This report presents waste materials and products for highway construction. The general legislation, local liability, and research projects related to waste materials are outlined. The waste materials and products presented include waste paving materials, industrial ash materials, taconite tailing materials, waste tire rubber materials and products, building rubble materials, incinerator ash products and materials, waste glass materials, waste shingle materials and products, waste plastics products, and slag materials. For each waste category, the legislation and restrictions, material properties, construction and application, field performance, and recycling at the end of service life if available are discussed. In addition, procedures for evaluation of and selection from waste alternatives are presented. Results from a survey sent to Minnesota city and county agencies are presented summarizing current practices in waste reuse for highway construction.
Waste Products in Highway Construction

Final Report

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1. Introduction

Highway construction projects are dependent on an adequate supply of aggregate and binder. The amount of aggregate and binder used in highway construction has increased due to pavement rehabilitation and reconstruction. In particular, the demand for construction aggregate is increasing where aggregate sources have been depleted, where the quality of available aggregate is low, or where aggregate cannot be utilized because of mining restrictions, environmental protection regulations, or appreciating land values. Most importantly, in addition to the road construction, other types of construction, such as building construction, exhaust our natural aggregate sources. Aggregate usage in Minnesota is divided between building and non-building construction in a ratio of 1:3 or 1:4[45].

In contrast, enormous quantities of domestic, industrial, and mining waste are generated annually in the United States. For example, approximately 180 million tons of Municipal Solid Waste (MSW) were generated in 1988. However, only 13.1 percent was recovered, 14.2 percent was incinerated, and 72.7 percent was landfilled[23]. In Minnesota, approximately 4.2 million tons of MSW were generated in 1991. Of that, 38 percent was recovered, 22 percent was incinerated, 4 percent was combusted, and 36 percent was landfilled. Finding suitable places for an increasing supply of waste products has been made more difficult due to a wide variety of environmental legislation enacted with regard to water and land pollution. As a result, disposal of waste has become expensive and complicated.

In the process of waste recovery or recycling, four major types of materials are produced: industrial raw materials, derived fuel materials, construction raw materials, and secondary waste materials.

Due to the present recycling technology, significant quantities of secondary waste materials are deposited into the waste stream. For instance, the entire supply of waste glass generated cannot be recycled by glass manufacturers since only color-sorted and contamination-free materials are considered feasible for reuse in the glass industry. Incinerator are a generator of secondary waste material in the form of waste incinerator residue. It was estimated that 25.5 million tons of MSW were burned in 1988 in the United States[23], and 1.1 million tons were burned in 1991 in Minnesota. If the refuse is relatively dry, most modern incinerators can be operated to give a well burned-out residue with about 90 percent reduction in volume and 70 to 80 percent reduction in weight. However, an average of 6.4 million tons of incinerator residue were still produced in 1988.

An extensive effort to reuse wastes for highway construction has been made by researchers and engineers for almost a century. At present, there are driving forces for an agency to consider the reuse of wastes:

- shortage of aggregates
- high cost of disposal
- commitment to environment
- resource reserve
- local availability
- political pressure
- environmental safety

Because of the wide variety of local restrictions on construction projects, current regular practice of reusing waste for roads in some locations is considered innovative in other locations. The understanding of waste material characteristics and reuse techniques is highly variable according to location.
Four issues are fundamental in the determination of the appropriate use of recycled waste materials in highway construction:

- cost effectiveness
- performance
- availability
- prevailing political climate

The high cost of reusing wastes in highway construction, and the uncertainty of their performance and durability require that a better justification of their use be provided. Therefore, cost effectiveness and performance has become the first important issues. Many suppliers have developed ways to recycle their own wastes for expanded markets. Also, the variable waste stream flow creates inconsistencies in the types of waste available for highway construction. As a result, the availability of proper waste plays an important role in decision making. Finally, political pressure creates legislative mandates to increase the use of recycled materials in highway construction[36].

This report discusses government regulations and agency liability relevant to waste reuses. A waste source inventory will be established with the technical definitions and sources of waste products. Following the waste material properties, waste material evaluation will be discussed with an emphasis on the selection of waste alternatives. The procedures and specifications of waste materials for highway construction are presented in Section 6. This section discusses, what to use waste for, how to use it, and the cost of using. Furthermore, field performance of roads built with waste materials is evaluated in Section 7.

The report includes survey results regarding the use of waste materials for highway construction in Minnesota, based on responses from city and county engineers. The performance of waste materials is also discussed in terms of technical feasibility, environmental consequences, and economic benefits. A list of references is included in the report for city and county engineers to have access to the detailed research results and project experiences.
2. Legislation and Research on Wastes

Legislation has been developed to minimize the dangers and hazards to human health and environment from wastes, especially from potentially hazardous wastes. It is important for highway engineers to be aware of legislative restrictions related to the handling of waste. Legislation does allow opportunities for proven practices and polices that, when applied properly and consistently, maintain or improve environmental quality. In addition, research programs have been developed to resolve the technical difficulties in construction with waste products. The research programs are always practiced under the environmental regulations. A discussion of current Minnesota legislation and national research on wastes are included in this report.

2.1 Government Regulations/Restrictions

Two different kinds of regulations apply to waste materials for highway construction. One is environmental related legislation and the other is the construction related requirements.

The National Environmental Policy Act (NEPA) requires that an environmental impact statement be prepared for all major construction projects undertaken or financed by the federal government. Under the Act, private citizens, associations or organizations may maintain an action in federal court against proposed projects that would significantly affect the quality of the human environment to protect aesthetic, conservational and recreational values [48].

2.1.1 State Law Definitions

The following definitions were quoted from Minnesota Rules, 1991[19]:

**Solid Waste**

"Solid Waste" means garbage, refuse, sludge from a water supply treatment plant or air contaminant treatment facility, and other discarded waste materials and sludge, in solid, semisolid, liquid, or contained gaseous form, resulting from industrial, mining and agricultural operations, and from community activities, but does not include hazardous waste; animal waste used as fertilizer; earth fill, boulders, rock; sewage sludge; solid or dissolved material in domestic sewage or other common pollutants in water resources, such as silt, dissolved or suspended solids in industrial waste water effluent or discharges which are point source subject to permits under section 402 of Federal Water Pollution Control Act, as amended, dissolved materials in irrigation return flows; or source, special nuclear, or by-product material as defined by The Atomic Energy Act of 1954, as amended.

**Waste By-Product**

"Waste by-product" means the liquids, or gases or other residues resulting from waste disposal, processing, or treatment activities.

**Sewage Sludge**

"Sewage Sludge" means the solids and associated liquids in municipal wastewater which are encountered and co-encountered by a municipal wastewater treatment plant. Sewage sludge does not include incinerator residues and grit, scum, or screening removed from other solids during treatment.
Demolition Debris
"Demolition debris" means concrete, blacktop, bricks, stone facing, concrete block, stucco, glass, structural metal, and wood from demolished structures.

Infectious Waste
"Infectious waste" means waste originating from the diagnosis, care, or treatment of a person or animal that has been or may have been exposed to a contagious or infectious disease.

2.1.2 Historical Development of State Law

A description of Minnesota’s major environmental laws from Earth Day 1970 to 1990 are listed below[18]:

1971 Chapter 734 Abandoned motor vehicles constitute a health hazard, a blight to the landscape, and a detriment to the environment. Abandoning a motor vehicle on public or private property is not allowed.

Chapter 904 Plans and Permits are required to operate a solid waste unit.

1973 Chapter 748 A state policy to encourage the reduction of the solid waste by recycling is declared. PCA is authorized to make grants-in-aids for the development of resource recovery facilities.

1974 Chapter 346 PCA is authorized to adopt standards for the identification, labeling, classification, storage, collection, transportation and disposal of hazardous waste.

1976 Chapter 179 Metro cities, counties, or towns are authorized to establish contracts, up to 30 years, for solid waste pickup.

Chapter 228 The Commissioner of DNR is authorized to sell certain lands located within the site selected for the disposal of Reserve Mining Company’s taconite tailings.

1980 Chapter 564 Each county in the metropolitan area is required to propose four sites within its boundaries for the disposal of mixed municipal solid waste and one for the disposal of demolition debris in accordance with statutory standards and subject to approval by the Metropolitan Council. The Metropolitan Waste Control Commission is required to go through a site selection procedure for facilities to dispose of solid waste and sewage sludge.

1981 Chapter 352 Metropolitan counties are authorized to issue revenue bonds to finance solid waste and related facilities, and are given contractual authority in connection with facility operation.
1982 Chapter 569  The Waste Management Board is provided to review proposals to designate resource recovery facilities according to specified standards.

1983 Chapter 373  The number of sludge ash candidate sites is reduced and alternatives to ash disposal is emphasized.

1984 Chapter 644  A $0.50/\text{yd}^3$ fee ($0.25$ for landfill abatement and $0.25$ for government cleanup) is imposed on trash disposal at landfills in the metropolitan area. Counties are allowed to charge solid waste operators in the county a fee limited to $0.25/\text{yd}^3$ for disposal. Equipment for processing solid or hazardous waste at a resource recovery site is exempted from sales tax.

Chapter 645  A $4 fee for initial motor vehicle registration and for each subsequent transfer of title is assessed and dedicated to a waste tire collection program and to clean up tire dumps. Counties are required to include collection and processing of waste tires in waste management plans.

1985 Chapter 274  The Metropolitan Council is allowed to authorize the issuance of general obligation bonds to provide funds for acquisition and improvement of resource recovery facilities.

1987 Chapter 348  It is prohibited for anyone to place a lead acid (automotive) battery in the solid waste stream or dispose of it or place used motor oil in the solid waste stream or in a disposal facility, unless the PCA authorizes it.

1988 Chapter 685  The $0.25/\text{yd}^3$ cap on the fee a metropolitan county may charge to dispose of mixed municipal solid waste is removed and allowed up to $0.35/\text{yd}^3$. It is prohibited to dispose of yard waste (garden waste, leaves, lawn cuttings, weeds, and pruning) in mixed municipal solid waste, in a disposal facility, or in a resource recovery facility (except for composting) after January 1, 1990 in a metropolitan area, and after January 1, 1992 outside the metropolitan area.

1989 Chapter 325  The fee that cities can charge at landfills is increased from $0.35/\text{yd}^3$ to $1/\text{yd}^3$, and a $2/\text{yd}^3$ fee is set on landfills in Greater Minnesota. The PCA is prohibited from issuing permits for new or additional mixed municipal solid waste resource recovery or disposal facilities unless each affected county has an approved waste management plan.

Chapter 337  It is prohibited to compact or mix infectious or pathological waste with other waste prior to incineration or disposal.

Chapter 1  Article 18  Metro counties are required to recycle 35% of their solid waste and non-metro counties to recycle 25% of their solid waste by December 31, 1993.
Article 19 The office of Waste Management is required to distribute money appropriated for recycling programs to counties based on population, with each county to receive at least $55,000 a year.

1992 Chapter 593 There will be a minimum 25 percent statewide per capita reduction in the amount of discarded packaging delivered to solid waste composting, incineration, refuse derived fuel and disposal facilities by December 31, 1995. Metro counties are required to recycle 45% of their solid waste and non-metro counties to recycle 30% of their solid waste by December 31, 1996.

