Life Cycle Benefits of Recycled Material in State DOT Road Construction

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EXECUTIVE SUMMARY

The use of recycled materials in highway construction has the potential to achieve significant benefits affecting the triple-bottom line (environment, prosperity and society). Although state departments of transportation (DOTs) have been in the forefront of introducing recycled materials infrastructure projects, it has been challenging to clearly convey the benefits in a quantitative and transparent manner using easily understood metrics. What is lacking is direct information on sustainability assessment characteristics, i.e. greenhouse gas emissions, energy and water consumption and waste generation.

To determine and assess the benefits of using recycled materials for DOTs, the Recycled Materials Resource Center (RMRC) conducted life cycle assessments (LCA) and cost analyses using recycled material quantities provided by six member state DOTs; Georgia (GDOT), Illinois (IDOT), Minnesota (MnDOT), Pennsylvania (PennDOT), Virginia (VDOT) and Wisconsin (WisDOT). PaLATE was used as the LCA analysis tool, after researching other publicly available tools to find an optimal analysis. Four environmental parameters (energy use, water consumption, carbon dioxide emissions and hazardous waste generation) showed percent reductions ranging between 70 and 99 percent when states used recycled industrial byproducts such as fly ash, and recycled roadway materials such as recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). The cost analysis indicated potential savings of up to 17 million dollars.

Any future research into sustainability assessment measurements should consider real time collection of the data, particularly in relation to virgin versus recycled material prices. Further case studies and developments using a material tracking tool developed by the RMRC and presented in this report can aide in determining project specific parameters, and therefore, more accurate future estimations of the economical and environmental of using recycled materials in highway pavements.

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1 INTRODUCTION AND BACKGROUND

Over 163,000 miles of highways in the National Highway System form the backbone of our 4-million-mile public road network. These highways are continuously being constructed and rehabilitated, requiring large amounts of natural raw materials, producing waste and consuming energy, (AASHTO, 2008; Gambatese & Rahendran, 2005). In order to reduce these economic and environmental costs, state Departments of Transportations (DOTs) have been reusing highway construction materials in various DOT projects.

The Recycled Materials Resource Center (RMRC, http://rmrc.wisc.edu), located at the University of Wisconsin-Madison, and many governmental agencies have developed fact sheets on various recycled materials and industrial byproducts for their use in highway construction applications. These fact sheets typically have addressed the engineering properties and environmental sustainability issues relevant to various applications and in some cases have incorporated design guidelines and construction specifications. However, direct information on sustainability assessment characteristics, i.e., GHG emissions, energy and water consumption and life cycle cost benefits is not yet readily available. State agencies may track yearly use of quantities for major recycled materials such as fly ash in concrete, recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), etc., but they have not yet calculated the life cycle and cost benefits accrued by substituting these materials for conventional materials. Project by project tracking of recycled materials using post-bid award information has been a challenge. With a lack of information or an easy way to track recycled material use, DOTs have not been able to clearly convey the benefits in a quantitative and easily understood manner.

1.1 Objectives

The main objective of this study is to quantify the life cycle benefits associated with the incorporation of recycled materials and industrial byproducts to highway pavement construction. In order to realistically quantify these benefits, data on the recycled materials quantities used by each RMRC member state DOT was collected and analyzed. A second objective of this study is to develop a tool by which state DOTs could track recycled material usage, and therefore, provide data for future life-cycle assessments (LCAs). The RMRC member state DOTs that have provided data for this study are: Georgia (GDOT), Illinois (IDOT), Minnesota (MnDOT), Pennsylvania (PennDOT), Virginia (VDOT) and Wisconsin (WisDOT).

2 COMMON RECYCLED MATERIALS

The following sections briefly describe the origins, applications and performance of commonly used recycled materials in highway construction. The presented materials are only those used by each member state in 2013 and do not include many other materials with potential to be used in highway pavements.

2.1 Blast Furnace Slag

The following section is based on, (Chesner, Collins, & Mackay, 1998; Collins & Ciesielski, 1994; EPA, 1978).

Origin: Blast furnace slag is a nonmetallic co-product in the production of iron and comprises about 20 percent by mass of iron production. Different forms of slag are produced depending on the method used to cool the molten slag product. These include air-cooled blast furnace slag (ACBFS) and ground granulated blast furnace slag (GGBFS).

ACBFS is formed if the liquid slag is poured into beds and slowly cooled under ambient conditions. The resulting lump slag with a crystalline structure can be crushed and screened.

GGBFS is formed if the liquid slag is cooled and solidified by water quenching. In this process there is little to no crystallization, resulting in sand size fragments. These fragments can be crushed to very fine cement-sized particles.

Applications: ACBFS is considered by many agencies to be a conventional aggregate and can be used in granular base, HMA, Portland cement concrete (PCC) and embankments or fill applications. The material can be crushed and screened to meet specific gradation requirements. Lack of consistency in physical properties such as gradation, specific gravity, adsorption and angularity require special quality control in the selection and processing of ACBFS.

GGBFS can be used as either an admixture for PCC or as a component of blended cement. The use of GGBFS in Portland cement is governed by AASHTO M302. When used in blended cements, GGBFS is milled to a fine particle size in accordance with AASHTO M302 requirements. The ground slag can be introduced and milled with the current feedstock or blended separately with cement after it is ground to meet requirements.

Performance: When used in HMA, ACBFS aggregates demonstrate friction and stripping resistance, but can break down under heavy loads. It is suited to surface treatments and light traffic pavements. HMA performance problems, such as flushing and raveling, may arise due to variability in physical properties.

When used as an aggregate in subbase and embankment applications, ACBFS displays the ability to stabilize wet, soft soils and provide good durability. However, discolored leachate with a sulfurous odor may result when ACBFS is used in poor drainage conditions or when in extended contact with stagnant or slow moving water.

2.2 Coal Bottom Ash/Boiler Slag

The following section is based on, (Chesner et al., 1998; Ramme & Tharaniyil, 2013).

Origin: Coal bottom ash and boiler slag are coarse, granular, incombustible by-products collected from the bottom of furnaces that burn coal. The type of by-product and characteristics of the by-product depend on the type of furnace used to burn the coal.

Bottom ash is produced from the dry, bottom pulverized coal boiler, common in the electric utility industry. About 80 percent of the unburned material is recovered as fly ash; the remaining 20 percent is dry bottom ash. The bottom ash is a sand size porous material and is collected in a water-filled hopper at the bottom of the furnace and is removed by high-pressure water jets. Bottom ash characteristics also depend on the transport system (wet or dry) and whether the bottom ash is ground prior to transport and storage.

Boiler slag is produced from two types of wet-bottom boilers: the slag-tap boiler and the cyclone boiler. In both boiler types, bottom ash is kept in a molten state that is collected in a solid base and is allowed to flow into an ash hopper. The ash hopper contains quenching water and when the molten slag comes in contact with the quenching water it fractures and crystallizes instantly forming pellets.

Applications: Bottom ash and boiler slag can be used as aggregate sources in HMA and surface treatments; most previous use of bottom ash has been in cold mix projects on low volume roadways. Bottom ash and boiler slag can be used as the fine aggregate or as the entire aggregate source in stabilized base and subbase mixtures. Coal bottom ash may also be used as an aggregate base, working platform and fill material for highway projects if it meets the required specifications.

Performance: Bottom ash can contain lightweight, pyrite, porous particles that result in low specific gravities and high losses during soundness tests. For this reason, bottom ash is used more frequently in cold mix asphalt mixtures than hot mix base course mixtures or shoulder construction which have stricter gradation and durability requirements. It is also recommended bottom ash be used under low compaction and loading conditions.

Boiler slag has been used more in hot mix asphalt because of its hard, durable particles, resistance to surface wear and resistance to stripping. Boiler slag is commonly blended with other aggregates for use in asphalt mixtures.

In general, the performances of bottom ash and boiler slag as a granular base and subbase stabilizer have been satisfactory. However due to a higher fines content when compared to conventional materials, it is recommended that there be good drainage conditions when using both materials.

2.3 Coal Fly Ash

The following section is based on, (Chesner et al., 1998; Ramme & Tharaniyil, 2013).

Origin: Fly ash is a by-product of the burning of coal in a coal-fired boiler. There are three types of coal-fired boiler furnaces used in the electric utility industry; dry-bottom boilers, wet-bottom boilers and cyclone furnaces, the most common being the dry-bottom furnace. Fly ash is a fine-grained powdery particulate material that is carried off in the flue gas and collected using electrostatic precipitators, baghouses or mechanically. Fly ash is classified as Class C or Class F based on its chemical and physical compositions. Class F fly ash that is produced from the burning of anthracite or bituminous coals is pozzolanic, and fly ash that is produced from burning of lignite or subbituminous coal is referred to as Class C fly ash. Class C fly ash has self-cementing properties unlike Class F.

Applications: The most common use of fly ash is in PCC. When used in PCC, fly ash can be used as a separate component/admixture or as a component of blended cement. When used as an admixture, fly ash acts as either a partial replacement or in addition to Portland cement and is added directly into the ready-mix concrete. This allows the flexibility of tailoring mixture proportions to obtain the required concrete properties for a particular application.

Fly ash can also be used as a supplementary cementitious material to stabilizing subgrade soils and recycled pavement sections.

Performance: Fly ash can enhance the workability of concrete, reduce heat of hydration, water demand, permeability and susceptibility to chemical attacks, and increase the ultimate strength and durability of concrete. The use of Class F fly ash usually results in slower early strength development, but the use of Class C fly ash does not and may even enhance early strength development.

Asphalt mixes containing fly ash as mineral filler have been shown to provide resistance to stripping, due to hydrophobic properties, and have higher retained strengths. Mineral fillers increase the stiffness of the asphalt, therefore improving the rutting resistance and durability of the pavement.

2.4 Foundry Sand/ Microsilica

The following sections is based on, (Chesner et al., 1998; Rowden, 2013).

Origin: Foundry sand consists of clean; high-quality silica sand with a binder content such as bentonite and it is a by-product from the production of both ferrous and nonferrous metal castings. Sands form the outer shape of the mold cavity and sand from collapsed molds or cores can be reclaimed and reused. Molding sand is recycled and re-used several times before it eventually degrades and can no longer be used, at which point it becomes a by-product. Almost all sand cast molds for ferrous castings are of the green sand type. Green sand consists of high-quality silica sand, about 10 percent bentonite clay, 2 to 5 percent water and about 5 percent sea coal. Chemically bonded sand cast systems are also used. These systems, more often used for nonferrous molds, involve the use of one or more organic binders along with catalysts and different hardening/setting procedures.

Microsilica is a by-product of the industrial manufacture of ferrosilicon and metallic silicon in high-temperature electric arc furnaces. Microsilica is also known as silica fume. Vapor rising from the furnace bed is oxidized and as it cools, it condenses into particles and is filtered. The recovered microsilica, is a gray powdery martial that consists of very fine solid glassy spheres of silicon dioxide, generally less than one micron in diameter.

Applications: The largest volume of waste foundry sand is used in embankments, road subbases and working platforms but it can be used as a substitute for fine aggregate in asphalt paving mixes. Prior to use, spent foundry sand requires crushing or screening in order achieve a uniform product. Stockpiles of sufficient size typically need to be accumulated so that a consistent and uniform product can be produced.

Microsilica is high in pozzolanic properties, making it ideal as an additive or cement replacement in concrete mixtures.

Performance: The commercial use of spent foundry sand in the United States is extremely limited. The use of foundry sand in paving mixtures has been limited and studies have shown mixed performance results. Increasing foundry sand in asphalt mix blends above 15 percent lowered the unit weight, increased the air voids, decreased the flow and stability of the mixes and reduced the indirect tensile strength, indicating potential stripping problems.

When used in geotechnical applications, foundry sand has been found to perform similar to that of natural sand. The hydraulic conductivity of the foundry sand was found to be considerably lower than that of natural sand.

When used as an admixture, microsilica can improve the properties of both fresh and hardened concrete. When used as a partial replacement for cement, microsilica can reduce alkalinity and reactivity of cement with aggregates. Microsilica has been shown to result in denser concrete with higher strengths, lower permeability and improved durability, if the concrete must be cured properly.

2.5 Reclaimed Asphalt Pavement

The following section is based on, (Chesner et al., 1998; Copeland, 2011; NCAT, 2009).

Origin: Reclaimed asphalt pavement (RAP) is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. These materials are usually generated from milling, pavement removal and waste. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt binder.

Asphalt pavement is generally removed either by milling or full-depth removal. Milling entails removal of the pavement surface using a milling machine to remove any distressed upper layer(s) of existing pavement to a given depth. Full-depth removal involves ripping and breaking the pavement including the base, which are then transported to be processed and crushed to a controllable size for recycling.

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

Although the majority of old asphalt pavements are recycled at central processing plants, asphalt pavements may be pulverized in place and incorporated into granular or stabilized base courses using a self-propelled pulverizing machine in a single or multiple passes. Hot in-place recycling and cold in-place recycling processes have evolved into continuous train operations that include partial depth removal of the pavement surface, rejuvenating to improve binder properties, laydown and compacting the resultant mix.

Applications: The principle use of RAP is as an aggregate and asphalt binder supplement in asphalt pavement. The use of RAP is primarily driven by the high costs of virgin aggregates and binders and transportation of these materials.

RAP in road base and subbase materials has been implemented by many state agencies. When used as a granular base or subbase material, RAP is used primarily as an aggregate and the asphalt binder potential is not recovered from the old pavement. RAP can be used as granular or stabilized base material for all pavement types, including paved and unpaved roadways, shoulders and as a fill material.

Performance: In general, there is little difference in designing asphalt mixtures with RAP compared to asphalt mixtures with raw materials until a high content of RAP is used. A recent study comparing virgin and recycled asphalt pavements was conducted by NCAT, where data from 18 projects across North America were analyzed. Asphalt pavements using 30 percent RAP were found to provide equal or better performance as virgin asphalt pavement, based on the distress parameters of rutting, cracking and raveling. Pavements with higher than 30 percent RAP (35) content were found to perform satisfactory, but had an increase of distress parameters in a separate FHWA research study.

The overall performance of RAP as a base or subbase aggregate has been described as satisfactory to excellent. When properly incorporated, RAP aggregates have shown adequate bearing capacity, good drainage characteristics and durability. RAP is a temperature sensitive material and this aspect needs to be taken into account in areas of high temperature. When RAP has not been properly processed to meet specifications, pavement performance has been poor.

2.6 Recycled Asphalt Shingles

The following section is based on, (Chesner et al., 1998; McGraw et al., 2010; Zhou, Li, Hu, Button, & Epps, 2013).

Origin: There are two types of roofing shingle scraps. They are referred to as tear-off roofing shingles and roofing shingle tabs, also called manufacturer waste scrap shingles. Tear-off roofing shingles are generated during the demolition or replacement of existing roofs. Roofing shingle tabs are generated when new asphalt shingles are trimmed during production to the required physical dimensions. The quality of tear-off roofing shingles varies.

Roofing shingles are produced by saturating and coating both sides of either organic felt or glass felt with a hot saturant asphalt and finally surfaced with mineral granules. Most roofing shingles produced are of the organic felt type. Both saturant and coating asphalts are produced by an "air-blown" process to increase the viscosity of the asphalt. The process infuses oxygen through the molten asphalt flux making the asphalt stiffer. The shingles are then covered with mineral granules to increase their durability and resistance to weathering In order to be successfully used in asphalt paving mixtures, asphalt shingles need to be shredded and ground down to pass at least a 12.5 mm sieve, according to AASHTO. Some state agencies require an even smaller particle size.

