the common factors can be summarized as follows:

- Byproduct sources more than about 30 to 50 miles away from the process using the byproduct will likely not be cost-effective. In these situations, an intermediate collection and byproduct post-processing facility is the most useful source for providing adequate quantities of quality controlled byproducts. It can be noted that the range of distances were reported in documents using past economic assessments (i.e., pre-2008). The actual economical distance will change with changes in materials and fuel costs.
- As improvements in technology are made to the industries producing the byproducts, the physical and chemical properties of the byproducts can change. More consistent byproduct properties are obtained when a history of legacy landfilling or plant changes are documented with key information about changes to the raw materials or industry processes.
- Post-processing of industry byproducts may be needed to ensure the byproduct properties meet the required application specifications.
- The highway applications that can use a particular byproduct need to be identified so byproduct materials can be sorted and/or post-processed based on the specified application properties. This may require a change in the disposal practices of the industry producing the byproduct or the establishment of a regional recycling facility.
- When various types of byproducts have substantially different properties of interest to the agencies, industries should provide separate disposal sites or stockpiles for each byproduct to improve the marketability of their byproducts and consistency of the byproduct properties.
- Key properties of each byproduct should be periodically determined and documented so additional matches between byproducts and highway applications can be made.

## HANDLING CONSIDERATIONS

Most handling changes arise once the byproduct is delivered to the contractor plant or to the construction site when used as is. If the material is to be stockpiled, the following needs to be considered:

- Proper drainage to prevent contamination of ground and storm water and to minimize water retention in the byproduct. Minimize fugitive dust for fine, dry byproducts. Stockpiles should be within the environmentally permitted area with good drainage.
- Some byproduct properties can be enhanced with weathering, whereas others can solidify in contact with water, so the time the byproduct is left in a stockpile needs to be addressed.
- Finer ash byproducts require a separate storage silo at ready-mix plants and for metering additional mineral filler in hot mix asphalt (HMA) production.

TABLE 35
SUMMARY OF TYPES OF BYPRODUCTS RESEARCHED AND/OR USED IN HIGHWAY APPLICATIONS

| Type of Byproduct | Asphalt Concrete or Asphalt Surface Treatments | | | | Portland Cement | | | Portland Cement Concrete | | | | | | | | Unbound and Semi-Bound Applications | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Filler | Asphalt Replacement or Modifier | Aggregate Replacement | Mix | Clinker | SCM | Mortar | Aggregate Replacement | Standard Mix | UHPC | HPC | SCC | CLSM | Sound Reduction | Precast | Flowable Fill | Fill | Rip Rap | Base | Stabilized Base | Dust Control |
| Cement Kiln Dust | X | | | | X | X | | | X | | | | X | X | | | | | | X | |
| Coal Combustion Bottom Ash | | | X | | | | | | | | | | | | | | X | | X | | |
| Coal Combustion Fly Ash | X | | | | X | | | | | | | | | | | | | | | | |
| Coal Combustion Type C Fly Ash | | | | | | X* | | | X* | | | | | | | | | | | X | |
| Coal Combustion Type F Fly Ash | | | | | | X | | | X | | | | | | | | | | | X+ | |
| Coal Combustion, FGD | | | | | | | | | | | | | | | | | | | | | |
| Coal Combustion, FBC | | | | | | X | | | | | | | | | | | | | | | |
| Ferrous Slag, GGBFS | | | | | | X | | | | X | X | | | | | | | | | X | X |
| Ferrous Slag, ACBFS | | | X | | | | | X | | | | | | | | | | | | | |
| Ferrous Slag, Expanded | | | | | | | | | | | | | | | | | | | X | | |
| Ferrous Slag, BOF Steel | | | | | | | | | | | | | | | | | | | | | X |
| Ferrous Slag, EAF Steel | | | | | | | | X | | | | | | | | | | | | | |
| Ferrous Slag, Ladle Steel | | | | | | | | | | | | | | | | | | | | | |
| Ferrous Slag, Steel | | | X | | | | | | | | | X | | | | | | | | | |
| Foundry Sands, Recycled | | | X | | | | | X | | | | | | | | X | X | | X | | |
| Glass, Processed Aggregate (Cullet) | | | X | | | | | X | | | | | | | | | X | | | | |
| Glass, Powdered | | | | | | X | | | | | | | | | | | | | | | |
| Mineral Byproducts, Large Size | | | | | | | | | | | | | | | | | | X | | | |
| Mineral Byproduct, Perlite | | | | | | X | | | | | | | | | | | X | | | | |
| Mineral Byproduct, Tailings | | | | | | | | | | | | | | | | | | | | | |
| Mineral Byproduct, Tungsten Mud | | | | | | X | | | | | | | | | | | | | | | |
| Minerals in Wash Water | | | | | | | | | | | | | X | | | | | | | | |
| MSW Fly Ash | | | | | X | X | | X | | | | | | | | | | | | | |
| MSW Bottom Ash | X | | | | | X | | X | | | | | | | | | | | X | | |
| MSW Combined Ash | | | | | | | | | | | | | | | | | | | X | | |

TABLE 35
(*continued*)

| Type of Byproduct | Asphalt Concrete or Asphalt Surface Treatments | | | | Portland Cement | | | Portland Cement Concrete | | | | | | | | Unbound and Semi-Bound Applications | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Filler | Asphalt Replacement or Modifier | Aggregate Replacement | Mix | Clinker | SCM | Mortar | Aggregate Replacement | Standard Mix | UHPC | HPC | SCC | CLSM | Sound Reduction | Precast | Flowable Fill | Fill | Rip Rap | Base | Stabilized Base | Dust Control |
| Non-Ferrous Slag, Copper | | | X | | | | X | | | | | | | | | | | | | | |
| Quarry Byproduct, Fines | | | | | | | | | | | | | | | | X | | | | | X |
| Quarry Byproduct, Limestone Fines | | | | | | X | | | | | | X | | | | | | | | | |
| Quarry Byproduct, Sand Size | X | | | | | | | X | | | | | | | | | | | | | |
| Quarry Byproducts, Screenings | | | | | | | | | | | | | | | | | | | X | X | |
| Non-Ferrous Slag, Nickel | | | | | | | | | | | | | | | | | | | X | | |
| Non-Ferrous Slag, Phosphorous | | | X | | | | | | | | | | | | | | | | | | |
| Non-Ferrous Slag, Zinc | | | X | | | | X | | | | | | | | | | | | | | |
| Paper Byproduct, Boiler Ash | | | X | | | | | | | | | | | X | | | | | | | |
| Paper Byproduct, Lime Mud | | | | | | | | | | | | | | | | | | | | X | |
| Paper Byproduct, Lime Grit | | | | | | | | | | | | | | | | | | | | X | X |
| Paper Byproduct, Sludge | | | | X | | X | | | | | | | | | | | | | | | |
| PCC, Fresh | | | | | | | | | X | | | | | | | | | | | | |
| PCC, Returned but Hardened | | | | | | | | X | | | | | | | | | | | X | | |
| RAP | | X | X | X | | | | | | | | | | | | | X | | | | |
| RCA, Construction Demolition Waste | | | X | | | | | X | | | | | | | | | | | X | | |
| RCA, In-Place Recycling | | | | | | | | | | | | | | | | | | | X | | |
| RCA, Plant Recycling | | | | | | | | X | X | | | | | | | | X | | X | | |
| Roofing Shingles, Manufacturer | | X | X | | | | | | | | | | | | | | | | | X | |
| Roofing Shingles, Tear-Offs | | X | X | | | | | | | | | | | | | | | | | X | |
| Scrap Tires, TDA | | X | X | | | | X | | X | | | | | X | X | | X | | X | X | |
| Sulfate Byproducts, Fluorogypsum | | | | | | X | | | | | | | | | | | X | | | | |
| Sulfate Byproducts, Phosphorous | | | | | | | | | | | | | | X | | X | X | | | X | |

SCM = supplementary cementitious materials; UHPC = ultra-high performance concrete; HPC = high-performance concrete; SCC = self-consolidating concrete; CLSM = controlled low-strength material; FGD = flue gas desulphurization; FBC = fluidized bed combustion; GGBFS = granulated ground blast furnace slag; ACBFS = air-cooled blast furnace slag; BOF = basic oxygen furnace; EAF = electric arc furnace; PCC = portland cement concrete; RCA = recycled concrete aggregate; TDA = tire-derived aggregate.
*While both types of fly ash have been used, Type F generally provides better PCC properties and stabilized bases.
+Type F fly ash typically needs an activator such as lime.

TABLE 36
SUMMARY OF AASHTO TEST METHODS PREVIOUSLY USED TO EVALUATE BYPRODUCTS AND HIGHWAY APPLICATIONS USING BYPRODUCTS

| Material Tested | AASHTO Method | Title |
|---|---|---|
| Aggregate | MP16 | Reclaimed concrete aggregate for use as coarse aggregate in hydraulic cement concrete |
| | T103 | Standard method of test for soundness of aggregates by freezing and thawing |
| | T104 | Standard method of test for soundness of aggregate by use of sodium sulfate or magnesium sulfate |
| | T11 | Standard method of test for materials finer than No. 200 (75 µm) sieve in mineral aggregate by washing |
| | T112 | Standard method of test for clay lumps and friable particles in aggregate |
| | T113 | Standard method of test for lightweight pieces in aggregate |
| | T19 | Standard method of test for bulk density (unit weight) and voids in aggregate |
| | T2 | Standard method of testing for sampling of aggregates |
| | T27 | Standard method of test for sieve analysis of fine and coarse aggregates |
| | T327 | Standard method of test for resistance of coarse aggregate to degradation by abrasion in the micro-Deval apparatus |
| | T85 | Standard method of test for specific gravity and absorption of coarse aggregate |
| | T96 | Standard method of test for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine |
| Soil | M145 | Classification of soil and soil-aggregate mixtures for highway construction purposes |
| | T145 | Classification of soil and soil-aggregate mixtures for highway construction purposes |
| | T180 | Standard method of test for moisture density relations of soils using a 4.54 kg (10 lb) rammer and a 457 mm (18 in.) drop |
| | T193 | Standard method of test for the California bearing ratio |
| | T215 | Standard method of test for permeability of granular soils |
| | T221 | Standard test method for repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements |
| | T290 | Standard method of test for determining the resilient modulus of soils and aggregate materials |
| | T299 | Standard method of test for rapid identification of alkali-silica reaction products in concrete |
| | T87 | Standard method of test for dry preparation of disturbed soil and soil-aggregate samples for test |
| | T88 | Standard method of test for particle size analysis of soils |
| | T89 | Standard method of test for determining the liquid limit of soils |
| | T90 | Standard method of test for determining the plastic limit and plasticity index of soils |
| | T99 | Standard method of test for moisture-density relations of soils using a 2.5 kg (5.5 lb) rammer and a 305 mm (12 in.) drop |
| Asphalt Cement and Asphalt Concrete | M320 | Standard specification for performance-graded asphalt binder |
| | MP15 | Use of reclaimed asphalt shingles as an additive in hot mix asphalt (HMA) |
| | PP19 | Standard practice for volumetric analysis of compacted hot mix asphalt |
| | R30 | Standard practice for mixture conditioning of hot mix asphalt |
| | T164 | Quantifiable extraction of bitumen from bituminous paving mixtures |
| | T166 | Bulk specific gravity of compacted hot mix asphalt mixtures using saturated surface dry specimens |
| | T170 | Standard method of test for recovery of asphalt binder from solution by Abson method |
| | T209 | Theoretical maximum specific gravity and density of hot mix asphalt paving mixtures |
| | T240 | Test method for effect of heat and air on a moving film of asphalt (rolling thin film oven test) |
| | T283 | Standard method of test for resistance of compacted for hot mix asphalt (HMA) of moisture induced damage |
| Asphalt | T312 | Standard method of test for preparing and determining the density of hot mix asphalt |