2.1.3 Local Liabilities

As noted in Section 2.1.2, the regulations have been changing due to the development of new technology and the knowledge of waste characteristics. For example, specific hazardous waste disposal problems were not a priority until the last half century when it became evident that solid waste disposal techniques and sanitation waste programs were unable to avoid adverse effects on human health and the environment. Therefore, different liability exists from the present to the past. The best possible understanding of waste is needed to appreciate its potential dangers and hazards to human health and the environment.

The scope of liability includes environmental risk and structural failure, which are closely related to chemical and physical characteristics of wastes. It is the waste-generator’s responsibility to characterize the waste stream. However, if the waste-generator does not supply adequate information and the disposal-operator of the waste chooses to accept the waste anyway, the disposal-operator becomes liable for obtaining the information. In particular, if a potentially hazardous waste is to be used, the disposal-operator must inspect and analyze each waste shipment received at the facility, and must also have a written waste analysis plan specifying test methods, sampling methods and frequency of analyses. The disposal-operator has a duty to select a competent, experienced and careful transporter of the waste. The disposal-operator may also have to explore the transporter’s fitness and ability to operate safely.

The liability of the disposal-operator and waste-generators is determined by the Superfund Act which imposes strict liability for the costs of cleanup of disposal sites. In the meantime the federal government is encouraging disposal-operator to construct adequate disposal units such as[20]:

1. construction and maintenance requiring continuous monitoring
2. chemical fixation
3. microbiological treatment
4. high temperature incineration

If the waste is disposed of or incorporated into highway construction, the disposal-operator is liable for the structural failure of the waste mixture. The physical and mechanical characteristics of the waste materials must be determined before they are used in highway construction. Counties and cities may be reluctant to use the waste in highway construction because of liability. However, with the development of waste recycling and processing techniques, the control of waste application continues to be improved.
2.2 Research Projects

In general, past and ongoing research projects regarding waste materials for highway construction have focused on those materials that are in large national supply and are promising aggregate replacements, binder supplements, or primary binders. These projects have been divided into two major groups: reuse of waste materials and recycling of pavement materials. Pavement materials which are not recycled but are stockpiled or disposed of are included in the first category. In addition, the first category contains projects that reuse wastes resulting from highway maintenance and repair. Recycling of pavement materials typically takes the form of old pavement taken up and crushed into a product that can be directly incorporated into the new pavement. Recycling of pavement materials is not discussed in detail in this report.

2.2.1 Past Research Projects

Pavement recycling research projects initiated in 1915[21]. A wide variety of recycling approaches has emerged since the 1930s. The standard procedures and specifications have also been developed through extensive research programs from laboratory, field, and Synthesis studies. The Synthesis study conducted by NCHRP in 1978 marks a milestone in the research development of pavement recycling[22]. Most importantly, research has resulted in the development of better equipment and facilities. The environmental impact of pavement recycling has also been studied to reduce the potential problem of air pollution from asphalt plant facilities by installing emission control devices.

The general waste materials produced from any possible source have been studied in a number of research projects. This research concentrated on waste materials as replacements for highway aggregates and were summarized by two comprehensive Synthesis studies. The first NCHRP synthesis study conducted by the University of Illinois in 1972 explored the possibility of producing synthetic aggregates, benefit of reusing unsuitable materials, and use of manufactured and waste materials as supplements and replacements for conventional aggregates in highway construction[24]. As a result, this study led to three kinds of research projects: characterization of acceptable aggregates, application of plastics to improve aggregates, and identification and cataloging of raw materials for use in the manufacturing of synthetic aggregates. A few waste products, such as salvaged structural rubble were included in this study. Four years later, another NCHRP synthesis study conducted by Valley Forge Laboratories outlined the types and amounts of waste materials that are potential replacements for highway aggregates, filler, and binder. The study summarized the recent research projects, identified a number of potential waste materials, and established a national inventory of waste resources. A list of 53 waste materials that have a potential for use as an aggregate, filler, and binder was presented in this study[25]. As indicated in the study, the research projects included the laboratory tests on waste characteristics, pilot plant operations on waste mix characteristics, and experimental impacts of road segments constructed with wastes. The waste materials that are frequently used in Minnesota are given in Table 1.
The past research projects have been intensified on several waste materials including flyash and scrap tire rubber. The first research project on the suitability of flyash as a pozzolanic ingredient for use in concrete was conducted by Davis et. al. (1937)[26]. Considerable pioneering and development work in this field was conducted throughout the 1940s and 1950s. Later on, the use of flyash alone or in combination with lime, sulfate waste, or soils, was studied for road base construction. A broad application of flyash use in highway construction has been achieved due to past research projects.

The use of scrap tire rubber for asphalt cement has been developing for over 25 years. However, since the late 1980s, the emphasis for this engineering technology began to focus on its potential for eliminating the environmental solid waste problem of scrap tires. Consequently, a wide variety of research projects were implemented with regards to the application of various waste tire rubber products to highway maintenance, construction, and rehabilitation.
2.2.2 On-going Research Projects

At present, most research projects are conducted by a joint effort of waste management, environmental protection, natural resource, and transportation researchers and engineers. The waste materials considered in ongoing research projects are the products and the secondary waste products produced from a recycler or an incinerator. Incinerator residue, roofing shingles, crumb rubber, and crushed glass are some examples. The changing interest in ongoing projects can be attributed to the development of legislation, recycling techniques, and construction techniques.

More crumb-rubber related projects are being planned for the coming months due to the ISTE. The Federal Highway Administration (FHWA) anticipate that in 1993 about 50 percent of states will be conducting projects involving tire rubber. Some asphalt-rubber marketers have begun offering three and five year guarantees on projects using their patented systems.
3. Waste Sources

A discussion of waste sources begins with definitions, which emphasize where the wastes are produced. Based on the definitions, the location, general properties, and quantity of the waste source are documented. In 1970, the approximated highway aggregate consumption in Minnesota was 31.6 million tons, whereas the approximated solid waste production was 107.1 million tons.

3.1 Scope of Waste Sources

Waste sources include any useless and worthless by-product from highway construction or from other sources such as crumb rubber, waste glass, municipal garbage, etc. The materials from these sources could be used for highway construction when an equal performance to virgin construction materials can be attained without any diverted impact on the environment and without any unjustified added costs. Any waste that can be directly recycled into product is excluded. Five categories of waste materials are outlined according to general sources.

3.1.1 Materials from Old Pavements

Materials from reconstruction or rehabilitation of roads are a major waste source. They have been reclaimed from an old pavement and cannot be used in the pavement recycling process because of economic feasibility, material variation, material contamination, technical knowledge and political limitations. Disposal methods of pavement wastes include landfilling and stockpiling with or without pretreatment, depending upon the chemical characteristics of the wastes.

3.1.2 Wastes from Production Processes

These wastes are produced by manufacturers, mines, processing plants, or metal production plants. Primary treatment of the waste must be completed to meet the waste release standards and regulations. Consequently, hazardous wastes are excluded from the waste stream.

3.1.3 Wastes from Consuming Streams

These wastes are called municipal solid wastes and are produced by consumers, service industries, offices, and food processing plants. As shown in Table 2, the municipal solid waste belongs to the Subtitle D waste category[23]. Subtitle D of the Resource Conservation and Recovery Act deals with wastes other than the hazardous wastes covered under Subtitle C. They must be separated into different groups according to waste management regulations. The hazardous wastes are not allowed to mix into the waste stream.
3.1.4 Secondary Wastes from Recycling Processes

These are secondary waste products produced in any recycling process. It is impossible for waste products to be recycled completely with current recycling technology. Therefore, the amount of secondary wastes is dependent on the development of recycling technology.

3.1.5 Wastes from Landfills

These wastes have been landfilled in the legal disposal sites. They may have been produced from any of the above mentioned sources. Because disposal sites may become a construction site and disposed materials may be used as construction material, the landfilled waste material might become a source for construction materials. Out of the total 180 million tons MSW generated in 1988, 131 million tons of MSW were landfilled in the U.S.[23].

3.2 Inventory of Waste Sources

Much effort has been made to inventory types, sources, and quantities of waste materials potentially suitable for highway construction. For example, the Midwest Industrial Waste Exchange (MIWE) was established by the St. Louis Regional Commerce and Growth Association in 1975. The MIWE waste inventory provides a source to determine least costly and potentially the most cost-effective alternatives for dealing with industrial wastes[27].
3.2.1 Road Construction and Reconstruction

Demolition and removal of roads, streets, curbs, gutters, sidewalks, and bridges provide an excellent source of highway construction materials. Some problems associated with processing concrete and asphalt rubble include the removal of reinforcing steel from concrete and the amount of reclaimable asphalt for new asphalt mixes. Usually, this type of waste is distributed widely and quantities are small unless it is stockpiled at a localized pit. It is predominantly available in metropolitan areas, but the reconstruction of any road results in wastes available for reuse.

Road wastes can be recovered using current recycling technology if it is impractical to reuse them locally for highway construction. As shown in Figure 1, five facilities were reported as markets for recycled concrete and asphalt rubble in 1988[28]. Stockpiled road waste is also a valuable source of highway construction materials.
Figure 1. Markets for Recycled Wastes
3.2.2 Industrial Production

The electrical power industry and the iron and steel industry are sources of industrial wastes. Two basic industrial wastes result from burning of pulverized coal form in the electrical power industry: ash, consisting of spray dryer residue, flyash, bottom ash, and boiler slag, and sludge. In the iron and steel industry, a uniform or nonuniform slag is produced simultaneously in the blast furnace, respectively. In addition, iron foundry operations result in several industrial wastes including arc furnace dust, sand reclaimer residue, and furnace dust. These wastes are generally located in concentrated industrial areas. The geographical locations of wastes from the electrical power industry and the iron and steel industry are shown in Figure 2.

3.2.3 Mining

A source of mineral waste is deposited in the form of mine wastes, mill tailings, washing plant rejects, processing plant wastes, and smelter slag and rejects. A large volume of mineral waste available in Minnesota is taconite tailings, located in the Iron Range area of the state (Figure 2). The annual quantity of taconite tailings produced in Minnesota and Michigan in 1970 alone was 150 to 200 million tons. Because of asbestos content, some tailings are not allowed for highway construction, and tailings from the east end of the Iron Range are prohibited in particular.
Figure 2. Aggregate Shortage Area and Locations of Wastes
3.2.4 Domestic Consumption

Domestic or municipal solid wastes are a large and growing source of wastes with more than half of them consisting of dry, organic materials. These wastes are growing at a faster rate than the population growth rate and come from residential, commercial, institutional, and industrial sources. The overwhelming percentage of these wastes can be found in urban areas (Figure 3), where the production of solid waste is directly related to the concentration and amount of population. These wastes include building rubble, discarded battery casings, incinerator residue, plastics, pyrolysis residues, sewage sludge, rubber tires, glass, shingles, and municipal garbage.

The development of waste management programs has produced a better inventory of domestic wastes and a network of waste collection stations. Figure 4 shows the collection locations of three major domestic wastes. These ordered waste sources benefit the reuse operations.

Incinerators are another domestic waste source. As shown in Figure 2, incinerators are located near metropolitan areas. At present, the two plants operated by the Metropolitan Waste Control Commission (MWCC) produce 21,000 tons per year of dry sewage sludge incinerator ash. There are twelve municipal and county trash incinerators in Minnesota.