Applications: Roofing shingles incorporated into asphalt paving mixes not only modify the binder, but also, depending on the size of the shredded material, function like aggregate or mineral filler. Organic felt and glass felt particles in particular tend to function like a mineral filler substitute. Substantial savings can be seen when using RAS in a specialized HMA mixture called stone matrix asphalt which is used for high volume and high stress roadways and requires the fiberglass found in RAS. RAS is also used as a fill material.

Performance: When used in asphalt paving applications, the properties of constituent materials must be well defined and consistent. Since the composition and properties of old, tear-off roofing shingles are likely to include foreign materials (such as nails, metal flashing and felt underlayment) as well as asbestos fibers, and can vary widely, prompt scrap that has been left over from the manufacture of new roofing shingles, and which exhibits more consistent properties, is preferred for incorporation into asphalt mixtures.

Studies in Texas and Minnesota found the addition of RAS will make a stiffer mix than designed and recommend using a softer grade of binder, particularly with tear-off shingles. It has also been found that RAS mixtures are more susceptible to cracking and therefore decrease the durability of the mix. The mineral fillers in asphalt shingles can serve as an anti-strip agent and decrease moisture susceptibility.

RAS is a temperature-sensitive material and this aspect needs to be taken into account when used as a fill material in areas of high temperature.

2.7 Recycled Concrete Aggregate

The following section is based on, (Chesner et al., 1998; Collins & Ciesielski, 1994; Gonzalez & Moo-Young, 2004).

Origin: Recycled concrete aggregate (RCA) is generated through the demolition of Portland cement concrete (PCC) elements of roads, runways and structures during road reconstruction, utility excavations, or demolition operations. Depending on the removal process and type of concrete, RCA may contain small amounts of soil subbase, foreign debris such as wood and sealants and metals. RCA can also be referred to as recycled concrete material (RCM) or crushed concrete.

The excavated concrete that will be recycled is typically hauled to a central facility for stockpiling and processing or, in some cases (such as large reconstruction projects), processed on site using a mobile crusher to a manageable fragment size. At the central processing facility, crushing, screening and any metal recovery and waste material removal operations occur. Present crushing systems, remove reinforcing steel and dowel bars with electro-magnets. Any steel removed in this manner will also be recycled as scrap metal.

In addition to RCA collected from demolition projects, excess and rejected concrete mixes and precast elements returned to the batch plant can also be used as sources of RCA. Aggregates can be reclaimed from any excess and rejected mixes by washing the aggregates and allowing its reuse in new mixes.

Applications: The use of RCA in many aggregate applications in pavement construction is well established and successful, particularly its use as a granular and stabilized base. RCA is also commonly used in PCC pavement applications and many fill applications. Other potential applications include its use as an aggregate in hot mix asphalt and surface treatments.

Performance: Reclaimed concrete aggregate (RCA) can be used as coarse and/or fine PCC pavements. RCA concrete is highly durable; resistant to freeze thaw, sulfate and can feature slow corrosion rates of embedded steel. RCA fines used as greater than 30 percent of the fine aggregate portion of a mix can lead to lower compressive strengths, greater water demand and decrease workability resulting in a reduction of quality of the mix. The coarse aggregate portion of RCA has no significant adverse effects on the workability of the concrete.

The properties of processed RCA generally exceed the minimum requirements for conventional granular aggregate bases. The residual cementitious material in RCA provides bonding of the base material, providing good load transfer when placed on weaker subgrade. The lower compacted unit weight of RCA aggregates compared with conventional mineral aggregates results in higher yield (greater volume for the same weight). The superior effects of using RCA as a base and subbase material can lead to higher than normal stiffness and therefore a decrease in rigidity. If the base becomes too stiff it can cause cracking in any overlaying course. RCA also exhibit higher resistance to freezing and thawing than natural aggregates.

RCA can be satisfactorily used in embankment or fill, however due to the high quality of RCA as an aggregate it is not often used in this application. RCA aggregates are considered by many specifying agencies to be conventional aggregate. It requires minimal processing to satisfy the conventional soil and aggregate physical requirements for embankment or fill material.

2.8 Scrap Tires/Crumb Rubber

The following is based on, (Bukowski & Harman, 2014; Chesner et al., 1998).

Origin: Recycle tire rubber from waste tires has been used in asphalt since the 1960's. Tire rubber can be used as an asphalt binder modifier and as an additive in asphalt mixtures. In order for tires to be used, several processes are required in order to remove any steel or fiber present and then reduce the tires to small particles for blending. The primary processes used today are cryogenic fracturing and ambient grinding.

When using cryogenic fracturing procedures, tire pieces are cut up to typically 50 millimeter particles, which are then frozen and fractured. Essentially, this involves using liquid nitrogen to reduce the temperature of the rubber particles to minus 87^{o}C (-125^{o}F), making the particles quite brittle and easy to shatter into small particles. The fracturing process produces a variety of particle sizes ranging from those passing the 75 micrometer sieve to about 5 millimeter sized particles. These particles are usually cubical with a smooth surface.

The ambient grinding process is similar to the cryogenic process in that the tires are cut and reduced to similar smaller sized particles. Instead of using a fracturing process to reduce the size of the cut tires, the tires are passed through shredders that grind and tear the rubber into smaller particles. This process produces particles with a rough texture and increased surface area.

Applications: Two processes, dry and wet, are used to blend the rubber with asphalt to produce asphalt rubber pavements. When using the dry process, the recycled tire rubber is considered a fine aggregate replacement. In the dry process the recycled tire rubber is added to the mix at the plant, similar to RAP. The dry process can be used for HMA asphalt paving mixtures in dense-graded, open-graded, or gap graded mixtures. It cannot be used in cold mix, warm mix, chip seals or in surface treatments. Mixtures including tire rubber as a portion of aggregate are sometimes referred to as rubber-modified asphalt concrete.

The wet process allows for the added recycled tire to react with the asphalt binder for a set amount of time, typically 45 to 60 minutes. During the reaction the rubber absorbs some of the light fractions of asphalt binder and swell, increasing the viscosity of the mix. This process can be performed on site or at a binder supplier site and then shipped to the mixing plant. The modified binder is commonly referred to as asphalt-rubber. The wet process can be used for HMA mixtures as well as chip seals and surface treatments.

Tire derived aggregate (TDA) is another application where shredded tire chips are used a light-weight fill material for construction over soft ground. TDA is also used as a drainage material.

Performance: The performance of rubber-modified asphalt using the dry process has been mixed and show little improvement in performance over conventional pavements. However, using the wet process to modify the binder has shown to be an effective improvement in performance over conventional pavements. Increased durability, especially in warmer climates, and reduced thicknesses have been observed. Also when used in chip seals, reflective cracking is reduced.

There have been issues with compaction and raveling of mixes in colder climates, but this has usually been due to construction and unfamiliarity of working with higher viscosity material. Slightly higher binder contents in modified mixtures and using warm mix technologies may improve the workability and compaction of the modified binder mixes.

TDA is used in numerous highway projects where a light-weight fill material is needed. TDA has potential for spontaneous self-combustion. However, guidelines to avoid this problem have been developed (ASTM D 6270 Practice for Use of Scrap Tires in Civil Engineering Applications).

2.9 Steel Slag

The following section is based on, (Chesner et al., 1998; Kandhal & Hoffman, 1997; Rowden, 2013).

Origin: Steel slag is a by-product of steel-making and is produced during the separation of the molten steel from impurities in steel-making furnaces, basic oxygen furnace or electric arc furnace. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling.

Depending on the stage of production, several types of steel slag are produced: tap (furnace) slag, raker slag, ladle slag and pit slag. The primary source of steel slag aggregate is furnace slag. Ladle slag is not a suitable replacement for aggregate due to high amounts of synthetic fluxing agents.

After cooling, the steel slag is processed to magnetically remove any free metallic material. The material is then separated and sized into categories based on its uses. For example, as a construction aggregate, ingredient in cement production and fill material. As with any aggregate material, steel slag must be crushed and screened to meet the specified gradation, handling and storing requirements.

Applications: The use of steel slag as an aggregate is considered standard practice with applications that include its use in granular base, embankments, engineered fill, highway shoulders and hot mix asphalt pavement.

In general, when processed steel slag is more angular, denser and harder than natural aggregates. These properties can result in favorable material properties including high frictional properties, high stability and resistance to stripping and rutting. Steel slag may also have large amounts of calcium or magnesium oxides present, which will hydrate and lead to rapid short-term and long-term expansion.

Performance: The use of steel slag in asphaltic mixes as coarse or fine aggregate results in successful use if properly processed, aged and tested. Steel slag can be used in dense and open graded HMA pavements, as well as in cold mix and surface treatment applications. Due to the potential for expansion, steel slag must be properly coated in asphalt binder.

If not properly processed, asphalt mixes containing steel slag can result in performance problems. Cracking in pavement is related to the volumetric instability associated with calcium or magnesium in the steel slag. The hydration of these free compounds results in expansion and slag particle, which in turn result in cracking of the pavement.

When used as a granular base, steel slag can be considered a conventional aggregate and can usually exceed any requirements for an aggregate base. The high stability, interlocking and soundness properties of steel slag aggregates can provide load transfer to weaker subgrades and therefore provide the necessary bearing capacity under high traffic loads. Tendency of expansion of the slag aggregates do not allow for the slag to be used in confined applications.

2.10 Waste Glass/Glass Beads

The following section is based on, (Chesner et al., 1998; Rowden, 2013; Su & Chen, 2002).

Origin: Glass is a product of the super cooling of a melted liquid mixture of sand (silicon dioxide), soda ash (sodium carbonate) and/or limestone to a rigid solid. The super cooled material does not crystallize and retains the organization and internal structure of the melted liquid mixture. Glass is produced in many forms, including packaging or container glass, flat glass and bulb glass. Glass can be recycled without any loss of its original quality and is therefore 100 percent recyclable. When waste glass is crushed to sand like particle sizes, similar to those of natural sand, it exhibits properties of an aggregate material.

Applications: Recycled waste glass has been used successfully as an aggregate substitute in concrete, road beds, pavements and the production of glass beads used in reflective paint for highways.

Crushed glass or cullet, if properly sized and processed, exhibit similar physical properties and chemical composition to that of sand and cement. Therefore, the use of glass in production of both cement and concrete is possible, but it is more commonly used as a fill material in road bed applications. The angular characteristics of crushed glass allow for higher stability, while retaining little moisture.

When use of crushed glass in both rigid and flexible pavement has produced mixed results. The high angularity of the glass can enhance stability of asphalt mixes and heat retention in mixes, but it has been shown that high percentages of glass can contribute to stripping and raveling problems. When used as an aggregate substitute in concrete, increasing the percentage of crushed glass up to 20 percent increased the compressive strength of concrete.

Glass beads are transparent, sand-sized, solid glass microspheres that are reflective. Glass beads are applied to surface of pavement markings in order to increase the nighttime visibility of these markings.

Performance: When use of crushed glass in both rigid and flexible pavement has produced mixed results. The high angularity of the glass can enhance stability of asphalt mixes and heat retention in mixes. Higher blends could potentially be used in base or binder course mixes. Hot mix asphalt surface course pavements with more than 20 percent waste glass may experience deterioration due to stripping of the asphalt binder from the waste glass. When used as an aggregate substitute in concrete, increasing the percentage of crushed glass up to 20 percent increased the compressive strength of concrete.

Waste glass that has been crushed and screened has the potential for use as a granular base material. Glass that has been reduced to a fine aggregate size fraction (less than 4.75 mm, No. 4 sieve, in size) exhibits properties similar to that of a fine aggregate or sandy material, with relative high stability, due to the angular nature of crushed glass particles. Blending with other coarse conventional materials will typically be required to meet required granular base gradation specifications.

3 OVERVIEW OF EXISTING LCA/LCCA TOOLS

The first step in developing a quantitative benefit assessment tool was to examine existing publically available pavement life cycle assessment (LCA) tools. LCA can assist in gaining a better understanding of the environmental impacts of materials and processes throughout the product life cycle (cradle-to-grave) and provide relevant data in order to make informed decisions (ISO, 2006). The International Organization for Standardization (ISO) 14040 series provides general principles and a framework for an LCA study, detailing four phases of an LCA: (1) definition of goals and scope, (2) inventory analysis, (3) impact assessment and (4) interpretation. In general, LCAs should have defined system boundaries, functioning units and inputs/outputs. For most pavement LCAs, the defined system boundaries are materials, construction, use, maintenance and end-of-life (Santero, Loijos, Akbarian, & Ochsendorf, 2011). For the purpose of this study, five existing publically available LCA tools were examined (Table 3-1), focusing on the scope of each tool, including the system boundaries and environmental impacts. The five tools were selected based on their availability to the public, licensing costs and the locations where they were developed.

Table 3-1 Life Cycle Assessment Tools

Tool	***Developer***	***Interface***	***Pavement Types***
asPECT	Transport Research Library	Graphic User Interface	Asphalt only
GreenDOT	AASHTO	Spreadsheet	All
PE-2	Michigan Technological University	Web-based	All
PaLATE	UC-Berkeley, RMRC	Spreadsheet	All
SimaPro	PRé Sustainability	Graphic User Interface	All

Sources: (Wayman, Schiavi-Mellor, & Cordell, 2014), (Horvath, 2004), (Cass & Mukherjee, 2011), (Santero et al., 2011), (PRè, 2015)

Each LCA tool assessed for this study follows the four phases of an LCA defined by the ISO. The goal of using LCA for this study is to calculate the environmental benefits of using recycled materials or industrial by-products in highway pavement. Ideally, the impacts in the chosen assessment would include GHG emissions and energy use at a minimum. Additionally, the chosen tool should be able to analyze as many of the DOTs reported recycled materials and their applications as possible. The following section discusses and compares each of the tools.

3.1 asPECT

The Transport Research Laboratory developed the Asphalt Pavement Embodied Carbon Tool (asPECT) to follow the material used in asphaltic pavement from raw material acquisition through the end of life processes of disposing or recycling the pavement materials, (Wayman et al., 2014). The main goal of asPECT is to calculate GHG emissions based on ten life cycle stages for a road from user inputs such as materials, fuels, transportation modes and distances and energy use. While this would be advantageous for an individual project, the tool was too specific for the purposes of a state-wide study. asPECT is only capable of analyzing asphaltic pavements, which does not allow for a complete analysis, and is therefore another limitation of using asPECT for this study.

3.2 PE-2

PE-2, developed by Michigan Technological University (2011), estimates the life cycle emissions associated with construction, maintenance and roadway use. Unique to this tool, it has a web-based interface and takes into account the costs of traffic delay caused by construction operations. PE-2 was designed solely for projects based in Michigan and is limited by pre-defined construction operations and fewer materials in its database. While PE-2 was found to be a good tool to use for a quick estimate of environmental costs, it was not considered to be capable of a more in-depth analyses needed for this project.

3.3 GreenDOT

GreenDOT, described by (Gallivan, Ang-Olson, Papson, & Venner, 2010), was specifically developed for state DOTs to calculate CO_2 emissions from operations, construction and maintenance projects. GreenDOT includes emissions based on four categories: electricity, materials, on-road vehicles and off-road vehicles. GreenDOT is able to calculate project-specific or state-wide emissions. GreenDOT is also unique in that it calculates emissions of the electrical components of a highway, for instance, traffic signals. Overall, GreenDOT was found to be user friendly, but limited in the amount of materials and equipment in its databases.