TABLE 36
(*continued*)

| | | |
|---|---|---|
| Cement and Asphalt Concrete | | (HMA) specimens by means of the Superpave gyratory compactor |
| | T313 | Standard method of test for determining the flexural creep stiffness of asphalt binder using the bending beam rheometer (BBR) |
| | T315 | Test method for determining rheological properties of asphalt binder using a dynamic shear rheometer |
| | T319 | Quantitative extraction and recovery of asphalt binder from asphalt mixtures |
| | T321 | Standard method of test for determining the fatigue life of compacted hot mix asphalt (HMA) subjected to repeated flexural bending |
| | T322 | Determining the creep compliance and strength of hot mix asphalt (HMA) |
| | T48 | Standard method of test for flash and fire points by Cleveland open cup |
| | T49 | Standard method of test for penetration of bituminous materials |
| | T53 | Standard test method for softening point of bitumen (ring-and-ball apparatus) |
| | TP2 | Method for the quantitative extraction and recovery of asphalt binder from hot mix asphalt (HMA) |
| | TP62 | Standard method of test for determining dynamic modulus of hot mix asphalt (HMA) |
| | TP7 | Standard test method for determining the permanent deformation and fatigue cracking characteristics of hot mix asphalt (HMA) using the simple shear test (SST) device |
| | TP9 | Standard test method for determining the creep compliance and strength of hot mix asphalt (HMA) using the indirect tensile test device |
| | T309 | Standard method of test for accelerated detection of potentially deleterious expansion of mortar bars due to alkali-silica reaction |
| Portland Cement and Portland Cement Concrete | T119 | Standard method of test for slump of hydraulic cement concrete |
| | T161 | Standard method of test for resistance of concrete to rapid freezing and thawing |
| | T177 | Standard method of test for flexural strength of concrete (using simple beam with center-point loading) |
| | T196 | Standard method of test for air content of freshly mixed concrete by the volumetric method |
| | T198 | Standard method of test for air content of freshly mixed concrete by the volumetric method |
| | T22 | Standard test method of test for compressive strength of cylindrical concrete specimens |
| | T260 | Standard method of test for sampling and testing for chloride ion in concrete and concrete raw materials |
| | T277 | Standard method of test for electrical indication of concrete's ability to resist chloride ion penetration |
| | T307 | Standard method of testing for rapid identification of alkali-silica reaction product in concrete |
| | TP31 | Standard test method for determining the resilient modulus of bituminous mixtures by indirect tension |
| | TP60 | Standard method of test for coefficient of thermal expansion of hydraulic cement concrete |
| Coal | M295 | Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete |
| | PP59 | Coal combustion fly ash for embankments |
| Glass | M318 | Standard specification for glass cullet use for soil-aggregate base course |
| Misc. | PP56 | Evaluating the engineering and environmental suitability of recycled materials |
| Shingles | PP53 | Design considerations when using reclaimed asphalt shingles (RAS) in new hot mix asphalt (HMA) |
| Slag | M302 | Standard specification for ground granulated blast-furnace slag for use in concrete and mortars |

TABLE 37
SUMMARY OF ASTM TEST METHODS PREVIOUSLY USED TO EVALUATE BYPRODUCTS AND HIGHWAY APPLICATIONS USING BYPRODUCTS

| Material Tested | ASTM Method | Title |
|---|---|---|
| Environmental | D3987 | Standard test method for shake extraction of solid waste with water |
| | D4874 | Standard test method for leaching solid material in a column apparatus |
| | D4972 | Standard test method for pH of soils |
| Aggregate | C117 | Standard test method for materials finer than 75-µm (no. 200) sieve in mineral aggregates by washing |
| | C127 | Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate |
| | C128 | Standard test method for density, relative density (specific gravity), and absorption of fine aggregate |
| | C131 | Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine |
| | C136 | Standard test method for sieve analysis of fine and coarse aggregates |
| | C142 | Standard test method for clay lumps and friable particles in aggregates |
| | C33 | Standard specification for concrete aggregates |
| | C395 | Standard guide for petrographic examination of aggregates for concrete |
| | C535 | Standard test method for resistance to degradation of large size coarse aggregate by abrasion and impact in the Los Angeles machine |
| | C566 | Standard test method for total evaporable moisture content of aggregate by drying |
| | C586 | Standard test method for potential alkali reactivity of carbonate rocks as concrete aggregates (rock-cylinder method) |
| | C88 | Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate |
| | D2419 | Standard test method for sand equivalent value of soils and fine aggregate |
| | D2940 | Standard specification for graded aggregate material for bases or subbases for highways or airports |
| | D3319 | Standard practice for accelerated polishing of aggregates using the British wheel |
| | D448 | Standard classification for sizes of aggregate for road and bridge construction |
| | D6928 | Standard test method for resistance of coarse aggregate to degradation by abrasion in the micro-Deval apparatus |
| | C4552 | Standard practice for classifying hot-mix recycling agents |
| | D113 | Standard test method for ductility of bituminous materials |
| | D1559 | Standard test method for resistance of plastic flow of bituminous mixtures using Marshall apparatus |
| | D1856 | Standard test method for recovery of asphalt from solution by Abson method |
| | D2041 | Standard test method for theoretical maximum specific gravity and density of bituminous paving mixtures. |
| | D217 | Standard test methods for cone penetration of lubricating grease |
| | D2170 | Standard test method for thermal stability of hydraulic oils |
| | D2172 | Standard test method for quantitative extraction of bitumen from bituminous paving mixtures |
| | D2669 | Standard test method for apparent viscosity of petroleum waxes compounded with additives (hot melts) |
| | D2950 | Standard test methods for density of bituminous concrete in place by nuclear methods |
| | D36 | Standard test method for softening point of bitumen |
| | D3910 | Standard practices for design, testing, and construction of slurry seal |
| | D4125 | Standard test method for determining bitumen content in bituminous paving mixtures by use of ignition oven |
| | D4402 | Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer |
| | D5 | Standard test method for penetration of bituminous materials |
| | D5505 | Standard practice for classifying emulsified recycling agents |
| | D6 | Standard test method for loss on heating of oil and asphaltic compounds |
| | D70 | Standard test method for density of semi-solid bituminous materials (Pycnometer Method) |
| | D7313 | Standard test method for determining fracture energy of asphalt-aggregate mixtures using the disk-shaped compact tension geometry |

TABLE 37
(*continued*)

| | | |
|---|---|---|
| | D92 | Standard test method for flash and fire points by Cleveland Open Cup Tester |
| | D979 | Standard practice for sampling bituminous paving mixtures |
| | C1012 | Standard test method for length change of hydraulic cement mortars exposed to a sulfate solution. |
| | C143 | Standard test method for slump of hydraulic-cement concrete |
| | C150 | Standard specification for portland cement |
| | C1556 | Standard test method for determining the apparent chloride diffusion coefficient of cementitious mixtures by bulk diffusion |
| | C191 | Standard test methods for time of setting of hydraulic cement by Vicat Needle |
| | C204 | Standard test methods for fineness of hydraulic cement by air-permeability apparatus |
| | C305 | Standard practice for mechanical mixing of hydraulic cement pastes and mortars of plastic consistency |
| | C452 | Standard test method for potential expansion of portland cement mortars exposed to sulfate |
| | C109 | Standard test method for compressive strength of hydraulic cement mortars [using 2-in. or (50-mm) cube specimens] |
| | C1202 | Standard test method for electrical indication of concrete's ability to resist chloride ion penetration |
| | C125 | Standard terminology relating to concrete and concrete aggregates |
| | C1260 | Standard test method for potential alkali reactivity of aggregates (mortar-bar method) |
| | C1293 | Standard test method for determination of length change of concrete due to alkali-silica reaction |
| | C1567 | Standard test method for determining the potential alkali silica reactivity of combinations of cementitious materials and aggregate (accelerated mortar bar method) |
| | C157 | Standard test method for length change of hardened hydraulic-cement mortar and concrete |
| | C1581 | Standard test method for determining age at cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage |
| | C173 | Standard test method for air content of freshly mixed concrete by the volumetric method |
| | C227 | Standard test method for potential alkali reactivity of cement aggregate combinations (mortar bar method) |
| | C289 | Standard test method for potential alkali silica reactivity of aggregates (chemical method) |
| | C29 | Standard test method for potential alkali reactivity of cement-aggregate combinations (mortar-bar method) |
| | C342 | Standard test method for potential volume change of cement aggregate combinations (withdrawn 2001) |
| | C39 | Standard test method for compressive strength of cylindrical concrete specimens |
| | C403 | Standard test method for time of setting of concrete mixtures by penetration resistance |
| | C469 | Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression |
| | C490 | Standard practice for use of apparatus for the determination of length change of hardened cement paste, mortar, and concrete |
| | C512 | Standard test method for creep of concrete in compression |
| | C642 | Standard test method for density, absorption, and voids in hardened concrete |
| | C666 | Standard test method for resistance of concrete to rapid freezing and thawing |
| | C672 | Standard test method for scaling resistance of concrete surfaces exposed to deicing chemicals |
| | C78 | Standard test method for flexural strength of concrete (using simple beam with third-point loading) |
| | C856 | Standard practice for petrographic examination of hardened concrete |
| | C944 | Standard test method for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method |
| | D6023 | Standard test method for density (unit weight), yield, cement content, and air content (gravimetric) of controlled low-strength material (CLSM) |
| | D6024 | Standard test method for ball drop on controlled low strength material (CLSM) to determine suitability for load application |