Waste recycling facilities also provide a secondary waste source. For example, a waste glass recycling unit produces non-recyclable glass. Most recycling facilities generate processed waste. In many cases, the processed wastes can be directly used for construction depending on cost considerations and specification requirements. Six permitted recycling and three transporting facilities are shown in Figure 5. Their products include crumb rubber, rubberized asphalt, and subgrade fill. The total current processing rate is 11.5 millions of tons per year.
Figure 3. Metropolitan Areas (the U.S. Bureau of the Census, 1990)
Figure 4. Waste Collection Locations
Figure 5. Waste Tire Recycling Facilities
4. Waste Materials and Products

Waste materials and products selected in this report include those which are generated in large quantities statewide. Also, waste materials and products whose use would have significant impact on the environment or which indicate significant potential even if they are not widely used in the state are discussed.

The transport of waste materials is mostly accomplished by truck, rail, and barge. Barge transport is the most reasonable form of transportation, where available. In the larger navigable waterways, barges are towed in combinations of as many as 30 jumbo barges. Rail transport is another alternative for waste transportation. Truck transport is the most popular mode of transportation for distances less than 40 to 50 miles. Pipelines, although advantageous from a cost standpoint, present problems regarding ownership and the type of material which can be pumped through the line.

Proper evaluation of a specific waste material requires a basic knowledge of its physical and chemical characteristics. These properties must be obtained in order to meet the requirements for construction materials and the environmental protection regulations. The material properties presented are based on the laboratory and field material tests conducted and documented in the literature.

After a waste material is evaluated and its use is justified, it can be applied to highway construction. Without any modification in properties and additional ingredients, a waste can be used as a filler, additive, or aggregate for highway construction. Many wastes are potential admixtures, particularly when processed. The processed wastes generally can be obtained from a recycling or processing facility. If properties of waste do not conflict with the properties of portland cement, the waste is a potential aggregate for concrete mix. After they are crushed, some wastes can be used as aggregates for an asphalt mix. The incorporation of these wastes into the asphalt mix usually results in mix properties equivalent to the conventional mix. If a waste can satisfy the base material specifications and leachate requirements with or without processing, it can be directly placed as a base course.

The most cost-effective use is to combine various wastes with conventional materials to produce reliable products. The technique of mixing wastes and virgin materials has been widely practiced.

Before the field performance of a specific waste or waste mixture is discussed, the conditions under which the performance data were taken should be addressed. There are two basic conditions for the field performance: experimental and routine. Under an experimental condition, a particular aspect of field performance is emphasized. In an experimental project, a test section is limited to the localized area and the amount of waste used is small. Most importantly, construction quality is more easily controlled in a pilot project. On a routine basis, construction projects are specification-orientated and need less quality control.

Performance of pavements with incorporated wastes is a complicated issue. Many factors could influence pavement behavior when normal structure and materials are used. For example, quality control in construction has a big impact on the performance. Pilot, demonstration, and experimental projects have better quality control and the resulting pavements behave relatively consistently. Most information collected on performance is based on experimental projects.

4.1 Paving Waste Materials

Most of the paving wastes discussed in this section are crushed concrete or pulverized bituminous.
4.1.1 Legislation and Restrictions

Recently passed federal legislation requires that the quantity of paving and construction waste materials deposited in landfills must be significantly reduced by 1996.

4.1.2 Material Properties

Generally, concrete rubble consists of a mixture of stone, dirt, wood, brick, organic material, and broken concrete with and without some reinforcing steel. Impurities such as reinforcing bars, wood, and inorganic material are removed from the crushed concrete. Having been crushed, the reclaimed material may be blended with virgin aggregate for reuse. A comprehensive laboratory study on the recycled Minnesota DOT Class 5 concrete as well as recycled concrete with 3/8 inch minus Dolomite has been conducted. The gradations of the tested materials conformed to Mn/DOT standards. Test results are shown in Table 3[29].

<table>
<thead>
<tr>
<th>Material</th>
<th>L.A. Abrasion</th>
<th>Absorption</th>
<th>$\gamma_{max}$</th>
<th>$\omega_{opt}$</th>
<th>Soaked CBR</th>
<th>$M_r$</th>
<th>R-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomite Class 5</td>
<td>41.6</td>
<td>3.19</td>
<td>139</td>
<td>7</td>
<td>162</td>
<td>23.0</td>
<td>85</td>
</tr>
<tr>
<td>RC I Class 5</td>
<td>37.1</td>
<td>5.56</td>
<td>123</td>
<td>8</td>
<td>170</td>
<td>18.5</td>
<td>84</td>
</tr>
<tr>
<td>RC II</td>
<td>38.3</td>
<td>4.94</td>
<td>128</td>
<td>8.5</td>
<td>270</td>
<td>19.2</td>
<td>85</td>
</tr>
<tr>
<td>RC with Dolomite</td>
<td>37.2</td>
<td>5.9</td>
<td>135</td>
<td>8</td>
<td>95</td>
<td>21.0</td>
<td>84</td>
</tr>
</tbody>
</table>

If old concrete pavements are ground, concrete grinding residue has much different material properties. Half of all concrete grinding residue is a sludge-like material. The pH value of the grinding slurry is high, in the range of 12.0 to 12.6, as it comes off the grinder. After sedimentation, filtration, and titration, the pH of the slurry is lowered to less than 8.5. It contains large volumes of water, depending on the time elapsed since placement and subsequent evaporation. Moisture contents are often as high as 140 percent. The size of the individual particles is similar to a silt or clay with a fines content of about 70 percent (minus No. 200 sieve)[30].

Pulverized bituminous materials have been used in cold in-place recycling, both as pavement and shoulder material. The material is also used as an aggregate surfacing in areas where washout is a problem.

4.1.3 Construction

Coarse and fine aggregates for concrete mixtures can be produced by crushing old concrete. Portable processing equipment has been used most successfully. Concrete mix with crushed concrete aggregates yields a compressive strength (180 days) which is about 300 to 1,300 psi lower than that of the conventional mix. The resistance to freezing and thawing is greatly improved when the concrete waste contains chert-gravel coarse aggregate and is close to that of a conventional mix when the concrete waste contains limestone aggregate[34].
Reclaimed portland cement concrete (PCC) and asphaltic concrete can be used as aggregates with added sand to make new portland cement concrete. The old slabs should be broken into 2 ft pieces on hot, dry days with a pneumatic hammer to minimize subgrade soil adhesion. Most steel can be removed during crushing. The asphaltic concrete should be removed with an excavator and stockpiled separately. The sand is added to modify grading for mix aggregate requirements. The mix design is not particularly different from mixes using virgin aggregates. Since virgin coarse aggregates cost more than $6 per ton, the reuse of crushed concrete for replacement of coarse aggregates is an economic alternative[38]. For example, virgin aggregate for PCC pavement was reported at a cost of nearly $7 per ton in Miami, while the crushed concrete was produced at less than $4 per ton. In North Dakota, the cost of virgin material ranges from $12 to $14 per ton, resulting in a savings of $35,000 to $50,000 per mile of concrete pavement when recycled coarse aggregate is used[46].

Old concrete can be crushed and used in a cement treated base for a new pavement. The crushed concrete is blended with 28 percent natural sand and 4 percent cement. The lean concrete (econcrete) base can also be constructed using crushed concrete with 250 pound per cubic yard cement added and its strength can reach 1,000 psi at 28 days[39]. The econcrete is usually placed with a slipform paver. In addition, the crushed concrete can be used as a drainage subbase topped by econcrete as a base[43]. Crushed concrete can be placed on drainage filter fabric setting on the subgrade.

4.1.4 Field Performance

Recycled concrete pavements constructed to date have generally performed excellently. The most economic alternative is to apply crushed concrete to base course as compared to surface course. Cracking of pavement surfaces containing crushed concrete aggregate is a problem. Recycled concrete pavement with "D" cracking aggregate also present problems.

Performance was compared by looking at the compatibility and California Bearing Ratio (CBR) of untreated RAP base versus conventional graded aggregate base (GAB). The untreated RAP did not compact well when compared to GAB and only compacted to 92 to 94 percent of the maximum density. The RAP base also yielded CBR values that were only a fraction of the CBR values for GAB from nearby quarries[47].

Pulverized bituminous material has performed excellently, especially in areas where it is used as an aggregate to prevent further washout.

4.2 Industrial Ash Material

Industrial ash is divided into two categories: flyash and bottom ash. Flyash is produced from a wide variety of industrial facilities. Some examples are coal flyash and spray dryer flyash. Bottom ash is coarser than flyash and has a different material characteristics.
4.2.1 Legislation and Restrictions

In response to Congressional requirements and incentives issued from 1976 to 1987 and an Environmental Protection Agency (EPA) Guideline published in 1983, discriminatory clauses against the use of flyash in portland cement concrete (PCC) have been removed. The use of flyash now is allowed on federal-aid projects at the state level [10]. In fact, as required by the Resource Recovery Act in the early 1970s, states should make flyash available as an option to contractors for use in concrete pavement as a replacement for a portion of the cement. To disallow the use of the flyash, states must find a reason why flyash would not work in their local specific situations. Recently passed federal legislation requires that the quantity of flyash material being deposited in landfills must be significantly reduced by 1996.

4.2.2 Material Properties

Properties of industrial ash strongly depend upon the process and equipment used to generate the waste ash. However, wastes with the same general material characteristics are discussed together to avoid a detailed subgrouping.

Coal flyash is defined as the finely divided residue that results from the combustion of ground or powered coal and is transported from the combustion chamber by exhaust gases. Flyash has pozzolanic properties. In itself, it possesses little or no cement characteristics but will, in a finely divided form and in the presence of moisture, chemically react with alkali and alkaline earth hydroxides at ordinary temperatures to form compounds possessing cementitious properties. Flyash is generally finer than portland cement (1 to 50 microns in diameter) and consists mostly of small spheres of glass of complex composition involving 40 to 50 percent silica oxide (SiO₂), 5 to 40 percent ferric oxide (Fe₂O₃), and 5 to 35 percent alumina oxide (Al₂O₃) [4]. Its composition varies with the source of coal. There are two major classes of flyash designated by the American Society of Testing and Materials (ASTM)[3]:

1. Class F: related to anthracite or bituminous coal and are not self-hardening but generally have pozzolanic properties. Class F flyash do not generally react without the addition of lime as a separate ingredient and can be stored in open stockpiles.

2. Class C: related to sub-bituminous coal and lignite and have pozzolanic properties but may also be self-hardening. In most cases this initial hardening occurs relatively quickly. The degree of cementitiousness varies with the calcium oxide (CaO) content of the flyash. Higher values of CaO denote higher cementitiousness. It must be either stored dry or conditioned with water and later pulverized.

The properties of flyash depend on the type of coal burning boiler[2]:

1. Stoker Fired Furnace - usually not good for highway construction.
2. Cyclone Furnaces - generally not good for use in PCC and not widely available.
3. Pulverized Coal Furnaces - usually the best in quality and in large quantities.
Several other factors affecting the properties of flyash are the ash content of the coal and the degree to which the coal has been pulverized prior to combustion. Because of many variables inherent in its production and collection, flyash exhibits a wide range of physical and chemical properties, even at the same source of production. The particle size and shape, density, color, and chemical composition of flyash vary widely[5].