3.4 PaLATE

PaLATE, developed at UC-Berkeley for the RMRC (Horvath, 2004), follows the production of materials, construction, maintenance and end-of-life processes. Initial material inputs are analyzed based on the equipment used to produce and transport them to the construction site. Emissions due to construction, maintenance and production are calculated from the equipment used in all processes. Many of the outputs of PaLATE are based upon the volumes or weight of materials used and the parameters of equipment used, such as the productivity and fuel consumption of each machine. PaLATE furthers its impact assessment by outputting not only GHG emissions, but also energy use, water consumption, particulate matter, waste generation and human toxicity potentials. The first and only version of PaLATE was developed in 2004, and while the range of environmental outputs of PaLATE is wide, these are limited by potential out-of-date databases. However, PaLATE can be updated with relative ease, unlike the other LCA tools. Based on the limitations and advantages of each LCA tool, PaLATE was found to be the best suited to accommodate the objectives of this project.

3.5 SimaPro

SimaPro was developed by PRé Sustainability and is the most widely used LCA software in industry. The North American version includes two methods for life cycle assessment, Building for Environmental and Economic Sustainability (BEES) and the Tool for the Reduction and Assessment of Chemical and other environmental impacts (TRACI). BEES is a partial combination of LCA and LCCA for building and construction materials. The impact categories of BEES include: global warming potential, acidification, eutrophication potential, natural resource depletion, solid waste and indoor air quality. TRACI is an LCA computer program developed by the EPA and uses specific US location input parameters. Environmental measures with potential effects including, ozone depletion, global warming, fossil fuel depletion and landuse effects are characterized by TRACI, (PRè, 2015). In order to use these methods, the user must create a life cycle inventory by entering the inputs and outputs for the processes they wish to analyze. They may select from pre-existing processes or create their own. If this was to be used for highway analysis, the user might input data for the average water consumption of one ton of aggregate production. SimaPro can be used as an LCA for any industry process and is not specific to highways, unless the user creates an inventory specific to highway construction. If a state DOT were to purchase the SimaPro software, they could build up an inventory to be reused in future LCA work. In order to use SimaPro for this project, many assumptions would have needed to be made in order to build an appropriate inventory and compare data across the six member states because the calculated measures of SimaPro are very dependent on the user defined inventory.

4 DATA COLLECTION METHODOLOGY

4.1 Recycled Materials Used in 2013

In the first phase (2013) of data collection, a survey was conducted within the RMRC six-member state DOTs (GA, IL, MN, PA, VA and WI) in order to determine the degree to which recycled materials were used and tracked by member states. The DOT responses can be seen in Table A-1 in Appendix A. The survey results showed that while many DOTs use commonly recycled materials, most track neither the breakdown of recycled materials used per each pavement layer nor the total annual quantities used. Overall, the six member states agreed that the availability of a recycled materials tracking tool would be useful.

In the second phase of data collection, RMRC member state DOTs were asked to report quantities of recycled materials for the calendar or fiscal year of 2013. Although recycled material use quantities were not being tracked by most of the DOTs, information on as-let items for projects within the time period for each state was available. In order to calculate the quantities of recycled materials from as-let material quantities, a set of assumptions regarding average design specifications needed to be determined for each state DOT. This was established through interviews and correspondence with engineers from each member state. These assumptions and averages (as seen in below) were then used to calculate the amounts of recycled materials used in hot mix asphalt (HMA), concrete mixes and base course layers.

1. A 1:1 replacement volume of virgin with recycled material was assumed, despite the known varying mechanical properties.
2. All densities of materials are assumed to be the listed densities in PaLATE.
3. All fly ash was assumed to be used as a replacement for cement in concrete pavement.
4. All blast furnace slag was assumed to be used as a replacement for cement in concrete pavement.
5. For all RAP used in HMA pavement, 6% was assumed to be used as asphalt binder replacement with the remaining 94% used as aggregate in the mix.
6. RAS was assumed to be used only in HMA.
7. For all RAS, 20% was assumed to be used as asphalt binder replacement with the remaining 80% used as aggregate in the mix.
8. Any RAP used in HMA was equated into virgin aggregate and asphalt. However, the RAP specifically identified for base course material was equated only into virgin aggregate.
9. All RCA was assumed to be used in base course, and therefore, used as a replacement to virgin aggregate.
10. All crumb rubber was assumed to be used in HMA as a binder modification.

It should be noted the assumptions listed above are general assumptions of the recycled materials reported by each state. Reported recycled materials and more state specific assumptions are listed in the corresponding overview portion of each states section, (Sections 8 through 13). Reported recycled materials and the calculated equivalent virgin material volumes are reported in Appendix A, Table A-2 through Table A-7.

4.2 Average Material Cost

After collecting data on recycled materials used in 2013 by RMRC member states, a third phase of data collection began to determine the average unit price of both recycled materials and virgin materials.

In general an average unit price (dollars per ton of material) of each recycled material was found by surveying providers, pavement associations and various material associations in each state. The unit cost of each material does not include transportation costs to the mix plant or to the site.

The unit cost of equivalent volumes of virgin materials was estimated using a weighted average of Engineering News-Record (ENR) historic material price indices. ENR tracks the price of raw paving materials of twenty cities on a monthly basis including: Atlanta, Baltimore, Chicago, Minneapolis, Philadelphia and Pittsburgh. The monthly prices starting in July of 2012 through January of 2014 were averaged in order to determine the average price of aggregate, base course materials and cement in each city. The individual city price averages were then averaged with the average price of all the cities in order to normalize any prices skewed high or low. Because most state DOTs track the price of liquid asphalt more frequently than ENR, these indices were used instead of ENR estimates. ENR does not track material price in a Wisconsin city, therefore local pavement associations and material providers were asked to estimate savings in a unit cost by using recycled materials.

Average price lists of the materials can be seen in Appendix A.

5 PALATE LCA ANALYSIS OVERVIEW

5.1 Assumptions

Because determining specific design parameters (such as pavement thicknesses and fly ash replacement of concrete) for every DOT project over the annual period was impractical, certain standard practice assumptions were made. These assumptions were based on the input of Mr. Gary Whited, program manager of the Construction and Materials Support Center of the University of Wisconsin – Madison. The general assumptions made when running the LCA analysis in PaLATE included:

1. A 1:1 replacement volume of virgin with recycled material was assumed, despite the known varying mechanical properties.
2. All material was assumed to be utilized in initial construction operations.
3. Both cement and fly ash were assumed to be delivered by cement trucks over a one-way distance of 200 miles from the processing site to the asphalt or concrete mix plant.
4. All RAP and RCA was assumed to be processed and reused on site with a transportation distance of zero miles.
5. All other materials included in HMA, ready-mix concrete and the base course were assumed to be delivered by trucks over a one-way distance of 25 miles from the processing site to the asphalt or concrete mix plant.
6. All equipment is assumed to be the default equipment type for each process in PaLATE.
7. All densities of materials are assumed to be the listed densities in PaLATE.

It should be noted the assumptions listed above are general assumptions of the recycled materials reported by each state. More state specific assumptions are listed in the corresponding environmental section of each states section, (Sections 8 through 13).

5.2 Approach to PaLATE Analysis

The quantities of recycled material used by each member state were analyzed in PaLATE to determine environmental impacts and benefits of the recycled material use. These environmental impacts and resulting benefits were analyzed comparatively by using the same equivalent volume of virgin material. Four environmental impact factors: energy, water consumption, CO_2 emissions and RCRA hazardous waste generation were deemed sufficient for evaluation of the state materials. RCRA Hazardous Waste, as stated by the U.S. EPA, is a waste with properties that make it dangerous or potentially harmful to human health or the environment; i.e. exhibits the characteristics of ignitability, corrosivity, toxicity or reactivity, 40 C.F.R. § 261 (1980). PaLATE determines the environmental impacts based on three categories: material production, material transportation and construction processes (equipment). Material production includes the processes associated with extracting or generating the materials, such as RAP milling and virgin aggregate quarrying. Material transportation incorporates the impacts associated with transporting each material the specified distance in the chosen vehicle. Processes (equipment) consist of the impacts associated with installing the material, such as paving, placing and compaction.

The first step in conducting the PaLATE analysis was to compile the collected recycled material data for all of the member states. Then, equivalent virgin material volumes were calculated for their recycled counterpart. Both the recycled and virgin material quantities were input into a PaLATE sheet, from which the specific environmental impact for each material in terms of production, transportation and processes were determined. Finally, the environmental impact of recycled versus virgin material was analyzed.

6 ECONOMIC IMPACT ANALYSIS OVERVIEW

6.1 Assumptions

Due to the nature of the collected data, a true LCCA could not be performed without making some significant and perhaps unreasonable assumptions. The purpose of an LCCA is to estimate the life-cycle costs of an individual highway/structure throughout its lifetime. Therefore, two LCCAs (a road using recycled materials and the same road without recycled material use) would need to be performed on each individual project where recycled materials were used in order to calculate the total life cycle-costs savings in each state. Given just material quantities and broad assumptions as to how each material was applied to a highway, an LCCA could not be performed. Instead the cost savings realized by each state in 2013 were estimated by comparing the prices of recycled and virgin materials.

The general assumptions made in the analysis are listed below. Included in these assumptions are also the assumptions used to calculate the total quantities of recycled materials utilized in 2013, (see Section 4.1).

1. The cost of hauling, either to the mixing plant or to the construction site, was not included in the unit price of each material.
2. Materials were assumed to be purchased individually and not as part of mixture, i.e. a distinction between the paving contractor and state agency was not made.

6.2 Approach to Economic Impact Analysis

In order to estimate the economic savings achieved, a comparison of prices of recycled material and virgin material per ton of material was needed. Determining the true savings realized by each state from the use of recycled materials would be extremely difficult, as explained in the previous section. Therefore, an estimate of savings realized by each state in just the year 2013 was made in order to determine the economic impact of using recycled materials.

The price of material is based on many factors, including competition in the region, transportation of material, production expenses, regulatory fees and quantity of material purchased. Furthermore, some materials are paid for as part of a mixture and not individually. Due to the many factors involved in calculating the price of material, this study determined the average purchase price per ton of both recycled materials and virgin materials without the cost of transportation. As with the environmental analysis, the recycled and virgin materials were first equated to equivalent volumes and then converted to corresponding weights. These weights were then used to calculate the cost of recycled materials and virgin materials used. Total savings and unit savings per ton of recycled material could then be estimated for each state.

These savings are meant to be a conservative estimate of the potential economic savings of using recycled materials. The true economic impact of using recycled materials cannot be determined unless all aspects of how both a recycled material and its equivalent virgin material is priced and applied in construction are known. A further breakdown of the economic impact of using recycled materials is presented in each states individual section.

7 RMRC MATERIAL TRACKING TOOL

7.1 Purpose

During the first phase of data collection it was found that while most states use the recycled materials reported on in this study as well as other recycled materials, the majority of these materials were not tracked by the DOTs. The assumptions listed in Section 4.1 were then required to estimate only a portion of the total recycled materials used. If state DOTs would track the quantity and average unit costs of these recycled materials, the environmental and economic benefits of using recycled materials could be easily calculated.

In order to promote the tracking of recycled materials used in DOT projects, the RMRC developed a Microsoft Excel based spreadsheet to track recycled materials. The program uses pavement mix designs in order to calculate the tons of recycled material used. The tracking tool can be used on an individual project basis; the resulting quantities can then be added to a state wide tabulation. While the tracking tool is not meant to act as an LCCA or even an LCA, the resulting total quantities can be used in LCA and cost comparison calculations using the same methodology as in this study. The tracking tool has been provided to the six DOTs participating in this study, as a resource to be used in tracking recycled materials and potentially as a prototype for developing their own systems of material tracking to better fit their individual systems. The recycled material tracking tool can be found on the RMRC website (rmrc.wisc.edu) along with a user manual. The following section describes the functionality of the tracking tool in further detail.

7.2 Functionality

The RMRC tracking tool was created based upon the WisDOT system of payment for measured quantities of bid items (sometimes as price indices). The bid items represent a material or processed used in pavement construction. The WisDOT system was used for the model of this tool because of the familiarity of the researchers at the University of Wisconsin – Madison, where the RMRC is located, and the similarity of the system to other DOTs.

The tracking tool is designed to use mix designs and bid items to calculate tons of recycled material. These two inputs were chosen because they are already known and used by WisDOT to track measured quantities for payment reimbursement. Once both the mix design and appropriate bid item are known, a quantity of recycled material can be calculated in one calculation. For example, if a project calls for 100 tons of HMA Pavement Type E-3, (WisDOT bid item #460.1103), and if this HMA Pavement Type E-3 calls for 16% RAP to be used in the mix, the resulting tons of RAP are:

$$0.16\left(\frac{tons\ RAP}{tons\ HMA}\right)\times(100\ tons\ HMA) = 16\ tons\ RAP$$

The user is able to modify the tracking tool to fit their system or use it on a system wide scale or on an individual project. The listed bid items can be changed from the WisDOT standard bid items to those of any state.

The recycled materials that are currently programmed to be tracked in the tool include the commonly used recycled materials, as reported in this report, as well recycled materials that are often used but not tracked. The recycled materials currently in the tool are described in Section 2 of this report, and include:

- Blast Furnace Slag
- Coal Bottom Ash/Boiler Slag
- Coal Fly Ash
- Foundry Sand/Microsilica
- Reclaimed Asphalt Pavement
- Recycled Asphalt Shingles
- Recycled Concrete Aggregate
- Scrap Tires/Crumb Rubber
- Steel Slag
- Waste Glass/Glass Beads

7.3 Testing and Future Use

The recycled material tracking tool has been used to calculate recycled materials used on the reconstruction and expansion of the eastbound Beltline, between Whitney Way and Seminole Highway in Dane County, WI. The project took place from March 2015 through November 2015 and was part of the Verona Road (US 18/151) Project. The calculated recycled materials have been used to perform an LCA on the project and estimate the environmental benefits of using recycled materials on the project.

As previously stated, the recycled material tracking tool has been provided to each participating DOT in order to promote the practice of not only tracking recycled material usage but also performing LCAs. LCAs are not currently used in the design-bid-build project system utilized in most of North America (Harvey, Meijer, & Kendall, 2014), in which the lowest bid is often times selected as the final project design. While there is currently not a generally accepted LCA tool specific to highway pavements, the FHWA predicts a number of LCA tools currently in development will become available in the next few years. The recycled material tracking tool can provide a framework for state DOTs as the practice of improving sustainability of pavements becomes prevalent in the industry.

8 GDOT ANALYSES – ENVIRONMENTAL AND ECONOMIC

8.1 GDOT Overview

GDOT 2013 Standard Specifications Construction of Transportation Systems details the requirements of using recycled materials in both rigid and flexible pavements in Georgia highways.

GDOT also allows for the use of reclaimed asphalt pavement (RAP), crushed concrete (RCA) and air cooled blast furnace slag in base and subbase applications. Subsections 800.2.01, 803.2 and 815.2.03 specify the use of RCA and slag as graded aggregate base and subbase materials and stabilizers. The use of RAP as a base material does not have any specific requirements as stated in Section 312, except that the contract will contain any necessary specifications.

