By-Product and Discarded Material Utilization in Highway Construction and Maintenance – A Literature Review

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Research Report
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BY-PRODUCT AND DISCARDED MATERIAL
UTILIZATION IN HIGHWAY
CONSTRUCTION AND MAINTENANCE
-- A LITERATURE REVIEW

by

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Transportation Research Engineer

and

John Tilley
Research Assistant

Kentucky Transportation Center
College of Engineering
University of Kentucky

in cooperation with
Kentucky Transportation Cabinet

and

Federal Highway Administration
U.S. Department of Transportation

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January 1994
**Title and Subtitle:**
By-Product and Discarded Material Utilization in Highway Construction and Maintenance -- A Literature Review

**Abstract**

This report summarizes the findings of an extensive literature search and review conducted to determine current attitudes relative to the use of recyclable and recoverable materials in highway construction and maintenance activities. Specifically, the literature search focused upon the engineering, economic, and performance aspects of using recyclable and recoverable materials in highway construction and maintenance projects. The literature review focused on asphalt and cement concrete pavement recycling, discarded tire recycling, reuse of paint removal wastes, fly ash, glass, alternative fuels, and other miscellaneous recycled and recovered materials as related to construction and maintenance of highways. Additionally, regulatory and policy matters associated with the use of recyclable and recoverable materials in the transportation area were investigated during the review of literature.

**Key Words**
## METRIC CONVERSION FACTORS

**APPROXIMATE CONVERSIONS TO METRIC UNITS**

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**APPROXIMATE CONVERSIONS FROM METRIC UNITS**

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**FORCE AND PRESSURE**

| | | | | |
| **FORCE** | pound-force | 4.44822 | newtons | N |
| psi | pound-force | 6.89476 | kilopascal | kPa |

**ILLUMINATION**

| | | | | |
| **ILLUMINATION** | foot-candles | 10.76391 | lux | lx |
| fl | foot-Lamberts | 3.42852 | candela/m² | cd/m² |

**TEMPERATURE (exact)**

| | | | | |
| **TEMPERATURE (exact)** | °F | Fahrenheit | °C | Celsius |
| temperature | (°F - 32)/1.8 | temperature | (1.8°C + 32) | Fahrenheit | °F | temperature |
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ACKNOWLEDGEMENTS

The authors wish to express their appreciation and gratitude to Ms. Laura Whayne, librarian at the Kentucky Transportation Center, for completing the literature search for this study through the library facilities at the Kentucky Transportation Center.
EXECUTIVE SUMMARY

One of the objectives of the Kentucky Transportation Cabinet is to promote the utilization of recovered and recycled materials within the Department of Highways to the fullest extent possible. The Kentucky Transportation Cabinet selected the Kentucky Transportation Center to develop an expert system for the utilization of recovered and recycled materials in highway construction and maintenance applications. The expert system will enable Kentucky Transportation Cabinet administrators to provide practical waste utilization plans and comply with any legislative mandates pertaining to waste utilization in highway construction and maintenance applications. The expert system will provide an opportunity for transportation officials to pre-examine the impact of various potential legislative actions relative to the mandated use of certain waste materials.

The expert system will utilize a multi-disciplinary data base that appraises all aspects of waste utilization relative to highway construction and maintenance. Specifically, the expert system will be designed to examine engineering, economic, regulatory and policy matters related to the use of waste materials in transportation. Furthermore, the expert system will have the flexibility such that modular expansion of the system will be possible as new materials and regulations are developed in the future. A comprehensive literature search was conducted using the facilities of the University of Kentucky Transportation Center Library. Articles and reports related to the use of recyclable and recoverable materials in highway construction and maintenance activities were thoroughly reviewed for general and detailed information that is being used for input to the expert system.

This report summarizes the findings of the extensive literature search and review that was conducted to determine current practices relative to the use of recyclable and recoverable materials in highway construction and maintenance activities. Specifically, the literature search focused upon the engineering, economic, and performance aspects of using recyclable and recoverable materials in highway construction and maintenance projects. The literature review focused on asphalt and cement concrete pavement recycling, discarded tire recycling, reuse of paint removal wastes, fly ash, glass, alternative fuels, and other miscellaneous recycled and recovered materials. Additionally, regulatory and policy matters associated with the use of recyclable and recoverable materials in the transportation area were investigated.
The Kentucky Department of Highways currently permits a maximum of 30 percent (by weight of the total mixture) recycled asphalt pavement (RAP) to be used in bituminous mixtures (20 percent if the RAP is salvaged from other sources). It was recommended the Department permit higher percentages of reclaimed materials to be used, provided the mixtures produced using the RAP meets the required specifications. Kentucky has been reusing portland cement concrete (PCC) pavements for a number of years by breaking and seating the existing PCC pavements and overlaying them with thick layers of asphaltic concrete. The Department also has used recycled concrete aggregate to construct an experimental section of crushed stone base. Other successful uses of recycled PCC aggregates identified in the literature review included use in concrete pavement mixtures and lean concretes. It was recommended the Department continue to monitor the performance of the experimental crushed stone base and to evaluate the use of recycled concrete aggregates in other construction or maintenance applications.

The use of discarded tires in highway construction has increased in recent years. The primary uses of discarded tires in highway construction and maintenance operations were identified as a crumb rubber additive to asphaltic concrete mixtures and as shredded tires for use in lightweight fills and embankments. Perhaps the most successful highway application is the use of tire chips in embankments. Far more tires can be utilized in the construction of a soil-tire embankment than in the construction of an asphalt rubber pavement layer. It was recommended the Department utilize known tire stockpiles should appropriate projects become available within close proximity to the waste tire stockpiles.

Waste glass has been used successfully as a partial replacement of fine aggregate in asphaltic concrete mixtures for low-volume roads, fine aggregate replacement in unbound base courses, mixed with embankment soils, as glass beads in line striping, and as pipe bedding and filter materials in edge drain systems. Waste glass should not be used in portland cement concretes. The availability of crushed glass appears to be limited to the larger metropolitan areas. Others have concluded that glass was generally non-beneficial to the properties of conventional construction materials and the performance of highway pavements. It was recommended the Department utilize waste glass only in those instances where minimal processing of the waste glass occurs, i.e., mixed with embankment soils.

Fly ashes have been used as additives or partial replacements in portland cement concrete for a number of years in Kentucky. Kentucky has also demonstrated that a bottom ash aggregate may be successfully utilized as an aggregate replacement in
asphaltic concrete mixtures. Fly ashes have been used successfully as mineral fillers in asphaltic concrete mixtures, as embankment and fill materials, stabilized aggregate base courses, and as a component in flowable fill applications. Ashes from coal-fired electric generation plants are a good source of highway construction materials and increased usage of the materials was recommended.

Use of virgin polymers to modify the characteristics of the asphalt cement binder in hot-mix asphalt (HMA) mixtures has been an acceptable practice in the highway construction industry. Now recycled plastic, in the form of polyethylene, is being used to produce polymer additives for asphalt cement. However, it will be essential to determine the recyclability of asphaltic concrete pavements containing recycled plastics. Limited studies suggest health hazards with recycled plastics are no different from hazards associated with hot-mixed asphalt. Not only is recycled plastic being used as an asphalt cement modifier, but it is being utilized successfully in many other highway devices. The principal uses of recycled plastics in highway construction is in the production of construction and traffic safety products. Sign substrates, flexible delineator posts, rebar support chairs and bolsters, guardrail offset blocks, geotextiles, traffic cones, barricade bases, and plastic lumber are all being manufactured from recycled plastic polymers and recycled rubber polymers. It may be unrealistic to use some recycled plastic products in certain applications due to impurities that can affect strength properties. It was recommended the Department utilize those products containing recycled plastics that are currently available and meet current standard specifications.

Thousands of bridges across the United States are coated with lead-based paints. Maintenance operations involving removal of the paint along with the abrasive from blasting generate enormous amounts of waste. However, the Department now utilizes a paint overcoating system for bridges. It was recommended the Department continue using the overcoating system and to minimize the volume of toxic paint waste.

The key to competent utilization of recyclable and recoverable materials in highway construction and maintenance operations is to find a common ground between what is good for the state’s highways and what is also good for the state’s environment. State legislators, highway industry officials, highway engineers, and environmentalists must find this common ground to benefit Kentucky’s travelling public.
INTRODUCTION

Finding itself in an environmental whirlwind, the highway construction industry is playing a leading role in America's "Green" movement. Highway agencies across the nation are recycling a diverse number of solid waste materials into asphalt and concrete mixes for use in roads all over the country. Environmentalists appear to have targeted construction and maintenance of America's streets, roads, and highways to ease the congestion of landfills by utilization of waste tires, glass, plastic, incinerator ashes, contaminated soils, and even roofing shingles. The influence comes not only from the environmentalists and legislators, but from inside the industry as well. Highway agencies are making the push to use as many solid wastes in road rehabilitation and new projects as possible for the betterment of both sides. Overall, society stands to reap the rewards of a successful partnership between the highway industry and their peripheral influences.

Recent years have seen as much as 180 million tons of solid waste produced in the United States. Of that figure, waste plastic has accounted for nearly 15 million tons, and discarded tires approximately 3.6 million tons. Around seven million tons of old roofing shingles are discarded each year, along with 12 to 13 million tons of waste glass. Meanwhile, the United States has an immense supply of existing aging asphalt and concrete pavements that are in dire need of repair and replacement.

Accompanying the rehabilitation that is being done each year is nearly 40 million tons of aggregate waste. The recycling of these worn out pavements appears to be the answer to the problem of conserving virgin materials, and preventing pavement waste from being dumped in America's landfills. According to the National Stone Association, only approximately 20 percent of the potentially recyclable pavements available are actually being recycled. It is no secret that aggregate in asphalt is not an unlimited resource and many recyclable materials can be used to take the place of aggregate, which accounts for 94 percent of an asphalt pavement. In deciding the applicability of a material in a potential recycling situation, there are a few basic rules to follow. Cost effectiveness, performance, availability, environmental and health concerns, and political issues will all be determining factors in whether or not a material will be used in highway construction or maintenance applications [1].