Spray dryer flyash is composed of conventional flyash particles coated with calcium and sulfur compounds, and smaller particles resulting from the reaction between calcium and sulfur. Spray dryer flyash for pollutants of concern is significantly below toxicity criteria limits and is classified as nonhazardous[5].

Bottom ash waste is the heavier, finely divided residue that falls down out of the coal fired burners used to generate electrical power. Two major types of bottom ash exist according to two basic types of boilers used:

1. **Dry bottom ash** - produced by the dry bottom boiler which has an ash hopper below an open grate at its base. The heavy ash collected by the ash hopper contains molten slag. Dry bottom ash is composed of fine angular particles which are gray to black in color and resemble fine sand. Some of the smaller particles have a glassy appearance and the surface of the particles is very porous. The grain sizes of dry bottom ash particles are in the range of a fine gravel to a fine sand with more than half of the grain sizes ranging from a No. 4 to No. 40 sieve. Its chemical composition includes 20 to 60 percent silica oxide (SiO₂), 5 to 35 percent ferric oxide (Fe₂O₃), 10 to 35 percent alumina oxide (Al₂O₃), and 1 to 20 percent Calcium oxide (CaO)[5].

2. **Wet bottom ash/boiler slag** - produced by the wet bottom or slag tap boiler which has a water-filled ash hopper at its base orifice. The molten ash collected by the water hopper quenches in the water, crystallizes, solidifies, and forms angular, black, glassy particles ranging from 0.25 to 0.5 inch in size. A typical chemical composition of wet bottom ash includes 42.7 percent silica oxide (SiO₂), 27.5 percent ferric oxide (Fe₂O₃), 21.0 percent alumina oxide (Al₂O₃), 6.4 percent Calcium oxide (CaO), and 2.2 percent other.

### 4.2.3 Construction

Flyash is used as an admixture at the concrete mixer or an ingredient in blended cement to produce the flyash concrete (FAC). Addition of flyash at the mixer allows the adjustment of the flyash to cement ratio, whereas the cement blended with flyash has a fixed flyash to cement ratio. The flyash is added to improve workability, reduce bleeding, replace fine aggregate, and most importantly replace a portion of portland cement. The material requirement for using flyash is included in ASTM C-618 and AASHTO M-295 specifications. To insure the uniform consistency of flyash, a sampling frequency of one sample for each 400 tons of flyash is required by the standard procedure listed in ASTM C-311 and AASHTO M-295.
The substitution rate of flyash for portland cement typically specified is a minimum of 1 to 1.5 pounds of flyash to 1 pound of cement. The amount of fine aggregate has to be reduced accordingly. The substitution amount is specified to allow a maximum in the range of 15 to 25 percent. The set time will be extended from two to four hours. Blended cements can be manufactured by either intimate blending of portland cement and pozzolan or intergrinding of the pozzolan with the cement clinker in the kiln. Type "I" cement (pozzolan modified cement) allows up to 15 percent replacement of cement with flyash and type "IP" and "P" cement (Pozzolan-modified portland cement), 15 to 40 percent replacement with pozzolan[3].

Flyash can be added to portland cement for the treatment of base materials. Four basic steps are needed including spreading flyash and cement over the pulverized mix, blending the materials together, wetting the mix, and compacting the mix with a vibratory roller. A typical mix contains 80 percent ground materials, 16 percent flyash and 4 percent cement.

In another base stabilization method, a pozzolan aggregate mixture (PAM) is used for base construction. PAM contains approximately 85 percent aggregate, 3 to 4 percent lime, and 12 percent flyash. The aggregate used in PAM should be well graded stone, sand, gravel, or slag with a maximum size of 1 inch. PAM can be preblended at a plant or mixed in-place. When working with Class C flyash, more precautions must be taken as the mixture usually tends to set more quickly than a mixture using a Class F flyash, the set time of which varies from several hours to several days. PAM should never be placed in lifts greater than 10 inches or less than 4 inches. A seal coat should be paced on the lift, or on each lift (if multiple lifts) immediately after compaction for curing purposes. Due to the pozzolan reaction, the temperature at which PAM is constructed should be above 40°F[15].

Flyash can be used as a fill material for roadway embankments. The construction on the grade consists of spreading, blading into 6 inch lifts, water spreading, and discing to achieve uniformity of moisture and to reduce lensing or crusting. Moisture control is a key factor for successful construction. An envelope of cohesive soil is required for the flyash embankment to serve as an erosion control device and to provide for vegetation support.

4.3 Taconite Tailing Material

Some taconite tailings have been used in highway construction for a few decades. Specifications for the use of these taconite tailings were developed by Mn/DOT ten years ago.

4.3.1 Legislation and Restrictions

Since 1975, some taconite tailings have been accepted by the State of Minnesota as an alternate to sand and gravel for embankment, base and some surfacing material in highway construction. These approved taconite tailing sources are Eveleth, U.S. Steel (Minntac), Inland Steel Co., Butler, and Jackson County Iron Co. Taconite[50]. Prohibited tailings contain asbestos that is harmful to humans. Both federal and state governments regulate the use of and exposure to asbestos[52].
4.3.2 Material Properties

Processing or pelletizing of the iron ore and taconite (a siliceous iron-bearing ore) supplies both coarse and fine tailings, with fine tailings comprising 60 to 70 percent of the total output. Coarse tailing particles are in the a No. 4 to No. 100 sieve size range with a well mixed gradation. Fine tailings are discharged as a slurry of 45 percent solids content with 85 to 90 percent of the particles smaller than a No. 325 sieve. Principal constituents of taconite tailings are 59.0 percent silica oxide (SiO₂), 15.0 percent iron (Fe), 2.7 percent alumina oxide (Al₂O₃), 2.7 percent calcium oxide (CaO), and 3.7 percent magnesium oxide (MgO), while minor constituents are 2.2 percent carbon dioxide (CO₂), 0.73 percent manganese (Mn), 0.012 percent sulfur (S), and 0.047 percent phosphorus (P).

4.3.3 Construction

Taconite tailings slag can be used as aggregate for an asphalt mix. The resultant mix is particularly suitable for thin overlays (0.625 to 1 inch thick) because taconite tailings have an acceptable gradation (Mn/DOT Spec. 2361) and require very little processing. In addition, good skid resistance can be obtained from the thin overlay. However, the mixtures generally do require from 1 to 2 percent more asphalt cement than conventional mixtures. A vibratory roller is normally used for compaction rather than a rubber-tired or steel-wheeled roller and adequate density of thin overlays can be readily achieved under Ordinary Compaction methods[35]. Other successful uses for taconite tailings have been embankment fill, base, seal coat, shouldering, and deicing.

4.4 Waste Tire Products and Materials

The waste tires can be used for different purposes according to different processing levels. The processing of waste tires supplies various kinds of rubber products.

4.4.1 Legislation and Restrictions

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) (P.L. 102-240 Section 1038) requires the increased use of recycled materials, specifically crumb rubber from waste tires, in asphalt pavement construction. ISTEA requires that by 1994, 5 percent of the total tons of asphalt paved in each state receiving federal highway funds should contain recycled rubber. The percentage increases to 10 percent in 1995, 15 percent in 1996, and 20 percent in 1997.

4.4.2 Material Properties

As a construction material, an unprocessed or whole tire is elastic and durable. A system of anchored tires has good structural capacity and stability and produces little diverse effect on the environment unless it is below the water table. Currently, PCA regulations do not permit placement of waste tires below the water table. Waste tires may be mechanically processed to achieve size and void reduction. Shredded tires are called tire scraps, and coarse tire scraps are lightweight rubber chips with mechanical characteristics similar to wood chips. However, rubber chips are non-biodegradable and thus more durable than wood chips. Tire scraps are buoyant and difficult to compact.
Tire scraps can be reduced to fine granules called crumb rubber additive (CRA) by cryogenic or mechanical processing such as the crackermill, granulator, and micro-mill process. Each process generates a unique particle with specific characteristics. The crackermill produces an irregularly shaped torn particle with a large surface area in the range of sizes from No. 4 (0.187 inch) to No. 40 (0.017 inch) sieve. These particles are commonly described as a ground CRA.

The granulator produces cubical, uniformly shaped cut particles with low surface areas and with sizes ranging from 3/8 inch (0.375 inch) to a No. 10 (0.079 inch) sieve. This material is called a granulated CRA. The micro-mill process produces a very fine ground CRA with sizes from a No. 40 (0.017 inch) to No. 200 (0.003 inch) sieve [13]. Crumb rubber contains special chemical additives such as antioxidants, antiozonants, vulcanization accelerators, extending oils, tackifiers, zinc oxide, stearic acid, sulfur and carbon black. The elastomer component may comprise styrene-butadiene copolymers, butyl, cis-polybutadiene, natural rubber or neoprene which originates from the thread, sidewall, carcass or inner liner of the original tire[9].

4.4.3 Applications and Construction

Crumb rubber additive (CRA) is the generic term for the product from finer or ground scrap tires used in asphalt products. Addition of CRA to asphalt paving materials is accomplished using two basic processes, wet and dry. During the wet process, which is used for sealants, surface treatments and hot mix asphalt (HMA), CRA is blended with hot asphalt cement prior to incorporating the binder into the mix to produce an asphalt-rubber binder. In a dry process, which is limited to HMA, CRA is mixed with hot aggregate before adding asphalt cement to produce a rubber modified hot mix asphalt mixture. The wet process is generally regarded as a promising way to incorporate significant amounts of crumb rubber from scrap tires into asphalt pavements[49]. The paving products resulting from the application of CRA to highway construction are as follows:

1. **Crack/joint (C/J) sealant:** 15 to 30 percent CRA is blended with the asphalt cement (e.g. ASTM D3406 and Mn/DOT Spec. 3719). Manufacturers provide a variety of sealants to meet different conditions and various ASTM specifications. These sealants are usually preblended and packaged in 50 pound blocks which must be remelted and reacted before they can be applied.

2. **Surface/interlayer sealcoating:** 15 to 30 percent CRA by weight is blended with the asphalt cement. The patented products include the Stress Absorbing Membrane (SAM) and the Stress Absorbing Membrane Interlayer (SAMI). SAM is a surface treatment using spray application in which cover aggregate is generally a uniform 0.374 to 0.248 inch in size and preferably hot precoated with 0.3 to 0.5 percent asphalt cement. The application of SAM can seal the underlying cracks, prevent the entry of surface water, and absorb the stresses which lead to reflective cracks. A typical spray application rate is 0.6 gal/yd² of diluted asphalt rubber and 35 lb/yd² of precoated cover aggregate[13]. Thickness of the application usually varies from 0.38 to 0.63 inch with SAM content from 0.50 to 0.65 gal/yd².
SAMI is an interlayer treatment using a spray application. There are two layer systems resulting from the application, a two-layer SAMI and a three-layer SAMI. A two-layer system consists of a SAMI layer placed on the existing pavement and a 1 to 3 inch thick HMA overlay. A three-layer SAMI system begins with the placement of a leveling course of HMA and ends with a 1 to 3 inch thick HMA, with a SAMI between each layer. This system applies when there is deterioration of the existing pavement cracks and joints. The intended purpose of SAMI is to reduce reflection cracking by cushioning or dissipating the stresses from underlying layers. Application rates for the SAMI materials is similar to that of SAM (Mn/DOT Spec. 3127, FA-3).

