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	Engineering and Design USE OF WASTE MATERIALS IN PAVEMENT CONSTRUCTION	
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
CEMP-ET Washington, DC 20314-1000

Technical Letter
No. 1110-3-503 15 September 1999

EXPIRES 30 SEPTEMBER 2004
Engineering and Design
USE OF WASTE MATERIALS
IN PAVEMENT CONSTRUCTION

1. Purpose. This Engineer Technical Letter (ETL) provides general information on the types and uses of waste materials in pavement construction, including environmental considerations.

2. Applicability. This ETL applies to all HQUSACE elements and USACE commands having military construction responsibility.

3. References. Appendix A contains a list of referenced and related publications.

4. Distribution. Approved for public release; distribution is unlimited.

5. Background.

a. The safe disposal of waste materials is an increasingly economic and environmental concern in the United States and around the world. When applicable, the inclusion of waste materials into pavement construction materials is a desirable goal. However, due to the importance of roads to commerce and personal mobility, the pavement structure should not become simply a waste disposal area. Waste materials that are included in the construction of the pavement must meet certain engineering, environmental, and economic criteria. The waste material must not have an unacceptable adverse effect on the performance of the pavement. The waste material should not have unacceptable health concerns to workers or users either during construction or while in use. The waste material should be properly contained within the pavement structure thereby posing no threat to the environment. The use of waste materials must be economically sound both initially and over the life of the pavement.

b. This ETL provides general information on the types, uses, and environmental considerations of waste materials in pavement construction. The information provided is for the use of waste materials in various applications of pavement construction.

6. Action Taken. Pending publication of permanent guidance, Appendix B of this ETL will be used to assist HQUSACE, major subordinate commands, district offices, and FOA in the design and construction of pavements using waste materials.

7. Implementation. This letter will have routine application for all future military projects as defined in paragraph 8c, ER 1110-345-100.

FOR THE COMMANDER:

2 Appendices
APP A – References
APP B – Use of Waste Materials in Pavement Construction

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APPENDIX A
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APPENDIX B

USE OF WASTE MATERIALS IN PAVEMENT CONSTRUCTION

B-1. Introduction

a. The safe disposal of waste materials is increasingly a major concern in the United States and around the world. Even with heightened awareness of the importance of recycling, the volume of waste materials continues to grow (Ciesielski and Collins 1993 and Ciesielski 1995). Between 1980 and 1988 the annual amount of waste recycled grew by 9 million tons; however, the amount of waste generated increased by 30 million tons per year (NSWMA 1990). In 1994, the total amount of waste produced in the U.S. reached 4,500 million tons per year (Shelburne and DeGroot 1998). At the same time that existing disposal facilities are reaching capacity, approval of additional facilities for waste disposal or treatment are becoming more difficult to obtain. Increasingly restrictive environmental regulations have made waste disposal more difficult. Together, these factors have significantly increased the cost of disposal of waste materials (Ciesielski and Collins 1993).

b. The use of waste materials (recycling) in the construction of pavements has benefits in not only reducing the amount of waste materials requiring disposal but can provide construction materials with significant savings over new materials. The use of these materials can actually provide value to what was once a costly disposal problem. Historically, because of the large volume of materials required for construction, pavements have been favorable structures for the recycling of a wide range of waste materials. Initially, this recycling was limited to the reuse of materials removed from previous pavement structures such as: recyclable asphalt pavement, recyclable portland cement concrete, and various base course materials. Recently, various other materials, not originating or historically associated with pavements, have come into use, for example various latex materials added to the asphalt cement. This ETL will discuss the origin and use of various types of waste materials available and the design, construction, and environmental considerations required with their use.

c. The majority of wastes discussed in this paper could be used to form a structural component of the pavement. Some have uses as replacements for conventional aggregates and some form part or all of the binder in the particular mixture. Existing hot-mix asphalt design and analysis procedures are often inappropriate for mixtures containing waste materials; therefore, procedures must be developed to provide for their consistently successful application (Terrel et al. 1994). Other materials such as animal manure, crop wastes, sewage sludge, and compost, unless they are incinerated or reconditioned, are used for treatment of soils and landscaping along pavement edges and rights of way. Some materials such as: carpet waste, slate waste, lime waste, used sand blasting grit, etc., are not included in this ETL because they have only minor applications or are limited in quantity.

d. The various types of waste material can be divided according to the source into four categories. These categories are agriculture, domestic, industrial, and mineral (Collins and Ciesielski 1994 and Shelburne and DeGroot 1998). Agricultural and mineral wastes are the major contributors to the overall volume of solid waste with domestic and industrial wastes contributing almost an order of magnitude less (Decker 1994 and Shelburne and DeGroot 1998). The primary types of waste materials available for construction are outlined below:

(1) *Agricultural.*

(a) Animal manure

(b) Crop wastes

(c) Lumber and wood

(2) Domestic

(a) Compost

(b) Glass and ceramics

(c) Incinerator ash

(d) Plastics

(e) Residual material from water treatment plants

(f) Sewage sludge

(g) Use motor oil

(h) Used tires

(i) Waste paper

(3) Industrial

(a) Baghouse fines

(b) Blast-furnace (iron) and steel slags

(c) Cement and lime kiln dusts

(d) Clean-burning ash material

(e) Coal ash by-products

(f) Construction and demolition debris

(g) Foundry wastes

(h) Non-ferrous slags

(i) Paper mill sludge

(j) Petroleum contaminated soils

(k) Reclaimed asphalt pavement

(k) Reclaimed concrete pavement

(l) Roofing shingles

(m) Silica fume

(n) Sulfate waste

(4) Mineral

(a) Coal refuse

(b) Mill tailings

(c) Phosphogypsum

(d) Quarry waste

(e) Spent oil shale

(f) Washery rejects

(g) Waste rock

B-2. Types and Pavement Applications of Agricultural Wastes. Agricultural wastes are produced at a rate of more than 2 billion tons annually in the United States (Collins and Ciesielski 1994 and Shelburne and DeGroot 1998). These agricultural waste materials can be divided into animal manure, crop wastes, and lumber and wood wastes. Animal manure makes up approximately 75 percent of the total annual agricultural waste produced in the U.S. The majority of this material, because of transportation costs, is used as a fertilizer on the farms where it is produced. At least one state department of transportation (DOT) has used it as fertilizer on highway rights of way.

a. Crop and animal wastes. The U.S. agricultural industry produces more than 400 million tons of crop wastes annually (Collins and Ciesielski 1994). Currently, the majority of this material is being used as animal feed. There have been two reported uses of crop waste material for pavement construction materials. The first was an investigation of the potential use of rice husk ash as a supplemental cementing material for the partial replacement of Portland cement in PCC mixtures. The replacement of up to 20 percent of the cement with an equal weight of the rice husk ash contributed to increased early (1 to 3 days) compressive strength and a decreased effect of alkali-aggregate reactivity (Mehta 1992). The second investigation involved converting cellulosic wastes (including crop residues, animal manure, and wood wastes) into binder materials. These materials could be converted into an oil that could serve as an asphalt extender (Collins and Ciesielski 1994 and Mehta 1992).

b. *Logging wastes.* About one third of the wood that is harvested yearly by the logging and lumber industry ends up as a waste material. This waste takes the form of logging residues, wood and bark chips, and sawdust. Currently, up to 70 million tons of this material is produced in the U.S. each year (Collins and Ciesielski 1994). The majority of this material is available in the Pacific Coast states. However, some would be available throughout many parts of the U.S. where logging occurs. A portion of the wood chips produced is used in the lumber industry to produce particleboard products. Finer particles have usually been used as mulching materials. Some wood waste materials have been used for exotic proposes such as soil reinforcement; however, the majority of use for pavement applications has been as lightweight fill (Sotir and Gray 1989, ENR 1986, and Nelson and Allen 1974).