(*continued on next page*)

TABLE 37
(*continued*)

| | | |
|---|---|---|
| | D6103 | Standard test method for flow consistency of controlled low strength material (CLSM) |
| | C33 | Standard test method for direct shear test of soils under consolidated drained conditions |
| | D1557 | Standard test methods for laboratory compaction characteristics of soils using modified effort |
| | D1566 | Standard test methods for density and unit weight of soil in place by the sand cone method |
| | D1633 | Standard test methods for compressive strength of molded soil-cement cylinders |
| | D1883 | Standard test method for CBR (California Bearing Ratio) of laboratory-compacted soils |
| | D2167 | Standard test methods for density and unit weight of soil in place by the rubber balloon method |
| | D2216 | Standard test method for laboratory determination of water (moisture) content of soil and rock by mass |
| | D2434 | Standard test method for permeability of granular soils (constant head) |
| | D2435 | Standard test method for one-dimensional consolidation properties of soils |
| | D2487 | Standard practice for classification of soils for engineering purposes (Unified Soil Classification System) |
| | D2488 | Standard practice for description and identification of soils (Visual-Manual Procedure) |
| | D2922 | Standard test methods for density of soil and soil aggregate in place by nuclear methods (shallow depth) |
| | D2974 | Standard test methods for moisture, ash, and organic matter of peat and other organic soils |
| | D3080 | Standard test method for direct shear test of soils under consolidated drained conditions |
| | D422 | Standard test method for particle size analysis of soils |
| | D4253 | Standard test method for maximum index density and unit weight of soils using a vibratory table |
| | D4254 | Standard test methods for minimum index density and unit weights of soils and calculation of relative density |
| | D4318 | Standard test methods for liquid limit, plastic limit, and plasticity index of soils |
| | D4547 | Standard guide for sampling waste and soils for volatile organic compounds |
| | D4643 | Standard test method for determination of water (moisture) content of soil by microwave oven heating |
| | D4647 | Standard test method for identification and classification of dispersive clay soils by the pinhole test |
| | D5030 | Standard test method for density of soil and rock in place by the water replacement method in a test pit |
| | D5084 | Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter |
| | D5101 | Standard test method for measuring the soil-geotextile system of clogging potential by the gradient ratio |
| | D5102 | Standard test method for unconfined compressive strength of compacted soil-lime mixtures |
| | D5311 | Standard test method for load controlled cyclic triaxial strength of soil |
| | D5333 | Standard test method for measurement of collapse potential of soils |
| | D5520 | Standard test method for laboratory determination of creep properties of frozen soils samples by uniaxial compression |
| | D559 | Standard test methods for wetting and drying compacted soil-cement mixtures |
| | D560 | Standard test methods for freezing and thawing compacted soil-cement mixtures |
| | D6276 | Standard test method for using pH to estimate the soil-lime proportion requirement for soil stabilization |
| | D6572 | Standard test methods for determining dispersive characteristics of clayey soils by the crumb test |
| | D6951 | Standard test method for use of the dynamic cone penetrometer in shallow pavement applications |
| | D698 | Standard test methods for laboratory compaction characteristics of soils using standard effort |
| | D854 | Standard test method for specific gravity of soil solids by water pycnometer |
| | G51 | Standard test method for measuring pH of soil for use in corrosion testing |

TABLE 37
(*continued*)

| | | |
|---|---|---|
| | G57 | Standard test method for field measurement of soil resistivity using the Wenner four electrode method |
| | D5050 | Standard guide for commercial use of lime kiln dusts and portland cement kiln dusts |
| | C593 | Standard specification for fly ash and other pozzolans for use with lime for soil stabilization |
| | C595 | Standard specification for blended hydraulic cements |
| | C618 | Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete |
| | D5239 | Standard practice for characterizing fly ash for use in soil stabilization |
| | D618 | Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete |
| | E2201 | Standard terminology for coal combustion products (withdrawn 2011) |
| | E2277 | Standard guide for design and construction of coal ash structural fills |
| | C148 | Standard test methods for polariscopic examination of glass containers |
| | C25 | Standard test method for chemical analysis of limestone, quicklime, and hydrated lime |
| | D5120 | Standard test method for inhibition of respiration in microbial cultures in the activated sludge process |
| | D2007 | Standard test method for characteristic groups in rubber extender and processing oils and other petroleum-derived oils by the clay-gel absorption chromatographic method |
| | D297 | Standard test methods for rubber products-chemical analysis |
| | D5054 | Standard test method for rubber chemicals-diphenyl guanidine (DPG) and di-o-tolyl-guanidine (DOTG) assay |
| | D6114 | Standard specification for asphalt-rubber binder |
| | D6270 | Standard practice for use of scrap tires in civil engineering applications |
| | D2178 | Standard specification for asphalt glass felt used in roofing and waterproofing |
| | D228 | Standard test methods for sampling, testing, and analysis of asphalt roll roofing, cap sheets, and shingles used in roofing and waterproofing |
| | D312 | Standard specification for asphalt used in roofing |
| | D450 | Standard specification for coal tar pitch used in roofing, damp proofing, and waterproofing |
| | D4990 | Standard specification for coal tar glass felt used in roofing and waterproofing |
| | D689 | Standard test method for internal tearing resistance of paper |
| | D69 | Standard test methods for friction tapes |
| | C441 | Standard test method for effectiveness of pozzolans or ground blast furnace slag in preventing excessive expansion of concrete due to the alkali silica reaction |
| | C989 | Standard specification for slag cement for use in concrete and mortars |
| | C1250 | Standard test method for nonvolatile content of cold liquid-applied elastomeric waterproofing membranes |
| | C1298 | Standard guide for design and construction of brick liners for industrial chimneys |
| | C177 | Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus |
| | D1193 | Standard specification for reagent water |
| | D1195 | Standard test method for repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements |
| | D3407 | Standard test methods for joint sealants, hot-poured, for concrete and asphalt pavements (withdrawn 1996) |
| | D3887 | Standard specification for tolerances for knitted fabrics |
| | D6130 | Standard test method for determination of silicon and other elements in engine coolant by inductively coupled plasma-atomic emission spectroscopy |

TABLE 38
SUMMARY OF EPA TEST METHODS PREVIOUSLY USED TO EVALUATE BYPRODUCTS AND HIGHWAY APPLICATIONS USING BYPRODUCTS

| | |
|---|---|
| EPA Method 8260 | Volatile organic compounds |
| EPA Method 8270 | Semi-volatile organic compounds |
| EPA SW-846 Method 1310 | Test methods for evaluating solid waste |
| EPA SW-846 Method 1311 | Test methods for evaluating solid waste, physical/chemical methods |
| EPA SW-846 Method 1312 | Test methods for evaluating solid waste |
| EPA SW-846 Method 1320 | Test methods for evaluating solid waste |
| EPA SW-846 Method 3050 | Test methods for evaluating solid waste |
| EPA SW-846 Method 3051 | Test methods for evaluating solid waste |
| EPA SW-846 Method 3052 | Test methods for evaluating solid waste |

- Some of the byproducts used to replace virgin materials may have substantially different particle sizes, which may or may not influence the efficiency of the plant particulate emissions removal system.
- Highway applications routinely monitor and pay on units of mass and/or volume. Some byproducts require plant adjustments to account for different specific gravities when controlling by volume by controlling weight, or to account for higher unit weights when calculating haul costs for the same volume of materials (e.g., steel slag in HMA).

## DESIGN ADAPTATIONS

The majority of the agencies interviewed for their experiences with byproducts in highway applications indicated some changes were needed during the mix design phase of the construction process. Volumetric mix designs, either HMA or portland cement concrete (PCC), need to consider the different specific gravities and absorption characteristics of byproducts. Highly absorptive byproducts can significantly increase the demand for asphalt cement needed for a desirable mix design. In the case of HMA, the in-place mat thickness can be specified in units of pounds per square yard and byproducts with high specific gravities will result in thinner mat thicknesses if the unit weights for the project are not adjusted. The in-place density is used as an indication of proper compaction that is required for good performance of the final pavement. Density is influenced by both absorbed asphalt and mat thickness. For PCC mixes, changes in absorption of the aggregate will produce changes in the quantity of water and cement. Lighter weight byproduct particles typically produce lower strength concretes, which in some cases can be addressed by using other additives to the mix.

When byproducts are used in unbound applications, density is a primary concern when calculating a load carrying design. The layer heights of the byproduct in an embankment or fill design may need to consider unusual factors such as the fire potential of shredded tires. Byproducts with the potential for ground-water contamination need to consider the location of the water table, both for the project and for the byproduct storage areas. In the case of air-cooled blast furnace slag and steel slag in unbound applications, the project selection criteria for using these byproducts requires a dry, well-drained area above the water table.

## CONSTRUCTION ADJUSTMENTS AND PRODUCT QUALITY CONTROL

Construction considerations depend on both the byproduct and the application. Byproducts in PCC applications that influence the set times and slump (workability) must be factored into the work schedule. When the set times for the initial hardening of the PCC are increased, the time at which finishing can be started or forms stripped are altered. If the byproduct decreases the slump, then water-reducing admixtures need to be considered (preferably during the mix design phase). Chemical byproduct and admixture interactions are to be evaluated.

Production quality control programs may need to be adjusted to account for increased application product variability. In some cases, research and/or experience suggests a reasonable threshold under which normal construction testing practices work well and above which additional testing and/or additional test methods are needed. One example would be a suggested limit of less than 35% slag for using standard quality control/quality assurance (QC/QA) PCC programs. Above 35%, additional preconstruction testing is needed to ensure compatibility (e.g., set times) of the byproducts and other materials in the application.