3. **Asphalt-rubber concrete (wet process):** 15 to 25 percent CRA by weight is blended with the asphalt cement and aromatic oils, such as kerosene, to form the asphalt rubber binder or modified binder (ASTM D-8). An asphalt cement modified with 15 percent CRA can increase the binder’s high temperature viscosity by a factor of 10. This modified binder exhibits enhanced binder properties by reducing the binder’s temperature sensitivity. Either dense, gap, or open graded aggregate is mixed with the resultant binder, such as McDonald’s asphalt rubber. Typical asphalt rubber binder content for gap graded mixes range from 8 to 9 percent.

4. **Rubber modified or rubberized asphalt concrete (dry process):** 3 percent granulated CRA by weight of the total mix is blended with hot aggregate, usually gap graded aggregate. The asphalt cement in the final mix has a content of 7.5 to 9 percent. A continuous compaction of the mix mat is required until it cools to below 140°F. RUBIT, a rubber modified HMA developed in Sweden, was patented for use in the U.S. under the trade name PlusRide.

The average cost of CRA ranges from $0.10 to $0.15 per pound for coarse and medium crumb (above 425 μm) and up to $0.25 per pound for fine ground crumb. The cost of C/J sealant ranges from $0.20 to $0.30 per pound excluding shipping and installation. The in-place cost for a SAM generally ranges from $1.40 to $1.90 per square yard and is 50 to 100 percent higher than a conventional surface treatment. The in-place cost for a SAMI is relatively high, ranging from $2.00 to $2.50 per square yard. The in-place cost of asphalt rubber HMA mixtures or rubber modified HMA has ranged from 50 to 100 percent higher than the conventional mix. Their projected future cost could be reduced to 20 to 30 percent for asphalt rubber HMA and 20 to 40 percent for rubber modified HMA, above the cost of conventional HMA if the mix is routinely applied.

Rubber tires are non-biodegradable and thus more durable than wood chips; therefore, shredded tires can be used as a lightweight fill material in embankment construction to prevent stability problems across soft soils. The construction involves excavating improper soils, spreading geotextile fabric on the bottom and sides of the excavation, placing of shredded tires, compacting with a dozer, encapsulating the shredded tires with geotextile fabric on top, and grading.
As indicated by leachate studies on shredded tires, shredded tire samples subject to a pH solution of 3.5 produced leachate metal concentrations that exceed the Minnesota Department of Health Recommended Allowable Limits (RALs) for drinking water standards[44]. Accordingly, two requirements were included in guidelines for using shredded tires as a lightweight fill material in construction: placement of shredded tires above the highest water table and adequate surface drainage to avoid water seepage through the tire material fill.

Tire scraps can be used to make protective crash cushions that reduce the severity of accidents involving fixed objects. There are two types of waste tire crash cushion: modular and stacked. A modular tire crash cushion consists of a series of tire modules fastened together with cables. These modules are made up of a large number of waste tires fastened in a prescribed pattern. A stacked tire crash cushion consists of stacks of tires. Tires in the stacked tire crash cushion are usually filled with different materials according to the design consideration. In an inertia-type design, stacked tires are filled with sand, and in a pendulum design, stacked tires are filled with empty beverage cans. The estimated costs for different cushions including conventional cushions show that the tire cushions are less costly than conventional cushions[1].

4.4.4 Field Performance

Performance and durability of rubber related pavements over the long term are still unresolved. Due to cost, the evaluation of the performance has been limited to asphalt-rubber C/J sealants, seal coats, and overlays. Based on a nine-year evaluation of C/J sealant field performance, Stephens (1989) reported that site-mixed materials performed better than pre-mixed materials[14].

The field performance of asphalt-rubber seal coats was documented in detail by Shuler, Pavlovich, and Epps (1985), based on the evaluation of 219 random sections in 48 states, relative to control sections. Where the performance of random sections was worse than that of a control section it appears to be due to poor construction. Flushing is a primary cause of poor performance, which occurs from inappropriate quantities of binder and aggregate. If the flushed sections had been properly designed, it is likely that the overall performance of the seal coats would be significantly better than the control sections. The asphalt-rubber seal coats are more effective for pavements displaying alligator cracks or random cracking at less than 8 ft intervals, for maintenance of low volume facilities in conditions under which conventional seal coat would oxidize and crack due to lack of use, and for facilities where conventional seal coats could not withstand high traffic volume[41].

A SAM test section was constructed on TH 63 near Rochester, Minnesota, in the spring of 1979 using a chip coat consisting of an asphalt rubber tack coat with a cover aggregate. The section was a 3-inch asphalt pavement, 25 years old, and badly cracked. Field performance of the section was evaluated with friction measurements and crack counts throughout the seven year period[54]. When compared to the control section, the SAM section performed effectively. Both sections exhibited acceptable friction numbers and small amounts of cracking. Another SAM project was conducted on Xerxes Avenue in Minneapolis, Minnesota, in September of 1985. This was an urban section with curb and gutter with a non-uniform surface due to cracking and patching. Construction on several rainy days resulted in the use of wet aggregate. Field performance of the section was evaluated using the surface condition rating system, and the failure of the section was denoted in the performance evaluation[55]. Difference between success on TH 63 and failure on Xerxes Avenue appears to have been the aggregate. If precoating had been used for the wet aggregate on Xerxes Avenue, the failure may have been avoided. A SAM section was also constructed on TH 63. Evaluation of field performance showed that a reduction rather than an elimination of cracking was apparent.
The gap-graded asphalt-rubber hot-mix overlays have been effective in controlling reflective cracking in the city of Phoenix and in various Southern California cities and counties. Since overlaid, the pavement sections carrying heavy truck traffic have exhibited few problems with distress. The field performance of these pavements also indicates additional benefits to the gap-graded asphalt-rubber overlays: enhancement of skid resistance, improvement of riding surface, and noise reduction. The rehabilitation projects using dense-graded asphalt-rubber hot-mix overlays have been constructed by Caltrans since 1978. Compared favorably to conventional dense-graded asphalt hot-mix overlays, the asphalt-rubber overlays tolerate higher deflections, decrease oxidation and aging, resist abrasion in snow regions, deter stress development, and require less maintenance. In Minnesota, the dense graded asphalt-rubber concrete sections with reconstructed pavements and overlays were constructed in 1984. Various combinations of asphalt rubber wear and binder, and conventional wear and binder were considered. Evaluation of pavement performance using the seven year crack counts indicated that both asphalt-rubber and conventional overlays experienced an equal amount of cracking. When used in a reconstructed pavement, the asphalt-rubber section exhibited less cracking than the conventional section. The 100 per cent increase in price over conventional mixes, however, does not appear to be justified[54].

Demonstration projects were conducted in Florida from 1989 to 1990 to evaluate open-graded friction or surface course mixtures using ground tire rubber and asphalt-rubber binder. Projections of the short-term performance of these pavements demonstrates improved durability, reduced age hardening, improved retention of the aggregate, and greater resiliency of the binder.

Experimental test sections of rubber mixtures were constructed in 1978 and 1979 on State Route 46 in Saginaw County, Michigan. A 1985 study for evaluation of section performance concluded that the 1.5 percent rubber mixtures performed poorly with respect to reflective cracking and surface disintegration. However, some reduction in rutting had occurred.

The use of shredded waste tires as light weight fill for road subgrade is a simple and cost competitive application which may use a significant amounts of waste tires.

4.4.5 Recycling at the End of Life

The recyclability of asphalt-rubber hot-mix concrete pavements is questioned because it could cause air pollution (blue smoke) problems when reclaimed asphalt pavement (RAP) containing rubber is introduced into a hot-mix asphalt plant and recycled in place. Another waste problem could be created when the pavement is eventually removed for resurfacing. However, a Florida study suggests that these will not be a problem if a relatively low rubber content is present in the total amount of RAP. A study conducted on worker exposure to asphalt-rubber hot-mix fumes showed no significant difference between those exposed to asphalt-rubber hot mixes and conventional hot-mix asphalt[49].

4.5 Building Rubble Material

Similar to crushed paving concrete, building rubble contains mostly concrete. However, a wide variety of materials exist in building rubble. Urban renewal activity may greatly increase its quantities, but building rubble is mostly landfilled.
4.5.1 Legislation and Restrictions

According to the MPCA, building rubble should not contain non-inert materials, such as waste paints, building putty, packaging, sealants, etc. Non-inert materials usually contain chemicals that can be harmful if leached into ground water.

4.5.2 Material Properties

Building rubble is what results from the demolition and removal of an existing structure. Building rubble is a heterogeneous mixture of concrete, plaster, steel, wood, brick, piping, asphalt cement, or glass. Asphalt cement is mainly obtained from roofing waste, another component of building rubble, which contains about 36 percent asphalt cement, 22 percent hard rock granules, 8 percent filler, and smaller amounts of coarse aggregate and miscellaneous materials[8]. Substantial variability in the constitution of building rubble is expected.

4.5.3 Construction

The rubble portion of demolition wastes is well suited for use as aggregate in subbase applications. Building rubble must be separated from other demolition wastes prior to use. The processing of building rubble includes crushing and sizing, which can be accomplished at either primary crushing plants or portable crushing operations.

4.6 Incinerator Ash Waste Products and Materials

The discussion of incinerator ash is separated from that of industrial ash. To some extent, an incinerator is a waste processor which produces materials. Therefore, there is a potential to alter the characteristics and amounts of incinerator ash residue to improve utilization operations. Also, technology exists to carry out, monitor, and control the process so as to confidently ensure no risks are posed to humans and/or the environment. There two major incinerator ashes: municipal solid waste and sewage sludge incinerator ash.

4.6.1 Legislation and Restrictions

Congress has not yet passed legislation that gives the U.S. Environmental Protection Agency (EPA) the authority to issue nationwide incinerator ash regulations. The agency could issue ash regulations anytime under Subtitle C (hazardous wastes) of the Resource Conservation and Recovery Act (RCRA).

In 1982, the state legislature required that the Metropolitan Council must investigate alternative uses for sewage sludge ash before it selects a disposal site. In 1988, the state legislature required the MPCA to develop regulations for the management and disposal of incinerator ash. Correspondingly, the MPCA is currently drafting rules to govern the use of incinerator ash (municipal garbage, sewage sludge, etc.) in pilot construction projects, such as road bases and surfaces. The proposed rules would divide the projects into several categories, from more restrictive to less restrictive. The rules would set up ash product testing protocols and monitoring requirements for soils, air, surface water, and ground waters near a project site.
In the interim, the state is operating under the "Temporary Management Program for Mixed Municipal Solid Waste Incinerator Ash". This program requires all incinerator facility operators to submit quarterly ash characterization results for separate samples of bottom ash, flyash, and combined ash using EPA's Method 312[53].

A 1991 Minnesota law requires that the amount of toxic heavy metals found within municipal garbage be reduced. Manufacturers are required to decrease the amounts of lead, cadmium, mercury and hexavalent chromium by 600 ppm by August 1, 1993, 250 ppm by August 1, 1994, and 100 ppm by August 1, 1995, respectively.