In base and subbase courses, GDOT allows for the use of fly ash and granulated iron blast furnace slag as soil stabilizing admixtures as outlined in Subsections 300.2, 301.2 and 326.2. The use of both fly ash and slag must meet the requirements of AASHTO M 295 and AASHTO M 302 respectively when used as an admixture in base and subbase courses. Slag may also be used as a portion of embankment material as stated in Section 208.

Fly ash and blast furnace slag may also be used as a partial replacement for Portland cement in Portland cement concrete (PCC), as stated in Section 430.2 of the GDOT standard specifications. If either fly ash or slag is used in the mixture, Type IP cement should not be used and their use must follow the limits in Table 8-1. The resulting concrete mixes must conform to the specifications outlined in Subsection 430.3.06 and the individual materials of fly ash and slag must meet the specifications of Subsection 831.2.03.

Table 8-1 PCC Mix Design Fly Ash and Slag Additive Limits

Fly Ash	***Granulated Blast Furnace Slag***
Does not replace cement quantity more than 15 percent by weight.	If the 5-day National Weather Service expects temperatures higher than 60° F, the slag quantity is less than 50 percent of cement quantity, by weight.
Must replace cement at a rate of 1.25 to 2.0 pounds of fly ash to 1.0 pound of cement.	If the 5-day National Weather Service expects temperatures lower than 60° F but higher than 40° F, the slag quantity is less than 30 percent of cement quantity, by weight.
.	If the 5-day National Weather Service expects temperatures lower than 40° F, do not use slag.
	Must replace cement with slag at a rate of 1 pound of slag to 1 pound of cement.

Source: (GDOT, 2013b)

Section 402 of the standards list specifications of HMA mixes incorporating RAP or reclaimed asphalt shingles (RAS). These HMA mixtures must conform to Section 828 which lists the requirements for all HMA mixtures including: open-graded surface mixtures, stone matrix asphalt mixtures, superpave mixtures and fine-graded mixtures. The following states any specific requirements for each material according to Section 402.

RAP

1. For non-interstate projects, limit the percentage of RAP allowed in recycled mixes so that the overall amount of alluvial gravel does not exceed 5 percent of the total mix.

2. RAP used in the recycled mixtures for mainline or ramps may make up from 0 to 40 percent of the mixture.

3. The maximum ratio of RAP material to the recycled mixtures other than SMA (stone matrix asphalt) is 40 percent for continuous mix type plants and 25 percent for batch type plants.

4. The maximum ratio of RAP material to the recycled mixture is 15 percent for SMA mixes.

5. 100 percent of RAP material must pass the 2 in sieve.

6. RAP must be recycled and stored as outlined in Section 403.

RAS

1. The amount of RAS used must be no greater than 5 percent of the total mixture weight.

2. 100 percent of the shredded RAS pieces must be less than 0.5 inches in any dimension.

3. All foreign materials, paper, roofing nails, wood or metal flashing, must be removed.

GDOT LCCA procedures for pavement alternatives are outlined in Chapter 10 of the GDOT Pavement Design Manual (2005). GDOT does not have a specific LCCA tool, but does define procedures for conducting LCCAs. The following section summarizes the contents of the Pavement Design Manual related to LCCAs. When an LCCA is required, it should be performed early in project development along with a decision matrix, as seen in Appendix B. GDOT projects requiring an LCCA include:

1. new location projects;

2. full-depth pavement reconstruction projects as supported by a Pavement Evaluation Study;

3. widening projects where the new lanes are physically separated from existing pavement being retained, and;

4. when deemed necessary by the Engineer of Record or the Pavement Design committee.

A deterministic or probabilistic method may be employed when conducting an LCCA. In a deterministic approach input factors are expressed as fixed values without variability. In a probabilistic approach by varying input factors over time and a risk analysis is taken into account. FHWA recommends a probabilistic approach to LCCA, especially if there is a considerable amount of uncertainty in the input variables or when a probability distribution of the results is desirable. Deterministic procedures can be appropriate when one alternative has a clear economic advantage over the other alternatives in both best and worst case scenarios.

The general approach to an LCCA analysis should use the following steps:

1. Develop the new work or pavement reconstruction alternatives to be considered. Table 8-2 shows GDOT recommended initial construction and subsequent maintenance and rehabilitation schedules for an LCCA.

Table 8-2 Common GDOT LCCA Pavement Rehabilitation Cycles

Pavement Type	***Cycle***
Asphalt	Every 15 years: 5% deep patching, mill and inlay
Jointed Plain Concrete Pavement	Every 20 years: Grind, 5% slab replacement, waterproofing joint and cracks
Continuously Reinforced Concrete Pavement	Every 25 years: 2.5% punch-out repair

Source: (GDOT, 2005)

2. Determine the length of the analysis period and the discount rate. For GDOT projects use an analysis period of 40 years.

3. Determine the performance period and sequence of rehabilitation for each alternative over the duration of the analysis period. GDOT uses a discount rate of 4%.

4. Determine the agency cost for each alternative and rehabilitation strategy. Agency costs include all costs incurred directly by the agency over the life of the project. Unit costs will typically be determined by the GDOT bid price data on projects with quantities of comparable scale and geographic location.

$$Initial\ Construction\ Cost = \sum(U_p * Q_p) \quad (8\text{-}1)$$

$$Rehabilitation\ Cost = \sum\left(U_p * Q_p * \left[\frac{1}{(1+i)^n}\right]\right) \quad (8\text{-}2)$$

Where:

U	=	unit cost
Q	=	quantity
p	=	pay item

i	=	discount rate
n	=	year of expenditure

5. Evaluate user costs for each strategy (if appropriate). User costs are the delay, vehicle operating and crash costs incurred by users of the highway. Vehicle operating and crash costs are unlikely to vary among alternative pavements. User costs may become significant if work zone capacity is reached and a large queue occurs in one alternative and not the other. If this occurs user costs should be considered in the analysis.

6. Compute the Net Present Value (NPV) and the Equivalent Uniform Annual Cost (EUAC) for each alternative. The NPV represents all initial and future costs as a present value, and the EUAC represents the NPV of all costs and benefits as if they were to occur uniformly throughout the analysis period. The basic formulas for NPV and EUAC are as follows:

$$NPV = Initial\ cost + \sum_{k=1}^{n} Rehab\ Cost_k * \left[\frac{1}{(1+i)^n}\right] \quad (8\text{-}3)^*$$

$$EUAC = NPV * \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (8\text{-}4)$$

Where:

i	=	discount rate
k	=	year of activity
n	=	analysis period

*Everything to the right of the summation sign is equal to the rehabilitation cost or Equation 8-2.

7. Review and analyze the results.

8. Adjust input variables and re-run the analysis to determine the sensitivity of the results to the input variables (best case/worst case) scenarios).

9. Use the data to assist in selecting the appropriate alternative.

Once completed the LCCA may be used in the pavement type selection along with the GDOT decision matrix and engineering judgment. The decision matrix consists of the following key GDOT Decision factors:

1. construction and future rehabilitation costs,

2. duration of construction and rehabilitation activities, and

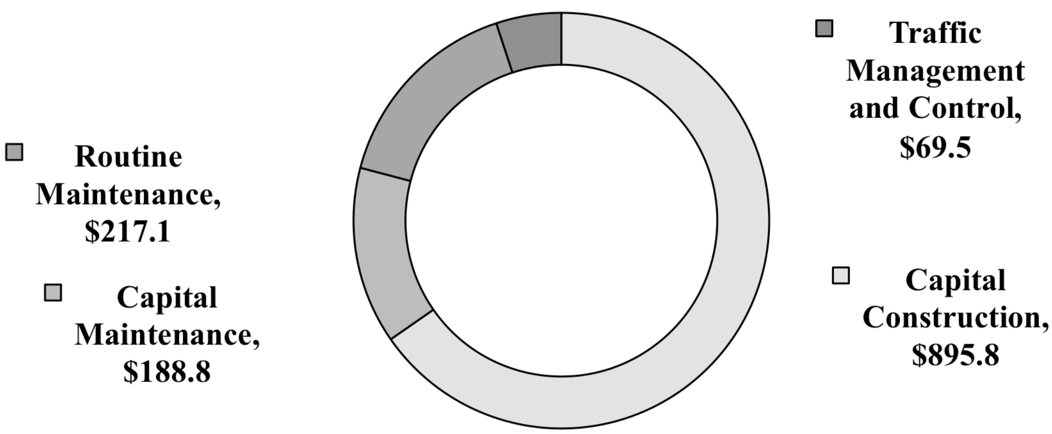
3. annualized costs (user and agency).

A sample decision matrix can be seen in Appendix B.

GDOT's FY 2013 budget was $2.24 billion, according the 2013 Investment Report distributed annually by GDOT. Federal funds, motor fuel taxes and other sources made up more than 99% of funding in the 2013 fiscal year. The rest of the funding was sourced from State General Funds and other sources of miscellaneous program income; a breakdown of the total FY 2013 budget can be seen in Appendix B. A further distribution of the FY 2013 State Motor Fuel Budget can also be seen in Appendix B. FHWA funds apportioned to GDOT were taken from the Governor's Budget Report for FY 2013.

A break down of the $1.4 billion portion of the GDOT put toward state maintained highways is shown in Figure 8-1. Less than one percent of the highway budget was funded by sources other than the motor fuel tax and FHWA funds, therefore those are not represented in Figure 8-1.According to the 2013 Investment Report there were a total of 18,000 centerline miles of federal and state roads managed by GDOT using the $1.4 billion dollar budget. The number of improved centerline miles of highway in 2013 by GDOT was not available.

Figure 8-1 GDOT FY 2013 Highway Construction and Maintenance Budget ($ millions)

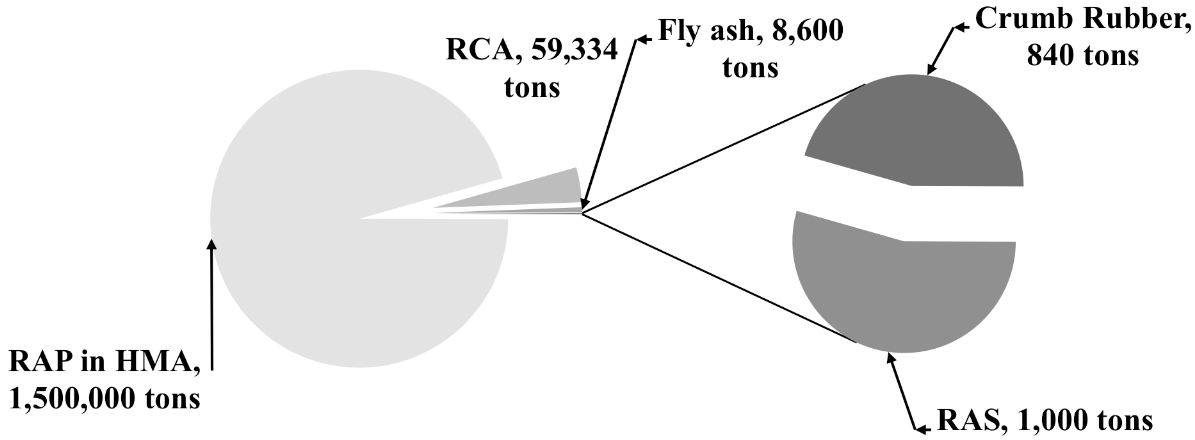


Source: **(GDOT, 2013a; OPB, 2013)**

Recycled materials used by GDOT in 2013 included RAP in HMA, RAS, RCA, fly ash and crumb rubber. It should be noted that recycled materials other than RCA, RAP, fly ash and RAS such as slag, are being incorporated into pavements, but the quantities of such recycled materials are not being tracked by GDOT. Figure 8-2 shows the total reported recycled material used in 2013 by GDOT, by weight. RAP in HMA was the most used material and comprised about 95% of the total tonnage of recycled material. It should be noted that RAP has a higher density than the other materials, making a comparison by weight somewhat misleading. The assumptions made in calculating the recycled materials used include those listed in Section 4.1, unless otherwise contradicted below, and the following:

- Approximately 25% of reported HMA mixes is RAP; the maximum RAP content in HMA is 40%, by weight.
- All fly ash was used in SMA as a filler material.

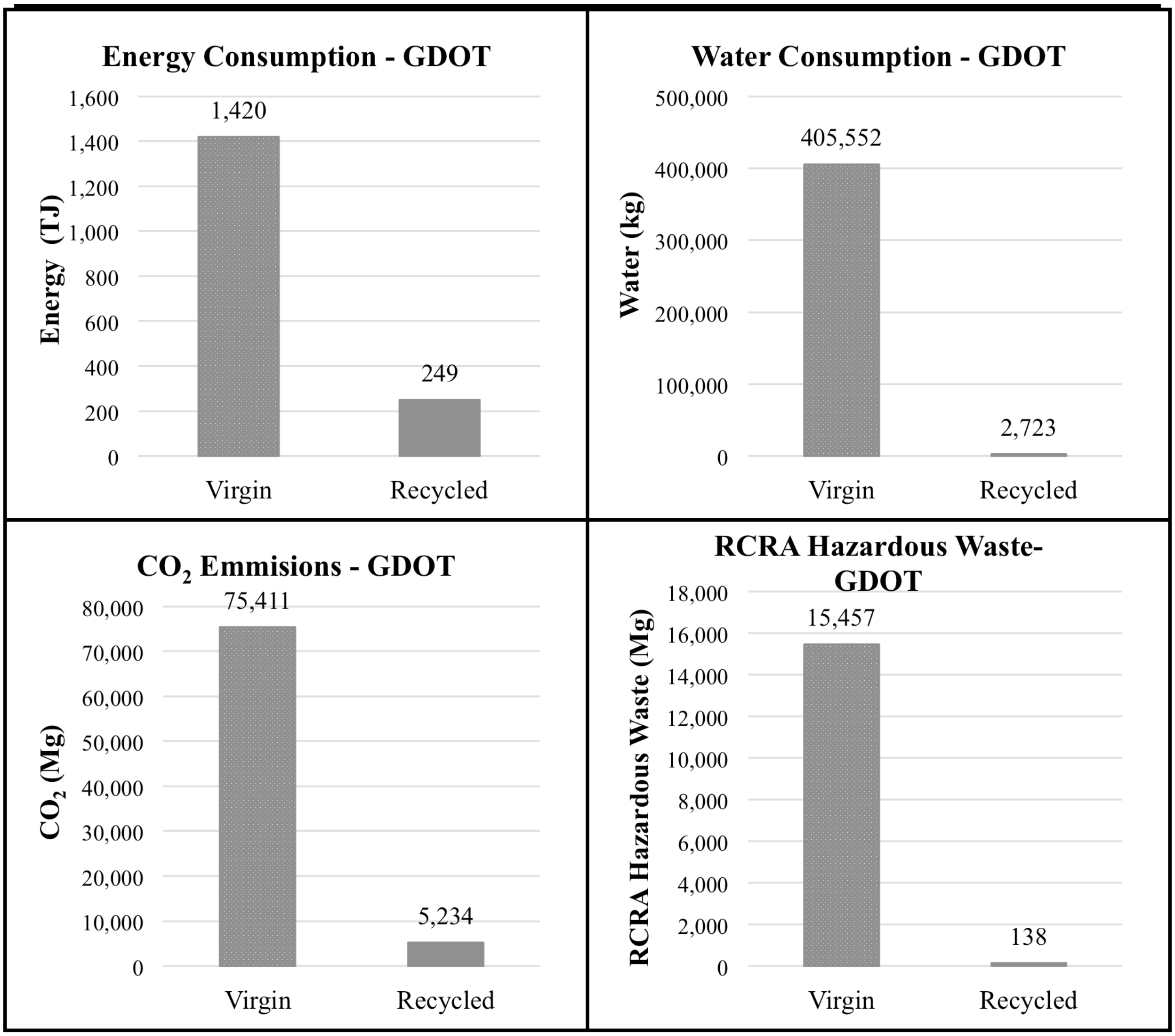
Figure 8-2 Reported Recycled Material Used in 2013 by GDOT



8.2 Environmental Analysis Results

The use of recycled material reduced the environmental impact in all the impact criteria; as seen in Figure 8-3. It is important to recall that these savings were calculated based on a one to one volume replacement of raw material with recycled material, i.e. these are the environmental savings because virgin materials had not been used. For a list of assumptions made in the LCA, reference Sections 4 and 5, as well as the assumptions listed in the previous section.