The use of standard test methods may need to be adjusted or allowable testing parameters more closely defined when testing materials with byproducts. Byproducts that can be degraded by handling may need to have specific requirements for sampling and handling of samples taken for quality control. Highly water-absorptive byproducts may require further restrictions or adjustments to laboratory drying times so that an accurate measure of moisture at the time of construction is obtained.

In the case of HMA applications, some byproducts can influence the density and/or ride quality of the pavement. Since these are usually pay items for the contractor, establishing a nonstandard rolling pattern or equipment sequencing could be considered. Additional testing during construction may be needed by the agency to ensure that performance-related characteristics such as air voids and initial pavement profiles are acceptable.

When using byproducts in embankments, fills, and stabilized bases, extra testing and monitoring of the optimum moisture are needed. All of these applications test for density during construction, which is strongly dependent on the optimum moisture content to achieve the required density. Monitoring wells for tracking changes in ground-water quality may be needed when byproducts are used in unbound or semi-bound applications.

One agency required a preconstruction trial mix program. Other published work suggested a quality control program, originally developed to control the use of granulated ground blast furnace slag in cements (Bouzoubaâ and Fournier 2005). Figure 25 summarizes the quality control responsibilities outlined by these authors for QC/QA programs when using byproducts in highway applications.

## COST CONSIDERATIONS

General cost information showed that:

- The lower the market value of the byproduct, the less likely the plant owner will be to spend money on improving the quality and consistency of the byproduct. Market value will depend on various parameters including the potential for long-term market demand and stability and consistency of environmental regulations.
- Transportation costs often limit the use of byproducts to local projects. From the financial point of view, byproducts need to be located close to the project location to provide a cost savings. Suggested distances were less than 30 to 50 miles from the project for an economic advantage to exist. Alternatively, a regional recycling facility can be used to economically produce a post-processed byproduct that can be packaged, bagged, or shipped longer distances.
- Byproduct generators without their own landfills have a higher economic incentive to find markets for byproducts. For example, typical power plant fly ash landfill costs

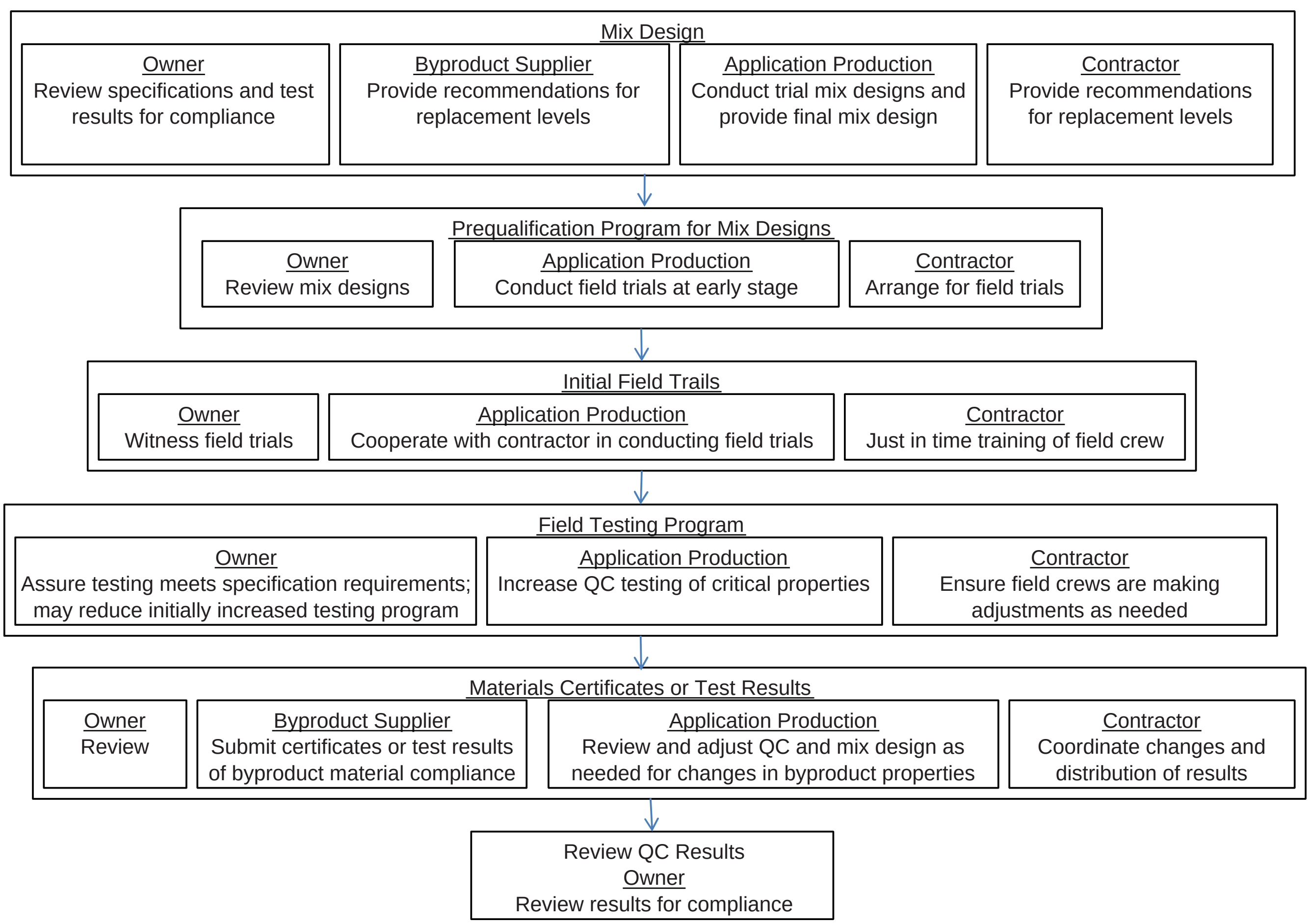


FIGURE 25 Example of QC program sequence when using byproducts in highway applications (after Bouzoubaâ and Fournier 2003, 2005).

range from $3 to $15/ton for plants where the byproduct producer owns the landfill, which increases to $10 to $35/ton when using a third-party landfill.

- When permitting is based on environmental issues, using environmentally friendly byproducts and processes can result in significant carbon dioxide reduction credits (noted in phone interviews).
- The high specific gravity byproducts make it more costly to haul the same volume of material compared with traditional materials.
- Higher quantities of absorbed water in the byproducts can result in increased drying costs during production of the highway application products.
- Higher liquid absorption capacities can increase the demand, and therefore the cost, for binders (portland cement or asphalt cement). Because the binders are typically the most expensive component of the product, this can be a significant increase in cost.
- The possible variability in the byproducts may require additional preconstruction and construction quality control testing to design and monitor the uniformity of the project. The additional testing will increase both the design and construction costs.
- State agency research found that at least three bidders on a project are needed to encourage the contractors to pass cost savings on to the agency.

## ENVIRONMENTAL CONSIDERATIONS

Benefits associated with using byproducts in highway applications include a reduction in the use of landfill space, lower greenhouse gas production (and particulate emissions), and conservation of natural resources. The main environmental disadvantage is the potential for air and water contamination. A number of software tools have been developed by researchers and agencies to assist engineers with assessing these environmental factors. Although some of the software tools were developed to deal with a specific byproduct, some of the software programs have the potential for use with other byproducts. In addition, there are a number of software programs to assist with environmental impacts such as leaching potential or emissions potential. Inputs for the software typically require the chemical components and heavy metal information as well as, in some cases, soil properties. Life-cycle environmental assessments are also available and use information on anticipated changes in energy and heat for both the traditional raw materials and byproducts in the application process. Examples include:

- **CalTOx**: This is a risk assessment model that calculates emissions of a chemical, the concentration of the chemical in the soil, and the risk of adverse health effect.
- **IWEM** (Industrial Waste Management Evaluation Model): Software is designed to minimize or avoid adverse ground-water impacts by evaluating types of liners, hydrogeological site conditions, and the toxicity and expected leachate concentrations from the recycled material.
- **PaLATE** (Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects): This is an Excel-based program that is designed to record inputs on design, initial construction, maintenance, equipment, costs and output cost results, and environmental results.
- **STUWMPP** (Screening Tool for Using Waste Materials in Paving Projects): Uses dilution–attenuation factors obtained from the seasonal soil compartment (SESOIL) model and relates leaching concentrations from byproducts and soils to concentrations in underlying ground water.
- **WiscLEACH:** This model is based on a three-analytical solution using the advection–dispersion–reaction equation to describe transport in the vadose zone and ground water. The development of the model was calibrated to results from HYDRUS-2D (Lin et al. 2005).

There are another two programs that can also be used, however these are marketed (i.e., purchase required):

- **IMPACT™**: Provides a method for conducting analyses for the transport and accumulation of contaminates. It also provides a method for calculating the dose or risk to humans.
- **HYDRUS-2D**: This software is a finite-element program for simulating the movement of water, heat, and multiple solutes in variably saturated media.

## GAPS

The most readily identifiable missing information in the literature and agency responses includes a lack of:

- Environmental tests and standards for stockpiles of byproducts (solid materials) and test methods and standards for liquid byproducts (or byproducts with a significant liquid content).
- Life-cycle cost data for various byproducts in different highway applications.
- Environmental assessments for various byproducts in different highway applications.
- Training and education programs for all stakeholders with regard to byproducts, potential uses, and how to evaluate the environmental and financial advantages and disadvantages.
- Standardized definitions of byproducts.
- Identification of spatial location and potential quantities of byproduct sources.
- Mineralogical, chemical, and mechanical properties for each source and type of byproduct over time.
- Byproduct specifications for physical and chemical properties.

- Standard test method adjustments needed to properly evaluate byproduct and highway application product properties and performance.
- Threshold values for standard material and application test method results.
- Best practices guidelines for stockpiling, handling, using and constructing applications, and QC/QA programs.
- Contractor and crew training.
- Construction cost information.
- Estimates of financial costs associated with preparing the byproducts for use in highway applications.
- Education of byproduct suppliers about highway application material property needs.

Other environmentally related gaps are the *lack of:*

- Estimates of environmental impacts in highway applications.
- Economic and environmental cost information.
- Environmental testing programs for byproduct assessment.
- Assessments of recyclability at the end of the service life of the application (i.e., sustainability).
- Communication between civil engineers, environmental engineers, contractors, and the public.
- Material Safety Data Sheet information that will include health and safety information associated with byproduct handling.
- Material Safety Data Sheet information also needs to be reviewed cautiously as it may not anticipate differences in hazards resulting from reactions or interactions of the byproducts with other application materials and additives.