4.6.2 Properties

MSW are separated or sorted for reuse, recycling, or landfilling. The total MSW produced in 1988 in the U.S. includes 40 percent paper and paperboard, 7 percent glass, 8.5 percent metals, 8 percent plastic, 2.5 percent rubber, 2.1 percent textiles, 3.6 percent wood, 7.4 percent food wastes, 17.6 percent yard wastes, 1.5 percent miscellaneous inorganic wastes, and 1.7 percent other material[23].

After sorting, it is still possible for the remaining municipal garbage to contain a wide variety of waste materials. The municipal garbage can be incinerated. This will produce ash waste or incinerator ash residue generated by a refuse derived fuel (RDF) or a non-energy type incinerator. Depending on the degree burned-out in combustion, three types of incinerator ash are defined by FHWA: well, intermediate, and poorly burned-out. Two ash products, bottom and flyash, are produced during combustion. Bottom ash from incineration is the unburned and incombustible residue left on the boiler gate after incineration. It consists of slag, glass, rocks, metals, and unbonded organic matter, and is composed of large particles (0.004 to 4 inch).

Flyash consists of burned and partially burned particles with a size ranging between 0.00004 and 0.02 inch.

The composition of the Hartford RDF incinerator bottom ash was compared to the FHWA well-burned residue by Garrick and Chan, as shown in Table 4. After chunks larger than 1 inch were removed from the residue, the gradation was characterized by \(D_0=0.187\) inch and \(D_{10}=0.0167\) inch with 3 percent fines. The bulk specific gravity and absorption were determined for coarse and fine residue. Coarse residue has the bulk specific gravity of 2.29 whereas fine has the specific gravity of 1.52; coarse has an absorption of 3.9 percent whereas fine has an absorption of 8.6 percent.

The components of flyash are largely dependent on the type of air pollution control device in use. Because of its relatively high concentration of lead and oversized particles, a chemical fixation and physical conversion must be conducted. The process for the fixation and conversion consists of screening off the various metals and large items to produce a consistent particle size. The ash is then chemically fixed using a patented product which causes the heavy metals, like lead, to form silicates thereby permanently reducing their solubility. The process was proposed for Hennepin County and laboratory tests done to date provide much promise for ash utilization. The treated ash pellets (TAP) from the process significantly reduce the leaching availability of cadmium and lead to below federal drinking water standards, even after multiple extractions. The TAP are smooth, round pebbles ranging in size from 0.125 to 0.75 inch and meet Mn/DOT aggregate requirements.
Table 4. Composition of Incinerator Residue[31]

<table>
<thead>
<tr>
<th>Components</th>
<th>RDF Residue (percent by weight)</th>
<th>FHWA well-burned residue (percent by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>23.0</td>
<td>17.1</td>
</tr>
<tr>
<td>Glass</td>
<td>35.0</td>
<td>39.9</td>
</tr>
<tr>
<td>Mineral (sand, brick, etc.)</td>
<td>40.0</td>
<td>39.5</td>
</tr>
<tr>
<td>Organic (wood, paper, etc.)</td>
<td>2.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Sewage sludge, after some form of primary treatment, consists of a low solids content dispersion of variable viscosity, depending on the moisture content. It is generally dark brown or black in color, and, although it may contain up to 10 percent by weight of twigs, cigarette butts, and rubber, it frequently has the appearance of a fairly homogeneous suspension. Sewage sludge generally has a solids content between 5 and 10 percent by weight, although some sludge may have over 40 percent solids. Major constituents of sewage sludge are volatile solid and ash, and it may contain a small amount of metals such as zinc, copper, lead, cadmium, and mercury. Because of low solid content and strength, sewage sludge must be incorporated in certain mixtures such as lime-flyash sulfate. The resulting composition generally has adequate strength for road embankment construction, low permeability, and after a suitable curing period, acceptable leaching characteristics[10].

4.6.3 Application and Construction

When MSW Incinerator ash is used as aggregates for asphaltic mix, processed incinerator ash should be mixed with conventional aggregates in a 50/50 blend. A study on unprocessed incinerator ash showed that when ash only is used as aggregate, the resultant mix has proven to be unsuitable in that the Marshall stability value was low (650 lb) and the air void content was excessively high (23.5 percent) because of unburned organic fine particles[31]. The best results are obtained when the unprocessed incinerator ash make up no more than 40 to 55 percent of the total aggregate[33]. The air voids content of the mix can be decreased to 7.2 percent by excluding some portion of particles between 0.1 to 0.187 inch, and total portion of particles less than 0.187 inch. However, the optimum asphalt content of the aggregate and unprocessed ash mixes can be up to 20 percent higher than that of a conventional aggregate mix. Incinerator residue compositions can be mixed, placed, and compacted using conventional bituminous construction apparatus and procedures.

When treated with bituminous, MSW incinerator ash can be used as a base aggregate after objects over 1 inch in size have been removed. Natural sand and limestone are needed for gradation modification to meet specifications. The design mix contains 68.5 percent residue, 15 percent concrete sand, 15 percent limestone, and 1.5 percent hydrated lime, with an asphalt cement content of 9 percent. The residue mixture is very sensitive to asphalt content and temperature. In the plant mixing, dust should be eliminated from the product, and the collected stack fines should not be mixed with the residue. Because of glass contents in the residue, lime is required as an anti-strip agent. Slurried lime is a more effective agent than dry lime. Vibrators can be used to prevent clogging at gates or bridging in bins, and care should be taken with temperature control. The residue base mixture can be placed using regular paving equipment[42].
The site of residential and industrial wastes landfilled in the past could become the only plausible location for a highway. In order to reduce the excessive settlement and differential settlement, compaction with heavy rollers should be completed before surcharging. The new method of deep dynamic compaction (DDC) in which a heavy weight is dropped repeatedly has been successful on projects in Arkansas and Colorado. Further stabilization can be accomplished by placing a surcharge with a base pad of granular material for a certain period before the fill is graded and paved[11].

4.7 Waste Glass Material

Waste glass is separated from MSW for recycling. The current recycling technology of glass has not reached the point where all glass can be recycled. Therefore, significant quantities of glass may be available as a secondary waste material.

4.7.1 Material Properties

Waste glass results from curbside recycling operations. The glass is separated by color (clear, amber, and green) and portions containing ceramic materials and other artifacts are discarded. Glass is composed mainly of silica or sand, but it also contains predetermined amounts of limestone and soda ash designed to produce glass of uniform quality and color. Among the three basic types of glass (borosilicate, soda-lime, and lead glass), soda-lime glass makes up 90 percent of all glass manufactured commercially. The chemical composition of soda-lime glass includes 73 percent silica oxide ($\text{SiO}_2$), 17 percent sodium oxide ($\text{Na}_2\text{O}$), 5 percent calcium oxide ($\text{CaO}$), and 3 percent magnesium oxide ($\text{MgO}$)[6].

Since only color-sorted and contamination-free waste glass is considered feasible for use in the glass industry, a significant amount of glass remains unused. These waste glasses can be crushed and used for highway construction, and the resulting material normally contains relatively large amounts of flat and elongated particles that have a smooth surface with little or no porosity. However, the use of glass particles has been reported to improve the thermal characteristics of paving mixtures[7].

4.7.2 Construction

The use of glass in asphalt mixes is technically feasible if glass content is restricted to 15 percent or less, the optimum asphalt content is determined with the target percent of glass, gradation controls are 100 percent passing the No. 3/8 in. sieve and a maximum of 6 percent passing the No. 26 sieve, and the tensile strength ratio of the mix is 0.9 or higher. Potential problems with the glass-asphalt mixes, or glasphalt include loss of adhesion between asphalt and glass, maintenance of skid resistance, and breakage of glass and subsequent raveling under studded tires.

4.8 Waste Shingle Products and Materials

High content of asphalt cement in shingles is an attractive factor for its reuse. Recently, waste shingle processing plants have emerged to supply asphalt products for highway construction.
4.8.1 Properties

Waste shingles are obtained from waste roofing and shingles manufacturers, and typically contain pieces as large as 3 square feet. About 70 percent by weight of the waste roofing is asphalt shingles, and roughly 60 percent of that is asphalt, a recoverable resource. Another 20 percent of waste roofing is dirt and pea gravel. Wood and metals comprise about 6 percent of the total and the remaining 3 percent are unusable materials including plastic film and paper[16]. Waste shingles produced from shingle manufacturers are relatively uniform. Organic and fiberglass shingles are presently produced in the U.S. and contain about 30 percent and 19 percent asphalt cement, respectively. Ends of runs, samples, off-color shingles, and tabs create about 5 percent of total shingle production during the manufacturing process. This shingle scrap can be obtained directly from a shingle manufacturing plant before they are landfilled[17].

4.8.2 Application and Construction

Before shingles can be used as an additive in asphalt mixtures, processing similar to that of scrap tires is necessary. A shingle processing facility in operation in Chicago is producing the recycled asphalt chips (less than 1.5 inch) and patch materials (less than 0.375 inch). The recycled asphalt material can be blended with aggregate (including some recycled crushed concrete) and an emulsion-type agent to produce cold patch materials. The initial batches can be mixed in a portable mortar mixer. The successful application of a patch requires that it not be overspread. The outline of the hole should be followed and the patch should be left about an inch high for traffic compaction. The recycled asphalt chips can be used as a paving product over a stone base. A 4 to 8-inch layer of chips should be spread over the base for better performance[16].

Waste shingles from manufacturers can be used with conventional aggregates in a 10/90 blend to reduce the demand of asphalt cement. The new mix meets the specification and demonstrates a significantly higher Marshall stability than the conventional mix[17]. A batch-type plant can be used to prepare the mixture. Waste shingles are then introduced through the plant’s recycled asphalt pavement inlet. Hot weather is preferable for construction, and a steel wheeled roller should be used.

4.8.3 Field Performance

Wearing course constructed on recreational trails with 9 percent of total aggregates from waste shingles exhibits a relatively open surface texture due to the coarse natural aggregates and is performing satisfactorily to date.

4.9 Plastic Products

Plastics waste is also separated from MSW for recycling. Because only a small amount of plastics waste is recycled, much is available for the use of plastics in highway construction.
4.9.1 Properties

Waste plastics are easily recyclable from the MSW. The recycling process of waste plastics will promote an effective utilization of recycled plastics even if the properties of waste plastics change during recycling. For example, waste plastics can be processed and recycled into mixed post-consumer plastic scrap. This scrap is melt-extruded into post and board shapes that can be applied to guardrail and fence posts. There are three major types of recycled plastics: polystyrene (PS), polyethylene terephthalate (PET), and high density polyethylene (HDPE). The presence of dirt and other contaminants in the scrap affect the failure behavior significantly. The unvented batch extrusion process used for recycling waste plastics results in posts with large voids, metal particles, unmelted polymers, and plastics content variation, all of which strongly influences the mechanical strength of the post products. The cross-sectional size and uniformity of composition (after extruding) have an effect on long-term warpage resistance with age and exposure. Some flexural tests show a higher ultimate flexural stress in the recycled plastics posts than that of concrete.

4.9.2 Application

Recycled plastic products or posts can be used in guardrails and fences. The manufacturers must verify the material properties are proper for safety reasons. Fire resistance should be considered anywhere, and cold weather resistance considered in northern states. These products can be used as sign substrates, flexible delineator posts, rebar support chairs and bolsters, and guardrail offset blocks[37].