Figure 8-3 Environmental Benefits as a Result of GDOT Using Recycled Materials in 2013



The greatest reductions are seen in water consumption and hazardous waste production, followed by CO_2 emissions and finally energy consumption. To put these environmental savings into perspective:

- GDOT could fill 2,365 bath tubs with the total amount of water saved[1],
- the amount of RCRA hazardous waste saved is equivalent to the average amount produced by 1,688,975 U.S. households in one year[2],

[1] The total mass of water to fill one tub is 179 kilograms. (PWB, 2016)
[2] The average U.S. household produces 9.07 kilograms of hazardous waste per year (EPA, 2016)

- GDOT's CO_2 savings are equivalent to the emissions of 14,931 cars in one year[3], and

- the energy savings are equal to the average energy use of 29,751 U.S. households in one year[4].

Table 8-3 lists the savings and percent reductions of each environmental impact category.

Table 8-3 Summary of Environmental Benefits Accumulated by GDOT in 2013

Impact Category	*Virgin*	*Recycled*	*Savings*	*Percent Reduction*
Engergy (TJ)	1,420	249	1,171	83%
Water consumption (kg)	405,552	2,723	402,829	99%
CO_2 (Mg)	75,411	5,234	70,178	93%
RCRA hazardous waste (Mg)	15,457	138	15,319	99%

Another parameter to measure environmental savings by using recycled materials is social carbon cost (SCC). While not a PaLATE output, SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This can include, agricultural productivity, human health, property damages from increased flood rise and the value of ecosystem services due to climate change, (EPA, 2013). Based on EPA estimates for SCC in 2013, 34 in 2007 dollars per metric ton CO_2, at a 3 percent discount rate (future values equated to present values), GDOT saved about 2.63 million in 2007 dollars in SCC. If inflation is considered, GDOT saved about 2.96 million in 2013 dollars and 3.02 million in 2016 dollars in SCC.

8.3 Economic Analysis Results

The estimated cost savings of using recycled material in 2013 is shown in Table 8-4. It should be noted that these savings reflect only the price of the material and do include the potential price of hauling to the construction site, hauling to a landfill or any landfilling disposal fees. A description of assumptions made in each materials unit cost savings can be found below as well as in Sections 4 and 6 of this report. For a more detailed explanation of virgin material replacement by recycled material reference the recycled material in Section 2 Common Recycled Materials. It should be noted crumb rubber was not taken into account in the cost savings analysis. Even though there are environmental benefits of reusing tire rubber, the primary purpose of crumb rubber in asphalt mixtures is to act as a binder modifier, not necessarily as a virgin material replacement.

[3] The average car emits 4,700 kilogram of CO_2 per/year.(EPA, 2008)
[4] The average U.S. household consumes 0.03936 terajoules of energy per year. (EIA, 2015)

Table 8-4 Calculated GDOT FY 2013 Cost Savings

Recycled Material	***Quantity (Tons)***	***Savings($/ton)***	***Total Savings ($)***
RAP in HMA	1,500,000	$6.62	$9,932,523
RAS	1,000	$67.65	$67,652
Fly Ash	8,600	$4.33	$37,235
RCA	59,334	$1.03	$60,849
Total	**1,568,934**		**$10,098,259**

The unit price of almost all material is given in dollars per ton (weight) of material. The unit weights of recycled materials and their corresponding virgin materials are not equal, i.e. the weight of one cubic yard of RCA does not equal the weight of one cubic yard of aggregate/gravel. For this reason, the volume of the known tonnage of recycled material was calculated using a known unit weight. The calculated volume of recycled materials was then assumed equal to the volume of the corresponding virgin material. The weight of the equal volume of virgin material was then calculated and used in a cost analysis to compare the prices of recycled and virgin material. Total savings and unit savings per ton of recycled material were then estimated for Georgia in FY 2013.

The unit cost of virgin materials in the state of Georgia was estimated using Engineering News-Record (ENR) material price list for the city of Atlanta and the total average price of the twenty cities tracked by ENR. Prices were averaged for both lists in a time period ranging from July 2012 and January 2014, in order to account for both the fiscal and calendar 2013 year. While there was not a significant change in average price for the twenty city average during this time period, prices among the individual cities varied and had a greater tendency for change. For this reason, the two price lists were averaged in determining the final purchasing price of the virgin materials. Because of the fluctuation in price, GDOT keeps a price index of asphalt cement. This was used instead of ENR to determine the price of liquid asphalt cement.

The unit cost of recycled materials was determined by contacting suppliers and state pavement associations and an average for the price of one ton of recycled material was determined. Suppliers were contacted in the second phase of data collection, sometimes one or more years after 2013. When available the 2013 pricing was used, but in some instances only the current price or pricing trends could be given.

Once the purchasing unit price of both the virgin and recycled materials was determined, the cost of the total quantity of recycled material and the total calculated quantity of virgin material were determined. The cost savings of using each recycled material was then calculated as the difference between the two. A unit savings could be found by dividing the total savings by the quantity of recycled material as shown in Table 8-4. All pricing data can be found in Table A-8 through Table A-10 in Appendix A.

8.4 GDOT Overall Findings

As stated in the overview section, there were 18,000 miles of road managed by GDOT in 2013. It should be noted these are the total miles of road throughout the state, not the number of miles of improved road in 2013. The total estimated savings of about $10.1 million equates to about $561 saved per mile of road in 2013. This estimation does not take into account potential future savings of using recycled materials. Future costs include hauling to a landfill, a disposing fee and potential higher rehabilitation costs. If the total cost savings were added to the highway related spending in FY 2013, it would account for 0.73% of funding. In other words, 0.73% of costs were cut to the state highway programs by using recycling materials.

Table 8-5 details the environmental savings per mile of road in FY 2013. To put this into perspective per mile GDOT is saving, (using the same conversions as in Section 8.2):

- the energy use of 1.7 U.S. households in one year,
- the water it would take to fill 0.13 bath tubs,
- the CO_2 emissions of 0.83 cars in one year, and
- the RCRA hazardous waste produced by 94 households in one year.

Table 8-5 GDOT Environmental Savings per Mile

Impact Category	***Savings Per Mile***
Energy (MJ)	65,056
Water consumption (kg)	22
CO_2 (kg)	3,899
RCRA hazardous waste (kg)	851

9 IDOT ANALYSES – ENVIRONMENTAL AND ECONOMIC

9.1 IDOT Overview

IDOT Standard Specifications for Road and Bridge Construction details the requirements of using recycled materials in highway pavements. The standards were last revised in 2016. The IDOT Bureau of Materials and Physical Research has also put out a list of policy memorandums regarding production, storage, testing and approval of materials that must also be followed for all state projects containing these materials.

Division 1000 of the IDOT standards provides the requirements needed for all materials used in construction. The main sections pertaining to recycled materials in pavements are: Cement (1001), Fine Aggregates (1003), Coarse Aggregates (1004), RipRap (1005), Finely Divided Materials (1010), Mineral Filler (1011), Portland Cement Concrete (1020) and Reclaimed Asphalt Pavement and Reclaimed Asphalt Shingles (1031). The following paragraphs list the applications of recycled materials and general specifications of mix designs if listed in the standards. The policy memorandums should also be consulted for physical requirements of the materials.

Also included in the standards are specifications for using crumb rubber in reflective crack control system mixtures and glass beads in pavement markings. In general, the accepted rubber blend should not be more than 25 or 33 percent by weight of binder, depending on the mixture. Glass beads shall be uniformly mixed throughout the material at the rate of at least 30 percent by weight of the thermoplastic compound, retained on a No. 100 sieve.

Fly ash (Class C or F), ground-granulated blast-furnace slag (GGBFS), microsilica and cement kiln dust, may be used as partial replacements of cement or in blended cements and as finely divided materials. In general, the maximum percent replacement by weight of the total blended cement for each material is:

Class C Fly Ash 30%

Class F Fly Ash 25%

GGBFS 35%

Microsilica 10%

Cement Kiln Dust .... Approval of Engineer

The PCC mixture shall not consist of more than two finely divided materials and shall constitute a maximum of 35.0 percent of the total cement plus finely divided materials.

Fine aggregate for bedding, backfill, trench backfill, embankment, porous granular backfill and French drains may consist of wet bottom boiler slag, air cooled blast -furnace slag (ACBFS), or GGBFS. For trench backfill, RCA sand (resulting from mechanical crushing of concrete) may also be used. Fine aggregate for HMA and SMA may consist of ACBFS and steel slag. When blended, the fine aggregate mixture must pass the No. 200 sieve requirements.

Recycled materials may be used as coarse aggregates in the base and subbase, embankments and both rigid and flexible pavements. These include RCA, RAP, ACBFS, steel slag and wet bottom boiler slag.

The following list shows allowable recycled material in applications other than HMA; Table 9-1 shows the allowable recycled material in HMA as a coarse aggregate

PCC: RCA, ACBFS (ACBFS should not be mixed with gravel, crushed gravel or crushed stone aggregates)

Base and Subbase: RCA, ACBFS

Embankment and Fill: RCA, ACBFS, wet-bottom boiler slag

Table 9-1 Recycled Material Coarse Aggregate Allowed in IDOT HMA Mixes

Use	***Mixture***	***Recycled Material Allowed***
Class A	Seal or Cover	ACBFS, Crushed Steel Slag, RCA
HMA Low ESAL	Stabilized Subbase or Shoulders	ACBFS, Crushed Steel Slag[1] (allowed in surface only), RCA
HMA High ESAL, Low ESAL	Binder IL-19.0 or IL-19.0L, SMA Binder	ACBFS, RCA[2]
HMA High ESAL, Low ESAL	C Surface and Leveling Binder IL-9.5 or IL9.5L, SMA Ndesign 50 Surface	ACBFS, Crushed Steel Slag[3], RCA[2]
HMA High ESAL	D Surface and Leveling Binder IL-9.5, SMA Ndesign 50 Surface	ACBFS, Crushed Steel Slag[3], RCA[2]
HMA High ESAL	E Surface IL-9.5, SMA Ndesign 80 Surface	ACBFS, Crushed Steel Slag, RCA[2]
HMA High ESAL	F Surface IL-9.5, SMA Ndesign 80 Surface	ACBFS, Crushed Steel Slag, RCA[2]

Source: (IDOT, 2016)
[1] Crushed Steel slag allowed in shoulder surface only.
[2] RCA not permitted in SMA mixes.
[3] Crushed steel slag shall not be used as leveling binder.

The use of RAP/FRAP (fractionated RAP) and RAS is also permitted in HMA mixes as both an aggregate and binder replacement. The amount of RAS permitted in HMA mixtures when used alone or with RAP or FRAP should not exceed 5.0 percent by weight of the total mix. Table 9-2and Table 9-3 show the maximum amount of asphalt binder replacement by either RAP or FRAP when used in alone or in conjunction with RAS.

Table 9-2 IDOT RAP/RAS Maximum ABR Percentage

HMA Mixtures[1]	***RAP/RAS Maximum ABR %***		
Ndesign	Binder/Leveling Binder	Surface	Polymer Modified
30	30	30	10
50	25	15	10
70	15	10	10
90	10	10	10

Source: (IDOT, 2016)
[1] For Low ESAL HMA shoulder and stabilized subbase, the RAP/RAS ABR shall not exceed 50 percent of the mixture by weight. When RAP/RAS ABR exceeds20 percent, the high and low virgin asphalt binder grades shall each be reduced by on grade. If WMA technology is utilized and production temperatures do not exceed 275̊ F, the high and low virgin asphalt binder grades shall each be reduced by one grade when RAP/RAS ABR exceeds 25 percent.

Table 9-3 IDOT FRAP/RAS Maximum ABR Percentage

HMA Mixtures[1]	***FRAP/RAS Maximum ABR %***		
Ndesign	Binder/Leveling Binder	Surface	Polymer Modified[2]
30	50	40	10
50	40	35	10
70	40	30	10
90	40	30	10

Source: (IDOT, 2016)
[1]For Low ESAL HMA shoulder and stabilized subbase, the FRAP/RAS ABR shall not exceed 50 percent of the mixture by weight. When RAP/RAS ABR exceeds20 percent, the high and low virgin asphalt binder grades shall each be reduced by on grade. If WMA technology is utilized and production temperatures do not exceed 275̊ F, the high and low virgin asphalt binder grades shall each be reduced by one grade when RAP/RAS ABR exceeds 25 percent.
[2]For SMA the FRAP/RAS ABR shall not exceed 20 percent. For IL-4.75 mix the FRAP/RAS ABR shall not exceed 30 percent.

The IDOT Mechanistic Pavement Design and Life-Cycle Cost Analysis is a spreadsheet that will perform the calculations required by Chapter 54 of the Bureau of Design and Environment Manual (2013) to determine a design pavement thickness and conduct an LCCA. The following section will summarize the selection basis, input parameters and calculation of the spreadsheet.

The selection of pavement design alternatives depends on the project type and is based on annual life-cycle costs. The project types consist of widening, new construction or reconstruction. When considering widening projects the alternative design with the lowest first cost is selected for construction. New construction and reconstruction projects follow a similar selection process that compares the difference in annualized costs between alternatives. If the difference in annualized life cycle costs is greater than 10 percent, then, the pavement alternative with the lower cost is selected. If the difference is less than 10 percent, then the selection is based on a bidding process and/or a Pavement Selection Committee. Both new construction and reconstruction projects must consider new pavement designs for both rigid and flexible pavements. A reconstruction project will also include supplemental pavement designs for unbonded jointed plain concrete (JPCP)/continuously reinforced concrete (CRCP) overlay and HMA overlay of rubblized PCC pavement. The designer shall choose which supplemental designs are appropriate options.

Inputs of the IDOT LCCA spreadsheet include maintenance and rehabilitation activity schedules and anticipated quantities of major pay items. IDOT also assumes a 45 year service life of the pavement and a discount rate of 3% to predict annual cost, therefore eliminating the need to adjust pay item costs for inflation. Appendix C, Table C-1 through Table C-3 present suggested maintenance and rehabilitation schedules for different pavement types.