B-3. Types and Pavement Applications of Domestic Waste. The amount of domestic wastes generated in the U.S. annually exceed 200 million tons (Shelburne and DeGroot 1998). Approximately 185 million tons of this waste is household or commercial waste (trash or garbage) (NSWMA 1989). About 75 percent of this waste is placed in landfills, 11 percent is recycled, and 14 percent is incinerated.

a. Compost. Compost is the relatively stable end product of a biological, aerobic process of decomposition of organic wastes. These wastes can include a wide range of materials including: crop wastes, sewage sludge, yard wastes, paper mill sludge, and food wastes (Collins and Ciesielski 1994). Compost has been used on highway and airport shoulders; although, some concerns with possible leachate problems, odors, worker health and safety, and public acceptance hinder the use of this material in many areas (Ahmed 1991 and Thoresen 1993). There are no specific regulations, standards, or guidelines pertaining to the use of compost (Ahmed 1991).

b. Glass and ceramics. Despite the increased usage of plastics for many applications, supplies of waste glass continue to be available, often due to recycling efforts. In 1988, 1.5 million tons of waste glass was recycled, while three years later 12.5 million tons of glass was still being discarded (NSWMA 1990). This amount can be expected to decline but not to be completely eliminated because of the decrease in the production of glass containers (Ahmed 1991). Currently, glass is only available in quantity in larger metropolitan areas (Collins and Ciesielski 1994), although recycling operations in smaller metropolitan areas can also generate considerable quantities (American City and County 1997). Waste glass, from an economical standpoint, should probably be used only to make more glass; however, only selected glass can be used for this process. This leaves a substantial amount of waste glass available for use in pavement applications (Ahmed 1991). Ceramic waste consists of china and porcelain from old or defective manufactured objects (Collins and Ciesielski 1994). This waste has historically been less available than glass, but as the amounts of waste glass decreases this may not remain true.

In the paving industry, crushed glass (cullet) has been used as a replacement for aggregate in hot-mix asphalt mixtures, known as *glassphalt* (Malisch et al. 1970, Collins and Ciesielski 1994). Experience has shown that the cullet can replace up to 15 percent by weight of total aggregate in hot-mix asphalt. These mixes should not be used in surface courses (Ahmed 1991, FHWA 1993, and Shelburne and Degroot 1998). The mixtures containing cullet have been shown to be susceptible to moisture damage. This effect is only somewhat offset by the use of antistripping agents (West et al. 1993). Several states add fine glass to paint to increase the reflectivity. The military currently utilizes the same process on airfield pavements. At least 10 states have experimented with glass beads as aggregate; however, only one, New Jersey, considers it to be an acceptable standard practice. One laboratory study investigated the use of cullet as an aggregate replacement for subbase, base, and embankment structures. They concluded that the cullet as an aggregate was strong, clean, safe, and economical. Compaction results with some cullet gradations showed a flatter maximum dry density versus moisture curve indicating, that in field construction, compaction could occur over a wide range of moisture conditions (Shin and Sonntag 1994). One small community has used cullet as a partial aggregate replacement for subbase construction of a city street (American City and County 1997).

California has constructed an acceptable unbound base course made from crushed porcelain. The crushed porcelain materials were found to have met or exceeded the quality requirements for concrete aggregates. The Wisconsin DOT has recently used broken glass and ceramic waste, along with several other waste materials as partial aggregate replacement (up to 15 percent) as a highway base course on a state roadway (Roads and Bridges 1998).

c. Incinerator ash. In the U.S. there are approximately 140 thermal reduction facilities operating in 32 different states that process municipal solid waste (Collins and Ciesielski 1994 and Rivard-Lentz et al. 1997). These plants produce heat to generate electricity and reduce the volume of material by up to 85 percent, resulting in about 8.6 million tons of incinerator ash or residue per year. This will amount to more than 15 million tons by the end of the century (Goodwin 1992). The percentage of incinerator bottom ash to incinerator fly ash produced varies from 60 to 90 percent depending upon the properties of the waste and the thermal process used (Lum and Tay 1992, Collins and Ciesielski 1994, Nicholson and Ding 1997, and Rivard-Lentz et al.1997).

The incinerator bottom ash, specifically that which is water cooled, exhibits physical properties similar to those of a well-graded gravelly sand, although the specific gravity will normally be lower than most natural sands (Ahmed 1991 and Kouda 1996). Incinerator ash has been used successfully as an aggregate replacement in structural fill applications (Rivard-Lentz et al.1997). A prepared (washed) incinerator ash was used to replace the fine aggregate fraction in an granite hot-mix asphalt mixture. This resulted in a very acceptable mixture, although it required a higher asphalt content than found in normal granite hot-mix asphalt (Ahmed 1991and Lum and Tay 1992). It also reduced the moisture susceptibility of the conventional mixture (Lum and Tay 1992). A similar result, of reduced moisture susceptibility, was found by Fwa and Aziz, when incinerator ash was used to replace the mineral filler portion of hot-mix asphalt mixtures (Fwa and Aziz 1995). One study in Japan successfully utilized incinerator ash as a partial aggregate replacement for both base course and hot-mix asphalt mixtures in a commercial haul road pavement (Kouda 1996). The incinerator fly ash produced in these plants may have uses similar to those detailed under *Coal ash by-products*, but the exact properties of the incinerator fly ash produced need to be evaluated. One investigation found that combining 15 percent incinerator fly ash with tropical fine-grained soils increased the shear strength and decreased the plasticity of the soils evaluated (Nicholson and Ding 1997). Some incinerator ash has been shown to possess substantial pozzolanic behavior (Goodwin 1992).

Prior to using incinerator ash in any application the environmental effects must be considered. Analysis has shown that most incinerator ashes are classified as nonhazardous under U.S. regulatory standards; however, each case should be evaluated for the application planned (Rivard-Lentz et al.1997 and NaQuin 1998).

d. Plastics. The amount of plastic waste materials generated increases each year. The plastic materials can be classified into 6 major types:

(1) LDPE - Low Density Polyethylene (film and trash bags)

(2) PVC - Polyvinyl Chloride (pipes, siding, and flooring)

(3) HDPE - High Density Polyethylene (milk jugs)

(4) PP - Polypropylene (battery casings and luggage)

(5) PS - Polystyrene (egg cartons, plates, and cups)

(6) PET - Polyethylene Terepthalate (soda bottles)

LDPE has been used for many years as an asphalt modifier in hot-mix asphalt mixes and other asphalt paving applications. At least seven states have used LDPE which is normally recycled into pellets for adding to hot asphalt cement (Collins and Ciesielski 1994). LDPE has been shown to be effective in reducing low temperature cracking and reducing rutting at high temperatures (Liang 1993). At low temperatures LDPE mixtures may be more susceptible to fatigue problems; however, the high temperature performance has usually been exceptional (Little 1993). HDPE has also been used to make signs and posts. The Florida DOT has had extensive experience with this material (Smith and Ramer 1996). PET bottles have been used to produce geotextiles and, when chemically modified to a thermoset polyester, they have been used to produce a polymer concrete. Direct references indicating use of the remaining plastic materials was not found.
A large part of the plastic waste is commingled; meaning it is a mixture of two or more plastics. These materials have been used to produce signs and posts and in granulated form have been used as a lightweight sand replacement in a PCC bridge deck.