4.10 Slag Material

Slags are derived from the iron and steel industry. They are perhaps the waste materials of greatest interest to the highway industry.

4.10.1 Legislation and Restrictions

Heavy metals leachate regulations are applicable to the use of slag waste. The amount of heavy metals leached from slag materials must be below acceptable limits.

4.10.2 Material Properties

Blast furnace slag is a non-metallic by product consisting of silicates and aluminosilicate of lime and other bases. Selective cooling of the liquid slag results in four types of blast furnace slag: air-cooled, foamed, granulated, and pelletized.

Steel slag is formed as the lime flux reacts with molten iron ore, scrap metal, or other ingredients. Steel slags have a high bulk density, and are expensive.
4.10.3 Construction

The principal use of steel slag is as a base course material. Steel slag must be aged for at least six or seven months prior to use in order to assure its completed expansion. During construction, the steel slag must be watered down and allowed to cure for six months.

A coarse boiler bottom slag can be used as a base material with the addition of flyash and lime. Maximum density can be obtained by adjusting the content of flyash to 27 to 33 percent. The lime content is based on the quantity needed for strength and durability. A strength of 1,800 psi, cured at 100°F for seven days can be obtained with 3 percent lime. The base mixture can be blended in a continuous flow pugmill watered to the optimum water content. The mix should be spread on the prepared subgrade in one full depth layer and compacted with a vibrating steel wheel roller. Curing is accomplished using a bituminous seal[40].

4.10.4 Field Performance

An asphalt concrete surface on a slag-lime-flyash base performs well. The only required maintenance is the placement of a double surface treatment to improve skid resistance. Road Rater data indicates no decrease in the structural capacity and the behavior is not sensitive to seasonal effects.

4.10.5 Recycling at the End Of Life

In August 1989, the Utah Department of Transportation contracted to apply a proprietary polymer-modified concrete as a thin bonded overlay on a 12 lane-mi, 25 year concrete highway (128,000 AADT). The overlay incorporated slag as an aggregate from the Kennecott copper smelting process. After 4 months, 15 percent had come off. Six months after the initial placement, UDOT started using full-scale grinding to remove the remaining overlay and to correct the rutting and faulting of the original concrete pavement. A high level of heavy metals was detected in the grinding residue. Because disposal regulations have become tougher, the only way to dispose of the grinding residue was to incorporate the waste into a construction project[30].
5. Waste Material Evaluation

A waste material should be tested and evaluated prior to its use in highway construction. The evaluation will help overcome the natural reluctance to use wastes and to guard against possible enthusiastic and sometimes exaggerated claims of researchers who have investigated the wastes in laboratory studies. A large number of factors influence the feasibility of using a waste. Therefore, a procedure is presented in order to objectively evaluate these factors so that meaningful recommendations can be made.

5.1 Procedure

This procedure considers three major aspects of waste source utilization: technical, economical, and environmental. The following steps should be followed:

1. Review relevant literature and contact experienced engineers.
2. List potential waste sources.
3. Perform initial screening process and eliminate wastes unable to meet minimum criteria.
4. Perform technical evaluation listing the technical properties of the waste.
5. Perform economic evaluation listing the economic properties of the waste.
6. Select materials for further evaluation.
7. Perform environmental evaluation listing the ecological properties of the waste.
8. Compare overall evaluation results.
9. Make final recommendations.

5.2 Evaluation

A good evaluation depends on the information available. Information on the changing regulations should be updated to determine the minimum environmental criterion. A waste stream has its own flow pattern which is strongly influenced by waste management regulations and activities. Information about the changes in waste flow and disposal sites is helpful to determine local availability. Most importantly, practical experience from other engineers can be obtained. With comprehensive information, waste candidates can be evaluated based on their technical and economic feasibility, and environmental impact. The evaluation procedure is basically a ranking process by factors or attributes using a weighted approach.

5.2.1 Initial Screening

The initial screening is a crucial start which leads to a cost-effective evaluation. The screening is based on various minimum criteria set up by environmental regulations, construction requirements, geographic limitations, quantity availability, and local conditions.

The minimum environmental criterion is that a waste candidate must be nonhazardous. A waste product should be identified following the standard procedures in order to determine if it is hazardous. A waste that is on the exempt list in the hazardous waste rules is automatically nonhazardous. Waste is hazardous if it is found in the hazardous waste list or exhibiting hazardous characteristics as described in the hazardous regulations. The hazardous characteristics include ignitability, oxidizers, corrosivity, reactivity, and toxicity. The detailed criteria for identifying hazardous waste can be found in Minnesota Rules Parts 7045.0120 to 7045.0135[19].
Material requirements for highway construction result in the minimum criteria for selecting waste materials. The potential waste replacements for cement or aggregate should satisfy the corresponding construction requirements[32]. The wastes can be modified by crushing, grinding, and mixing for this purpose. The waste material must be located within a reasonable geographic distance from a construction site or transportation costs will be prohibitive; forty to fifty miles is considered a maximum economic hauling distance for truck transport and one hundred miles for rail transport. The minimum criteria for quantity of waste varies with what a waste is used for. If a waste is to be used as aggregate, 50 thousand tons per year is considered to be the minimum for an annual road improvement program at the municipal level. Accumulated quantities of such a waste should be at least 500,000 tons to meet quantity demands by the construction industry[25].

5.2.2 Technical Evaluation

The technical feasibility of using a waste in construction can be evaluated based on its technical properties. The technical properties include general, physical, mechanical, chemical, thermal, and optical properties related to specific highway applications such as surface, base, and shoulder uses. A simple evaluation system can be established by listing relevant technical properties of waste candidates to the application considered. Clearly, the reliability of the system depends on the data availability. Evaluating the number of relevant properties to the application, waste candidates are classified. The more relevant properties a waste possesses, the more potential it has, and the higher it will be ranked. A four-class technical evaluation system could be used as follows:

**Class 1:** wastes that have the highest potential for use and require a minimum of processing prior to use.

**Class 2:** wastes that have relatively high potential and require more extensive processing such as pelletizing and sintering.

**Class 3:** wastes that have relatively low potential for use and may require a formidable amount of processing, may have some outstanding undesirable physical properties, and may have rather non-uniform characteristics.

**Class 4:** wastes that have no or little potential. At best might be used in small amounts as a filler or in very specialized applications.

A number of waste materials were evaluated for their potential use as aggregates using the four-class system, as shown in Tables 5-7. The wastes listed in each class are also ranked[25].
### Table 5. Technical Feasibility for Aggregate Use in Base

<table>
<thead>
<tr>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>Slate Mining Waste</td>
<td>Phosphate Slime</td>
<td>Iron Ore Tailings</td>
</tr>
<tr>
<td>Bottom Ash</td>
<td>Steel Slag</td>
<td>Rubber Tires</td>
<td>Sewage Sludge</td>
</tr>
<tr>
<td>Boiler Slag</td>
<td>Anthracite Coal Refuse</td>
<td>Foundry Waste</td>
<td></td>
</tr>
<tr>
<td>Shingle scrap</td>
<td>Taconite Tailings</td>
<td>Dredge Spoils</td>
<td></td>
</tr>
<tr>
<td>Zinc Smelter Waste</td>
<td>Lead-Zinc Tailings</td>
<td>Bituminous Coal Refuse</td>
<td></td>
</tr>
<tr>
<td>Gold Mining Waste</td>
<td>Phosphate Slag</td>
<td>Battery Casings</td>
<td></td>
</tr>
<tr>
<td>Paving Waste</td>
<td>Incinerator Residue</td>
<td>Sulfate Sludge</td>
<td></td>
</tr>
<tr>
<td>Waste Glass</td>
<td>Feldspar Tailings</td>
<td>Scrubber Sludge</td>
<td></td>
</tr>
<tr>
<td>Blast Furnace Slag</td>
<td>Building Rubble</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Technical Feasibility for Aggregate Use in Bituminous Mix

<table>
<thead>
<tr>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>Anthracite Coal Refuse</td>
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</tr>
<tr>
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<tr>
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<td></td>
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<tr>
<td>Boiler Slag</td>
<td>Steel Slag</td>
<td>Battery Casings</td>
<td></td>
</tr>
<tr>
<td>Zinc Smelter Waste</td>
<td>Feldspar Tailings</td>
<td>Iron Ore Tailings</td>
<td></td>
</tr>
<tr>
<td>Gold Mining Waste</td>
<td>Copper Tailings</td>
<td>Slate Mining Waste</td>
<td></td>
</tr>
<tr>
<td>Paving Waste</td>
<td>Phosphate Slag</td>
<td>Dredge Spoils</td>
<td></td>
</tr>
<tr>
<td>Waste glass</td>
<td>Incinerator Residue</td>
<td>Sulfate Sludge</td>
<td></td>
</tr>
<tr>
<td>Blast Furnace Slag</td>
<td>Phosphate Slime</td>
<td></td>
<td>Scrubber Sludge</td>
</tr>
</tbody>
</table>

### Table 7. Technical Feasibility for Aggregate Use in Concrete Mix

<table>
<thead>
<tr>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>Feldspar Tailings</td>
<td>Bituminous Coal Refuse</td>
<td>Sewage Sludge</td>
</tr>
<tr>
<td>Bottom Ash</td>
<td>Taconite Tailings</td>
<td>Building Rubble</td>
<td>Waste glass</td>
</tr>
<tr>
<td>Boiler Slag</td>
<td>Anthracite Coal Refuse</td>
<td>Iron Ore Tailings</td>
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<tr>
<td>Shingle scrap</td>
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<tr>
<td>Gold Mining Waste</td>
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<tr>
<td>Paving Waste</td>
<td>Incinerator Residue</td>
<td>Slate Mining Waste</td>
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<tr>
<td>Blast Furnace Slag</td>
<td>Phosphate Slime</td>
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</tr>
<tr>
<td>Phosphate Slag</td>
<td>Copper Tailings</td>
<td>Battery Casings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lead-Zinc Tailings</td>
<td>Sulfate Sludge</td>
<td>Scrubber Sludge</td>
</tr>
</tbody>
</table>
5.2.3 Economic Evaluation

The reuse of wastes results in many intangible benefits. These factors should be included in the guideline for evaluating the economic feasibility of using a waste. The evaluation procedure is outlined as follows[25]:

1. Develop local cost figures including disposal, processing, transportation, and construction costs for wastes; versus material, processing, transportation, and construction costs for conventional materials.

2. Develop economic attributes such as annual quantity, economic location, resource value, application acceptability, ecological influence, energy conservation, and social consideration for wastes.

3. Rank waste candidates for each cost item and economic attribute.

4. Classify wastes in an order from the highest to the lowest potential.

Table 8 shows the evaluation results of selected wastes for aggregate use using this procedure.