Kentucky Department of Highways' officials are committed to increased utilization of recycled and waste materials in highway projects where it appears promising, feasible, and needed. Department personnel have already utilized a significant number of waste materials in projects, including coal fly ash and bottom ash, boiler slag, blast furnace slag, steel slag and reclaimed pavement materials. Reclaimed pavement materials, fly
Ash and blast furnace slag are used on a routine basis throughout the state. Over 40,000 tons of blast-furnace slag are used each year within the state as additives in bituminous surface wearing courses [2]. During 1990, more than 130,000 tons of reclaimed asphaltic concrete paving materials were used throughout the state. During the five year period from 1985 to 1990, an average of 160,000 tons per year of reclaimed asphaltic concrete paving materials were used. The Kentucky Transportation Center is currently monitoring a section for the Department of Highways that contains a crumb rubber modifier. The experimental surface was placed during the summer of 1993. Plans are also underway to develop Special Construction Notes for the proposed construction of a highway fill containing discarded tire chips.

The construction, rehabilitation, and maintenance of the nation’s highways annually requires nearly 350 million tons of both natural and manufactured construction materials. Included in that figure are 20 million tons of asphalt, ten million tons of portland cement, and 320 million tons of natural aggregates, paving mixtures, and synthetic surfacing and coating materials [3]. As noted previously, questionable availability and rising costs of high-quality aggregates has warranted investigating the usage of alternative materials such as recyclable wastes and industrial by-products. The threat of environmental and economic damage adds strength to the recycling argument. Kentucky Department of Highways’ officials have developed and is continuing to develop and implement procedures to include a variety of waste and recycled materials in highway construction and rehabilitation in direct response to the increasing environmental concerns about waste disposal practices.

The Kentucky State Legislature directed the Finance and Administration Cabinet to establish and promulgate regulations for minimum recycled content for goods, supplies, equipment, materials and printing used in state agencies. The result of this action was Kentucky Administrative Regulation 200 KAR 5:330, which took effect January 1, 1992. The regulation covers state agency contracts for construction, repair, renovation and demolition of public facilities, and implements the provisions of Kentucky Revised Statute 45A.520. Every state agency must require, to the extent practicable, that every contractor use goods, supplies, equipment, materials, and printing which meet the requirements for the minimum recycled content indicated in the administrative regulation. Furthermore, every state agency authorized to issue bonds must require, to the extent practicable, that every project within the Commonwealth, fifty percent or more of the cost of which is financed with proceeds of bonds issued by the agency, be undertaken with goods, supplies, equipment, materials, and printing which meet the requirements for the minimum recycled content indicated in the regulation. A detailed
account of this regulation and other laws affecting Kentucky is contained within this report.

**BACKGROUND**

One objective of the Kentucky Transportation Cabinet is to promote the utilization of recovered materials, as well as recycled materials, within the Department of Highways to the fullest extent possible. The Cabinet requested Kentucky Transportation Center investigators to make an assessment of existing efforts within the Department of Highways to utilize recycled and recovered materials and to provide recommendations to Cabinet officials that would indicate where improvements and increased utilization of those materials could be successfully implemented [4]. Continuing with that investigation, Cabinet officials selected the Kentucky Transportation Center to develop an expert system for use by Kentucky Department of Highways' personnel. The expert system would utilize a multi-disciplinary data base that appraises all aspects of waste utilization relative to highway construction and maintenance. Specifically, the expert system will examine the engineering, economic, regulatory and policy matters related to the use of waste materials in transportation. The expert system will be designed so that modular expansion will be possible as new materials and regulations are developed in the future.

The objective of this research study is being accomplished by performing tasks deemed necessary to develop an expert system. A comprehensive literature search has been conducted using the facilities of the University of Kentucky Transportation Center Library. Articles and reports related to the use of recyclable and recoverable materials in highway construction and maintenance activities have been thoroughly reviewed for general and detailed information. However, for input to the expert system, follow-up interviews with the principal engineers may still be required to determine specific engineering and economic data associated with the use of the waste materials and the overall field performance of the materials.

Waste materials that have been used successfully elsewhere in highway construction and maintenance activities, but not in Kentucky, as identified through available literature will be recommended for laboratory and/or field trial evaluations. Any application that would require putting waste materials in a confined condition should be worthy of serious consideration for trial evaluations. Field trials and evaluations are required to document invaluable engineering experience and performance aspects related to the use of
recovered and recyclable waste materials in highway construction and maintenance activities. Laboratory evaluations and/or field trials will not be accomplished under this study but should be investigated and reported under a separate study. Development of preliminary specifications for the use of waste materials in highway construction and maintenance will be accomplished during this study. Specifications developed under this study related to use of the waste materials in highway construction and maintenance activities will be revised, as needed, as results of the long-term performance monitoring become apparent.

The expert system decision model developed under this study will be designed to assist in addressing a large number of multi-disciplinary issues. These issues most likely will include, but not be limited to, environmental impact, legal or legislative mandates, performance, life-cycle cost, and implementation. Data input to the model will include all aspects of waste utilization in highway construction; engineering considerations, economics of their use, and performance aspects of the use of the waste materials as compared with the performance of conventional materials. Regulatory considerations, as well as policy matters, will also be input data for the developed model. Initial input data for development of the model will be obtained from the literature review and conducted interviews. Additional input data for the expert system will be developed through laboratory evaluations and performance of field trials. The decision model will provide an opportunity for transportation officials to pre-examine the impact of various potential legislative actions relative to the mandated use of certain waste materials. The model will enable Kentucky Transportation Cabinet administrators to provide practical waste utilization plans and comply with legislative mandates dealing with waste utilization. This report contains a summary of findings compiled from a review of pertinent literature, a review of legislative mandates regarding use of recycled and recovered materials in Kentucky, and preliminary recommendations for field trials. A subsequent interim report will include a draft version of the expert system decision model. The final report for the study will contain a revised version of the expert system decision model. Further revisions and updates to the system will be necessary as additional information regarding the use of waste materials in highway construction and maintenance activities become available.

LITERATURE REVIEW

A search of the literature was conducted to identify articles and reports regarding recycling in the field of transportation. The primary search was on the computer data
Asphaltic Concrete Pavement

Asphalt pavement recycling did not become practical until the 1970's [5]. Today, 80 percent of the estimated four million miles of streets and highways in the United States contain recycled asphaltic materials [6]. Reclaimed asphalt pavement (RAP) is used to lower street and highway maintenance costs, reduce energy consumption, and conserve landfill space. Recycling saves materials and typically speeds up the rehabilitation so the road is opened to traffic sooner [7].

Vollor has also identified cost, environmental and design incentives for recycling asphalt pavements [8]. The cost of asphalt cement and aggregates that are used in asphalt pavements has risen dramatically in recent years. Transportation costs have also increased. The further new materials must be hauled, the higher the cost. By recycling and reducing the amount of material being carried, the transportation costs can be lowered. Environmental considerations also have an impact on implementing recycling efforts. Proper disposal of old pavement is expensive. More importantly, there is a limited supply of natural resources needed for road construction (oil, good aggregate). The location of these materials is unevenly distributed, meaning the materials often are hauled long distances. Reported design advantages of recycling include the following: reflective cracking is eliminated or retarded; dead loads on bridges can be maintained; clearances through tunnels and under bridges are unaffected; drainage patterns can be maintained; existing grades to adjoining surfaces can be met; only that area of pavement needing repair has to be repaired; and, base courses can be repaired. Other advantages include the strengthening of pavements for increased loads or increased traffic, and improved surface conditions such as skid resistance, smoothness, and weather resistance [8].

A number of processes exist for recycling asphalt and several publications give descriptions of these processes which are briefly described.
**Cold Planing**

Cold planing involves the removal of a certain depth of asphalt pavement with a milling machine. With further treatment, the reclaimed asphalt pavement can be recycled into a smooth pavement that possesses improved performance qualities. There are several advantages to cold planing: immediate use of the planed surface by traffic; minimal interruption in traffic flow; reclaimed material can be saved for future use; and, the procedure can be utilized on small and large projects. The only disadvantage appears to be that only surface distresses are corrected by cold planing [9].

An advancement in cold planing has given the process greater flexibility. Cold planers can now be fitted with a liquid additive system enabling the machine to accomplish base recycling as well as milling. This modified milling machine is a Caterpillar PR-450C cold planer fitted with an optional liquid additive system. The machine is owned by the Galveston County Road and Drainage Department in Galveston, Texas. "The half-lane planer, with a 79-inch wide rotor, can mill up to ten inches deep, and simultaneously inject and blend metered amounts of asphalt emulsion with the milled material" [10]. Galveston County officials say the recycling machine will typically work at depths up to six inches, milling the asphalt pavement layer into the base to produce upgraded base material. The final mix design for their project had 0.8 percent recycled surface, 84.7 percent recycled base, and 4.5 percent emulsion. That worked out to 1.44 gallons of emulsion per square yard, for a total asphalt content in the new base of about four percent.

A major benefit with the dual purpose cold planer is the cost savings. The main saving is a reduction in the cost of materials needed to create the upgraded base. One expert estimated that Galveston County spent about half as much on material as they would have if using the older, conventional way of repairing roads and streets. Not only was there a significant reduction in cost, but there were several options that made the cold planer a multi-faceted machine. Those options included: milling work; recycling the surface layer and base; and, recycling just the surface layer. These options were available with simple removals and installations. Another notable benefit with the cold planer is the speed with which it works. Estimates have the equipment taking only two hours to recycle, grade and compact one city block length.

**Cold In-Place Recycling**

Faced with economic and environmental constraints, inflationary trends in the costs of construction materials, and limited aggregate supplies, both governmental and private
road builders have been forced to look for alternatives to conventional pavement rehabilitation. The most promising and effective alternative appears to be cold-in-place recycling. Cold in-place recycling (CIR) is becoming an economically and environmentally feasible rehabilitation technique that conserves construction materials and energy while producing no waste. Oregon, Indiana, and New Mexico have successfully been using the process since the 1980's. With the millions of miles of roads that run through the United States, the opportunities for a cost-effective means of highway construction involving recycling are seemingly endless [11].