Commingled plastic has been used with steel pipe to produce composite piles (Heinz 1993 and Shelburne and Degroot 1998).

e. Residual material from water treatment plants. Treating water normally requires the removal of fine solid particles, organic matter, and cations of various materials such as calcium, iron, and aluminum (Raghu et al. 1997). The high water content and resulting low shear strength and high compressibility of the residual materials removed during this process prevent direct application for construction. A study by Raghu et al. (1997) showed that blending topsoil with this material would provide a suitable fill material for construction purposes. In their case, the fill served as a landfill liner. As with any construction involving fill, control of the water content was critical in achieving good engineering properties such as density, strength, and durability.

f. Sewage sludge. There are more than 15,000 municipal water treatment plants throughout the country that produce in excess of 8 million tons of dry solid sewage sludge annually (Collins and Ciesielski 1994). This sludge is normally composed mostly of organic materials such as nitrogen and phosphorus, with minor amounts of various contaminants. About 20 percent of this material is incinerated with equal amounts of the remainder either composted, used in land applications, or placed in sanitary landfills. Sewage sludge disposal is regulated by a combination of state and federal EPA regulations. In 1989, there were 282 incinerators burning sludge in the U.S.; however, burner emission considerations have become a limitation on this type of process (Morse 1989). Incinerator ash has been used in pellet form as a coarse aggregate for concrete and in ash form as a filler for hot-mix asphalt (Collins and Ciesielski 1994, Bhatty et al. 1992). Concrete made with the pellets has achieved compressive strengths up to 15 percent greater than comparative concrete when they made up 35 percent of the aggregates in the mixture. In those laboratory tests, fracture occurred through the pellets, indicating lower strength when compared to the limestone aggregate used in the tests. The pellets have a relatively low unit weight making them useful where lighter weight concrete is desirable (Bhatty et al. 1992).

Dewatered sewage sludge has been used mainly as an additive to topsoil. One study using dewatered sewage sludge with soil, lime, and fly-ash additives in different proportions, found that the material, when properly modified with the additives, could be used in embankments, provided the water content was kept low (Wang et al. 1992).

g. Used motor oil. Over two billion gallons of lubricating oil is produced every year. About 90 percent of what is reclaimed is burned as fuel. At least 3 DOTs have experimented with burning the oil in asphalt plants (Collins and Ciesielski 1994).

h. Used tires. The estimated amount of used tires that are discarded annually varies between 235 to 300 million (Papp et al. 1997 and Shelburne and Degroot 1998). Current trends to smaller and longer-wearing tires have resulted in a relatively small increase, if any, in number of tires from about 240 million in 1990 (Ahmad 1991). The disposal of waste tires is as follows: approximately 80 percent of the tires were placed in landfills, 10 percent were used as fuel, about 8 percent used the tire whole or shredded for pavement applications and other miscellaneous uses related to pavements, and about

2 percent were ground into crumb rubber for use in asphalt rubber (Collins and Ciesielski 1994 and Epps 1994). There are an estimated 2 to 3 billion tons of used tires stockpiled across the country. Nearly half of the states have enacted legislation that prohibits continued placement of used tires in landfills. Recent estimates indicate that more than 69 percent of all used tires were being used for some type of application. By 1996, there had been over 70 roadbeds constructed using tire chips nationwide (Nightingale and Green 1997).

Pavement uses of whole, chopped, or shredded used tires have included: fills and embankments, retaining walls, drainage structures, and specialized pavement hardware (Ahmed and Lovell 1992). The literature shows that one advantage, and often a reason for selection, of the used tires in fill or embankment applications is the lightweight (low unit weight) of the in-place material (Ahmed 1991). Alternative fill materials such as wood chips are not as durable and lightweight aggregates or have relatively high unit weights and are more expensive. The use of shredded used tires requires a design allowance for the relative compressibility during construction and high deflections under load in relation to most other construction materials (Ahmed and Lovell 1992, Newcomb and Drescher 1994, and Bernal et al. 1997). One study found improved results when the shredded tire layer roadway pavements were overlaid with a 3-foot thick versus a 1-foot thick soil cap (Bosscher et al. 1992). Studies using shredded tires as an aggregate or soil replacement for subbase construction and other uses have found that the addition of the tire chips reduces the unit weight, CBR values, and resilient modulus values (Papp et al. 1997 and Tatlisoz et al. 1997). A study of the pullout resistance of a geogrid in shredded tire and a shredded tire - sand mixture, determined that the use of geogrids could decrease deformations for shredded tires with or without added sand (Bernal et al. 1997). One study found that the addition of silty soils could provide increased compressive strength of shredded tire fills similar to those provided by adding sand. However, clay materials had a detrimental effect on strength. Compressive strength values increased for tire contents up to about 25 percent (Tatlisoz et al. 1997). When shredded tires are used as replacement for aggregate, the change in properties of the conventional subbase must be considered in design. Early in 1996 two roadbeds constructed with shredded tires self-heated and caught fire. These sites contained thick sections of tire chips of 7.9 m (26 ft) and 15 m (45 ft) thick. The exact cause of these fires is not known, but thick applications using tire chips need further investigation in this regard (Nightingale and Green 1997). In 1997, the Maine DOT used tire chips to stabilize a riverbank and an embankment backfill during construction of a bridge. They took steps to prevent and monitor possible self-heating, the project appeared to be successful and after more than one year temperatures were decreasing after a slight initial increase (Humphrey et al. 1998). Studies of the effects of shredded tires on water quality found that there were negligible effects on the groundwater (Bosscher et al. 1992 and Humphrey et al. 1997). However, some researchers recommend using shredded tire only in unsaturated zones (Shelburne and Degroot 1998).

A number of states and other agencies have utilized waste tires for miscellaneous, site specific pavement applications or as research projects, not as standard practice. The use of the rubber from used tires is generally known as crumb rubber modifier (CRM). CRM has been used, at least to some extent in most other developed countries. Australia has used it successfully in various applications since the 1950's, with a large amount used in stress alleviating membrane interlayers (SAMI) applications (Leask 1983). CRM has been used in other varied applications such as crack/joint sealants and surface/interlayer treatments (Ahmed 1991 and Ahmed and Lovell 1992). Used tire rubber has been used in hot-mix asphalt pavement applications for more than 35 years (Epps 1994). The vast majority of states and most federal agencies have used CRM in paving projects, with no major problems reported during the preparation and construction (FHWA 1993). The use of CRM can be broken down into two processes: (1) the wet process, where the CRM is blended and partially reacts with an asphalt cement prior to use; and (2) the dry process, where the CRM is added to the aggregate in a hot-mix central plant operation prior to adding asphalt cement (Heitzman 1992). CRM has been used in gap-graded hot-mix asphalt pavements in the US to reduce tire and therefore overall vehicular traffic noise (Nicholson 1998). As of 1993, there had been two documented instances of CRM pavements themselves being recycled to become part of a new pavement.