## BARRIERS

The barriers identified by the agencies and found in the literature start with the need to be economically advantageous when using byproducts. The perception of the user that the byproduct is a waste product with little to no performance advantage is also a common barrier. Limited sources of byproducts in a region of the country prevent some agencies from using potentially beneficial byproducts. In some cases, there may be a local requirement to use more of a byproduct in highway applications when the supplier has a greater financial incentive for an alternate use.

The byproduct variability is a consistent concern with the agencies. However, byproduct suppliers are not always motivated to provide their byproducts in a form that is useful or best for highway applications. Producers may not separate stockpiles of different byproducts from the same process (e.g., power plants). This is possibly a financial or site consideration with available square footage. It is also possible that the byproduct supplier is not aware of the specific needs for each highway application. Suppliers may also resist additional post-processing of the byproduct such as crushing the material to a specific range of sizes or instituting a drying process for byproducts in slurry form. Some byproducts may need time in the stockpile to weather, which may force the need for more storage capacity at the processing or contractor site.

Key byproduct properties that relate to the application product properties and constructability are to be conveyed to the byproduct supplier. Agencies and contractors need to understand the original materials and processes that produce the byproduct. Byproduct suppliers must be aware that the size, size distribution, particle shape, specific gravity, absorption capacity (water), toughness, and durability are primary concerns for highway applications. Byproducts that have a high water absorption capacity may generate problems with frost heave in unbound applications in cold, wet climates. Byproducts with primarily one-sized fine particles (e.g., foundry sand) are a desirable quality for casting operations, but may create gradation problems when used as fine aggregates in PCC or HMA applications. Some byproduct reactions with other components result in destructive expansive reaction or a loss of ultimate application product strength. In some applications appearance is also a consideration, so any influence of the chemistry, color, or texture of the byproduct can be important. This information, at a minimum, needs to be communicated to the byproduct suppliers.

Byproduct suppliers, contractors, and agencies need to be aware of the chemistry of the byproducts, their potential for air and ground-water contamination, and potential chemical interactions with other application materials. Leaching of heavy metals is a major consideration when using nontraditional materials in highway applications. The ultimate recyclability of the application product at the end of life needs to be assessed so that agencies can evaluate the long-term environmental and construction impacts.

Environmentally related barriers include additional sets of environmental regulations when using byproducts, lack of federal guidance, inadequate state environmental guidance, increasingly rigorous air and water quality standards, and difficulty in finding and using environmental software by engineers and contractors.

Other barriers include arbitrary limits on material properties (e.g., a maximum specific gravity for aggregates) and maximum or minimum limits on use as a replacement (e.g., fly ash and GGBFS), lack of contractor experience, lack of agency experience, inadequate test data to support the use in a given application, cost information, performance history, and needed adjustments to traditional empirical relationships (e.g., PCC compressive strength used to estimate flexural strength).

"Stove piping" by byproduct generators and users of the byproducts in highway applications also limits increased use.

Stove piping refers to the lack of generators and users understanding of each other's needs and limitations. Each stakeholder group is limited to an understanding of the processes of their own industries.

## RECOMMENDATIONS FOR RESEARCH ROADMAP

Agencies are interested in byproducts that can be used in highway applications for a number of reasons including improved performance, lowering cost, decreasing environmental impact, and pro-acting green interests. Recycling efforts for using specific byproducts in highway applications can also be driven by legislation, regional programs for maximizing recycling, environmental protection, and limited space in landfills rather than by value-added engineering. Too often agencies have limited historical information for identifying the best application for given byproducts. In a number of cases, there is insufficient technological information about the industry supplying the byproducts; for example, fly ash is commonly used for improved durability of PCC. There are both AASHTO and ASTM specifications for Type F and C fly ash; however, there is little apparent understanding that advances in technology as a result of increasingly restrictive environmental regulations are resulting in chemical changes to the traditional coal byproducts. Alternatively, byproduct producers have little understanding of what is needed by the agencies that use byproducts in highway applications.

Research that focuses on improving communication and information exchange between byproduct producers and users/end-use will have the most impact on the improved use of these materials. The best method of increasing the beneficial use of byproducts in highway applications is to focus on the local and regional uses, because byproduct use will be highly dependent on the near-source parameters such as local competition with natural materials suppliers, transportation costs, byproduct availability, product production facilities (e.g., concrete and HMA plants), regional environmental conditions, and traffic volumes. The general framework for future research programs was laid out in a research document by Petavratzi and Barton (2006) and is presented in Figure 26.

In Phase One, each local byproduct producer needs to identify current and potential future process changes that impact their individual waste streams. It is important that the agencies identify what applications would most economically and environmentally benefit from improvements.

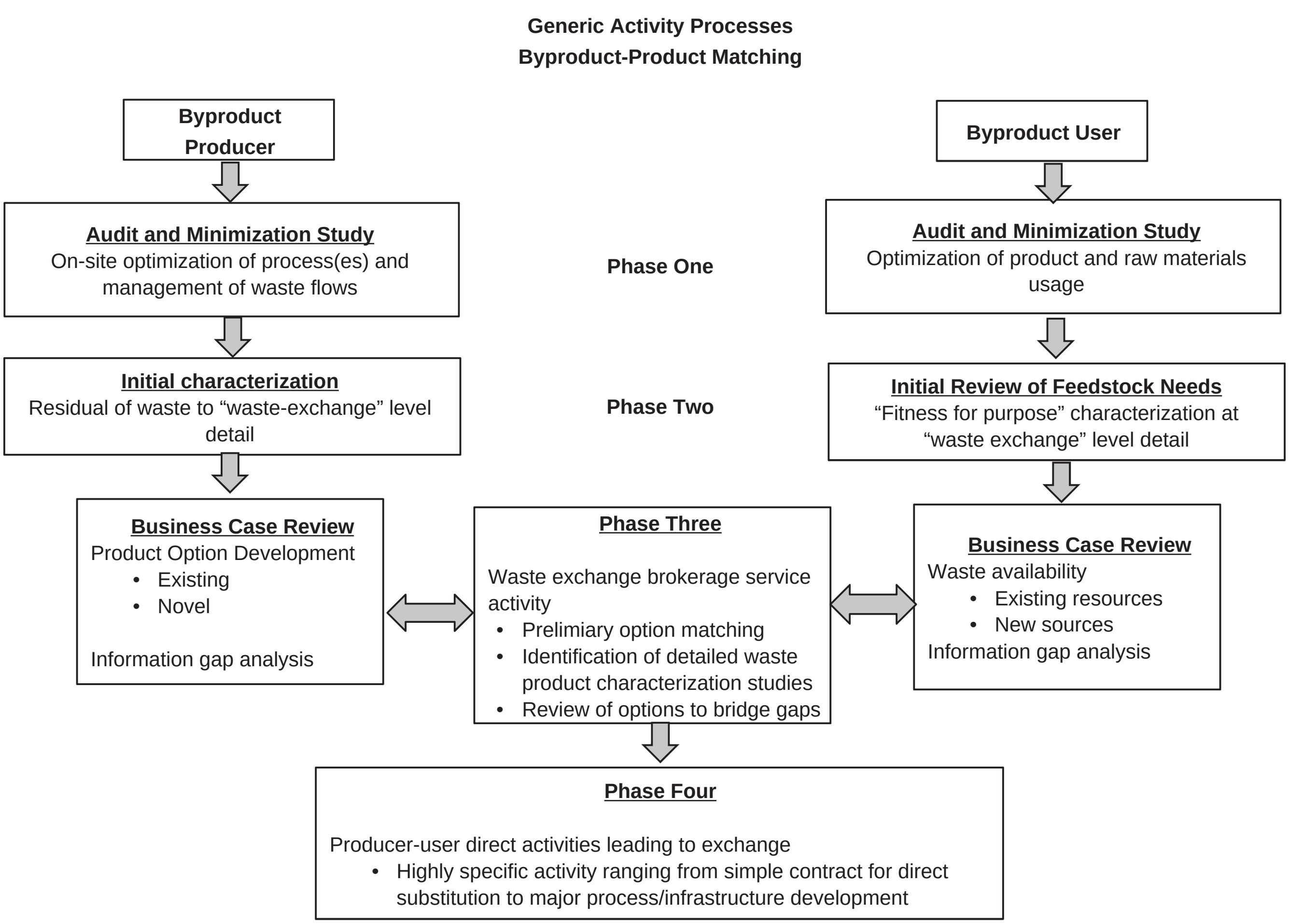


FIGURE 26 Conceptual model used to develop sustainability assessment database (after Petavratzi and Barton 2006).

In Phase Two, the byproduct producer needs to provide the initial characterization of *each* waste stream. If the byproduct producer intends to market for a specific highway application it will be important to directly address the key material properties needed for the agency application. The agency also needs to provide a list of key raw material and final product properties and quantities that are necessary for each application. Both quality and quantity information is needed because it is likely that some smaller waste streams may have desirable properties for an application but not have sufficient quantities to make their use in large projects a practical choice. Planning for reuse of a byproduct in a specific application will help produce more manageable byproduct characteristics and decrease byproduct variability. It will also help identify when waste streams are to be kept separate or when they can be combined.

Phase Three brings together the information from both the byproduct producer and user for a more extensive evaluation of applications with the most potential for performance, economical, and environmental benefits. In this phase, the producer needs to evaluate if the waste stream can be used as is or if post-processing is needed to become a beneficial recycled product. The producer might also consider using the waste stream to create a secondary product such as a synthetic aggregate. The agency needs to provide information with regard to existing and potentially new sources of materials (e.g., location of aggregate quarry and life expectancy). The agency will review byproduct characterizations to help the producer identify any missing information needed for its environmental and application use. Laboratory studies for emissions, leachates, application structural and performance properties, constructability, and recyclability are required in this phase.

Phase Four is the development of pilot projects for the most promising byproducts and applications.

### Byproduct Producer (Phases 1 and 2)

Byproduct generator information is needed to describe, as best possible, the specific type of a given category of byproduct used in previously constructed or to-be constructed projects. At a minimum, the location of the point source(s) of byproducts within the process generating the byproduct (e.g., bottom ash and pollution control system), the technology used to generate the byproduct (e.g., precalciner kiln, wet cement kiln, and dry cement kiln), quantities of each type of byproduct, stockpiling practices, geographic location of byproduct sources, and current disposal costs (e.g., tipping fees and on-site landfill containment facilities), and identification of any environmental regulations that apply to the classification and reuse of the byproduct are necessary.