Cold in-place recycling involves milling or pulverizing the existing pavement to a predetermined depth and processing the material to a certain size; screening and crushing, if needed, to satisfy a required gradation; treating the millings with a polymer-modified asphalt emulsion and mixing; and placing the recycled cold mix on the roadway as one continuous procedure using conventional paving and compaction equipment [11, 12]. The advantages to CIR are numerous: significant cost savings through energy and materials conservation; reduced environmental impact; use on pavement that is severely cracked providing it is structurally sound; minimal traffic disruption and moderate limitation to the distressed lane; unlike hot-in-place recycling, it is not limited only to pavements with surface defects; is self-healing and retards reflective cracking; and, the recycled mat is accessible to traffic immediately after compaction and detours are necessary only as the uncured mat proceeds down the highway [11, 13].

The disadvantages of cold in-place recycling have been identified as: limited to warm weather; requires a fog seal, a thin overlay, or surface treatment to resist moisture and abrasion; and, due to the relative newness of CIR, there is an absence of standard mixture and thickness design procedures [11, 13]. In fact, it is this absence of standard mixture and thickness design procedures for CIR pavements that is a consistent factor with most reported projects. Several studies have been undertaken with the sole purpose of developing standard methods. Although most reports still echo the lack of a widely accepted design, there are a number of significant findings. For instance, authors report smooth construction with minimal problems as well as significant cost and energy savings from the use of CIR versus other conventional means of rehabilitation. Nearly as prevalent is the improvement in ride quality, attributable to fewer surface defects. Furthermore, certain studies have shown CIR pavements to exhibit less distress than conventional pavements and the absence of widening cracks over the same periods of time [11, 14]. Where mixture properties are concerned, those of the CIR mix differ only slightly from conventional mixes. In general, CIR pavements have reportedly performed well and are in better condition than the conventional pavements [13, 14].
With some of the immediate successes of CIR, it's easy to forget the relatively short time the process has been in use (early 1980's). Therefore, it's not surprising that several facets of CIR still require additional work: augmentation of the depth of CIR treatment; analysis of long-term distress characteristics of CIR mixes at comparably higher traffic volumes; standardization of the mixture and thickness design procedures; verification of the binder type; and, method and timing of compaction efforts on the CIR mat [11, 13].

**Hot In-Place Recycling**

The purpose of hot in-place recycling of asphalt pavement surfaces is to replace the old existing, cracked, rutted, or worn surface to the same condition as a new hot-mix overlay. The key is to do it in a cost-effective way. Hot in-place recycling can be performed in situ. Asphalt pavements suitable for this process generally have adequate structural condition (no structural flaws past localized sections that can be rehabilitated) without previous treatments (rubberized asphalt, epoxy patching, surface treatment, etc.) that might prevent recycling, unless eliminated first (by milling, for example) [15]. Hot-mix recycling in-place is an economically advantageous alternative where pavements have become worn due to environmental factors. Signs of environmental pavement deterioration include reflection cracking, block cracking, longitudinal or transverse cracking, or where weathering and raveling are apparent [16].

As a consequence of surface rehabilitation equipment and technology advancements in Japan and Europe, the procedure has developed over the last ten years from simple heater scarification to hot, in-place surface recycling. The process has the capability to rejuvenate pavement by placing the new, hot-mix overlay in one pass [15]. The procedure generally revolves around three machines: two preheaters and one reformer. The reformer has an infrared heating device, a hopper for aggregate or hot mix, a scarifier to help break up the pavement surface, a rejuvenator spray bar, and three mixers that blend the rejuvenated mixture ahead of two screeds for spreading. The preheater is a self-propelled, propane-fueled infrared heater capable of producing heat in excess of 25 million BTU per hour [17].

**Hot Mix Recycling**

Hot mix recycling (HMR) is a procedure whereby reclaimed asphalt pavement (RAP) materials, reclaimed aggregate materials, or both, are mixed with virgin asphalt and/or recycling agents, and/or virgin aggregate, as needed, in a central plant to produce hot-mix paving mixes. If done correctly, the final product meets all the required standard
material specifications and construction guidelines for the type of mix being produced [18].

**Hot mix recycling is one of several alternatives for rejuvenating distressed or worn asphalt pavements.** One of the major benefits of HMR is attained by adding asphalt to untreated granular material in the lower layers of the pavement structure, and then placing the material back in the same thickness. This increase in the thickness of the layers that are asphalt bound increases the strength of the pavement structure, thus increasing its load-carrying capacity. By this means, existing composite structural sections can be converted to a high-quality thick lift of full-depth asphalt pavements (a full-depth asphalt pavement is one in which asphalt mixtures are used for all courses above the subgrade or improved subgrade).

Cost effectiveness and the need to conserve natural resources are reasons enough for employing HMR in planning road rehabilitation. But there are several other advantages from the process. In fact, the benefits are numerous. They include: significant structural improvements can be attained with little or no variation in thickness; supplementary right of way is unnecessary and traffic disruptions are minimal; the possibility of detrimental frost action may be reduced; problems of base and surface distortions can be corrected; existing mix defects can be remedied; and, overall problems are minor and few. Problems that may arise include air quality problems at the plant site if inappropriate equipment is used, or if the percentage of RAP specified for the mix is too high. In short, acquiring a quality finished product might require more care than is involved when starting with virgin materials.

Most all hot-mix recycling of RAP is performed by the heat-transfer method. Both batch and drum-mix plants are employed to successfully produce recycled mixes. Only minor modifications are required. The heat-transfer method in batch plants uses intensely heated aggregate (new and/or reclaimed) to raise the temperature of the RAP. The heat-transfer process also takes place in the drum-mix process. Three main methods have been used to complete this procedure. The first depends entirely on indirect heating by exhaust gases. The second method employs convection heating by containing the complete combustion process and by turbulent air mixing action which develops a uniform gas temperature distribution. The third process heats the new or reclaimed aggregate in the front of the drum, introduces the reclaimed asphalt pavement at approximately the center of the drum and heats, by convection and conduction, and mixes through the remainder of the drum. The finished product, either from batch or drum-mix plants, is released into a surge bin or haul trucks. The mix is then placed on the roadway using conventional paving and compaction equipment [18].
Microwave heaters are another means of recycling hot mix asphalt. Since the mid to late 1980's, microwaves have been commercially recycling asphaltic concrete pavement with no visible emissions. A Los Angeles plant has been recycling hot mix asphalt since 1988 - heating and treating 100 percent reclaimed asphalt pavement as hot mix for reuse as base and surfacing on city streets and highways [19]. Cyclean Incorporated, Georgetown, Texas, has devised a system of equipment to recycle old asphalt pavement into HMA to be used in lieu of virgin material. The procedure involves drying and preheating the RAP to an original temperature of about 230° F on a fluidized bed conveyor. A microwave-powered heating tunnel then finishes the heating to the predetermined final temperature before a rejuvenator is mixed in to revive the physical and chemical properties of the original mix.

**Full-Depth Reclamation**

Full-depth reclamation involves turning a roadway into the base material for a new surface. The asphalt used is typically from reconstruction of a deteriorating road. It is blended with the gravel base and liquid calcium chloride. A portion of the underlying material and the existing pavement is pulverized, blended, shaped, and compacted. The process is intended to eliminate underlying defects in a multiple-layer roadway [20, 21].

The implementation of a full-depth reclamation program with calcium chloride appears to be a workable, cost-effective solution to the deterioration of roads [21]. The procedure can reportedly cut costs as much as fifty percent compared to conventional means. It is especially effective when asphaltic roadways are severely degenerating from aging, base problems, and drainage. Typically, roads in this condition have been maintained with only the application of a periodic seal coat or an overlay. Because overlays last only a limited time before cracking begins to reflect through the surface and because of insufficient funding to completely reconstruct roadways, full-depth reclamation is a significant pavement recycling process throughout the country.

**Foamed Bitumen Recycling**

The stabilization of roads with foamed bitumen is a relatively old technique that has been typically applied to fine, poorly graded materials. The process has been used in many parts of the world, but has been especially prevalent in South Africa. However, in the United Kingdom, two new procedures have been introduced. They are FOAMSTAB in-situ recycling, and FOAMSPRAY surface dressing [22].
FOAMSTAB employs the injection of cold water under controlled conditions and with certain additives into hot penetration grade bitumen before application through specially designed nozzles and spray bar. The technique restores the structural integrity of road pavements, can be rapidly executed, conserves available resources, and is very efficient [23]. Reportedly, FOAMSTAB recycling has the ability to produce in-situ, full-depth bituminous pavements of equivalent strength to new hot-mix pavements without the need for removal and replacement of any existing material. In the United Kingdom, roads have been renewed by FOAMSTAB recycling to save up to one-half the cost, two-thirds the time and three-fourths the energy needed for traditional remove and replace rehabilitation methods [22].

The FOAMSPRAY technique applies hot penetration bitumen directly to the road without the need for emulsified bitumens. The FOAMSPRAY technique has been used successfully in surface dressings in the United Kingdom and France with cost and performance benefits [22]. Cold in-place recycling using foamed bitumen has been tested in the United Kingdom. A portion of a road was recycled while the other part had conventional reconstruction. The compacted foamed bitumen possessed a uniform density and exhibited high resistance to deformation in universal creep stiffness tests. The recycled road was strong enough to withstand light traffic immediately after repair and interruptions to traffic were minimal. Additionally, a significant energy savings was realized [24].

Based on a survey reported in Better Roads, most states are using some form of recycling to improve pavement cost effectively [25]. Recycling operations have been in use since the 1970's in Iowa, Illinois, North Dakota, New Jersey, and Nebraska. Quite a few other states started recycling asphalt pavements in the 1980's. The states that issue contracts with an option to use recycled material at a specified percentage include Maine, North Carolina, Maryland, Nevada, Virginia, Indiana, and Ohio. South Carolina at one time had the option but discontinued it because of problems with RAP stockpiles. Several states stipulate that the recycled material that is used must comply with the standard requirements of a virgin mix. These states are Colorado, New Jersey, Idaho, and Oklahoma. The processes used by the states include hot-mix, cold-mix, and milling.

Several states mentioned their satisfaction with recycling. The fact that it continues to be used is also an indication that recycling is worthwhile. Maryland mentioned a problem that was encountered with RAP. Whole sections of pavement were lifting from the surface and moving. This problem was attributed to inconsistent quality of the milled materials in the stockpiles. Research indicated that the problem could be resolved through improved quality control of the milled material. Tampa, Florida officials
determined that single-pass, in-place surface recycling of asphalt pavement saves $5,000 per day [26]. This process has been used since 1984 but is limited to rehabilitation of the top inch of the surface. It is inappropriate where pavement distresses are caused by traffic loads. Wallace reported that Tampa found this method to have great potential for conservation of energy and resources, reductions in traffic delays, material costs, and personnel.