Despite the relatively long term and widespread use of CRM, the majority of states and agencies still consider it as experimental process. A survey of state transportation departments reported that the states had used the wet process more than twice as often as the dry process. The states reported successful applications of the wet process in more than 50 percent of their projects, while the majority considered the dry process to have been unsuccessful (Epps 1994). A new dry process has been used in California for the last three years and the results indicate performance better than or equal to the wet process (Nicholson 1998). The effect of CRM on properties of hot-mix asphalt can vary with the process when compared to conventional hot-mix asphalt; however, either process will improve the fatigue life of the pavement (Hansen and Anderton 1993, Epps 1994, and Nicholson 1998). Studies using the wet process have found that the addition of CRM decreased the oxidative hardening of the asphalt binder and improved the fatigue resistance of the pavement (Ramaswamy and Aziz 1992 and Rebala and Estakhri 1995). One study using a devulcanized CRM (a wet process) showed improvement of the low temperature performance of hot-mix asphalt mixtures (Morrison 1995). Other studies found that CRM would provide improvement to low temperature cracking, especially when a softer than normal asphalt was used (Hansen and Anderton 1993). Evaluation of CRM mixtures indicates a potential for reducing thermal cracking (Lundy and Zhou 1993, Stroup-Gardiner et al. 1996, and Nicholson 1998). Some studies have found that field performance did not correspond to laboratory performance, indicating that field studies are needed for decisive information (Heitzman 1992). As of 1995, approximately 20 percent of all states were mandating the use of some form of rubber in all state DOT paving projects. Recent evaluations of CRM in asphalt mixtures have been accomplished using Strategic Highway Research Program (SHRP) Performance Grade asphalt test methods (Troy et al. 1996 and Gowda et al. 1996).

One study of the use of crumb rubber, both in the wet and dry processes, found that emission levels during the hot-mixing process resulted in slightly higher but acceptable levels of the various emission materials investigated (Baker and Connolly 1995). Other studies with crumb rubber have found that a properly designed, managed, and operated facility can satisfy all air, solid waste, liquid effluents, and health requirements (FHWA 1993 and Emery 1995).

i. Waste paper. Waste paper accounts for approximately 40 percent of the solid domestic wastes produced each year. The paper, including: cardboard boxes, newspapers, office paper, etc., that is not recycled into more paper can be used as a mulching material. A few state DOT's have used waste paper as a mulch (Collins and Ciesielski 1994).

B-4. Types and Pavement Applications of Industrial Waste. Industrial wastes, as a group, are probably the most widely reused of the waste materials generated. The amount of industrial wastes generated in the U.S. exceeds 400 million tons annually. Of this amount, approximately 100 million tons are recycled pavement and 70 million tons are coal ash. These materials are recycled at approximately 50 and 25 percent, respectively (Shelburne and DeGroot 1998).

a. Asphalt Plant Baghouse fines. The majority of asphalt plants in the U.S. use a dry dust collection system. These dusts, which are finely graded, are typically immediately added back into the aggregate stream of the hot-mix asphalt (Collins and Ciesielski 1994). Depending on the aggregate and the mixture being produced, excess baghouse fines can be produced. These can be added to other hot-mix asphalt mixtures, when additional fines are required.

b. Blast-furnace (iron) and steel slags. Iron ore, coke, and limestone are superheated in a blast furnace to produce pig iron. A waste product of this procedure is blast-furnace slag, which essentially consists mainly of silicates and alumino-silicates of lime (Ahmed 1991 and Collins and Ciesielski 1994). Variations in the cooling process results in 4 types of blast-furnace slag: air cooled (under ambient conditions), expanded (with controlled quantities of water), granulated (quick water quenched to a vitrified state), and pelletized (water and air quenching in conjunction with a spinning drum). In 1989, 15.5 million tons of blast-furnace slag were sold, mainly for construction purposes; about 90 percent of this was air-cooled blast-furnace slag and expanded slag made up the next largest portion. In 1994, this had risen to more than 13 million tons and almost all the blast-furnace slag produced in the U.S. was reused for construction purposes (Schriefer 1997). This slag is fairly porous with a low unit weight that can range from 1,200 to 1,450 kg/m^3 (62 to 75 pcf). Blast-furnace slag is available in numerous states, generally in the northeast and midwestern states of the U.S. Blast-furnace slag is classified as a mineral waste and is therefore not considered a hazardous waste (FHWA 1993).

Some slag bases and embankment applications have experienced problems with the formation of tufa (calcium hydroxide, $Ca(OH)_2$), which deposits on drainage structures, leading to increased maintenance requirements (Gupta et al. 1994). The tufa is formed by carbon dioxide (CO_2) in the water combining with free lime (CaO) in the slag. Steel slag and blast-furnace slag from open-hearth and basic-oxygen furnaces have been shown to be susceptible to the formation of tufa (Gupta et al. 1994). Only air-cooled blast furnace slag does not have the potential for the formation of tufa, other slags should be evaluated for the existing field moisture and drainage conditions (Gupta et al. 1994 and Kneller et al. 1994).

Air-cooled blast-furnace slags have been used by more than 20 states and other agencies in many construction applications in recent years. The most common uses are as aggregates for base course, concrete, and hot-mix asphalt, but the slag is also used as an embankment material, especially over low strength subgrades. These slags are used worldwide wherever they are readily available. Australia has successfully employed slags for most of the applications mentioned above (Leask 1983). Granulated blast-furnace slag has gained some acceptance as a cementitious material. One study used a granulated slag as an additive to a cement-bentonite mixture to provide increased shear strength of a slurry wall (Khera and So 1997). One consideration is the use of slag in hot-mix asphalt is the increased requirement for asphalt cement, due to the porous nature of the slag (Ahmed 1991).

Steel slag is formed in a steel furnace as the lime flux reacts with molten iron ore, scrap metal, and other possible ingredients. After removing any entrapped metal by magnetic separation, the slag consists of a fused mixture of oxides and silicates, mainly calcium, iron, unslaked lime, and magnesium (Ahmed 1991 and Collins and Ciesielski 1994). There are three different types of steel furnaces: open hearth, basic oxygen, and electric arc. Over one-half of the furnaces currently in use are electric arc; however, there are still substantial quantities of open-hearth slag in stockpiles. Steel slag has a tendency to expand when exposed to moisture, unless it is previously aged with water. This expansion is caused by the hydration of calcium and magnesium oxides (Ahmed 1991). One company recently developed a new method of processing steel slag that completely eliminates possible expansion (Schriefer 1997). It has a higher unit weight than blast-furnace slags and is relatively hard, stable, and abrasion resistant. In 1989, 7.9 million tons of steel slag were sold by the 26 producing states in the U.S. The slag was used mainly for construction purposes (Collins and Ciesielski 1994).