Equation 9-1 is used by IDOT to determine the annual costs of alternatives during the selection process.

$$A = D + M + CRF_n * [C + R_1(PWF_{n1}) + R_2(PWF_{n2}) + \ ... + R_n(PWF_{nn})] \qquad (9\text{-}1)$$

Where:

A	=	total annual cost per mile
D	=	annual administrative and overhead cost per mile (assumed equal for all pavement types)
M	=	total annual maintenance cost per mile (assumed to be equal for all pavement types)
CRF_n	=	capital recovery factor for year n calculated as:

$$CRF_n = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (9\text{-}2)$$

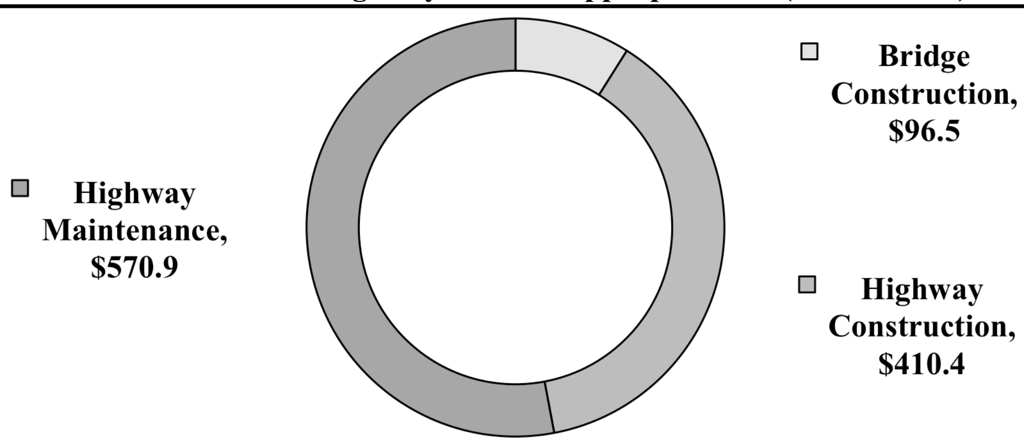
i	=	discount rate (0.03)
n	=	year within analysis period in number of years after initial construction
C	=	initial construction cost per mile
R_1	=	first rehabilitation cost per mile
R_2	=	second rehabilitation cost per mile
R_n	=	n^{th} rehabilitation cost per mile
PWF_{nn}	=	present worth factor for the nth number of years after initial construction that the nth rehabilitation activity is performed:

$$PWF_{nn} = \frac{1}{(1+i)^{nn}} \qquad (9\text{-}3)$$

n1	=	number of years after initial construction that the first rehabilitation activity is performed
n2	=	number of years after initial construction that the second rehabilitation activity is performed
nn	=	number of years after initial construction that the n^{th} rehabilitation activity is performed

The IDOT 2013 Budget actual appropriations can be found in the FY 2015 state budget. IDOT had a total operating budget of $2.6 billion dollars with about $1.1 billion appropriated to highway construction and maintenance as seen in Figure 9-1. The recommended budget according the FY 2103 state budget was about $2.7 billion with about $1.6 billion appropriated to highway construction and maintenance. Due to the nature of this report, the portion of the operating budget relating to only state-maintained highways will be summarized. The total FY 2013 actual appropriations can be found in Figure C-1 in Appendix C. According to the FY 2015 budget report about 85% of the appropriated state construction dollars was accomplished. In 2013 IDOT improved 661 miles of a total 16,000 centerline miles of state maintained roads.

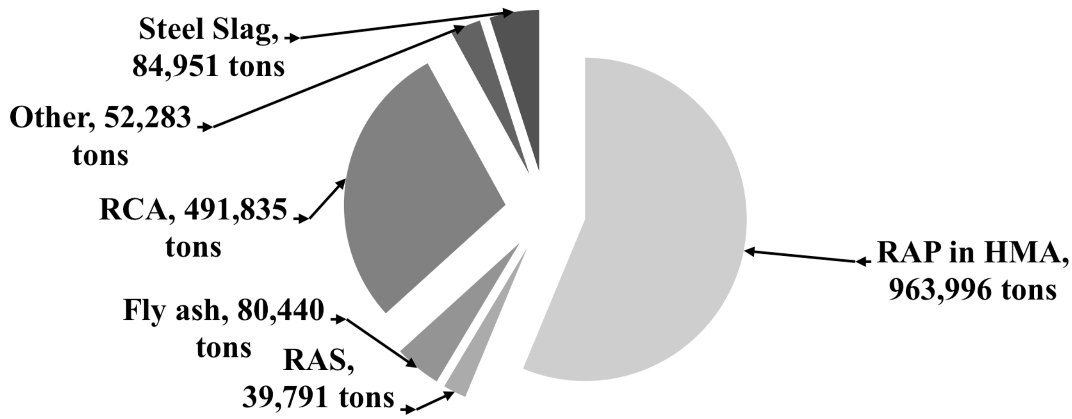
Figure 9-1 IDOT FY 2013 Highway Related Appropriations ($ in millions)



Source: **(OMB, 2015)**

Recycled materials used by IDOT in 2013 included RAP in HMA, RAS, RCA, fly ash and steel slag, as shown in Figure 9-2. The Other category in Figure 9-2 comprises recycled materials that amount to one percent or less of the total weight of recycled materials used by IDOT. These include ACBFS, by-product lime, crumb rubber, glass beads, GGBFS, microsilica and steel reinforcement. Of the member state DOTs, IDOT is the only DOT required to report their recycled material usage, as such the reported recycled material was taken directly from the Illinois Center for Transportation report *Illinois Highway Materials Sustainability Efforts of 2013*.RAP in HMA was the most used material, equaling about 56 percent of the total weight of recycled materials. The amount of RCA used was about 30 percent of the total weight, while each of the rest of the recycled materials took up less than 5 percent of the total weight.

Figure 9-2 Reported Recycled Material Used in 2013 by IDOT

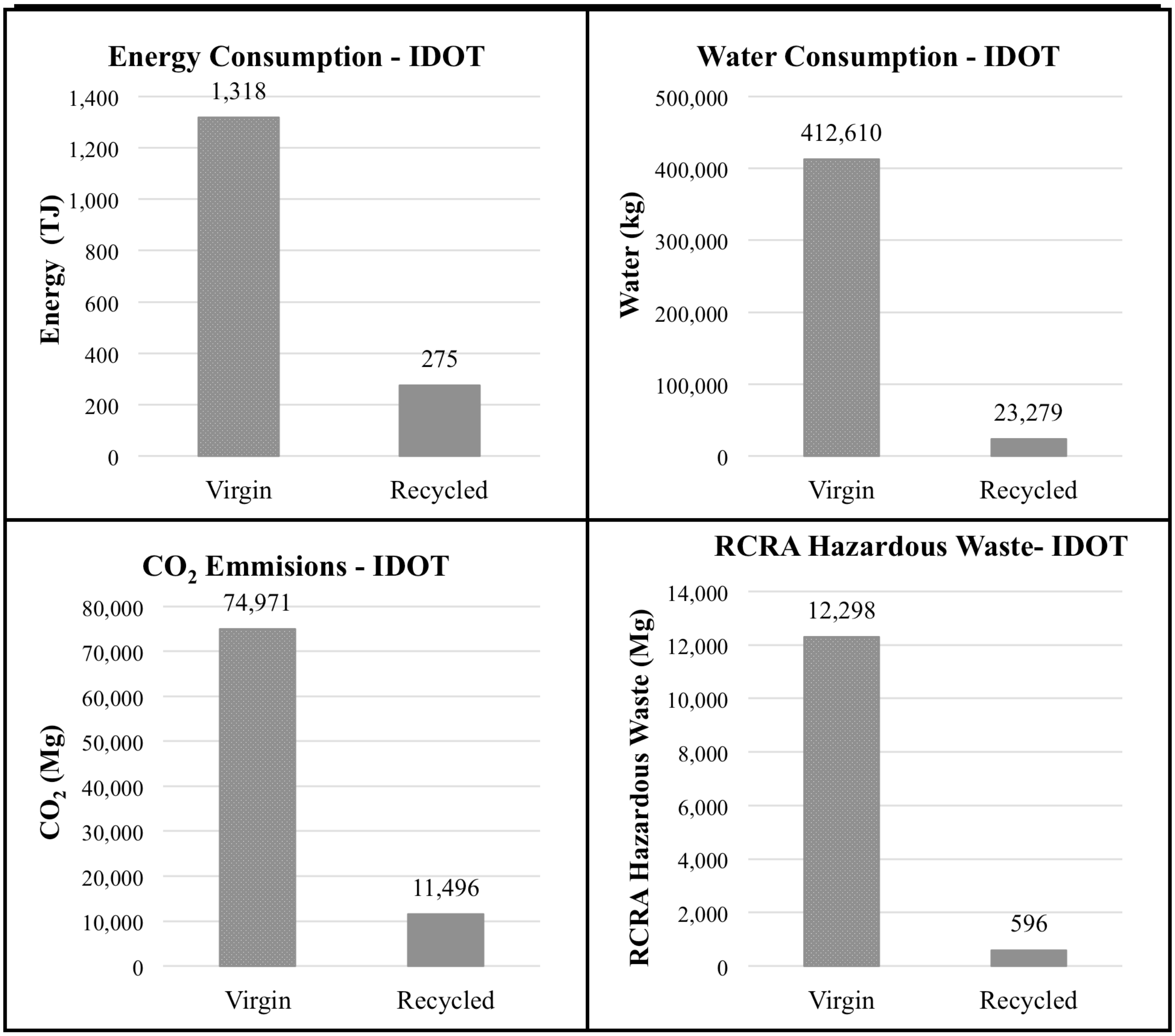


Source: **(Lipper et al., 2014)**

9.2 Environmental Analysis Results

The use of recycled material reduced the environmental impact in all the impact criteria; as seen in Figure 9-3. It is important to recall that these savings were calculated based on a one to one volume replacement of virgin material with recycled material, i.e. these are the environmental savings if resulting from the use of recycled materials. Any recycled materials reported for IDOT that comprised less than one percent of the total recycled materials, by weight, were assumed to have negligible effects on the LCA and were therefore not included. Steel slag was also not included in the analysis because it is not included in PaLATE. For a list of assumptions made in the LCA, reference Sections 4 and 5.

Figure 9-3 Environmental Benefits as a Result of IDOT Using Recycled Materials in 2013



The greatest reductions are seen in hazardous waste production, followed by water consumption, CO_2 emissions and finally energy consumption. To put these environmental savings into perspective:

- IDOT could fill 2,286 bath tubs with the total amount of water saved[1],
- the amount of RCRA hazardous waste saved is equivalent to the average amount produced by 1,290,187 U.S. households in one year[2],

[1] The total mass of water to fill one tub is 179 kilograms. (PWB, 2016)
[2] The average U.S. household produces 9.07 kilograms of hazardous waste per year. (EPA, 2016)

- IDOT's CO_2 savings are equivalent to the emissions of 13,505 cars in one year[3], and

- the energy savings are equal to the average energy use of 26,499 U.S. household in one year[4].

Table 9-4 lists the savings and percent reductions of each environmental impact category.

Table 9-4 Summary of Environmental Benefits Accumulated by IDOT in 2013

Impact Category	*Virgin*	*Recycled*	*Savings*	*Percent Reduction*
Engergy (TJ)	1,318	275	1,043	79%
Water consumption (kg)	412,610	23,279	389,331	94%
CO_2 (Mg)	74,971	11,496	63,475	85%
RCRA hazardous waste (Mg)	12,298	596	11,702	95%

Another parameter to measure environmental savings by using recycled materials is social carbon cost (SCC). While not a PaLATE output, SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This can include, agricultural productivity, human health, property damages from increased flood rise and the value of ecosystem services due to climate change, (EPA, 2013). Based on EPA estimates for SCC in 2013, 34 in 2007 dollars per metric ton CO_2, at a 3 percent discount rate (future values equated to present values), IDOT saved about 2.38 million in 2007 dollars in SCC. If inflation is considered, IDOT saved about 2.67 million in 2013 dollars and 2.73 million in 2016 dollars in SCC.

9.3 Economic Analysis Results

The estimated cost savings of using recycled material in 2013 is shown in Table 9-5. It should be noted that these savings reflect only the price of the material and do include the potential price of hauling to the construction site, hauling to a landfill or any landfilling disposal fees. A description of assumptions made in each materials unit cost savings can be found below as well as in Sections 4 and 6 of this report. For a more detailed explanation of virgin material replacement by recycled material reference the recycled material in Section 2 Common Recycled Materials.

[3] The average car emits 4,700 kilogram of CO_2 per/year. (EPA, 2008)
[4] The average U.S. household consumes 0.03936 terajoules of energy per year. (EIA, 2015)

Table 9-5 Calculated IDOT FY 2013 Cost Savings			
Recycled Material	***Quantity (Tons)***	***Savings($/ton)***	***Total Savings ($)***
Fly Ash	80,440	$43.36	$3,487,531
GGBFS	15,045	$16.04	$241,267
RAP in HMA	963,996	$6.46	$6,231,942
RAS	39,791	$55.02	$2,189,116
RCA	491,835	-$0.01	-$5,101
Total	**1,591,107**		**12,144,755**

The unit price of almost all material is given in dollars per ton (weight) of material. The unit weights of recycled materials and their corresponding virgin materials are not equal, i.e. the weight of one cubic yard of RCA does not equal the weight of one cubic yard of aggregate/gravel. For this reason, the volume of the known tonnage of recycled material was calculated using a known unit weight. The calculated volume of recycled materials was then assumed equal to the volume of the corresponding virgin material. The weight of the equal volume of virgin material was then calculated and used in a cost analysis to compare the prices of recycled and virgin material. Total savings and unit savings per ton of recycled material were then estimated for IDOT in FY 2013.

The unit cost of virgin materials in the state of Illinois was estimated using Engineering News-Record (ENR) material price list for the city of Chicago and the total average price of the twenty cities tracked by ENR. Prices were averaged for both lists in a time period ranging from July 2012 and January 2014, in order to account for both the fiscal and calendar 2013 year. While there was not a significant change in average price for the twenty city average during this time period, prices among the individual cities varied and had a greater tendency for change. For this reason, the two price lists were averaged in determining the final purchasing price of the virgin materials. Because of the fluctuation in price, IDOT keeps a price index of asphalt cement. This was used instead of ENR to determine the price of liquid asphalt cement.

The unit cost of recycled materials was taken as the equivalent unit values presented as part of the Illinois Center for Transportation report, *Illinois Highway Material Sustainability Efforts of 2013*. The report also provided the total reclaimed materials used in Illinois in 2013.

Once the unit purchasing price of both the virgin and recycled materials was determined, the cost of the total quantity of recycled material and the total calculated quantity of virgin material were determined. The cost savings of using each recycled material was then calculated as the difference between the two. A unit savings could be found by dividing the total savings by the quantity of recycled material as shown in Table 9-5. All pricing data can be found in Appendix A.

9.4 IDOT Overall Findings

As stated in the overview section, there were 661 miles of road improved by IDOT in 2013. The total estimated savings of about $12 million equates to about $18,400 saved per improved mile of road in 2013. This estimation does not take into account potential future savings of using recycled materials. Future costs include hauling to a landfill, a disposing fee and potential higher rehabilitation costs. If the total cost savings were added to the highway related spending in FY 2013, it would account for 1% of funding. In other words, 1% of costs were cut to the state highway programs by using recycling materials.

Table 9-6 details the environmental savings per mile of road in FY 2013. To put this into perspective per mile IDOT is saving, (using the same conversions as in Section 9.2):

- the energy use of 40 U.S. households in one year,
- the water it would take to fill 3.5 bath tubs,
- the CO_2 emissions of 20cars in one year, and
- the RCRA hazardous waste produced by 1,950 households in one year.