Responding to legislative pressure to use waste materials, some states have incorporated the use of certain waste materials in hot mix asphalt pavements. These waste materials include: industrial wastes such as cellulose wastes, bottom ash, fly ash, and wood lignins; domestic/municipal wastes including waste glass, roofing shingles, incinerator residue, and scrap rubber; and, mining waste in the form of coal mine refuse. Along with the use of these materials comes a list of legitimate concerns: engineering concerns (effect on engineering properties) such as strength and durability, impact on production, and future recyclability; environmental concerns such as handling and processing procedures, leaching, emissions, fumes, and odor; and, economic concerns such as life cycle costs, salvage value, and lack of monetary incentives [27].

Cement Concrete Pavement

Recycling of worn portland cement concrete (PCC) in the United States has intensified in recent years. With environmental and cost-efficiency issues taking the forefront, it has become increasingly important to the highway industry to find potential sources of aggregate that can be reused. Many of the older concrete pavements were not designed to handle the heavier traffic and axle loads of today. Therefore, these roads need some type of rehabilitation in order to make them serviceable again.

Concrete recycling permits the concrete material from the original pavement to be broken, removed from the roadbed, crushed to specific gradation and reused as an aggregate base material or as an aggregate to produce portland cement concrete. Reclaimed concrete also has been used in hot-mix asphalt (HMA) mixtures [28]. Other applications of salvaged PCC include aggregate for bases, surfaces, and chip seals. It can also be used as rip-rap and filter material, and as a supply source for independent commercial operations. Salvaged PCC is even used for shoulder concrete, porous granular fill, and open-graded drainage layers [29].

A variety of machines can be used to break the pavement. They include gravity drop hammers, sonic or resonant vibrators, trailer-mounted diesel hammers, spring-arm
hammers, vibrating-beam breakers and whip hammers [28, 30]. Portland cement concrete pavement breaking, steel removal, hauling, crushing, and sizing can be performed for about $3.50 to $4.50 per square yard of pavement or from about $7.00 up to $9.00 per ton of aggregate produced. Pavement breaking and steel removal prices are in the range of $0.50 to $1.50 per square yard of pavement. Steel removal remains a labor-intensive, low-production operation. Reinforcing steel is commonly removed from the roadbed by a rhino horn, a large curved steel tooth, attached to an excavator or bulldozer [28]. Breaking and crushing operations should be improved such that large quantities of coarse aggregate are produced from PCC. Also needing improvement are field operations in order to reduce the amount of base course contamination [30].

The initial PCC pavement recycling occurred in the mid 1940’s. During World War II, Illinois used crushed pavement as an unstabilized base. After the war, Europe took advantage of building rubble for new concrete construction. In the United States, recycled PCC was not used again until the 1960’s. In 1964, crushed concrete was used as a cement-treated subbase at the Dallas - Fort Worth Airport. Then in 1969, recycled PCC was used as an aggregate for asphaltic concrete pavement on another large-scale job in Texas. California first used recycled PCC in an econcrete, or lean concrete, section in 1975. Iowa became the first state to use crushed PCC in a PCC pavement in 1976. Through the 1980’s, the use of recycled PCC pavements became common in a number of states [29]. Many states routinely use reclaimed concrete in highway projects today. Wisconsin, Illinois, Iowa, Minnesota, Texas, Oklahoma, Florida, California, and Michigan all can claim significant experience with the use of recycled cement concrete pavement [28]. Kentucky is only beginning to use recycled PCC aggregate in roadway construction.

The greatest source of aggregate waste is the highway, but not only is reclaimed concrete collected from roadways, it is gathered from other sources as well. Construction applications such as sidewalks, curbs, gutters, and buildings serve as quality aggregate sources for highway use. And there’s plenty out there. The Strategic Highway Research Program estimates that approximately 40 million tons of scrap aggregate result from the repair and rejuvenation of pavements every year. Additionally, 10 million tons of scrap aggregate comes from private construction every year [28].

As with any developing technology, there were many questions and concerns that had to be addressed with the use of reclaimed concrete material as aggregate. These questions included quality of the reclaimed aggregate, cost effectiveness of the material, economical steel removal techniques, proper proportioning of concrete mixtures using reclaimed course and fine aggregates, and the magnitude of strengths which could be obtained with
the use of reclaimed concrete materials as aggregates [28]. Those questions and others were largely answered in a 1981 report, *Recycling Portland Cement Concrete*, by William A. Yrjanson. Yrjanson implied that through innovation and research on the part of contractors and federal agencies, these and other questions were answered. Studies conducted throughout the 1970's by contractors, state DOT's and federal agencies illustrated that a quality aggregate, suitable for use in road bases, as well as in portland cement concrete and hot-mix asphalt mixtures, could be economically produced using reclaimed concrete aggregate [28].

Many factors can be attributed to the greater use of reclaimed PCC pavements. They include: engineering opportunities, or the simple idea that it makes sense to use the aggregate that's already been broken up instead of hauling it to a landfill; shrinking virgin aggregate supplies; increasing cost of obtaining aggregates; increasing cost of construction waste disposal; and, new technological developments. Other advantages such as a reduction in land disruption and road haul damage near the project make recycling an attractive alternative [29].

Yrjanson cited laboratory studies which determined that the use of recycled aggregate produced strong, durable concrete suitable for PCC pavements in all areas of the United States. Coarse aggregates produced from reclaimed cement concrete pavement had no harmful influences on mixture proportions or workability when used in a cement concrete mixture and compared with control mixtures containing conventional aggregates [28]. The success of recycling PCC into roadways has made the technique an attractive option when looking to rehabilitate our highways.

### Discarded Rubber Tires

The disposal of scrap tires has become an issue of national concern and it is no longer debatable as to whether it is in fact a serious problem or not. The volumes of scrap tires scar and pollute our landscape, and cause environmental and health concerns which every county and state must face. As of 1991, the mountainous piles of tires were growing at a rate of 279 million per year and it is estimated that over two billion waste tires are currently stockpiled across the country representing over four million tons of scrap waste [31].

The solution was once thought to be landfilling, but unlike other solid wastes, a tire will not remain buried in a landfill. Over a period of time, a tire will gradually work its way to the surface. Another alternative, storing tires above ground, does not appear to be the
answer either. In fact, storing waste tires above ground poses at least two major threats. First, piles of scrap tires are a fire hazard, not so much because they are so flammable, but once set afire, the burning rubber is nearly impossible to extinguish. Secondly, because tires cannot be stockpiled without retaining water, they become an intense breeding ground for mosquitoes. The bugs carry a disease called La Cross encephalitis, which the EPA estimates causes current yearly health care costs related to the disease to reach $5.4 million [32].

Because of the many health and environmental dangers posed by the improper stockpiling of waste tires, many governments already have, or are considering laws, mandating the discarding of waste tires and the reduction of existing piles. The tire disposal problem has reached a level of urgency in large part because the industry has failed to develop any effective large-scale means of using this negative value resource. That responsibility has fallen on the government, and they are forcing the highway industry to find a solution to the problem [32]. Federal legislation, in the form of the Intermodal Surface Transportation Efficiency Act of 1991, requires states to use crumb rubber in five percent of their asphalt tonnage placed in 1994. The percentage must rise to ten percent in 1995, 15 percent in 1996 and, ultimately 20 percent in 1997 and succeeding years. If a state fails to meet these benchmarks, the U.S. Department of Transportation will withhold a share of the state’s federal apportionments. The mandate has forced states to act quickly to find the most effective ways possible to incorporate scrap rubber into asphalt mixes [33].

In fact, some agencies feel the mandate is forcing states to act too quickly. The National Asphalt Pavement Association is one of those agencies. A report from NAPA states that "the group is not opposed to the use of asphalt rubber technology per se." What concerns NAPA most is that the industry and the states are being asked, or rather forced, under threat of losing federal funds, to use a product before certain critical issues are resolved. The issues are, of course, health and environmental effects, recyclability, and performance. Furthermore, the high cost of asphaltic concrete which contains crumb rubber means fewer miles of highway will be constructed and NAPA maintains that highway user fees should not be used to subsidize solid waste disposal [34]. NAPA also makes the claim that definitive research results will not be available from the Federal Highway Administration (FHWA) or the Environmental Protection Agency (EPA) before the federal minimum use requirements become effective in 1994. Congress is requiring the federal agencies to report results of the research by July 1993, which NAPA maintains will be only a compilation of existing information [34].
Nonetheless, conventional thought has been that waste tires should either be used as additives to asphalt or for fuel. However, converting the tires to energy appears to be in direct conflict with the interests of Congress to improve national air quality standards [34]. Therefore, the burden to clean up old stockpiles of scrap tires and promote recycling of today’s discarded tires appears to rest with highway agencies. For highway applications, Dr. C.W. Lowell, a Civil Engineering professor at Purdue University, categorizes waste tires into three groups: whole tires or tire sidewalls, shredded tires and crumb rubber [39].

**Use in Asphalt Concrete Mixtures**

The two basic methods for using waste tire rubber in asphalt mixes are the dry process and the wet process. The scrap tire rubber is usually referred to as crumb rubber modifier (CRM) in both the wet and dry processes. Also known as Plusride technology, the dry process employs the use of granulated, cube-shaped CRM to replace a segment of the aggregate in hot-mix asphalt (HMA). The result of the dry or Plusride process is a type of rubber aggregate known as rubber-modified hot-mix asphalt (RMHMA). The dry process is defined by the FHWA as those methods that mix the crumb rubber with the aggregate before the mixture is charged with asphalt binder. The dry process is limited to use solely in HMA mixtures [33].

The wet process is used to produce asphalt rubber. The FWHA defines the wet process as any method that blends the crumb rubber with the asphalt cement prior to incorporating the binder in the project [35]. Therefore, the difference between the dry process and the wet process is that ground CRM is blended with the asphalt cement binder in the wet process rather than used as an aggregate replacement. In addition to its use in HMA, asphalt rubber also can be used in crack sealants and surface treatments [33].