Steel slags have been used as aggregates for base course, concrete, and hot-mix asphalt; although only about one-half as many states have used it as have used blast-furnace slag. Any applications other than in hot-mix asphalt require that the steel slag be properly aged with water. Steel slag provides a hard, tough, and durable aggregate. It has been used in pavement surfacings because of its resistance to polishing and resulting long-term skid resistance (Ramaswamy and Aziz 1992). There have been instances of leachate originating from slag fills and bases, while others report satisfactory environmental effects (Ahmed 1991, FHWA 1993, and Collins and Ciesielski 1994). However, steel slag continues to be used in base course applications (Roads and Bridges 1998).

c. *Cement and lime kiln dusts*. Cement kiln dust is produced in high temperature kilns where raw materials are used to produce a cement clinker. The dust collected during this operation consists of fine powdery materials, the exact components of which depend upon the component materials added to the kiln and where in the dust collection system is located (Collins and Ciesielski 1994). As of 1992, more than 3.5 million metric tons of cement kiln dust were generated each year (Todres et al. 1992). Lime kiln dusts are physically similar to cement kiln dusts, but differ in chemical make up and are by-products of the manufacture of lime. As of 1994, about 2 to 4 million metric tons of lime kiln dust is generated in commercial lime plants (Collins and Ciesielski 1994). Kiln dusts have had some usage as mineral fillers in hot-mix asphalt, stabilizers for base courses, and as stabilizers for sewage sludge. Only a few states have used kiln dusts for pavement applications and the results of these have not always been successful (Collins and Ciesielski 1994). One study using cement kiln dust found that the material could be used to reduce the incidence of wetting-induced failure or collapse of highway embankments (Miller et al. 1997). In one application involving the stabilization of a roadway test section base course, a cement kiln dust and a fly-ash were successfully used as a replacement for either lime or portland cement. During construction it was found that delaying placement of the mixture for 8 hours after wetting resulted in substantial increases in strength (Lin and Zhang 1992).

d. Coal ash by-products. Coal ash is a by-product of the burning of coal for power generation. The coal ash generated consists of fly ash captured from the exhaust gases and bottom ash and boiler slag remaining after combustion is complete (Ahmed 1991). Coal burning plants are located in at least 44 states throughout the United States. In 1992, these plants generated 66 million tons of coal ash, consisting of 48 million tons of fly ash, 14 million tons of bottom ash, and 4 million tons of boiler slag. About 12 million tons of the fly ash was used for a variety of applications (Collins and Ciesielski 1994 and American Coal Ash Association 1992). In 1998, 90 tons of fly ash were produced and 12 million tons were utilized in portland cement concrete (ASCE 1998 and NaQuin 1998).

Fly ash is a pozzolan, meaning that when combined with calcium and water, it reacts to form cementitious materials. Fly ash can be classified as either Class F or Class C, depending on the type of coal burned. While both classes are considered to be pozzolanic, Class C ashes are usually self hardening (Halstead 1986). Fly ash is one of the few waste materials which has an ASTM standard for procedures of sampling and testing. The use of fly ash in portland cement concrete mixtures is the most widely used and accepted application by state and federal agencies. Depending on the use and requirements, fly ash can be used to replace some of the cement in the mixture. When fly ash is to be used as a replacement for cement, it requires considerably more testing and monitoring of quality compared to other uses such as fill materials or as an additive to hot-mix asphalt (Halstead 1986). Fly ash can not only reduce the overall cost of the concrete, but it can make the concrete more dense and less permeable (ASCE 1998). Many producers of fly ash are taking actions to assure or improve the quality of their product for the users. The Corps of Engineers (CE) and many other Federal and state agencies use fly ash. Fly ash has been used in roller compacted concrete mixtures (Shelburne and Degroot 1998). The one common limitation to fly ash replacement of portland cement is the increased cure time. The necessary cure time can vary depending upon the particular fly ash used and local climatic conditions. Cement replacements of up to 50 percent have been used in mass foundations of bridge piers; however, replacements of 25 percent are more common (Collins and Ciesielski 1994 and NaQuin 1998).

Fly ash has been used successfully in various ways in embankments (Ahmed 1991). Fly ash seldom provides desired properties by itself, but when combined with other aggregates or other solid wastes it can be an excellent construction material (Lee and Fishman 1993). A laboratory study of fly ashes from various sources showed their suitability for stabilizing various soils for low volume roads (Turner 1997). Another study showed that a sand mixture stabilized with the addition of 20 percent Class C fly ash resulted in reduced permeability, increased compressive strength, and improved weathering resistance (Taha and Pradeep 1997). The suitability of a particular fly ash - soil combination should be evaluated prior to use. Fly ash has also been used by several states as an additive to hot-mix asphalt. The CE has successfully used fly ash as a stabilizing material in a stone matrix asphalt (SMA) mixture (Shoenberger 1997). A laboratory evaluation, in the Netherlands, showed that combinations of two different fly ash materials could be combined to produce a satisfactory stabilized material for base course applications (Mulder 1996).

Bottom ash and boiler slag have been used as embankment materials, aggregate base course (both stabilized and unstabilized) and aggregate in hot-mix asphalt by several state agencies (Collins and Ciesielski 1994 and Roads and Bridges 1998). Two states permit the use of bottom ash as a sand replacement in flowable fill mixtures. The use of these materials, when there is no previous experience, should be thoroughly investigated to determine their effect on performance.

Another coal ash is available as a by-product from “clean” coal-burning technologies. These clean-burning ash materials are available from technologies including: fluidized bed combustion, spray drying, and dry limestone or sodium furnace injection (Collins and Ciesielski 1994). These technologies use a dry chemical reagent to react with the flue gas from the burning coal to remove the sulfur dioxide from the emissions. Both bottom ash and a lesser amount of fly ash are produced in these processes. The resultant ashes are often high in sulfate and may contain unreacted lime that gives them an expansive tendency.

c. *Construction and demolition waste*. It is estimated that anywhere from 20 to 30 million tons of construction and demolition (C&D) waste are generated every year in the U.S. (Collins and Ciesielski 1994). A large percentage of this material, specifically wood and plaster, is not suitable for most pavement applications. The remaining materials include: glass, metal, concrete, brick, asphalt concrete, shingles, plastic and other miscellaneous materials. When the quantity of any of these individual materials is sufficient, they can be used individually in pavement construction (see the appropriate sections of this report). All organic material or any other hazardous material such as asbestos, should be kept separate from the C&D wastes. One location after removing concrete, metal, paper products, and most wood and other organic material; generates a soil product that is suitable as a top soil in pavement projects (McMahon 1997). Several states have used or investigated the use of C&D waste materials, either as embankment material, base course material, or as an aggregate in asphalt concrete. The limited use has generally provided acceptable results. Of course the benefit derived from not having to landfill or otherwise treat the material is a large consideration. Other factors affecting use include the cost of treating the waste to make it environmentally acceptable and the relative cost of local aggregates (Ahmed 1991).

d. Foundry wastes. Foundry wastes include foundry sands, furnace dust, and arc furnace dust, with sands being the largest volume of waste produced. In 1992, the yearly production of these wastes was between 10 and 15 million tons (Collins and Ciesielski 1994). Foundry sands have been the only foundry waste used in pavement construction, with the majority of this being as a fine aggregate for hot-mix asphalt. It has also been used as an embankment material, as a pipe bedding material, and as an aggregate replacement in base course construction for a roadway (Roads and Bridges 1998). One study successfully used foundry sands in flowable fill mixtures (Bhat and Lovell 1997). Prior to any application, the sand must be investigated for possible trace chemicals which could cause environmental problems (Collins and Ciesielski 1994 and Bhat and Lovell 1997).