**Table 8. Economic Feasibility for Aggregate Use in Highways**

<table>
<thead>
<tr>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>Incinerator residue</td>
<td>Rubber tires</td>
<td>Phosphate Slime</td>
</tr>
<tr>
<td>Shingle scrap</td>
<td>Slate Mining Waste</td>
<td>Battery Casings</td>
<td>Sulfate Sludge</td>
</tr>
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<td>Blast Furnace Slag</td>
<td>Gold Mining Waste</td>
<td>Lead-Zinc Tailings</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper Tailings</td>
<td></td>
</tr>
</tbody>
</table>
5.2.4 Environmental Evaluation

The environmental impact of a waste is also evaluated by a ranking system, which includes four major attributes: recycling, processing, constructing, and operating. The recycling effects are related to disposal-induced environmental problems, natural resource conservation, and virgin material shortage. Types of processing, amount and disposal of secondary wastes, and location of a processing operation with respect to populated areas affect the rank of a waste. Constructing effects include construction related environmental problems such as dust and spill, and the operating effects in the highway life span are ground water contamination due to leachate and runoff. All possible wastes used as aggregates were ranked by Miller and Collins (1976) in terms of the most benefit (or least damage) to the environment, as shown in Table 9[25].

Table 9. Ranking of Wastes According to the Environment

<table>
<thead>
<tr>
<th>Recycling</th>
<th>Processing</th>
<th>Highway Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite Coal Refuse</td>
<td>Waste Glass</td>
<td>Shingle scrap</td>
</tr>
<tr>
<td>Shingle scrap</td>
<td>Copper Tailings</td>
<td>Blast Furnace Slag*</td>
</tr>
<tr>
<td>Bituminous Coal Refuse</td>
<td>Gold Mining Tailings</td>
<td>Paving Wastes</td>
</tr>
<tr>
<td>Phosphate Slime</td>
<td>Feldspar Tailings</td>
<td>Rubber Tires*</td>
</tr>
<tr>
<td>Phosphogypsum</td>
<td>Nickel Tailings</td>
<td>Waste Glass</td>
</tr>
<tr>
<td>Dredge Spoil</td>
<td>Blast Furnace Slag</td>
<td>Steel Slag*</td>
</tr>
<tr>
<td>Flyash</td>
<td>Steel Slag</td>
<td>Building Rubble</td>
</tr>
<tr>
<td>Bottom Ash</td>
<td>Lead Tailings</td>
<td>Gold Mining Waste*</td>
</tr>
<tr>
<td>Boiler Slag</td>
<td>Zinc Tailings</td>
<td>Nickel Tailings*</td>
</tr>
<tr>
<td>Foundry Waste</td>
<td>Shingle scrap</td>
<td>Feldspar Tailings*</td>
</tr>
<tr>
<td>Incinerator Residue</td>
<td>Bituminous Coal Refuse</td>
<td>Alumina Mud*</td>
</tr>
<tr>
<td>Building Rubble</td>
<td>Rubber Tires</td>
<td>Boiler Slag*</td>
</tr>
<tr>
<td>Rubber Tires</td>
<td>Taconite tailings</td>
<td>Flyash*</td>
</tr>
<tr>
<td>Blast Furnace Slag</td>
<td>Iron Ore Tailings</td>
<td>Bottom Ash*</td>
</tr>
<tr>
<td>Steel Slag</td>
<td>Boiler Slag</td>
<td>Incinerator Residue*</td>
</tr>
<tr>
<td>Taconite Tailings</td>
<td>Flyash</td>
<td>Foundry Waste*</td>
</tr>
<tr>
<td>Iron Ore Tailings</td>
<td>Bottom Ash</td>
<td>Dredge Spoil*</td>
</tr>
<tr>
<td>Alumina Mud</td>
<td>Anthracite Coal refuse</td>
<td>Copper Tailings*</td>
</tr>
<tr>
<td>Lead Tailings</td>
<td>Paving Wastes</td>
<td>Phosphate Slime*</td>
</tr>
<tr>
<td>Zinc Tailings</td>
<td>Foundry Wastes</td>
<td>Phosphogypsum*</td>
</tr>
<tr>
<td>Paving Wastes</td>
<td>Incinerator Residue</td>
<td>Bituminous Coal Refuse*</td>
</tr>
<tr>
<td>Copper Tailings</td>
<td>Alumina Mud</td>
<td>Anthracite Coal Refuse*</td>
</tr>
<tr>
<td>Gold Mining Wastes</td>
<td>Dredge Spoil</td>
<td>Taconite Tailings*</td>
</tr>
<tr>
<td>Waste Glass</td>
<td>Building Rubble</td>
<td>Iron Ore Tailings*</td>
</tr>
<tr>
<td>Feldspar Tailings</td>
<td>Phosphogypsum</td>
<td>Zinc Tailings*</td>
</tr>
<tr>
<td>Nickel Tailings</td>
<td>Phosphate Slime</td>
<td>Lead Tailings*</td>
</tr>
</tbody>
</table>

* Leachate consideration
6. State-of-the-Practice

To obtain information on the current practices of waste reuse for highway construction in Minnesota, a questionnaire was developed and distributed to all city and county agencies. The questionnaire requested information on the type of waste materials currently used in highway constructions, their applications, field performance and case studies. Of the 198 questionnaires distributed, 79 cities and counties have responded (40 percent). Besides providing answers to the specific questions, respondents also sent information concerning their own use of various waste materials in highway construction. The survey helped in determining the latest trends, applications, and experiences in the use of waste materials.

6.1 An Overview of Current Statewide Practice

Among responding agencies, 39 had experience in the reuse of wastes for highway construction, 4 had experience in recycling wastes other than paving waste, 1 is considering the reuse of waste, and 35 had no experience (Figure 6). As shown in Figure 7, there are many waste materials used by agencies. These are recycled paving wastes, coal flyash, waste glass, building rubble, coal bottom ash, sewage sludge, rubber tire, asphalt shingle, waste paper, mine tailing, and wood chips.

![Figure 6: Use of Wastes in Minnesota](image-url)
A total of 14 waste products have been identified that are currently in use and/or being studied experimentally in a variety of highway applications (Table 10). Of the 14 waste products, only 4 are presently used by more than 10 percent of the respondents. These include waste paving materials, flyash, scrap tires, and mine tailings. Current practice indicates that waste paving materials, flyash, and scrap tires are used by a large number of respondents. The evaluation of waste materials with respect to economic, technical, and environmental factors is generally reported. Most waste materials used were evaluated as at least competitive with the conventional materials, satisfactory and acceptable, respectively. However, the use of steel slag, mine tailings, and scrap tires were considered as uneconomical. The survey results are shown in Table 11.
Table 10. Current Uses of Waste Materials in Minnesota Highway Construction

<table>
<thead>
<tr>
<th>Waste Products</th>
<th>Wastes Used as Additive to</th>
<th>Wastes Used as</th>
<th>Landscaping</th>
<th>Others Specify</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wearing Course</td>
<td>Base</td>
<td>Subbase</td>
<td>Subgrade/ Embankment</td>
</tr>
<tr>
<td>Highway</td>
<td>General</td>
<td>6</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Milling Residue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal Flyash</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Asphalt Shingles</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paper Mill Sludge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel Slag</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal Bottom Ash</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sawdust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wood Chips</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>Mine Tailings</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Sewage Sludge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Building Rubble</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waste Glass</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tire Scrap</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>


Table 11. Evaluation of Waste Materials

<table>
<thead>
<tr>
<th>Waste Products</th>
<th>Economic</th>
<th>Performance</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost-Effective</td>
<td>Uneconomic</td>
<td>Very Good</td>
</tr>
<tr>
<td><strong>Highway</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>21</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Milling Residue</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Industrial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal Flyash</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Asphalt Shingles</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Paper Mill Sludge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Slag</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Coal Bottom Ash</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sawdust</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Wood Chips</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Mineral</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Tailings</td>
<td></td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Domestic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sewage Sludge</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building Rubble</td>
<td>2</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Waste Glass</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tire scrap</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
6.2 Case Studies

6.2.1 Case 1: Shredded Tires, Benton County

Near Rice in Benton County, shredded tires were used as a lightweight fill materials for State Aid Highway 21. This road as constructed actually floats over swampy soils. The two-lane highway was originally constructed with a sand and gravel subbase and was performing well. Over the years, the surrounding water levels increased to the level of the road, and an attempt to raise the roadway with the conventional granular fill overloaded the underlying 12 ft thick layer of peat and muck and caused an embankment failure. After performing a cost/benefit analysis, the county decided to use shredded tires as a lightweight fill material for reconstruction.

Reconstruction on the 250 ft section began in the fall of 1989. The first step was to excavate to a point one-half foot above the swamp/marsh level. Next, a geotextile fabric was sewn together and positioned at the bottom of the excavation. Following the fabric, approximately 52,000 shredded tires were deposited in a 2 foot lift to a level of 3.5 foot below the top of the subgrade elevation. The shredded tires had a size less than 8 inch square or round and shorter than 1 inch in length. The shredded tires were compacted and overlaid with another geotextile fabric layer. Then, the granular materials were placed over the fabric and the fill was compacted with ordinary compaction. Finally, the gravel base and subbase was replaced and the roadway was allowed to settle naturally for several months. The bituminous surface was put down the following spring. To date, the county road has not experienced any significant settlements and the bituminous surface is performing well.

6.2.2 Case 2: Waste Glass, Sibley County

Sibley County, the Office of Waste Management, and Mn/DOT combined efforts in a project to utilize waste glass with low grade aggregate for better base materials. The mixed base materials were used to rebuild Sibley County Road 6.

Three hundred and thirty tons of mixed glass which were not suitable for recycling by glass industry were used. The disposal tipping fee of $20,000 made it economically feasible to crush the glass was with low grade virgin aggregate to make Class 5 gravel base. A front end loader took a bucket of glass and spread it in the gravel pit. Ten buckets of the mixed material were then loaded from the gravel pit into the crusher so that about 10 percent of the mixture was glass. The introduction of the glass not only reduced the percentages passing the 3/8 inch, #4, #10, #40 as anticipated, but it also raised the portion passing the #200 sieve about 2 percent, which was not anticipated.

The mixed glass aggregate was placed in a 1,000 ft test section on the 3.7 mile construction project. Three 3-inch lifts were placed with a final 4 in. lift of virgin Class 5 aggregate and surfaced with 3 inches of bituminous. During construction, the glass-aggregate section was exposed to local traffic without incident of tire puncture or any other apparent problems. Raveling of the surface appeared to be less than the rest of the roadway. Grading and compacting of the material went without incident except that more power and a down shifting of gears was necessary to place the mix because of greater friction.

Preliminary results indicate that low quality "sandy" aggregate can be enhanced with the introduction of crushed glass, thus increasing the utilization of low quality aggregate as well as disposing of an otherwise useless waste aggregate.
7. Closing Remarks

An evaluation based on the technical, environmental, and economic factors indicated that waste paving materials, flyash, incinerator ash, waste shingles, rubber tires, and slag have significant potential to replace portions of conventional paving materials. Reuse of these waste products can be realized by a combined effort among waste management, natural source reserve, environmental protection, and highway construction agencies.

Waste recycling and processing provide more and more construction materials as well as secondary waste materials. Specifications and procedures are needed for these materials to be applied to highway construction. After pilot projects have been successfully conducted and specifications implemented, these materials could be used on a routine basis. In the future, a complete closed-loop recycling process can be built: product to waste to infrastructure.

Waste processing by incinerating or composting also produces more and more waste products that can be used as construction materials. Post combustion treatment technologies, which include stabilization, vitrification, and residue metals extraction have potential to improve the residue characteristics for utilization in highway construction. Under controlled construction, these processing residues can be utilized without imposing environmental risk. In this way, controlled disposal and construction are combined into one practice, thereby resulting in a cost-effective alternative.
References