Both the dry and wet processes share many of the same concerns and questions. Overall, it is 50 to 100 percent more expensive to produce and place RMHMA than conventional HMA. Depending on what type of process is used, the Asphalt Institute declares that the cost of rubber asphalt mix is as much as 160 to 200 percent of the cost of conventional HMA [34]. Although that does not take into account the possible life cycle cost benefits that may be realized through the use of RMHMA. At this point, according to many in the asphalt industry, data on performance and durability are not available due largely to the relative short period of time that RMHMA pavements have been in place. Another concern voiced is over the potential recyclability of RMHMA pavements. Fears apparently exist over the possibility of air pollution in the form of blue smoke being
created as reclaimed asphalt pavement (RAP) containing rubber is introduced into the asphalt plant, or reused via the technique of hot in-place recycling [33]. Lastly, there are environmental concerns over stack emissions and potential health problems associated with worker exposure to asphalt fumes.

Suggested potential benefits stemming from the use of RMHMA originating from the dry process include: reduced rutting; improved skid resistance; enhanced elasticity and adhesion; resistance to reflective cracking; and, resistance to ice formation. Similar possible advantages also result from RMHMA derived from the wet process. The characteristics of the asphalt binder can potentially help asphalt pavements to: resist rutting; resist thermal cracking; reduce oxidation and aging; resist reflective cracking; and, reduce stripping [8].

Rubber-modified asphalt concrete contains ground recycled tire rubber particles added to a gap graded aggregate and then mixed with hot asphalt cement [36]. In the United States, this system of paving is referred to as Plusride. It has been found to yield a better form of ice control in wintertime climates due to increased flexibility and protruding rubber particles. Plusride, in cold weather, appears to improve resistance to tensile cracking, decrease tire noise, and improve skid resistance on slippery road conditions. Another additive to asphalt mixtures, Verglimit, also works to prevent the formation of ice on asphalt pavements. However, greater cost and increased susceptibility to moisture damage are two reported weaknesses of this product [36, 37].

The very latest in asphalt-rubber technology indicates that to produce an acceptable asphalt-rubber binder, it is necessary to establish the digestion temperature and proper time for a specific combination of asphalt cement and crumb rubber. Viscosity of the blend is checked at different time intervals during the digestion process. Viscosity of the blend increases with time and then levels off. Achieving a reasonably constant viscosity indicates that the initial reaction is nearly completed and the binder is ready to use. If the asphalt-rubber blend is too viscous, an extender oil is normally added. However, if less than ten percent crumb rubber (by weight of asphalt cement) is used, extender oil is not needed. The asphalt-rubber blend is to be used as soon as possible after the initial reaction. Until used, the asphalt-rubber blend should be recirculated continuously. Sometimes blends have been allowed to cool in storage tanks and reheated prior to use without difficulty. When asphalt-rubber binder is used in hot-mix asphalt, the following temperature ranges have been used: (a) dense-graded HMA mixes 325 to 375°F; and (b) open-graded HMA mixes 275 to 325°F [38].
Use in Lightweight Fills and Embankments

A greater volume of waste tires may be used by constructing lightweight and conventional embankment fills with them. In fact, researchers have shown that the use of an asphalt-rubber overlay for a one-mile long, two-lane pavement would result in the use of about 3,600 tires while approximately five million waste tires can be used to construct a 20-foot high embankment of a one-mile long, two-lane pavement [39]. Lightweight fill material may be any material used to replace a heavier in-situ soil so that the overall load burden on the underlying soil is reduced. Shredded waste tires have been utilized for lightweight fill in the United States and in other countries since the mid 1980’s. Various states have used shredded waste tires as a fill material. These states include Minnesota, Maine, Oregon, Wisconsin, North Carolina, Washington and Vermont. Minnesota has by far the greater experience, constructing over 23 projects utilizing shredded tires. The state of Minnesota has employed a variety of methods to utilize waste tires in lightweight fills. A study conducted for the Minnesota Local Road Research Board (LRRB) concluded that waste tires were an inexpensive lightweight fill material and work well under many conditions. Shredded tires are easily placed using standard construction equipment. Thus far, design parameters for the use of shredded tires for lightweight fill materials are based largely on field trials that have been conducted. However, the waste tires may not be placed below the water table and any potential use of shredded waste tires as a lightweight fill material must be approved by the state’s Pollution Control Agency.

Other Uses of Waste Tires

Other uses for scrap tires include: minimizing highway shoulder erosion problems by providing shoulder reinforcement on highway slopes; use for channel slope protection, backfill for retaining walls, and as barriers to mechanically control blowing sand in low rainfall areas until vegetative windbreaks become established [40]. Using waste tires in these manners has proven to be a good solution to reducing the multitudes of tire stockpiles. The state of California is using scrap tires in all the areas mentioned above and have noted the following in research findings: (a) tires remained stable in low velocity sheet flow drainage; (b) immediate and economical solutions; (c) excellent strands of vegetation grew and effectively stabilized the upper slope; and (d) shoulder reinforcement provides a safer highway by development of a wider traveled way [40]. Wisconsin has also used whole tires to successfully construct noise abatement systems [39]. The Carsonite International Corporation has developed a new process wherein scrap tire waste can be used in combination with fiberglass-reinforced polymer composite tongue-and-groove building planks to create a very aesthetically pleasing, functional, and
long-lasting noise barrier wall [41]. A ten-foot high, one-mile long wall may consume as much as 125 tons of scrap tire rubber. The Carsonite noise barrier is also economically competitive with other noise abatement systems. The Carsonite noise barrier can be constructed for about $15 to $17 per square foot.

To even further accelerate the use of scrap tires, some states are adopting strict legislation and comprehensive reduction plans. One state leading the way in this category is Minnesota. Minnesota’s Waste Tire Act prohibits dumping scrap tires in landfills, provides for extensive reduction of all existing stockpiles, and has created a tire disposal fund to finance start-up costs of new tire recycling facilities. Minnesota’s law also provides for a commission to study further the waste tire problem within the state. The process the state has adopted for tire recycling is unique in that no part of the scrap tire is wasted. The procedure converts an environmental hazard into a material with profound commercial value to the plastics and rubber industry.

**Plastic Wastes**

Among the many reclaimed and solid waste materials, and engineering by-products being tested and considered for use in highway pavements, recycled plastic materials are receiving their share of attention from the transportation industry. The question of what to do with discarded shopping and grocery bags is one deserving of merit. With that in mind, highway agencies are responding. They are recycling these polymer (plastomer) substances in the production of modifiers or additives for asphalt cement binder. In addition, recycled plastic is also being employed in the manufacture of many highway devices such as sign substrates, delineation posts, guardrail offset blocks, and rebar support chairs and bolsters [42, 43]. Inclusion of plastic waste in highway applications keeps the material out of landfills. Furthermore, the products manufactured from recycled plastic may actually perform as well or better than products made from more conventional additives and modifiers.

Use of virgin polymers to modify the characteristics of the asphalt cement binder in hot-mix asphalt (HMA) mixtures has been an acceptable practice in the highway construction industry [42]. Recently however, recycled plastic in the form of polyethylene has been employed in the production of asphalt cement polymer additives. While ethyl vinyl acetate polymer additives and polypropylene plastics are being recycled and used in other applications, the bulk of the research on and production of recycled plastic additives for use in asphalt cement is focused on polyethylene materials [42]. Mixed with paving
grade asphalt cement, recycled polyethylene aids in forming a modified asphalt cement designed to reduce rutting, shoving, and increase durability [1].

Most experts in the asphalt industry feel that many questions must be answered before plastic should be used on a regular basis in asphalt mixtures. Some of those questions and concerns include: (a) performance and durability; (b) cost-effectiveness; (c) availability; (d) recyclability; and, (e) health and environmental concerns. Pavements containing recycled polyethylene modifiers appear to be performing fine, but the oldest pavements of this kind have only been in place for about seven years. Overall, the cost of asphalt cement modified with recycled plastics is generally 18 to 25 percent higher per ton than conventional asphalt mixes. As far as availability is concerned, there appears to be a system in place to supply the need, it's just a matter of qualifying the potential suppliers. The only tests on recyclability involving polyethylene modifiers have been a few laboratory tests. It will be essential to know if the inclusion of plastic in asphalt will allow the pavement to be recycled after the end of its useful life. Studies suggest health hazards with recycled plastics to be no different from hazards associated with HMA [42].

Questions and concerns aside for the moment, there appear to be many purported prospective benefits of using recycled polyethylene to modify asphalt binders. They include: reduced permanent deformation in the form of rutting and shoving; reduced fatigue and low temperature cracking; increased load-bearing capacity of the pavement at low temperatures; increased pavement resiliency and durability; reduced stripping and raveling due to enhanced binder cohesion to the aggregate; reduced binder oxidation and aging of the pavement; extended pavement life; and, reduced maintenance [42].

Besides use in asphalt cement binders, there are other ways in which highway agencies are using recycled plastics. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) calls for studies to determine the feasibility of using recycled plastic, and other recycled materials, in highway devices, appurtenances and highway projects. In addition, if found feasible, recycled plastic may be substituted for up to five percent of the recycled rubber that is mandated for use in asphalt pavements as a percentage of the total tons of asphalt laid in a state on federally funded projects. This means it is possible that the entire five percent of the recycled rubber mandated in the bill to be used in 1994 could be replaced by recycled plastic. In turn, half of the ten percent of the recycled rubber mandated for use in 1995 could be substituted with recycled plastic [42].

In order to clearly understand the solid waste situation, the overall environmental picture must be put in proper perspective. The hard numbers tell us that waste plastic
accounts for approximately 17 million tons of the 190 million tons (1990 figures) of the country's solid waste whereas scrap rubber only accounts for about four million tons. The most likely reason for the heavy concentration on recycling tires is that stockpiles are stacked by themselves and are much more visible than waste plastic grouped with other solid waste in landfills. In addition, the media coverage given recent tire pile fires has fueled the interest in recycling rubber. One estimate from the industry tells us that if five percent of recycled plastic was incorporated in all asphalt mixtures in the United States, between 2.3 billion and 2.5 billion pounds of recycled plastic could be reused each year [42].