Another material similar in properties to foundry sands is waste sands that are generated as a by-product of the casting industry. The sands are normally reused several times, depending upon the casting process involved, until they are sufficiently altered and become waste sands. One study using waste sand from a green sand molding of gray iron products found that a replacement of up to 15 percent of the fine aggregate in a hot-mix asphalt did not adversely affect the mixture's properties (Javed et al. 1994). Another study successfully used the same type of sands to construct two roadway embankments. This study examined possible environmental problems relating to metallic elements as well as other possible contaminants using the toxicity characteristic leaching protocol (TCLP) procedure and other tests. After more than one year of monitoring the water quality, no pollutants were detected (Fox et al. 1997). It should be noted that these foundry sands may require some cleaning or washing prior to use.

g. Non-ferrous slags. Non-ferrous slags are produced from the thermal processing of copper, lead, zinc, nickel, and phosphate ore. The majority of these smelters are in the western half of the U.S. Approximately 10 million tons of slag is produced each year, the majority of which is either copper or phosphate slag. The slags are produced in either air-cooled or granulated form, and each contain some concentration of the metals from which they were produced (Collins and Ciesielski 1994).

Non-ferrous slags have been used successfully in asphalt and PCC mixtures, base courses, and as railroad ballast. Only a few states have used non-ferrous slags, despite the relative success of mixtures containing these slags. Some state DOTs have concluded that some zinc and copper slags should not be used for PCC mixtures (Collins and Ciesielski 1994). In the early 1970's the use of zinc smelter residues was investigated for use in stabilized base courses, hot-mix asphalt, and PCC. The results of this study indicated that the material was suitable as aggregate in stabilized mixtures and hot-mix asphalt, but not for PCC because of an unacceptable cement-aggregate reactivity (Hughes and Halliburton 1973).

h. Paper-industry wastes. The paper industry generates spent sulphite liquor or lignin sulphonate, which have been used as dust palliatives and for soil stabilization (Collins and Ciesielski 1994). The Florida DOT has successfully used a small percentage (8 percent) of bark ash with fly ash as a replacement for portland cement in concrete mixtures. The bark is burned, along with pulverized coal, and the bark residue ash is collected. The bark ash/fly ash combination is considered to be equivalent to a Class F fly ash (Collins and Ciesielski 1994).

i. Petroleum contaminated soils. It is estimated that there are more than 3,000,000 underground storage tanks in the U.S. (Ratz et al. 1997). It is also estimated that 25 percent of all tanks over 2 years old have some leakage and that each leaking tank will result in approximately 30 to 50 yd^3 of contaminated soil. The federal government has mandated the removal of all underground storage tanks that were constructed without leak detection and containment systems. Any facility that handles or stores petroleum materials may be involved with generating petroleum contaminated soil, even if the petroleum is not stored underground. In one instance, soil contamination was found at a fuel pump house for an above ground storage facility (Swearingen and Ginter 1998). Whenever an insitu treatment is not feasible, the soil becomes a possible construction material. There is a draft Engineering Technical Letter (ETL) concerning the use of petroleum contaminated soils in pavement construction (ETL 1998).

There are several possible methods available for using the contaminated soils for pavement construction purposes. These include stabilizing with cement, including them as aggregate in cold-mix asphalt mixtures, or treating the soil in the heating unit of an asphalt plant to burn off the contamination. It is generally accepted that a small increase in the quantity of light petroleum substances would not damage hot-mix asphalt mixtures. Contaminants are not normally removed during the drying process in conventional hot-mix asphalt plants because the temperatures achieved are not sufficient to burn off these materials. However, at least one plant in New Jersey was modified to expose the contaminated soils to the higher temperatures necessary to burn-off contaminates and produce hot-mix (Meegoda et al. 1991). Using this type of process, contaminated soils were used at levels up to 35 percent of the total aggregate in hot-mix asphalt. Depending upon the method used, contaminated soils have been used for a wide range of paving applications from subbases to base courses to either hot- or cold-mix asphalt concrete (Meegoda and Mueller 1993). Petroleum contaminated soils have been used as partial aggregate replacement in cold-mix asphalt mixtures in several secondary road applications (Neeley 1990 and Shoenberger 1999). Generally, the asphalt mixtures, whether cold or hot mix, are evaluated through the compacted mixture having passed various leachate tests, thus meeting environmental concerns (Meegoda and Mueller 1993 and Shoenberger 1997).

j. *Reclaimed asphalt pavement*. Reclaimed asphalt pavement (RAP) is being used, in some form, by practically every state DOT and federal agency (Ciesielski 1995 and Shelburne and Degroot 1998). The CE has had considerable experience in the use of RAP material in both hot and cold recycling. The CE guide specification for hot-mix asphalt contains information for utilizing recycled mixtures containing RAP (CEGS-

02749). Further information concerning RAP material is available in the Technical Instructions Manual (TI 822-08/AFMAN 32-1131V8(I)) *Standard Practice Manual for Flexible Pavements*. In 1994, it was estimated that about 50 million tons of RAP were being milled annually (Collins and Ciesielski 1994). RAP can be used to make hot mixes, cold mixes, or in-place mixes. The percentage of RAP in a hot mix normally varies from 10 to 50 percent. Heating of the RAP without burning or damaging the asphalt cement is the limiting factor, although methods that allow 100 percent RAP, using microwaves for high temperature heating, have been used (Shoenberger et al. 1993 and FHWA 1993).

One state DOT has used RAP as an aggregate in PCC mixtures. Others have used it as either a stabilized or unstabilized base or subbase course material. The most predominant use is in hot-mix asphalt paving mixtures. The use of RAP in hot-mix asphalt is generally an excepted process, with an overall positive impact on the environment (Ahmed 1991). At least seven states mandate the use of some RAP material in all hot-mix asphalt placed by the state DOTs (Ciesielski 1995). As a general rule, RAP is not considered to be hazardous material. The only exception might be when the pavement was constructed with a hazardous material as one of the components (Thompson and Haas 1992).

k. Reclaimed concrete pavement. Reclaimed concrete pavement (RCP) has many uses including: aggregate for new PCC mixtures, unbound base course aggregate, cement-treated base, embankment base material, and as an asphalt paving aggregate. RCP has been used successfully for all of these types of applications and in some instances, it is a viable alternative to concrete pavement rehabilitation (CPR) or an overlay. It is not recommended for structural concrete (e.g., abutments, bridge decks) because of concerns with reduced compressive strength and possible deleterious materials (Shelburne and Degroot 1998). RCP from distressed pavements, caused either by D-cracking or alkali-silica reaction, can produce strong, durable concrete for pavements (Collins and Ciesielski 1994).