Table 9-6 IDOT Environmental Savings per Improved Mile in 2013

Impact Category	***Savings Per Mile***
Energy (MJ)	1,577,912
Water consumption (kg)	589
CO_2 (kg)	96,029
RCRA hazardous waste (kg)	17,703

10 MNDOT ANALYSES – ENVIRONMENTAL AND ECONOMIC

10.1 MnDOT Overview

MnDOT Standard Specifications for Construction 2016 Edition provides standards for using recycled material in highway pavements. Recycled materials that can be used include fly ash, granulated blast furnace slag, silica fume, recycled concrete material (RCA), reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS). The following paragraphs highlight the general specifications listed in the standards for surface and base courses.

Sections 3102 and 3103 of the standard lists the requirements of using slag, fly ash and silica fume in blended hydraulic cement to be used in PCC pavement. The blended cement must meet the requirements of AASHTO M 302 (Grade 100 or Grade 102), AASHTO M240, Type IS or Type IP, or Type IL. Both Class F and Class C fly ash may be used, but must meet the requirements ASTM C 618 standard. Fly ash may also be used as mineral filler. The maximum percentage of the total blended cement mixture that each material may constitute is:

Fly Ash 25%

Slag 35%

Silica Fume 7.0%

Aggregate applications for recycled materials include both rigid and flexible surface pavements, as a granular material and as a base aggregate. When used in PCC as described in Section 3137, RCA is classified as Class R and can be used as in blend with other classes of coarse aggregates. Any reinforcing steel and material passing the No. 4 sieve must be removed from the RCA before its use.

When used as a granular material, RAP, RCA and recycled aggregate material may be used for products not required to use 100% virgin aggregates. The bitumen content of the blended materials should be no greater than 3.0% and the RCA content should be no greater than 75 percent of the material blend.

RAP, RCA, recycled glass and recycled aggregates may be used as base course and surface course aggregates provided they meet the requirements listed in Table 10-1 and Section 3138. In addition to the requirements listed in Table 10-1, as surface aggregates, RCA can only be used for roadway shoulder, glass cannot be used and there is no restriction on the bitumen content, if used for shouldering.

Table 10-1 MnDOT Quality Requirements for Recycled Material in Base Course

Requirement	*Classes 1, 3, 4, 5, 5Q and 6*
Maximum Bitumen Content of Composite	3.5%
Maximum Masonry block %	10%
Maximum Percentage of glass[1]	10%
Maximum size of glass[1]	¾ in.
Crushing (Class 5, 5Q and 6)[2]	10% for Class 5 60% for Class 5Q and 15% for Class 6[3]
Maximum amount of Brick	1.0%[4]
Maximum amount of other objectionable materials including but not limited to: wood, plant matter, plastic, plaster and fabric	0.3%[4]

Source: (MnDOT, 2015)

[1] Glass must meet certification requirements on the Grading and Base website. Combine glass with other aggregates during the crushing operation

[2] Material crushed from quarries is considered crushed material

[3] If material ≥ 20% RAP and/or Concrete, Class 5 crushing requirement is met;
If material ≥ 60% RAP and/or Concrete, Class 5Q crushing requirement is met;
If material ≥ 30% RAP and/or Concrete, Class 6 crushing requirement is met

[4] The contractor/supplier may not knowingly allow brick and other objectionable material and must employ a QC process to screen it out, before it becomes incorporated into the final product.

In bituminous mixtures, RAP, RAS and steel slag may be used as specified in Section 3139. If used, steel slag cannot exceed more than 25% to the total mixture aggregate.

Control Recycled materials used in mixture by evaluating the ratio of new added asphalt binder to total asphalt binder: When using RAP and RAS, the requirements of Table 10-2 must used to control binder content and the addition of either recycled material.

Table 10-2 MnDOT Requirements for Ratio of Added New Asphalt Binder to Total Asphalt Binder[1] (min%)

Specified Asphalt Grade	*RAS Only*	*RAS and RAP*	*RAP Only*
PG XX-28, PG 52-24, PG 49-34, PG 64-22 Wear, Non-Wear	70, 70.	70, 70	70, 65
PG 58-34, PG 64-34, PG 70-34 Wear and Non-wear	80	80	80

Source: (MnDOT, 2015)

[1] The ratio of added new asphalt binder to total asphalt binder is calculated as (added binder/total binder) x 100

MnDOT LCCA procedures are presented in Chapter 7 of the MnDOT Pavement Design Manual. MnDOT also provides spreadsheets (MnLCCA) in order to perform LCCA computations following the processes outlined in the manual, which will be summarized in the following section. MnDOT has two pavement design categories which are used to determine the LCCA process to perform; one for pavements with a design life (DL) of at least 20 years and one for pavements with a DL less than 20 years. Pavements with a DL of at least 20 years include:

- New/reconstructed HMA or PCC
- Full-depth reclamation (FDR)/stabilized full-depth reclamation (SFDR)
- Rubblization of PCC
- Cold-in-place recycling (CIR)
- PCC overlays
- Other

Pavements with a DL less than 20 years includes all HMA overlays 5.0 inches or less but greater than 2.0 inches. Any pavement with a thickness of at most 2.0 inches does not require an LCCA.

MnDOT has two LCCA processes; Formal and District. The Formal LCCA should be used for projects that have 60,000 or more contiguous square yards of pavement in the DL ≥ 20 category or any project the district wants to evaluate. The District LCCA should be used for projects that have more than 7,500 square yards but less than 60,000 contiguous square yards of pavement in the DL ≥ 20 category or projects that have 60,000 or more square yards of pavement in the DL < 20 category and does not meet the requirements for the Formal LCCA process. The required alternatives for each LCCA process are shown in Table 10-3.

Table 10-3 MnDOT LCCA Required Alternative Pavement Designs

	Required Alternatives for DL ≥ 20			***Required Alternatives for DL < 20***		
Alternate #	1	2	3	1	2	3
Pavement Material	HMA	PCC	PCC	As proposed in Scoping or Project Development	HMA	PCC
Design Life	20 years	20 years	35 years	For pavement design proposed	20 years	20 years

Source: (MnDOT, 2016)

After an LCCA process is chosen the net present cost of each alternative can be determined by using the MnLCCA spreadsheets. Each spreadsheet is updated with the most recent standard prices. Required inputs from the user include the analysis period, initial cost of a representative one-mile segment and pavement design of each alternative. Once the user enters all the necessary data the LCCA spreadsheet will determine the necessary maintenance and rehabilitation schedules, future costs of the alternatives and the net present cost of each alternative. The formulas used to for each LCCA processes can be seen in Chapter Seven of the Pavement Design Manual and the rehabilitation schedules used can be seen in Appendix D.

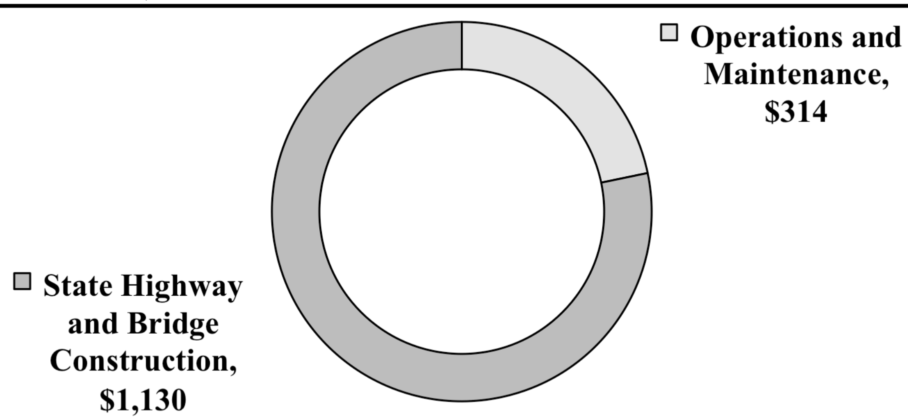
Once the net present values are calculated the alternative pavement design must be selected. If the District LCCA process was performed, then the alternative with the lowest net present cost is selected. If the Formal LCCA process was performed, then the selection must follow these guidelines:

- If a HMA alternate and a PCC alternate have net present costs within 10%, then the lowest PCC and HMA alternates will continue to alternate bidding
- Otherwise the alternate with the lowest net present cost.

Exceptions for not choosing the low cost alternate may be made based on the judgment of the Engineer.

The MnDOT FY 2013 Transportation Funding is detailed in the FY 2013 MnDOT funding statement, prepared by MnDOT and Minnesota Management & Budget (MMB). MnDOT had a total budget of $3.14 billion in FY 2013. Sources of the transportation funds and the breakdown of all the uses of funds can be seen in Appendix D. Due to the nature of this report, the portion of the operating budget relating to only state-maintained highways will be summarized and are shown in Figure 10-1. MnDOT managed about 12,000 centerline miles of state highways in 2013. The number of centerline miles improved in 2013 using the total highway budget of $1.4 billion was not available to use in this report.

Figure 10-1 MnDOT FY 2013 Highway Construction and Maintenance Budget ($ in millions)

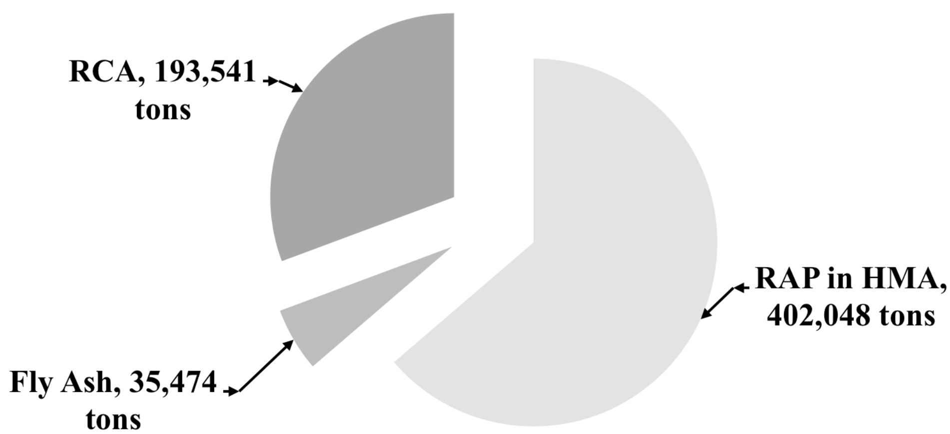


Source: **(MnDOT, 2013)**

Recycled materials used by MnDOT in 2013 included RAP in HMA, RCA and fly ash. It should be noted that recycled materials other than RCA, RAP and fly ash such as slag and RAS, are being incorporated into pavements, but the quantities of such recycled materials are not being tracked by MnDOT. Figure 10-2 shows the total reported recycled material used in 2013 by MnDOT, by weight. RAP in HMA was incorporated the most and comprised about 64 percent of the total tonnage of recycled material. The assumptions made in calculating the recycled materials used include those listed in Section 4.1, unless otherwise contradicted below, and the following:

- The average percent of RAP per ton of HMA, was assumed to be 18%. The HMA pavement density was assumed to be 138 lbs/CF.
- The average percent of RCA in PCC was assumed to be 80%. The PCC pavement density was assumed to be 142 lbs/CF.
- The quantity of fly ash in PCC was assumed to be 170 lbs/CY.

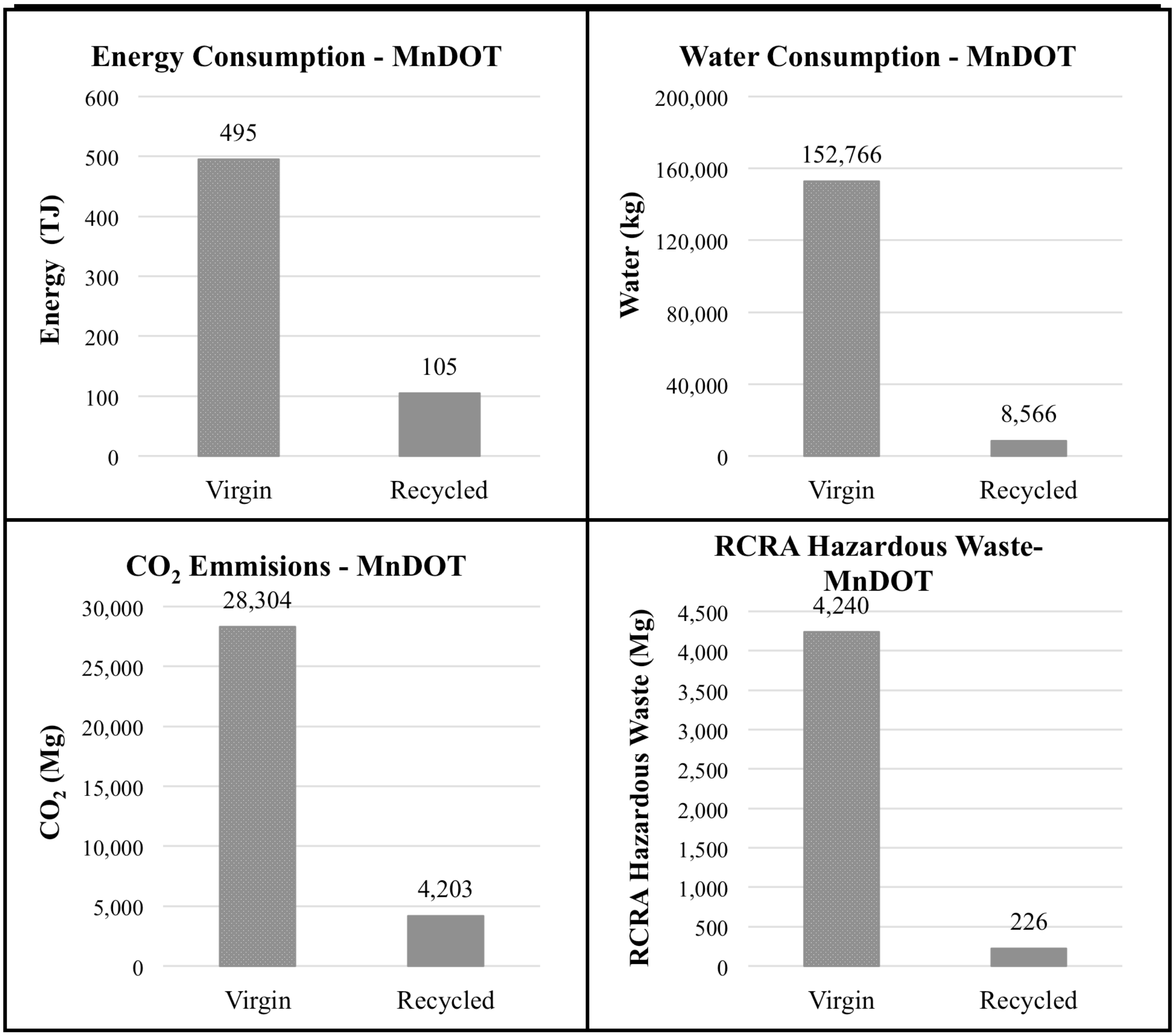
Figure 10-2 Reported recycled material used in 2013 by MnDOT



10.2 Environmental Analysis Results

The use of recycled material reduced the environmental impact in all the impact criteria; as can be seen in Figure 10-3. It is important to recall that these savings were calculated based on a one to one volume replacement of virgin material with recycled material, i.e. these are the environmental savings as a result of the use of recycled material. For a list of assumptions made in the LCA, reference Sections 4 and 5, as well as any listed in the previous section.