Not only is recycled plastic being used as an asphalt cement modifier, but it is being utilized in many other highway devices. Sign substrates, flexible delineator posts, rebar support chairs and bolsters, guardrail offset blocks, traffic cones, barricade bases, and plastic lumber are all being manufactured from recycled plastic polymers and recycled rubber polymers [42, 43]. To date, many companies have found that recycled plastic has not tested well enough or consistent enough in crash simulations to be trusted on the road. For this reason, many companies are dropping the idea of using recycled plastic in crash barriers. However, some manufacturers are using virgin plastics in their highway devices and making them highly recyclable in order to keep them out of landfills. Several companies have initiated programs of buying back their devices for the purpose of recycling them.

Glass Wastes

Staying true to the glitz and glamour that Hollywood has become synonymous with, the city of Los Angeles resurfaced a 1.2-mile strip of Hollywood Boulevard with "glasphalt". The mix was chosen specifically for its aesthetic, sparkling qualities when illuminated at night [44]. There is no debate as to the aesthetic value of glass in asphalt. However, there is much discussion over whether the material has sufficiently sound engineering characteristics to accompany its obvious beauty. Currently, research provides no support for this notion. But according to indications from testing, if glass is tested carefully and used in the proper proportion, it can provide qualities structurally similar to those of conventional aggregate. Glass is of course made of sand, a common aggregate or filler used in hot-mix asphalt mixtures [44]. It would seem logical then to use glass as an aggregate or sand substitute in HMA mixes.

Not only does the composition of glass make it a seemingly logical additive or modifier in asphalt, but the need to clean up the country's landfills by recycling gives the
"glasphalt" concept an added gleam. In areas where there was an excess of waste glass, experimentation fueled efforts to find ways to use the material. Accessibility has become more convenient as many communities are sponsoring curbside recycling programs to ease the stockpile of waste glass and other materials. A problem with the recycling of glass is the number of colors in which it is manufactured: clear, green, and amber. Of these colors, clear glass is the only one with profitability in the recycling market. Currently, there are no uses for the green or amber colored glass, and therefore colored glass becomes a hindrance to the collector. In addition to the problem of color, quality is a factor in whether a recycler will accept the glass. The glass must be clean and consistent, and meet the required specifications. If not, the glass must then be hauled to a landfill where the collector must pay a tipping fee. Everything included, disposal costs typically run from $20 to $50 per ton. With this in mind, a Virginia Department of Transportation (VADOT) study suggests the main cost benefit of using glass in HMA is avoidance of the tipping cost [45].

Realizing the high cost of disposal, governmental highway agencies in New York and Los Angeles are arranging to receive glass at no charge to the hauler. Thus, the hauler often saves transportation and disposal costs. The agency must then face the task of having the glass crushed or crush it themselves. It must be crushed to required specifications which typically costs around $3.00 per ton. Some larger cities like Los Angeles and New York have their own in-house processors. However, most cities and states do not have this type of system to receive the glass at no cost to the hauler or crush it, and therefore must endure both costs. The expense can become great, especially if the agency is without close access to waste glass at a recycling plant. The city of Baltimore estimates the cost to place HMA containing glass waste to be $5.00 to $10.00 more per ton than conventional asphalt pavements. The taxpayer will ultimately absorb the extra cost of using glass in HMA mixtures. Currently, the added expense has made widespread use of glass in HMA impractical. The city of Baltimore has discontinued use of HMA mixtures containing glass. Only where aggregate costs are higher per ton than glass does it make financial sense to use glass in asphalt mixtures. When collectors can avoid the expense of hauling and landfill tipping fees, the use of glass in asphalt mixtures becomes more economically feasible [44].

Besides cost effectiveness and availability, other factors such as recyclability, health, mix design specifications, and perhaps most important, performance, play a role in the feasibility of HMA mixtures containing glass. Durability and length of service appear to be the overriding concerns in evaluating performance. Apparently, very few records have been kept regarding past roads paved with asphalt mixtures containing waste glass. This is changing, but it will still be some time before large amounts of data are available
because most pavements have only been in place for a short time. One city that can produce data is New York. Their first few "glasphalt" projects experienced frequent stripping problems because of the use of high percentages of glass and large gradations. The loss of large chunks of glass material could be seen in the gutters. But the city made the proper refinements in the mix and now effectively produces 43,000 tons of the mixture each year. Many of the first projects involving glass in asphalt used high percentages of glass by weight of the mix (15 to 25 percent in the cases of New York and Baltimore) and with large glass gradations of 1/2 to 3/4-inch maximum size [44]. These large gradations coupled with high percentages of glass in asphalt appear to be associated with stripping problems -- the biggest engineering problem with the use of glass in asphalt pavements. Without the ability to absorb any of the asphalt cement binder, glass is difficult to work with in large pieces and percentages. Glass is also hydrophilic, which means it is susceptible to moisture intrusion. The two problems combine to make water damage a major area of concern with asphalt mixtures containing waste glass. But to combat the problem, most highway agencies are using smaller percentages of glass by weight (five to ten percent) and smaller gradations of glass (3/8-inch maximum size) [44].

Stripping, skid resistance, degradation, rutting, and flat tires are all concerns that pertain to performance. Stripping tends to be less of a problem than it has been in the past because most cities are using smaller percentages of glass, usually five to ten percent and smaller glass gradations in the mix. Although results were on the lower end of the scale, the "glasphalt" pavements passed skid resistance tests in New York. For this reason, New York City confines the "glasphalt" projects to heavily congested downtown areas where traffic is slower [44]. The conventional thought is that asphalt mixtures containing waste glass are better suited for base course layers than in surface courses. The VADOT study did not recommend the use of "glasphalt" in either dense-graded or open-graded surface courses [45]. Degradation results when broken pieces of glass are used in larger gradation sizes. Rutting is a normal occurrence in asphalts containing glass but when used in small quantities, glass appears to perform much like conventional aggregate (aside from the skid resistance factor).

With very little known about the recyclability of asphalt mixtures that contain glass, there is concern that a greater waste disposal problem may be created if asphalt mixtures containing glass cannot be reused in new asphalt pavements. Even though glass tends to act like sand when used in small amounts, studies still must be conducted to confirm how asphalt mixtures containing glass will recycle. There also are health concerns with glass because like sand, it is a silica, and is hazardous to human health.
Precautions should be taken to avoid exposing workers to large amounts of glass over long periods of time [44].

A study conducted by the Connecticut Department of Highways to determine the feasibility of using glass waste in portland cement concrete mixtures indicated that glass was not a suitable alternative to the use of conventional aggregates [46]. The conclusions were based largely on research conducted and reported by Johnston [47]. Johnston determined that glass was highly susceptible to alkali-aggregate reactions which caused expansion of the glass and weakening of the concrete. Johnston also observed that the elongated pieces, typical of recycled glass, hampered the workability of concrete mixtures.

Other uses of waste glass have been considered by several states [2, 48]. Some states permit the use of waste glass in unbound aggregate base layers, gravel backfill, pipe bedding, french drain construction, and embankment construction. The Washington State Department of Transportation prepared a general special provision which accommodates the use of waste glass in an aggregate-glass blend provided the blend conforms to standard aggregate specifications [48]. Halstead, who reviewed literature concerning waste glass usage in highway construction, concluded that the optimum use of waste glass was in the construction of embankments and fills [49].

**Paint Wastes**

Thousands of bridges all across the United States are coated with lead-based paint. Maintenance operations that involve removal of the paint along with the abrasive from blasting creates an enormous amount of waste. The Environmental Protection Agency (EPA) requires that paint removal wastes be treated before being disposed. A problem now exists with rising costs of disposal and slow, infrequent maintenance, and the type of procedure used appears to have little bearing on these factors [50].

There are three general strategies for dealing with lead paint removal: (a) stabilization and disposal; (b) incineration; and (c) material reuse. To recycle paint removal waste, the waste may be unseparated or it may be minimized. Unseparated wastes consists of the abrasives, paint chips, corrosion and by-products, and dust, which could possibly be used in construction materials such as asphalt or brick. Procedures for minimization of waste include use of recycling abrasives, cryogenic blasting materials, hand or power tool cleaning, ultra high pressure water jetting, and waste separation.
Due to problems in disposal of blasting abrasive wastes from bridge maintenance operations, the Pennsylvania Department of Transportation (PennDOT) began a study in 1989 to identify and evaluate possible beneficial reuses of such wastes [51]. The identified beneficial uses had to meet state and federal environmental regulations. One study determined that recycling blasting abrasive was feasible, but it should be considered a supplementary rather than a primary operation. Whatever the application, the material being recycled required some upgrading before being usable.

The beneficial reuse options considered in the PennDOT study examined reuse of spent blasting abrasives in Portland cement concrete, asphalt concrete mixes, cement kiln feeds, blasting abrasive reuse, polishing abrasives, airport anti-skid material, lead smelter feeds, structural clay products, and glass/fiber felt production. The process that met all the criteria and exhibited the most promise for Pennsylvania was the use of abrasive wastes as a feed material replacement for structural clay products (bricks). Some of the improvements or advantages included improved performance and strength, similar appearance to bricks, less energy needed for firing the bricks, and the hazardous lead compounds were chemically altered and stabilized. The PennDOT study did not recommend the use of blasting waste in asphalt concrete pavement although the mixture had acceptable strength and lead leaching characteristics [52].

### Ash Related By-Product Materials

Dating all the way back to the days of the Roman Empire, fly ash has been used extensively in highway applications. The Romans used volcanic ash in their concrete mixes to keep paving stones in place on the Appian Way. Volcanic ashes were also used during construction of the Roman Coliseum. As far back as 1914, U.S. News magazine reports cited research results that recognized the beneficial effects that could be gained by adding fly ash to Portland cement concrete (PCC). According to industry sources, fly ash has been used in large PCC construction projects, such as dams, since the late 1930’s and 1940’s [53].

Fittingly enough, the federal government made fly ash the first reclaimed solid waste material, or engineered by-product, to be actively promoted for use in highway-related applications in the United States [53]. The Resource Conservation and Recovery Act (RCRA) coupled with an endorsement from the Environmental Protection Agency enabled coal fly ash to gain official recognition and added acceptance in the highway industry [53]. With the approval of the federal government, fly ash has become a vital, widely accepted product as well as a viable engineering substance useful in cement and concrete.
highway applications. Fly ash has become such a part of the industry that PCC companies have started to join the market. In some cases, companies will buy up the fly ash distributors and drive the price up to meet the cost of portland cement.