Some industries have undertaken byproduct risk assessment testing programs that will likely contain chemical properties of the byproducts that are associated with environmental impacts. These data may be useful, if available, in the development of anticipated chemical variability of the byproducts by region of the country and process technology as well as material safety data sheets. Data for the mechanical and physical properties of these sources will also be necessary so that byproduct material specifications for highway applications can be developed.

The current methods for byproduct disposal, stockpiling, and any post-processing of the byproducts need to be identified. At this point, an assessment of individual plant post-processing or the establishment of regional recycling centers for byproduct use needs to be considered.

### Byproduct User (Phases 1 and 2)

Agencies need to assemble material on the physical and chemical properties that need to be evaluated for each potential use of byproducts. This was described by Petavratzi and Barton (2006) as "fitness for use" characteristics. It is important that both agencies and contractors identify any environmental regulations that apply to the classification and reuse of byproducts in a particular application.

The Recycled Materials Resource Center website (2010) provides a list of test methods used to assess a wide range of highway application products, and includes general information on values primarily associated with testing historically used natural materials. These test methods need to be more closely evaluated once the preliminary byproduct–product matches are identified (i.e., in Phases 3 and 4).

The fiscal tipping point for using a given type of byproduct in a specific application product needs to be estimated. For example, a byproduct to be used as a portland cement substitute at a given percent by weight for a specific number of cubic yards of concrete needed each year is to be calculated and then compared with the locally available supply so that the capital cost for an additional material storage silo can be estimated. The impact of requested production changes on agency and contractor sampling, testing, and training also need to be considered. Information on the cost and availability of currently used raw materials are to be collected so the impact of substituting or adding recycled materials can be assessed.

### Matching Byproduct Producer with Byproduct User (Phases 3 and 4)

A match between each type of byproduct and each specific highway application is essential. Agencies require guidance for identifying enhanced performance possibilities that can be obtained from using byproducts in their projects. The guidance needs to consider the various types of byproducts that may be provided by the byproduct supplier. Currently, the most well-defined type of byproduct is fly ash, which has specifications for Type C and Type F. However, each byproduct type yields application products with differences in the performance of individual application; that is, fly ash has different impacts on PCC versus stabilized base performance characteristics. Any regulations governing the byproducts are to be addressed by both the byproduct producer and user so that the most beneficial and economical paring can be achieved.

Another example is the use of steel slag in HMA applications. Several agencies noted they use steel slag in surface treatments to improve pavement friction, while one state used steel slag to construct an entire lift of HMA pavement. The states using the byproduct for a surface treatment reported excellent results, whereas the agency placing the full life of steel slag HMA reported major problems with construction and durability. Specific specifications need to be developed for byproduct properties as well as their use in specific applications.

Test methods require careful selection and review for byproduct material properties, mix designs, application characterization for performance (e.g., compressive strength), and construction QC/QA testing such as density measurements. Test methods for the byproduct material property testing will be assessed for ruggedness. For example, ASTM E1169-07, Standard Practice for Conducting Ruggedness Tests, can be used to identify any test method preparation or procedure factors that need to be adjusted when testing byproducts. It is likely that sample sizes, drying times, reagents, and number of measurements necessary per lot will have to be adjusted. The precision of the test methods form the basis for allowable material QC/QA specification limits, which may require adjustment when using recycled materials.

Two components are needed to fully assess the cost of using byproducts in highway applications: economical impact(s) and environmental impact(s). The financial life-cycle cost inputs require information on the cost of raw materials, application, production, transportation, placement, testing, expected life of the application product, and salvage values/costs associated with using the different types of byproducts. The performance and salvage value and costs will be the most difficult to collect and/or estimate.

The environmental evaluation requires energy and emissions data for each type of byproduct, application usage, product placement, and potential recycling processes. Information will be required for particulate emissions, gaseous emissions, energy, and heat. The assessment of the environmental impacts will depend on the characteristics for a particular geographical area that needs to be defined for each analysis. A standard level of evaluation should be established for consistently reported information.

Education and training requirements have to be addressed at this point. Both byproduct producers and users engage in technology transfer. Field and lab technicians are to be introduced to any required testing changes or additions. Public awareness programs are needed to improve environmental stewardship perceptions of agency practices and policies.

# ACRONYMS, ABBREVIATIONS, AND TERMS

| | |
|---|---|
| ACAA | American Coal Ash Association |
| ACBFS | Air-cooled blast furnace slag |
| ACFM | Actual exhaust gas flow |
| ACI | American Concrete Institute |
| ACPA | American Concrete Pavement Association |
| AFBC | Atmospheric fluidized bed combustion |
| AIV | Aggregate impact value |
| ANOVA | Analysis of variance |
| AOD | Argon oxygen decarburization |
| AQA | Aggregate and Quarry Association |
| ASR | Alkali silica reactivity |
| BBR | Bending beam rheometer |
| BCS | Blended calcium sulfate |
| BFBC | Bubbling fluid bed combustion |
| BFS | Blast furnace slag |
| BOF | Basic oxygen furnace |
| BS EN | British Standard of European Standard |
| CAST | Coaxial shear test |
| CBR | California bearing ratio |
| CCP | Coal combustion product |
| CCR | Crushed concrete aggregate (recycled from returned fresh PCC) |
| CDF | Control density fill |
| CD&I | Construction, demolition, and industrial |
| CDW | Construction and demolition waste |
| CIPEC | Canadian Industry Program for Energy Conservation |
| CIWMB | California Integrated Waste Management Board |
| CLSM | Controlled low strength material |
| CML | Centre for Environmental Studies |
| CMRA | Concrete Material Recycling Association |
| CMOD | Crack mouth opening deformation |
| COC | Certificate of compliance |
| CRC CSRP | Cooperative Research Center for Sustainable Resource Processing |
| CRM | Crumb rubber modified |
| CRMA | Construction Recycled Materials Association |
| CSH | Calcium silicate hydrate (abbreviation for one of the portland cement reactions with water) |
| CV | Coefficient of variation |
| $D_x$ | Particle size with “x” percent passing |
| DCP | Dynamic cone penetrometer |
| DIN | German standard designation |
| DMS | Department of Materials Specifications |
| DNR | Department of Natural Resources |
| DOD | Department of Defense |
| DOTD | Department of Transportation and Development |
| DSCFM | Dry exhaust gas flow, standard cubic feet per minute |
| DSCMM | Dry exhaust gas flow, standard cubic meters per minute |
| DSR | Dynamic shear rheometer |
| EAF | Electric arc furnace |

| | |
|---|---|
| EAPA | European Asphalt Pavement Association |
| EDIP | Environmental Design of Industrial Production |
| EDX | Energy-dispersive X-ray spectroscopy |
| EERC | Energy and Environmental Research Center, University of North Dakota |
| EIA | Environmental impact assessment |
| EN | European standard designation |
| EP | Extraction procedure |
| EPA | Environmental Protection Agency |
| EPT | Extraction Procedure Toxicity |
| FASI | Fly ash slurry injection |
| FBC | Fluidized bed combustion |
| FGD | Flue gas desulfurization |
| FPRIDI-DOST | Forest Products Research and Development Institute of the Department of Science and Technology |
| FDOT | Florida Department of Transportation |
| FT | Fischer-Tropsch |
| FWD | Falling weight deflectometer |
| GGBFS | Granulated ground blast furnace slag |
| GHG | Green house gases |
| GIS | Geographical Information Systems |
| GPC | Gas permeation chromatography |
| GPR | Ground penetrating radar |
| HMA | Hot mix asphalt |
| HPA | Headline performance indicators |
| HRWR | High range water reducer |
| HVAC | Heating, ventilation, and air conditioning |
| HVFA | High-volume fly ash |
| IBM | Immediate bearing value |
| ICP | Inductively coupled plasma |
| IRI | International roughness index |
| ISO | International Standards Organization |
| ISS | International Surface Sealing |
| JIS | Japan standard designation |
| KPI | Key performance indicators |
| KSLT | Korean Standard Leachate Test |
| L/S | liquid to solid ratio |
| LBR | Limestone bearing ratio |
| LCA | Life-cycle assessment |
| LCA | Life-cycle analysis |
| LCI | Life-cycle inventory |
| LD | Ladle slag |
| LEED | Leadership in Energy and Environmental Design |
| LLD | Longest linear dimension |
| LOI | Loss on ignition |
| LTRC | Louisiana Transportation Research Center |
| LTPP | Long-term pavement performance |
| MDOT | Michigan Department of Transportation |
| MnDOT | Minnesota Department of Transportation |
| MOC | Ministry of Construction |
| MoDOT | Missouri Department of Transportation |
| MPCA | Minnesota Pollution Control Agency |
| MSE | Mechanically stabilized embankment |

| | |
|---|---|
| MSW | Municipal solid waste |
| MTO | Ministry of Transportation Ontario |
| NAHB | National Association of Home Builders |
| NAPA | National Asphalt Pavement Association |
| NCAT | National Center for Asphalt Technology |
| NEN | Spanish standard designation |
| NEPA | National Environmental Policy Act |
| NETL CBRC | National Energy Technology Laboratory Combustion Byproducts Recycling Consortium |
| NFPA | National Fire Protection Association |
| NRM | Non-hazardous recycled materials |
| NSA | National Slag Association |
| ODOT | Oregon Department of Transportation |
| OGFC | Open-graded friction course |
| OH | Open hearth |
| PAV | Pressure aging vessel |
| PBM | Polymer-modified bitumen |
| PCB | Polychlorinated byphenols |
| PCC | Portland cement concrete |
| PCI | Pavement condition index |
| PFBC | Pressurized fluid bed combustion |
| PG | Performance grade |
| PLT | Plate load test |
| PMAR | Polymer modified asphalt rubber |
| QA | Quality assurance |
| QC | Quality control |
| QC/QA | Quality control and quality assurance |
| RA | Recycling agent |
| RA | Recycled aggregate (from construction and demolition waste) |
| RA | Recycling agent |
| RAL | Regulatory allowable limits |
| RAP | Reclaimed asphalt pavement |
| RCA | Recycled concrete aggregate |
| RCC | Recycled crushed concrete |
| RCM | Reclaimed concrete materials |
| RDF | Refuse-derived fuels |
| REAS | Rubberized emulsion aggregate slurry |
| RMA | Rubber Manufacturers Association |
| RMRC | Recycled Materials Resource Center |
| RPA | Rubber Pavements Association |
| RSST-CH | Repeated simple shear test at constant height |
| RTFOT | Rolling thin film oven test |
| SAM | Stress absorbing membrane |
| SAMI | Stress absorbing membrane interface |
| SAR | Synthetic acid rain |
| SBS | Styrene-butadiene-styrene |
| SC | Sulfur concrete |
| SCC | Self-consolidating concrete |
| SCM | Shin Caterpillar Mitsubishi |
| SCR | Selective catalytic reduction |
| SEA | Sulfur extended asphalt |
| SEAM | Sulfur extended asphalt mix |