Most recycling, utilizing RCP, has involved replacement of coarse aggregates. RCP, when used as a fine aggregate, generally is less workable and requires more cement, because of the increased water requirements (Yrjanson 1989). With currently available equipment, all types of PCC can be recycled including: reinforced concrete and even continuously reinforced pavements. At least one third of state DOT's have used or actively use RCP material (Yrjanson 1989). RCP would not be considered a hazardous material unless the pavement had been constructed with a hazardous material as one of the components (Thompson and Haas 1992). The CE has used RCP in many instances to produce stabilized base course and new PCC. Further information on RCP is available in TM 5-822-7/AFM 88-6, Chap.8, *Standard Practice for Concrete Pavements*. The CE recommends that when recycling D-cracked concrete, the concrete should be crushed to a maximum particle size of 19 mm (3/4 in.). There is little long-term experience in recycling with alkali-silica reaction cracked concrete; therefore, prior to its use the concrete mixture should be evaluated with the same methods used on a new aggregate concrete mixture.

l. Roofing shingles. In 1995, the yearly U.S. production of waste roofing shingles was estimated at 12 million tons (Ali et al. 1995). Roofing shingle waste generated from manufacturing operations is suitable for use in either hot-mix or cold-patch materials. Roofing shingles obtained from roofing or demolition contractors are generally too contaminated to be useful, without extensive processing, as a paving material (Paulsen et al. 1987). In 1994, three state DOTs indicated that they had used roofing shingles in asphalt mixtures. One application, in Illinois, involved using the shingles as aggregate in a cold-patch material. Another study evaluating the use of shingles in asphalt paving mixtures found the roofing shingles could be satisfactorily placed in both dense and SMA mixtures (Newcomb et al. 1993). In 1993, a Minnesota DOT pavement containing 5 to 7 percent shingles, by weight, reported good performance after two years (FHWA 1993). A laboratory study in Canada found that satisfactory hot-mix asphalt mixtures could be made with up to 25 percent by weight of the mixture being roofing shingles (Ali et al. 1995).

m. Silica fume. Silica fume (condensed silica fume) or microsilica is a by-product in the manufacture of silicon and ferrosilicon alloys. Nearly 100,000 tons of silica fume are produced each year. Silica fume is pozzolanic because of its high silica content and its high specific surface area. Silica fume is 10 to 20 times finer than fly ash. Silica fume is marketed as either a powder or a slurry for partial replacement of cement in PCC mixtures.

Research has shown that silica fume increases the bond between the paste and the aggregate. This occurs when finely divided amorphous silica particles combine with available lime to form a calcium silicate hydrate. This requires good dispersion of the silica fume throughout the mixture. High-range water reducers or superplasticizers are generally required. Silica fume, reduces permeability, improves resistance to freezing and thawing, and improves resistance to chemical intrusion. Because of these properties, silica fume is widely used for bridge decks, parking garages, and other surfaces requiring a low permeability surface. Silica fume is usually used at a rate of 10 to 20 percent by weight of cement (Collins and Ciesielski 1994).

Several state DOTs have used or are investigating the use of silica fume in PCC mixtures. The CE has also investigated and recommends the use of silica fume where it would be economically feasible. Many standard applications of concrete pavement do not require the special properties of silica fume.

n. Sulfate waste. Sulfate wastes are mainly a by-product of the wet scrubbing of flue gases at coal-burning power plants. The by-product generated contains various forms of calcium sulfate, and is referred to as flue gas desulfurization (FGD) sludge. In the early 1990s there were at least 52 web-scrubbing systems, with more planned for construction. These plants generated approximately 18 million tons of FGD sludge annually. To be a useful construction material, the sludge must be dewatered. Combinations of lime-fly ash, cement fly ash, or portland cement can be used to stabilize the FGD.

B-5. Types and Pavement Applications of Mineral Waste. Mineral wastes are produced from various mining processes. The amount of mineral waste generated in the U.S. is about 1.8 billion tons annually. The largest percentage of this amount, over 1 billion tons, is waste rock (Shelburne and DeGroot 1998).

a. Coal refuse. Coal refuse can be any material that is removed during the cleaning and processing of the mined coal. The amount generated depends upon the purity or absence of unwanted seams of material within the coal (Collins and Miller 1976). In 1994, approximately 120 million tons of coal refuse were being produced each year, with the total existing amount of coal refuse probably in the range of 4 billion tons; although all of it may not be available for use, due to ownership questions (Collins and Miller 1976 and Collins and Ciesielski 1994).

The majority of the refuse is slate or shale, with some sandstone or clay. Coal refuse is sized from coarse to fine, with the 4.75 mm (No. 4) sieve as the dividing point. The coarse portion is normally well graded and makes up roughly 80 percent of the amount produced.

Several large coal producing states in the north central and north east U.S. have constructed embankments with coal refuse, and at least one state used it as a stabilized subbase (Collins and Ciesielski 1994). Applications of this type of construction have not been widespread. If placed in thick layers there is a possibility of spontaneous combustion and the possibility of acidic leachate moving into the groundwater.

b. Mill tailings. Mill tailings are the wastes produced during the processing of various types of mineral ores. These ores include: copper, iron ore and taconite, lead-zinc, uranium and to lesser degrees gold, molybdenum, phosphate, and alumina (Collins and Miller 1976 and Collins and Ciesielski 1994). The total amount of tailings produced each year is approximately 500 million tons.

The size of the tailings produced can vary widely, depending upon the type of mineral ore and the method of processing. The leaching characteristics of the tailings should be investigated prior to use. Because of increased surface area, pre-use testing becomes more important for fine-grained tailings.

Mill tailings have been used extensively for some time in areas where the mining or processing occurs. They have been used as fill in embankments, in subbase and base courses and as aggregate in concrete and hot-mix asphalt mixtures (Collins and Miller 1976 and Collins and Ciesielski 1994). For example, in 1970, more than 3 million tons of copper tailings were used to construct embankments along an interstate highway in Utah (Collins and Ciesielski 1994).

c. Phosphogypsum. Phosphogypsum is a solid by-product of the production of phosphoric acid a major component of agricultural fertilizers (Taha and Seals 1992a). In 1992, it was estimated that about 800 million tons were stockpiled, with another 35 to 60 million tons being produced yearly (Taha and Seals 1992 and Collins and Ciesielski

1994). Central Florida, Louisiana, and southeastern Texas are the locations where the majority of phosphogypsum is produced and stockpiled in the U.S. There are also sizable stockpiles of this material in various other countries, including Australia and Japan (Taha and Seals 1992).

Phosphogypsum has been used in several experimental cement stabilized road base applications. Laboratory studies have also shown that phosphogypsum can be used successfully in stabilized mixtures (Taha et al. 1992). Louisiana State University has investigated the use of a phosphogypsum slag, a by-product of a sulfuric acid production process, as an aggregate in hot-mix asphalt (Taha and Seals 1992b). Another research study found that the slag aggregate would perform well as a coarse aggregate in PCC for pavement applications (Foxworthy et al. 1994). In 1989 the Environmental Protection Agency (EPA) issued a ban on the use of phosphogypsum, due to concerns related to radon gas emissions (Lea et al. 1992). This ban covered research studies as well as any other applications and there are no current or planned research projects.

d. Quarry waste. Quarry waste consists mainly of excess fines generated from crushing, washing, and screening operations at quarries. These wastes are normally stockpiled or exist in ponds and therefore generally require dewatering prior to use. Quarry waste is being generated, at a rate of about 175 million tons per year (Collins and Ciesielski 1994). The material properties of this waste vary with the source, but are relatively constant at a particular site.