So what makes fly ash such a viable additive in concrete and asphalt mixes? The answer -- fly ash is a pozzolan. Fly ash interacts with lime in the presence of water (hydration) producing a cementitious material. The material produced features excellent structural properties. Fly ash is produced from coal fired electric generating plants. Fly ash is the finely divided residue resulting from the combustion of ground or powdered coal which is transported from the firebox through the boiler by flue gases. The coal is pulverized and blown through a burning chamber where it instantly ignites and heats boiler tubes. The resulting material either becomes bottom ash, wet bottom boiler slag, or fly ash. The bottom ash and slag particles fuse together to form a heavier ash which collects at the bottom of the boiler. The lighter fly ash particles are suspended in the flue gases and collected by a bag house, which acts like a giant vacuum cleaner, or an electrostatic precipitator, or other method before exiting the stack [53].

Of the 85 million tons of coal ash (fly ash, bottom ash, boiler slag, and flue gas desulfurization) produced in 1990 in the United States, fly ash constituted about 50 million of those tons. The highway industry uses approximately 20 to 30 percent of the fly ash available for use. Transportation applications include PCC pavements (fly ash concrete [FAC]), stabilized road bases, structural fills and embankments, subgrade stabilization, pavement undersealing, roller compacted concrete, mineral filler in asphalt mixes and flowable mortar backfill [53]. Bottom ash aggregates from a coal-powered electric generation unit were successfully substituted for a portion of the coarse limestone aggregate in a bituminous surface mixture placed on Kentucky Route 3 in Lawrence County [54]. Overall performance and skid resistance properties of the experimental section were excellent.

Depending on the conditions of a project, there can be many advantages to using fly ash. However, not all of the advantages can be realized in every case, and there are some special concerns with the use of fly ash that need to be addressed. The use of fly ash in highway operations can result in the following benefits: (a) reduced concrete cost because fly ash generally costs less than cement; (b) increased ultimate strength of concrete; (c) greater workability of the mix due to the spherical shape and small size of fly ash particles; (d) less water is allowed in the process; (e) heat problems are minimized in mass concrete pavements because fly ash reaction generates heat more slowly than portland cement; (f) resistance to alkali aggregate and sulfate attack; and, (g) reduction of permeability by the formation of cementitious compounds which block bleed channels.
Areas of concern when using fly ash in PCC have been air entertainment problems, low early strength of the mixtures, and seasonal limitations [53].

The current push concerning fly ash in the highway industry is to increase the percentage used. Although states typically allow fly ash levels of 15 to 25 percent for substitution of portland cement in concrete mixes, the fly ash industry is working to increase these amounts used in highway projects [53]. Fly ash is also being used with more frequency in flowable fill applications, and other pavement applications such as embankments and stabilized aggregate bases. Kentucky Special Provision 70D(91) outlines the requirements for stabilized aggregate bases.

Ash from the incineration of municipal solid waste (MSW), a potential threat in metropolitan cities, has been used in various highway recycling applications, but there has been little uniform utilization of the ash due to its high variability. Applications have included use in road embankments and subgrades, lime-stabilized road bases, bituminous paving aggregate, and fused residue aggregate [55]. Incinerator ash also contains significant levels of heavy metals. However, test results have shown that concretes made with the ash are below established toxicity threshold limits [56]. Sewage sludge and scrubber sludges, along with slag from steel mills is also finding its way into our roads. Sludges are being used as structural fill materials [55]. Steel mill slag is frequently used as an alternate aggregate source for skid resistant surfaces [28].

**Other Discarded or By-Product Materials and Their Applications**

In addition to the widely used and accepted reclaimed materials and their applications, there are several less publicized materials that are making an impact on recycling in the highway industry. Roofing shingles, contaminated soils, antifreeze, wood chips, beets, and incinerator ashes are presented herein with respect to their effectiveness in highway recycling projects.

**Roofing Wastes**

Most experts in the industry feel the prospect of using roofing material as an additive or modifier in pavements holds great promise. Roofing shingles are believed to work well in asphaltic concrete pavements largely because asphalt roofing products, like shingles, consist of much of the same material that is used in cold mixes and HMA. Because of the relatively high content (19 to 30 percent) of asphalt in roofing shingles, less virgin asphalt cement is needed in the production of cold mix and HMA [57]. However,
presently there is only one commercially available reclaimed asphalt roofing waste material HMA additive on the market. ReClaim's ReActs HMA holds that distinction. But there are other additives on the way [57].

Purported potential benefits of using roofing waste in cold mixes include: (a) extended placements and solid performance, (b) cost effectiveness, (c) extended shelf life, and, (d) easy application. Asphalt roofing wastes in HMA pavements have the potential to help the mix: (a) resist rutting and shoving, (b) resist reflective cracking, and, (c) resist aging. Besides the usual environmental concerns, many key questions have been answered concerning roofing waste in pavements. All that remains now is the true test of time. Pavements containing the mix have not been in place long enough to accurately assess their long-term performance and durability [57]. Currently, only two states have used roofing shingle waste in their pavements [39].

**Petroleum Contaminated Soils**

Throughout the United States, contaminated soils and what to do with them are problems. At present, millions of tons of junk soil are stockpiled while government officials figure out what to do with them. According to the American Reclamation Corporation (AMREC), the answer is recycling. Specifically, AMREC is concentrating on oily soil contaminated with petroleum products and has developed a proprietary process for production of an asphaltic concrete containing oil-contaminated soil. The key point with the recycling of oily soil is that a waste material which is a potential environmental hazard can be turned into a valuable resource for the production of a useful product [58]. Chemically, the properties in petroleum products are similar to those in asphalt. One of the by-products from the petroleum refining process is asphalt. The oil-contaminated soil provides sand and gravel which replaces virgin sand and gravel as aggregate, and it provides a petroleum product which mixes readily with the asphalt [58]. While the environmental benefits appear obvious, AMREC officials also claim that the process is cost-effective and no more complex than arranging proper landfiling. In addition, they claim performance to date has been successful [58].

A new and exciting way of treating contaminated soils is through bioremediation. Bioremediation is the use of natural or engineered microbes to degrade wastes. Bioremediation is a slow cleanup process, but appears to be gaining favor among federal and state agencies [59]. Just recently, government officials endorsed the development of this technology. However, some in the bioremediation industry fear that a worsening economy could hurt interest within the private industry. Despite the economic concerns,
the EPA stands by the technology as the way of the future. The EPA appears committed to this innovative environmental clean up technology [59].

**Antifreeze**

The rising cost of antifreeze, its availability status, and danger to the environment have prompted research in the area of recycling the substance. One example is Philadelphia Electric's fleet shop. They have begun recycling coolant for a material cost of about 40 cents per gallon. The company responsible for the recycling system is FPPF Chemical Company of Buffalo, New York. They have developed a rejuvenated, modified 50/50 blend of antifreeze and water. In fact, FPPF has been marketing their Glyclean system since 1988 [60].

**Wood Chips and Wood Lignins**

High volume waste from the manufacture of paper, wood lignin has been the object of an effort to convert the by-product into a highway binder material to be used separately as a substitute for asphalt cement or as an extender for asphalt cement in HMA mixes. Recent studies have indicated that HMA mixes containing lignin-asphalt binders can be designed to match the structural strength of HMA mixtures containing conventional materials [61].

Wood chips are most commonly used as lightweight fill in low volume road construction. Most experts agree that wood chips are an excellent fill material. However, with little exception, they must be maintained in a saturated state to avoid biodegradation [61].

**Alternative Fuels**

In an effort to reduce emissions from the two traditional fuels -- gasoline and diesel -- the United States has begun experimenting with alternative fuels. The threat of automotive air pollution from vehicle exhaust prompted legislation aimed at cleaning up the air. The Clean Air Act of 1990 mandates several programs involving fuel modifications. They are the reformulated gasoline program, the California pilot and clean-fueled fleet programs, transit buses, particulate matter in emissions, and renewable fuels [62]. Currently, the leading alternative fuels are methanol, ethanol, compressed natural gas, liquefied petroleum gas, reformulated gasoline, and reformulated diesel fuel [63].
Alternative fuels and their use in fuel cells and internal combustion engines is detailed in a report by an Austrian university. Alternative fuels are meant to be economic replacements for the present regular fuels for fuel cells and internal combustion engines, namely hydrogen as pure gas and gasoline as a liquid, represented by isoctane. Technically, hydrogen may be available as compressed gas in cylinders or as liquid in cryogenic containers, also as impure gas produced in steam-reformer or cracking units. Ammonia (transportable in liquid form in low pressure tanks) is an alternative fuel, suitable for fuel cells after catalytic cracking and directly usable in internal combustion engines. In 1981 the chemical industry within the United States produced 38.1 billion pounds of ammonia (via hydrogen from natural gas), 8.4 billion pounds of methanol and 1.1 billion pounds of ethanol. These two alcohols are therefore also clearly available as fuel alternatives [64].

Other examples of efforts to utilize alternative fuels include one city’s attempt at fuel savings by converting part of their vehicle fleet to run on either compressed natural gas (CHG) or liquid petroleum gas (LPG) fuels [65]. On a much larger scale, General Motors has initiated an alternative power plant development program. It involves use of an electric vehicle, the gas turbine, and the stratified charge engine [66]. In 1991, the electric utility and auto industry joined forces and began production on the Electric G-Van, a modern, American-made electric van. They have since followed up with the TEVan, an electric minivan. Industry officials predict the G-Van to be just one in a long line of vehicles that will compete in an ever-growing market of alternative fuel vehicles [67].

Despite sentiment within the electric and automotive industries that developing alternative fuels is the answer to cleaning up air pollution, the oil industry is of a different opinion. The oil industry believes cleaner gasoline is the answer to all the problems caused by the gasoline-powered cars of today. The oil industry emphasizes that the elimination of lead from gasoline during the 1980’s illustrates that clean gasolines can be developed and at lesser costs than developing vehicles that utilize alternative fuels [68].