| | |
|---|---|
| SEM | Scanning electron microscopy |
| SESOIL | Seasonal Soil Compartment Model (environmental software) |
| SFS | Steel furnace slag |
| SMA | Stone matrix asphalt |
| SMBA | Sulfur-modified base aggregate |
| SMBA | Sulfur-modified bottom ash |
| SNCR | Selective $N_{ox}$ catalytic reduction |
| SNEA | Societe Nationale Elf-Aquitaine |
| SPLP | Synthetic Precipitation Leaching Procedure |
| SPC | Sulfur polymer concrete |
| SPS | Specific pavement study |
| SRC | Sulfur rubber concrete |
| SRV | Soil reference value |
| SWMCB | Solid Waste Management Coordinating Board |
| SWPPP | Storm-water pollution prevention plans |
| TCE | Trichloroethylene |
| TCLP | Toxicity Characteristic Leaching Procedure |
| TDA | Tire-derived aggregate |
| TFHRC | Turner–Fairbanks Highway Research Center |
| TFV | Ten percent fines value |
| TGA | Thermal gravimetric analysis |
| TLA | Trinidad Lake Asphalt |
| TR | Tire rubber |
| TRL | Transportation Research Laboratory |
| TRMSS | Tire rubber-modified slurry seal |
| TSI | Temperature sensitivity index |
| TSR | Tensile strength ratio |
| TSRST | Thermal stress restrained specimen test |
| TTI | Texas Transportation Institute |
| TxDOT | Texas Department of Transportation |
| UK | United Kingdom |
| UNE | Spanish standard designation |
| USC | Unified soil classification |
| USGS | United States Geographical Survey |
| USWAG | Utility Solid Waste Activities Group |
| VDOT | Virginia Department of Transportation |
| VFA | Voids filled with asphalt |
| VMA | Voids in mineral aggregate |
| VSS | Valley slurry seal |
| W/C | Water to cement ratio |
| w/cm | Water to cementitious materials ratio |
| WLR | Weighted logistic regression |
| WMA | Warm mix asphalt |
| WofE | Weight of evidence |
| WSDOT | Washington State Department of Transportation |
| WSI | Water sensitivity index |
| WSU | Washington State University |
| WWP | Waste product pairing |
| XRD | X-ray defraction |
| YCP | Yamanaka Cone Penetrometer |

# SIEVE SIZE CONVERSIONS

| Sieve Designation | | Nominal Sieve Opening | | |
|---|---|---|---|---|
| **Standard** | **Mesh** | **Inches** | **mm** | **Microns** |
| 25.4 mm | 1 in. | 1 | 25.4 | 25,400 |
| 22.6 mm | 7/8 in. | 0.875 | 22.6 | 22,600 |
| 19.0 mm | 3/4 in. | 0.75 | 19 | 19,000 |
| 16.0 mm | 5/8 in. | 0.625 | 16 | 16,000 |
| 13.5 mm | 0.530 in. | 0.53 | 13.5 | 13,500 |
| 12.7 mm | 1/2 in. | 0.5 | 12.7 | 12,700 |
| 11.2 mm | 7/16 in. | 0.438 | 11.2 | 11,200 |
| 9.51 mm | 3/8 in. | 0.375 | 9.51 | 9,510 |
| 8.00 mm | 5/16 in. | 0.312 | 8 | 8,000 |
| 6.73 mm | 0.265 in. | 0.265 | 6.73 | 6,730 |
| 6.35 mm | 1/4 in. | 0.25 | 6.35 | 6,350 |
| 5.66 mm | No.3 1/2 | 0.223 | 5.66 | 5,660 |
| 4.76 mm | No. 4 | 0.187 | 4.76 | 4,760 |
| 4.00 mm | No. 5 | 0.157 | 4 | 4,000 |
| 3.36 mm | No. 6 | 0.132 | 3.36 | 3,360 |
| 2.83 mm | No. 7 | 0.111 | 2.83 | 2,830 |
| 2.38 mm | No. 8 | 0.0937 | 2.38 | 2,380 |
| 2.00 mm | No. 10 | 0.0787 | 2 | 2,000 |
| 1.68 mm | No. 12 | 0.0661 | 1.68 | 1,680 |
| 1.41 mm | No. 14 | 0.0555 | 1.41 | 1,410 |
| 1.19 mm | No. 16 | 0.0469 | 1.19 | 1,190 |
| 1.00 mm | No. 18 | 0.0394 | 1 | 1,000 |
| 0.841 mm | No. 20 | 0.0331 | 0.841 | 841 |
| 0.707 mm | No. 25 | 0.0278 | 0.707 | 707 |
| 0.595 mm | No. 30 | 0.0234 | 0.595 | 595 |
| 0.500 mm | No. 35 | 0.0197 | 0.5 | 500 |
| 0.420 mm | No. 40 | 0.0165 | 0.42 | 420 |
| 0.354 mm | No. 45 | 0.0139 | 0.354 | 354 |
| 0.297 mm | No. 50 | 0.0117 | 0.297 | 297 |
| 0.250 mm | No. 60 | 0.0098 | 0.25 | 250 |
| 0.210 mm | No. 70 | 0.0083 | 0.21 | 210 |
| 0.177 mm | No. 80 | 0.007 | 0.177 | 177 |
| 0.149 mm | No. 100 | 0.0059 | 0.149 | 149 |
| 0.125 mm | No. 120 | 0.0049 | 0.125 | 125 |
| 0.105 mm | No. 140 | 0.0041 | 0.105 | 105 |
| 0.088 mm | No. 170 | 0.0035 | 0.088 | 88 |
| 0.074 mm | No. 200 | 0.0029 | 0.074 | 74 |
| 0.063 mm | No. 230 | 0.0025 | 0.063 | 63 |
| 0.053 mm | No. 270 | 0.0021 | 0.053 | 53 |
| 0.044 mm | No. 325 | 0.0017 | 0.044 | 44 |
| 0.037 mm | No. 400 | 0.0015 | 0.037 | 37 |

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# APPENDIX A

# Survey

**NCHRP 40-01 Recycled Materials and Byproducts in Highway Applications**

A 1994 survey focused on identifying research on waste products in a limited number of highway applications. In only 15 years, waste products are now considered recycled materials and byproducts that are used in a broad range of highway applications. In 1994, products were generally classified by the main source of the waste stream. Today, a number of these waste streams have been refined and separated into a number of individual secondary byproducts used in a range of highway applications. This survey will define the current uses for these byproducts.

The survey is comprised of 7 groups of recycled materials and byproducts:

* Combustion
* Slag
* Mineral processing and quarry byproducts
* Hot mix asphalt
* Concrete industry
* Tire rubber
* Manufacturing or miscellaneous byproducts

The first question in each group is designed to capture the range of individual byproducts that are used in general categories of highway applications (e.g., concrete, geotechnical, etc.). This first question in the sequence is a matrix which limits the respondent's options to predetermined choices.

The next three questions in the sequence are designed to capture the respondent's experiences with performance, barriers, and identification of projects that demonstrate performance (good or bad) and barriers (overcome or existing).

When you select the "Next Page" option, your survey answers are saved. The survey can then be restarted later from the saved page. This allows respondents to pass the survey on to various people within the agency or for one respondent to take the survey in sections.
If you have questions, please e-mail mstroup-gardiner@csuchico.edu or call Mary at (530) 898-6032.

**1) Respondent Information**

| | |
|---|---|
| First Name: | ____________________ |
| Last Name: | ____________________ |
| Title: | ____________________ |
| Agency: | ____________________ |
| Division or Department | ____________________ |
| Phone Number: | ____________________ |
| E-mail address: | ____________________ |

**2**) Combustion Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the specific type of combustion byproduct that has been used in your state, check the Combustion Ash, unknown type at the bottom of the list.

* Boiler slag: collected at the bottom of wet-bottom coal fired boilers
* Coal ash: particulate in flue of coal fired boiler.
* FGD: particulate captured by flue gas desulphurization (FGD) technology added to coal fired power plants
* MSW bottom ash: municipal solid waste (MSW) combustor ash which remains at the bottom of the ash stream
* MSW combined ash: any collection of particulate form municipal solid waste combustion process
* Sewage sludge ash: ash from combustion of dewatered sewage sludge
* Type C fly ash: coal combustion flue gas particulate with more than 20% lime
* Type F fly ash: coal combustion flue gas particulate with less than 10% lime

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|
| Boiler Slag | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Coal Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| FGD Scrubber Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| MSW—Bottom Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| MSW—Combined Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Sewage Sludge Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Type C Fly Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Type F Fly Ash | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Combustion Ash, Unknown Type | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**3)** Combustion byproducts: Comment on your experience with the *performance* of the application(s) that used any combustion byproduct.

______________________________________________________________________________
______________________________________________________________________________
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**4)** Combustion byproduct: Comment on *barriers* to the use of combustion byproducts in highway applications that have been either overcome or still exist.

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**5)** Combustion byproduct: If possible, identify one or more *projects that demonstrate these experiences*. Please provide contact information for these projects.

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**6)** Slag Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the specific type of slag that has been used in your state, check the Slag, Unknown Type at the bottom of the list.