A 1994 survey showed that six states have used quarry waste in pavement applications (Collins and Ciesielski 1994). One study of potential uses of quarry waste recommended its use in cement-treated subbase and flowable fill as well as mineral filler in hot-mix asphalt and as slurry seal aggregate (Kumar and Hudson 1993). Another study found that combining 10 percent quarry tailings (waste) with a mixture of municipal solid waste ash would provide an effective landfill cover material (Lee and Nicholson 1997).

e. Spent oil shale. There are large deposits of oil shale on federal lands in Colorado, Utah, and Wyoming. These deposits may contain up to several billion barrels of oil (Collins and Ciesielski 1994). During the oil crisis of the 1970's several projects were established to remove the oil from the shale, resulting in an oil shale ash. This ash was mainly granular with some particles up to 75 mm (3 in.) in diameter (Miller and Collins 1976). These facilities all closed in the 1980s; however, several million tons of the ash are stockpiled, mainly in northwestern Colorado. The only documented research regarding use of this material as a pavement construction material found that replacing various percentages of the asphalt cement in a hot-mix asphalt resulted in improved mixture stiffness and reduced stripping potential (Khedaywi 1988).

f. Washery rejects. This category includes by-products of the phosphate and aluminum industries. These wastes are very fine clay-like materials, which are produced in slurry form (Collins and Ciesielski 1994). These materials have proven very difficult to dewater and after many years of stockpiling still have a relatively low solids content (Collins and Miller 1976). The phosphate wastes are located mainly in central Florida, with some in North Carolina and Tennessee. The alumina wastes are located Louisiana, Texas, Arkansas, and Alabama (Collins and Ciesielski 1994). There has been very limited research with these wastes and currently there is no known use for them in pavement construction.

g. Waste rock. Waste rock is rock removed during mining operations that has little or no mineral value. The amount of waste generated varies with the type of mining operation, although the greatest amounts usually occur at surface (open pit) mining operations (Collins and Miller 1976). The quality of the rock can vary widely with the location of the mine and to the extent that impurities are present. It is estimated that approximately 1 billion tons of waste rock and overburden are generated each year (Collins and Ciesielski 1994). Due to the nature of the mining operations, the wastes are generally located in remote areas far from where they are needed for construction. Limited use of this waste has been reported, mainly due to the remote locations and the availability of other suitable construction aggregates. New York State reports satisfactory results with using waste rock as fill for embankments and riprap for drainage uses (Collins and Ciesielski 1994).

B-6. Available Specifications

a. Specifications are generally not available, except for a few waste materials that have had extended usage. Specifications exist for reclaimed asphalt pavement, scrap tires, iron and steel slags, reclaimed concrete pavement, fly ash, and plastic waste. These materials have been widely used; at least in areas of the country that produce the particular waste material. Some type of local specification probably exists for other waste materials that have been used in construction of a pavement. Construction specifications for the use of materials such as foundry sands for fills will be basically the same as those used for typical granular backfill materials. These specifications provide requirements for lift thickness and compaction requirements (Abichou et al. 1998).

b. One requirement for satisfactory specifications is the development or availability of suitable test and evaluation methods. One study provided recommendations for testing and construction using tire chips (Edil and Bosscher 1994). In many instances test methods suitable for use in design and construction specifications have been developed; however, they are often not standardized for ready usage in standard specifications.

c. The CE has a guide specification that covers the use of reclaimed asphalt pavement in hot-mix asphalt (CEGS 02749). There are two manuals (TI 822-08 and TM 5-822-7) which address the use of reclaimed asphalt pavement, iron and steel slags, reclaimed concrete pavement, and fly ash. The CRD-C and ASTM standards that pertain to the classification and use of fly ash are listed below:

(1) CRD-C 255 & ASTM C 618 - Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

(2) CRD-C 256 & ASTM C 311 - Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete

B-7. Environmental Considerations. One basic consideration involving the use of waste materials, aside from cost, is the environmental affect of using the waste material in a pavement application. There have been at least some initial investigations into the environmental effects in pavement applications of many of the waste materials described in this text. Many waste materials require special consideration for the same reason most of them are considered as hazardous materials when used or stockpiled in non-pavement applications. The possible environmental effects of the use of waste materials must be considered during material preparation, during construction, and during pavement use. Within most state DOT's and other agencies the use of most waste materials is handled on a case-by-case basis; therefore, without the benefit of an established approval procedures it is often difficult to utilize the waste materials.

B-8. Cost Considerations (Economic Factors)

a. The economics of using waste materials in pavement applications must be favorable for their widespread use to become a reality. The economic benefit can come either from improved pavement performance with the added waste material or from consideration of other treatment or landfill costs concerning the waste material if not used productively. One consideration that is rarely adequately addressed, is the effect that waste materials may have on the pavement once it has deteriorated to the point where it requires rehabilitation. What effect will the current use of waste materials have on the future use of the pavement materials? Will it be possible to recycle or will the material still be considered a hazardous or controlled material?

b. Accurate life-cycle cost analysis for most waste materials is difficult due to the limited number of applications of a particular material. Some waste materials possess pozzolanic properties that would allow them to replace or reduce the amount of portland cement used in some applications. Some types of incinerator ash possess this property, which could provide substantial savings in liner and other applications (Goodwin 1992). Economically, waste glass should be used only to make more glass; however, limits on the type and quality of the glass result in a substantial amount of waste glass being available for use in pavement applications (Ahmed 1991). A limited study of paving mixtures using roofing shingles and other waste showed cost savings of up to 20 percent (Epps and Paulson 1986). Crumb rubber is one waste material with a substantial amount of previous usage. One study found that the dry process was economically unfavorable, while the wet process showed promise of being economically favorable (Emery 1995). The life-cycle costs of using rubber in paving applications is not well defined. The use of this material will increase the initial cost by 40 to 100 percent; however, it has been shown to provide an increase in performance (Thirumalai 1992).

c. The use of RAP and RCP are additional waste materials with a substantial history of usage in pavement construction. Especially for RAP, cost savings of 20 to 50 percent, compared to new paving materials, have been demonstrated (Thirumalai 1992). One state DOT study showed that the costs of using RCP would be equal to using virgin aggregates, when disposal and all other costs were considered (Ahmed 1991). This would make RCP more attractive in areas that do not have access to low cost, quality aggregate. True life-cycle analysis must include not only the initial cost, but also the increased performance and the effects of the waste material on the pavement materials recyclability at the conclusion of its useful life.

d. Finally, state and federal regulations and policies can have a strong influence on the use of waste materials in pavement construction. Federal programs such as the 1976 Resource Conservation and Recovery Act and the 1984 Hazardous and Solid Waste Amendments promoted the use and recycling of waste materials. The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) required that all DOT's use a certain percentage of crumb rubber in asphalt mixtures. This was later rescinded through the significant opposition of many states (Shelburne and DeGroot 1998).