**LEGISLATIVE MANDATES**

The Kentucky State Legislature empowered the Finance and Administration Cabinet to mandate regulations for the minimum recycled material content for goods, supplies, equipment, and materials used by state agencies. The result was Kentucky
Administrative Regulation 200 KAR 5:330. This regulation covers state agency contracts for repair, construction, renovation, and demolition of public facilities. In addition, 200 KAR 5:330 mandates the implementation of Kentucky Revised Statute KRS 45A.520 which states that every state agency must require, to the extent practicable, that every contractor use goods, supplies, equipment, and materials, which meet the requirements for minimum recycled content indicated in the regulation. Furthermore, every state agency authorized to issue bonds must require, to the extent practicable, that every project within the Commonwealth of Kentucky, fifty percent or more of the cost of which is financed with proceeds of bonds issued by the agency, be undertaken with goods, supplies, equipment, and materials, which meet the requirements for the minimum recycled content in the regulation. Kentucky Revised Statute KRS 45A.520 defines the following materials as such:

**Post Consumer Waste** - those materials which have been diverted, separated, or removed from the solid waste stream after a solid waste practice.

**Recovered Fly Ash** - the component of coal which results from the combustion of coal, and is typically the finely divided mineral residue which is usually collected from boiler stack gases by electrostatic precipitator or mechanical collection devices.

**Rerefined Oils** - oils from which the physical and chemical contaminants acquired through previous use have been removed through a refining process.

The materials most often used in highway construction and maintenance and required to contain postconsumer waste or recovered materials are as follows:

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<tr>
<th>Five percent</th>
<th>Ten percent</th>
<th>Twelve percent</th>
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<tr>
<td>Cement</td>
<td>Gabions</td>
<td>Aluminum bars</td>
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<tr>
<td>Concrete cribbing</td>
<td>Metal bridge planks</td>
<td>Aluminum bolts and nuts</td>
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<tr>
<td>Ready-mix concrete</td>
<td>Metal pipe</td>
<td>Aluminum channels</td>
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<td></td>
<td>Boiler slag</td>
<td>Aluminum handrail post</td>
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<td></td>
<td>Sign brackets</td>
<td>Aluminum sign blanks</td>
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<tr>
<td></td>
<td>Steel cribbing</td>
<td>Aluminum sign panels</td>
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<td></td>
<td>Steel piling</td>
<td>Aluminum pipe</td>
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<td></td>
<td>Steel post, sign, and delineator</td>
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<tr>
<td>20 percent</td>
<td>Steel, open-grid flooring</td>
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<tr>
<td>Guardrail</td>
<td>Hot-mix asphalt</td>
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<td>Guardrail post</td>
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<td>Guardrail components</td>
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<td>25 percent</td>
<td>50 percent</td>
<td>100 percent</td>
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<tr>
<td>Engine lubricating oils</td>
<td>Glass beads</td>
<td>Plastic sign blanks</td>
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<tr>
<td>Hydraulic fluid</td>
<td>Reflective powder</td>
<td>Railroad rails</td>
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<td>Gear oils</td>
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The remaining pertinent piece of legislation that directly affects the state of Kentucky is the state’s Solid Waste law. Senate Bill No. 2 as enacted by the Kentucky General Assembly in 1991 mandates reductions in the solid waste stream. Specifically, the law requires that each county in the state reduce its solid waste stream by 25 percent by the year 1996. At the national level, there are many pieces of legislation affecting the management of solid wastes that are currently reaching maturity. These mandates will typically affect each of the discarded materials discussed herein.

**SUMMARY, CONCLUSIONS AND RECOMMENDATIONS**

From using bioremediation to neutralize contaminated soil all the way to using roofing shingles in asphalt pavements, there are many recycling options that have the potential to impact roads in Kentucky. The discarded or by-product materials identified in this report that can be reclaimed or recycled for use in many highway projects include asphaltic and portland cement concrete pavements, scrap tires, glass, coal ashes, slags, plastic waste, paint waste, and wood chips/lignins. Existing, aging asphalt and concrete pavements are in need of repair and replacement all over Kentucky. Recycling these pavements by procedures such as cold planing, cold in-place recycling, hot in-place recycling, and hot mix recycling is a way of conserving virgin aggregates, and simultaneously keeping discarded pavement materials out of the area landfills.

The Kentucky Department of Highways currently permits a maximum of 30 percent (by weight of the total mixture) recycled asphalt pavement (RAP) to be used in bituminous mixtures (20 percent if the RAP is salvaged from other sources). It is recommended that the Department permit higher percentages of reclaimed materials to be used, provided the mixtures produced using the RAP meet the required specifications. Typically, conventional hot-mix plants can produce hot mix asphalt mixtures containing up to about 50 percent RAP. Currently, there are only three processes that can successfully incorporate about 80 percent RAP into bituminous mixtures. These processes are cold in-place recycling, hot in-place recycling, and hot mix recycling. Cold in-place recycling involves milling or pulverizing the existing pavement to a predetermined depth, usually about two inches, and processing the material to a certain size; screening and crushing, if needed, to satisfy a required gradation; treating the millings with a polymer-modified asphalt emulsion and mixing; and placing the recycled cold mix on the roadway as one continuous procedure using conventional paving and compaction equipment. Pavements that exhibit excessive distress are not recommended for this process.
Hot in-place recycling of asphalt pavement is typically limited to two inches also. Hot in-place recycling is used to replace the old existing, cracked, rutted, or worn surface to the same condition as a new hot-mix overlay. Asphalt pavements suitable for this process generally have adequate structural condition (no structural flaws past localized sections that can be rehabilitated) and no previous treatments (rubberized asphalt, epoxy patching, surface treatment, etc.) that might prevent recycling, unless they are eliminated first (by milling, for example). Hot-mix recycling in-place is an economically advantageous alternative where pavements have become worn due to environmental factors. Signs of environmental pavement deterioration often include reflection cracking, block cracking, longitudinal or transverse cracking, or where weathering and raveling are apparent.

A number of states are currently recycling portland cement concrete (PCC) pavements. Kentucky has been reusing PCC pavements for a number of years by breaking and seating the existing PCC pavements and overlaying them with thick layers of asphaltic concrete. The Department also has used recycled concrete aggregate to construct an experimental section of crushed stone base. Other successful uses of recycled PCC aggregates identified in the literature review included use in concrete pavement mixtures and lean concretes. It was recommended the Department continue to monitor the performance of the experimental crushed stone base and to evaluate the use of recycled concrete aggregates in other construction or maintenance applications.

The use of discarded tires in highway construction has increased in recent years. The primary uses of discarded tires in highway construction and maintenance operations, identified through the literature review, included use as a crumb rubber additive to asphaltic concrete mixtures and as shredded tires for use in lightweight fills and embankments. Perhaps the most successful highway application is the use of tire chips in embankments. Far more tires can be utilized in the construction of a soil-tire embankment than in the construction of an asphalt rubber pavement layer. It would seem that engineered applications involving large volumes of discarded tires will be the key to eliminating the numerous waste tire piles that have accumulated across Kentucky. The first step in the utilization process will be identifying these stockpiles and implementing innovative construction techniques that are practical and cost effective. The Division of Waste Management of the Kentucky Department of Natural Resources and Environmental Protection Cabinet has identified tire stockpiles in Kentucky. The largest such stockpile, containing over 2,000,000 tires, is located in Campbell County. It is recommended that the Kentucky Department of Highways utilize this tire stockpile should an appropriate project become available. Other innovative uses of waste tires also
were identified such as use in noise barriers and as backfill materials for retaining walls.

Waste glass has been used successfully as a partial replacement of fine aggregate in asphaltic concrete mixtures for low-volume roads, fine aggregate replacement in unbound base courses, mixed with embankment soils, as glass beads in line striping, and as pipe bedding and filter materials in edge drain systems. Waste glass should not be used in portland cement concretes. The availability of crushed glass appears to be limited to the larger metropolitan areas. Typically, if the haul distance for the glass exceeds thirty miles and the cost of crushing and processing the glass exceeds $3.00 per ton, then the costs associated with its use will be prohibitive. Bloomquist, et al, concluded that glass was generally non-beneficial to the properties of conventional construction materials and the performance of highway pavements [69]. It is recommended that the Department consider utilizing waste glass only in those instances that require minimal processing of the waste glass, i.e., mixed with embankment soils.

Fly ashes have been used as additives or partial replacements in portland cement concrete for a number of years in Kentucky. Kentucky has also demonstrated that a bottom ash aggregate may be successfully utilized as an aggregate replacement in asphaltic concrete mixtures. Fly ashes have been used successfully as mineral fillers in asphaltic concrete mixtures, as embankment and fill materials, stabilized aggregate base courses, and as a component in flowable fill applications. Ashes from coal-fired electric generation plants are a good source of highway construction materials and increased usage in highway construction and maintenance is recommended.

Use of virgin polymers to modify the characteristics of the asphalt cement binder in hot-mix asphalt (HMA) mixtures has been an acceptable practice in the highway construction industry. Now recycled plastic, in the form of polyethylene, is being used to produce polymer additives for asphalt cement. However, it will be essential to determine the recyclability of asphaltic concrete pavements containing recycled plastics. Limited studies suggest health hazards with recycled plastics are no different from hazards associated with hot-mixed asphalt. Not only is recycled plastic being used as an asphalt cement modifier, but it is being utilized successfully in many other highway devices. The literature review suggests that the principal uses of plastics in highway construction is in the production of construction and traffic safety products. Sign substrates, flexible delineator posts, rebar support chairs and bolsters, guardrail offset blocks, geotextiles, traffic cones, barricade bases, and plastic lumber are all being manufactured from recycled plastic polymers and recycled rubber polymers. It may be unrealistic to use some recycled plastic products in certain applications due to impurities that can affect strength properties. It is recommended that the Department of Highways utilize those
products containing recycled plastics that are currently available and meet standard specifications. Because of the increased cost associated with recycled plastic products, analyses should be conducted to assess the life-cycle costs of these products. Substantial increases in the economic lives of these products must be realized if they are to be feasible for use in highway construction and maintenance applications.

Thousands of bridges across the United States are coated with lead-based paints. Maintenance operations involving removal of the paint along with the abrasive from blasting create an enormous amount of waste. For this, and other reasons, the Kentucky Department of Highways now utilizes a paint overcoating system for bridges.

The solution for waste utilization in highway construction and maintenance operations is to find a common ground between what is good for the state's highways and what is good for the environment. If legislators, industry officials, and environmentalists can do this, it can only benefit all of society -- especially Kentucky's highways.
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