* Air-cooled blast furnace slag (BFS): liquid slag cooled slowly
* Expanded BFS: Molten slag to which air, water, or steam is added to foam (light weight)
* Granulated BFS: molten slag cooled and solidified by rapid water quenching to a glassy state
* Copper and nickel slag: Non-ferrous slag produced by removing sulfur from ore
* Lead, lead-zinc, and zinc slags: Non-ferrous slag from pyrometallurgical treatment of sulfide ores
* Phosphorous slag: Non-ferrous slag from elemental phosphorous refining process
* Steel slag: byproduct from steel manufacturing process
* Vitrified, pelletized BFS: molten slag cooled and solidified with water, air quenched in spinning drums

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|
| Air-Cooled Blast Furnace Slag (ACBFS) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Blast Furnace Slag, General | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Granulated Ground Blast Furnace Slag | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Expanded Blast Furnace Slag | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Copper and Nickel Slag | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lead, Lead–Zinc, and Zinc Slags | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Phosphorous Slag | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Steel Slag | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Vitrified Pelletized Blast Furnace Slag (BFS) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Slag, Unknown Type | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**7)** Slag byproducts: Comment on your experience with the *performance* of the application(s) that used any slag byproduct.

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**8)** Slag byproduct: Comment on *barriers* to the use of slag byproducts in highway Applications that have been either overcome or still exist.

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**9**) Slag byproduct: If possible, identify one or more *projects that demonstrate these experiences*. Please provide contact information for these projects.

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**10)** Mineral Processing and Quarry Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the type of material used in your state, check the Mineral or Quarry Byproduct, unknown type box at the end of the list.

* Coal refuse: reject material from coal preparation or washing
* Mill tailings: extremely fine particles rejected from grinding, screening or procession of raw material
* Pond fines: fines obtained from washing crushed aggregate
* Screenings: smaller aggregate fractions left after primary and secondary crushing operations
* Waste rock: waste from surface mining operations

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|
| Baghouse Fines (agg. production) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Coal Refuse | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Mill Tailings | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pond Fines | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Screenings | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Waste Rock | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Mineral or Quarry Byproduct, Unknown Type | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**11)** Mineral or quarry byproduct: Comment on your experience with the *performance* of the application(s) which used any mineral or quarry byproduct.

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**12)** Mineral or quarry byproduct: Comment on *barriers* to the use of mineral or quarry byproducts in highway applications that have been either overcome or still exist.

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**13)** Mineral or quarry byproduct: If possible, identify one or more *projects that demonstrate these experiences.* Please provide contact information for these projects.

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**14)** Hot Mix Asphalt (HMA) Industry Recycled Materials and Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the type of reclaimed asphalt pavement (RAP) used in your state, check the RAP, unknown type box at the end of the list.

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|
| Baghouse Fines (HMA plant) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| HMA, Unmilled (chunks) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| HMA, Plant/ Project Fresh Left-Over Mix | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| RAP, as Milled and Stockpiled | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| RAP, Separated into Sized Stockpiles | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| RAP, Unknown Type | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**15)** HMA (additional information): If you use RAP in HMA, what are the differences in use between base, intermediate, and surface HMA mixes?

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**16)** HMA recycled materials: Comment on your experience with the *performance* of the application(s) that used any HMA recycled materials.

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**17)** HMA recycled materials: Comment on *barriers* to the use of HMA recycled materials in highway applications that have been either overcome or still exist.

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**18)** HMA recycled materials: If possible, identify one or more *projects that demonstrate these experiences*. Please provide contact information for these projects.

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**19)** Concrete Industry Recycled Materials and Byproducts: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the type of recycled concrete materials (RCM) used in your state, check the RCM, unknown type at the end of the list.

* Concrete plant, end of day waste and water: any material not used at either the plant or in the trucks by the end of the day's production, including any water used to clean the equipment
* Reclaimed (hardened) concrete materials (RCM): produced by the demolition of concrete roads and structures
* Reclaimed concrete material, crushed and washed: RCM processed for size and fines content
* Returned fresh mix added to new batches: mixing older fresh mix with new batch of concrete

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|
| Concrete Plant, End of Day Waste and Water | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Reclaimed Hardened Concrete Material | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Reclaimed Concrete Material, Crushed and Washed | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Returned Fresh Mix Added to New Batch | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| RCM, Unknown Type | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**20)** Concrete recycled materials: Comment on your experience with the *performance* of the application(s) that used any concrete recycled materials.

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**21)** Concrete recycled materials: Comment on *barriers* to the use of concrete recycled materials in highway applications that have been either overcome or still exist.

**22)** Concrete recycled materials: If possible, identify one or more *projects that demonstrate these experiences.* Please provide contact information for these projects.

**23)** Tire Rubber: Is your state using, or has ever used, these byproducts in highway applications? If you do not know what type of tire byproduct your state uses, check the Tire type, unknown type box at the end of the list.

* Ground tires: typically a no. 80 mesh (finely ground rubber)
* Shredded or chipped tires: primary processing produces shredded tires (12 to 18 in. long by 4 to 9 in. wide). A secondary process produces chips (0.5 to 3 in.)
* Slit tires: tires slit in half
* Whole tires: used as-is
* Crumb rubber aggregate (dry process): small size chips used as aggregate replacements
* Crumb rubber modifier (wet process): small size chips used as a binder modifier (e.g., substitute for polymer modification of asphalt)

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|
| Ground Tires | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Shredded or Chipped Tires | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Slit Tires | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Whole Tires | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Crumb Rubber Aggregate (dry process) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Crumb Rubber Modifier (wet process) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Tires, Unknown Type or Size | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**24)** Tire rubber byproducts: Comment on your experience with the *performance* of the application(s) which used any tire rubber byproduct.

**25)** Tire rubber byproducts: Comment on *barriers* to the use of tire rubber byproducts in highway applications that have been either overcome or still exist.

**26)** Tire rubber byproducts: If possible, identify one or more *projects that demonstrate these experiences*. Please provide contact information for these projects.

**27)** Manufacturing or Miscellaneous Construction Byproducts: Is your state using, or has ever used, these byproducts in highway applications?

* Kiln dust, cement: airborne particles from the portland cement rotary kiln
* Kiln dust, lime: airborne particles from the lime production process
* Kiln dust, combination: blending of both cement and lime kiln dusts
* Paper pulp, lime mud: residual materials from paper mills
* Roofing shingles, fiberglass backed: byproduct from production of fiberglass-backed roofing material
* Roofing shingles, paper-backed: byproduct from production of paper-backed roofing material
* Roofing shingles, tear-offs: construction debris from reroofing or demolition of existing structures
* Sand blasting waste: sand along with finishing materials after resurfacing
* Sand, foundry: high-quality sand recycled after metal castings of products
* Sulfate waste, fluorogypsum: byproduct from the production of hydrofluoric acid from fluorspar
* Sulfate waste, phosphogypsum: byproduct of phosphoric acid production
* Waste glass: post-consumer glass byproducts

| | Asphalt Cements or Emulsions | Crack Sealants | Drainage Materials | Embankments | Flowable Fill | HMA | Other | Pavement Surface Treatments (non-structural) | PCC | Soil Stabilization |
|---|---|---|---|---|---|---|---|---|---|---|
| Kiln Dust, Cement | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Kiln Dust, Lime | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Kiln Dust, Combination of Cement and Lime | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Roofing Shingles, Fiberglass-Backed | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Roofing Shingles, Paper-Backed | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Roofing Shingles, Tear-Offs | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Roofing Shingles, Unknown Type | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Roofing, Build-Up Roofing (BUR) | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Paper Pulp, Lime Mud | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Paper, Manufacturer | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Paper, Post-Consumer | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Sand Blasting Waste | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Sand, Foundry | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Sulfate Waste, Fluorogypsum | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Sulfate Waste, Phosphogypsum | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Waste Glass | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |

**28)** Manufacturing or miscellaneous byproducts not listed: Please indicate any other materials you have used in highway applications.

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**29)** Manufacturing and miscellaneous byproducts: Comment on your experience with the *performance* of the application(s) that used any manufacturing or miscellaneous byproduct.

**30)** Manufacturing or miscellaneous byproducts: Comment on *barriers* to the use of manufacturing or miscellaneous byproducts in highway applications that have been either overcome or still exist.

**31)** Manufacturer or miscellaneous byproducts: If possible, identify one or more *projects that demonstrate these experiences.* Please provide contact information for these projects.

**32)** Environmental Issues: Were any of the recycled material(s) or byproduct(s) listed below tested by your organization for biodegradation, leaching, or ecotoxicity before use in highway application(s)?

* Combustion ash
* Slags
* Mineral processing and quarry byproducts
* Hot mix asphalt
* Concrete
* Tire rubber
* Manufacturing or miscellaneous byproducts

☐ Yes
☐ No
☐ Not sure

**33)** Environmental issues: Which recycled material(s) or byproduct(s) listed in any of the survey questions, did your agency evaluate and which tests were used?

**34)** What question(s) should be added to future surveys?

Thank you for participating in our survey!

Abbreviations used without definitions in TRB publications:

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| A4A | Airlines for America |
| AAAE | American Association of Airport Executives |
| AASHO | American Association of State Highway Officials |
| AASHTO | American Association of State Highway and Transportation Officials |
| ACI–NA | Airports Council International–North America |
| ACRP | Airport Cooperative Research Program |
| ADA | Americans with Disabilities Act |
| APTA | American Public Transportation Association |
| ASCE | American Society of Civil Engineers |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATA | American Trucking Associations |
| CTAA | Community Transportation Association of America |
| CTBSSP | Commercial Truck and Bus Safety Synthesis Program |
| DHS | Department of Homeland Security |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FHWA | Federal Highway Administration |
| FMCSA | Federal Motor Carrier Safety Administration |
| FRA | Federal Railroad Administration |
| FTA | Federal Transit Administration |
| HMCRP | Hazardous Materials Cooperative Research Program |
| IEEE | Institute of Electrical and Electronics Engineers |
| ISTEA | Intermodal Surface Transportation Efficiency Act of 1991 |
| ITE | Institute of Transportation Engineers |
| MAP-21 | Moving Ahead for Progress in the 21st Century Act (2012) |
| NASA | National Aeronautics and Space Administration |
| NASAO | National Association of State Aviation Officials |
| NCFRP | National Cooperative Freight Research Program |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| RITA | Research and Innovative Technology Administration |
| SAE | Society of Automotive Engineers |
| SAFETEA-LU | Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005) |
| TCRP | Transit Cooperative Research Program |
| TEA-21 | Transportation Equity Act for the 21st Century (1998) |
| TRB | Transportation Research Board |
| TSA | Transportation Security Administration |
| U.S.DOT | United States Department of Transportation |