Figure 10-3 Environmental Benefits as a Result of MnDOT Using Recycled Materials in 2013



The greatest reductions are seen in water consumption and hazardous waste production, followed by CO_2 emissions and finally energy consumption. To put these environmental savings into perspective:

- MnDOT could fill 847 bath tubs with the total amount of water saved[1],
- the amount of RCRA hazardous waste saved is equivalent to the average amount produced by 442,558 U.S. households in one year[2],

[1] The total mass of water to fill one tub is 179 kilograms. (PWB, 2016)
[2] The average U.S. household produces 9.07 kilograms of hazardous waste per year. (EPA, 2016)

- MnDOT's CO_2 savings are equivalent to the emissions of 5,128 cars in one year[3], and

- the energy savings are equal to the average energy use of 9,909 U.S. household in one year[4].

Table 10-4 lists the savings and percent reductions of each environmental impact category.

Table 10-4 Summary of Environmental Benefits Accumulated by MnDOT in 2013

Impact Category	***Virgin***	***Recycled***	***Savings***	***Percent Reduction***
Engergy (TJ)	495	105	390	79%
Water consumption (kg)	152,766	8,566	144,200	94%
CO_2 (Mg)	28,304	4,203	24,101	85%
RCRA hazardous waste (Mg)	4,240	226	4,014	95%

Another parameter to measure environmental savings by using recycled materials is social carbon cost (SCC). While not a PaLATE output, SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This can include, agricultural productivity, human health, property damages from increased flood rise and the value of ecosystem services due to climate change, (EPA, 2013). Based on EPA estimates for SCC in 2013, 34 in 2007 dollars per metric ton CO_2, at a 3 percent discount rate (future values equated to present values), MnDOT saved about 903 thousand in 2007 dollars in SCC. If inflation is considered, MnDOT saved about 1.02 million in 2013 dollars and 1.04 million in 2016 dollars in SCC.

10.3 Economic Analysis Results

The estimated cost savings of using recycled material in 2013 is shown in Table 10-5. It should be noted that these savings reflect only the price of the material and do include the potential price of hauling to the construction site, hauling to a landfill or any landfilling disposal fees. A description of assumptions made in each materials unit cost savings can be found below as well as in Sections 4 and 6 of this report. For a more detailed explanation of virgin material replacement by recycled material reference the recycled material in Section 2 Common Recycled Materials.

[3] The average car emits 4,700 kilogram of CO_2 per/year. (EPA, 2008)
[4] The average U.S. household consumes 0.03936 terajoules of energy per year. (EIA, 2015)

Table 10-5 Calculated MnDOT FY 2013 Cost Savings

Recycled Material	*Quantity (Tons)*	*Savings($/ton)*	*Total Savings ($)*
Fly Ash	35,474	$28.61	$1,015,076
RCA	193,541	$0.11	$21,979
RAP in HMA	402,048	$14.72	$5,916,697
Total	**631,063**		**$6,953,752**

The unit price of almost all material is given in dollars per ton (weight) of material. The unit weights of recycled materials and their corresponding virgin materials are not equal, i.e. the weight of one cubic yard of RCA does not equal the weight of one cubic yard of aggregate/gravel. For this reason, the volume of the known tonnage of recycled material was calculated using a known unit weight. The calculated volume of recycled materials was then assumed equal to the volume of the corresponding virgin material. The weight of the equal volume of virgin material was then calculated and used in a cost analysis to compare the prices of recycled and virgin material. Total savings and unit savings per ton of recycled material were then estimated for MnDOT in FY 2013.

The unit cost of virgin materials in the state of Minnesota was estimated using Engineering News-Record (ENR) material price list for the city of Minneapolis and the total average price of the twenty cities tracked by ENR. Prices were averaged for both lists in a time period ranging from July 2012 and January 2014, in order to account for both the fiscal and calendar 2013 year. While there was not a significant change in average price for the twenty city average during this time period, prices among the individual cities varied and had a greater tendency for change. For this reason the two price lists were averaged in determining the final purchasing price of the virgin materials. Because of the fluctuation in price, MnDOT keeps a price index of asphalt cement which was found to be more representative of binder prices. This was used instead of ENR to determine the price of liquid asphalt cement.

The unit cost of recycled materials was determined by contacting suppliers and state pavement associations and an average for the price of one ton of recycled material was determined. Suppliers were contacted in the second phase of data collection, sometimes one year or more after 2013. When available the 2013 pricing was used, but in some instances only the current price or pricing trends could be given.

Once both the purchasing price of both the virgin and recycled materials was determined, the cost of the total quantity of recycled material and the total calculated quantity of virgin material were determined. The cost savings of using each recycled material was then calculated as the difference between the two. A unit savings could be found by dividing the total savings by the quantity of recycled material as shown in Table 10-5. All pricing data can be found in Appendix A.

10.4 MnDOT Overall Findings

As stated in the overview section, there were 12,000 miles of road managed by MnDOT in 2013. It should be noted these are the total miles of road throughout the state, not the number of miles of improved road in 2013. The total estimated savings of about $7 million equates to about $580 saved per mile of road in 2013. This estimation does not take into account potential future savings of using recycled materials. Future costs include hauling to a landfill, a disposing fee and potential higher rehabilitation costs. If the total cost savings were added to the highway related spending in FY 2013, it would account for 0.48% of funding. In other words, 0.48% of costs were cut to the state highway programs by using recycling materials.

Table 10-6 details the environmental savings per mile of road in FY 2013. To put this into perspective per mile MnDOT is saving, (using the same conversions as in Section 10.2):

- the energy use of 0.83 U.S. households in one year,
- the water it would take to fill 0.07 bath tubs,
- the CO_2 emissions of 0.43 cars in one year, and
- the RCRA hazardous waste produced by 37 households in one year.

Table 10-6 MnDOT Environmental Savings per Mile

Impact Category	***Savings Per Mile***
Energy (MJ)	32,500
Water consumption (kg)	12
CO_2 (kg)	2,008
RCRA hazardous waste (kg)	335

11 PENNDOT ANALYSES – ENVIRONMENTAL AND ECONOMIC

11.1 PennDOT Overview

PennDOT Publication 408/2016 Specifications list the requirements of using recycled materials in highway construction. Allowable recycled material includes ground granulated blast-furnace slag (GGBFS), fly ash, reclaimed concrete material (RCA), reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), bottom ash, reclaimed aggregate material (RAM), silica fume and steel slag. The standard was last updated in 2016. The following paragraphs highlight the general specifications listed in the standards for surface and base courses.

Section 724 of the standard lists the requirements of using GGBFS, fly ash and silica fume in blended cement or as a partial replacement to cement for use in PCC pavement. GGBFS must meet the requirements of AASHTO M 302 (ASTM C 989), Grade 100 or 120. Class F, C or N fly ash may be used, but must meet the requirements of the AASHTO 295 standard. Silica fume must meet the requirements of AASHTO M 307. Fly ash and GGBFS may not be used in the same mix. These materials may also be used in a PCC base course as stated in Section 301. The maximum percentage of the total blended cement mixture that each material may constitute is:

Fly Ash 15%

Slag .... 25 - 50%

Combination of Fly ash or GGBFS, and silica fume 50%

Allowable materials in the base and subbase course include RCA, RAP, steel slag and GGBFS as specified in Section 703. Steel slag may also be used as a select granular material, shoulder material, selected material surfacing and in bituminous surface courses. Section 220 states flowable backfill may contain Class C or F fly ash, GGBFS and bottom ash.

Section 409.2 states the specifications of using RAP, RAS and RAM in bituminous surface courses. If RAP is used, at least 5 percent of the mixture by weight must be RAP. If RAS is used, 5 percent of the total mixture by weight must be RAS. For wearing course mixtures containing RAM, 5 percent or more RAP and/or 5 percent RAS can be used; the total RAM and RAP combination must be at most 15 percent of the total mixture, by weight. If RAS is used, it must meet the following requirements:

- 100% passing the ½ in. sieve
- If RAS and fine aggregate are blended, they must be mixed in equal portions by weight.
- Any RAS used must not be post-consumer.
- Fiberglass felt and organic felt shingles must always be separate and never used in the same mixture.

PennDOT LCCA procedures are detailed in Chapter 3 of the PennDOT Pavement Policy Manual (PPM), 2015 Edition. PennDOT provides an Excel spreadsheet to perform an LCCA following these guidelines which can be downloaded from the Engineering and Construction Management System (ECMS) File Cabinet. The following section summarizes the LCCA procedures as defined in the PPM. An LCCA must be performed for all new construction, reconstruction or rehabilitation projects with at least 30,000 square yards of mainline pavement, including shoulders.

Alternative pavement designs are compared by estimating the total present worth costs over the same analysis period. Factors included in the analysis are:

1. A Discount Rate applied to all future maintenance and user delay costs within the analysis period. The current Discount Rate can be found in the ECMS File Cabinet.

2. Construction item quantity estimates based on a typical cross section.

3. The differences in costs for pavement related items and earthwork items when calculating initial costs.

4. The costs of pavement resurfacing and any other modifications including shoulder construction and maintenance.

5. User delay costs; idling cost, time value costs and stopping costs. Delay costs may be calculated using the total number of days of construction, production rates and delayed vehicle values as determined in Chapter 5 of the Innovative Bidding Toolkit.

6. Maintenance and rehabilitation schedules of each alternative. Schedules can be seen in Appendix E.

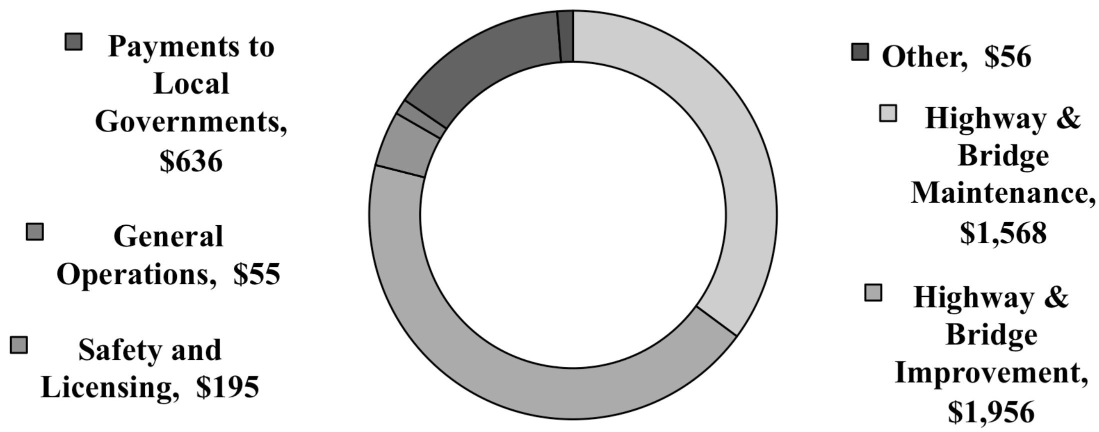
The following should be used to determine the alternative pavement type selected, (alternative pavement type bidding may also be used, as seen in Appendix E):

1. A difference of 10 percent or more in life-cycle costs, excluding user delay.

2. A difference of 20% or more in life-cycle costs, including delay costs.

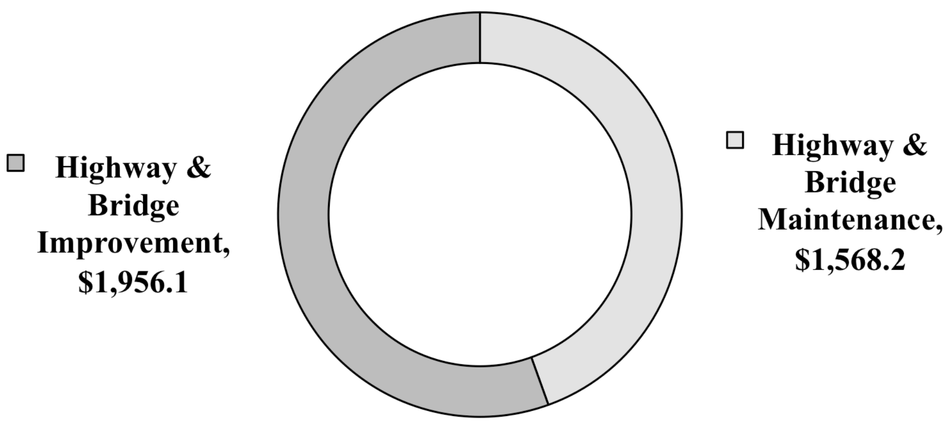
The PennDOT FY 2013 Budget is detailed in the PennDOT 2013 Annual Report which highlights the accomplishments of the past year and challenges to be met in the future by the DOT. The available funds for PennDOT in 2013 totaled about $6.9 billion; a breakdown of the uses of the available funds can be seen in Appendix E. The total highway related spending was about $4.4 billion (73.8%) with about $3.5 billion put towards DOT managed highways and the rest put towards general operations and local governments. as seen in Figure 11-1 and Figure 11-2. According to the PennDOT 2012-13 Report on State Performance, there were 4,956 miles of 39,792 total miles of state maintained highways improved in FY 2013.

Figure 11-1 2013 PennDOT Highway Related Spending ($ in millions)



Source: **(PennDOT, 2013)**

Figure 11-2 2013 PennDOT State Managed Highway Spending ($ in millions)



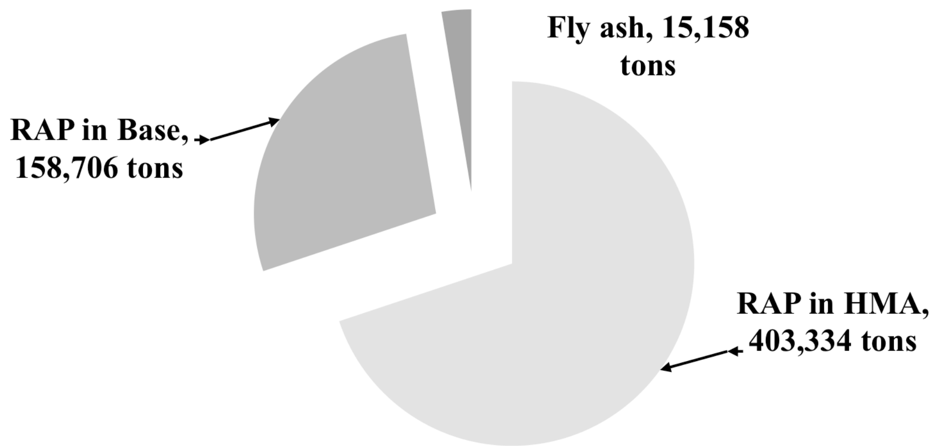
Source: **(PennDOT, 2013)**

Recycled materials used by PennDOT in 2013 included RAP in HMA, RAP in base course and fly ash. It should be noted that recycled materials other than RAP and fly ash such as slag and RAS, are being incorporated into pavements, but the quantities of such recycled materials are not being tracked by PennDOT. Figure 11-3 shows the total reported recycled material used in 2013 by PennDOT, by weight. RAP was incorporated the most and comprised about 97% of the total tonnage of recycled material. The assumptions made in calculating the recycled materials used include those listed in Section 4.1, unless otherwise contradicted below, and the following:

- It was assumed that RAP comprises 18.8% of HMA pavement, by weight.
- Any excess RAP was assumed to be used in base course.

- Fly ash was assumed to replace 15% of cement, by weight.
- The depth of paving concrete was assumed to be 10 inches.

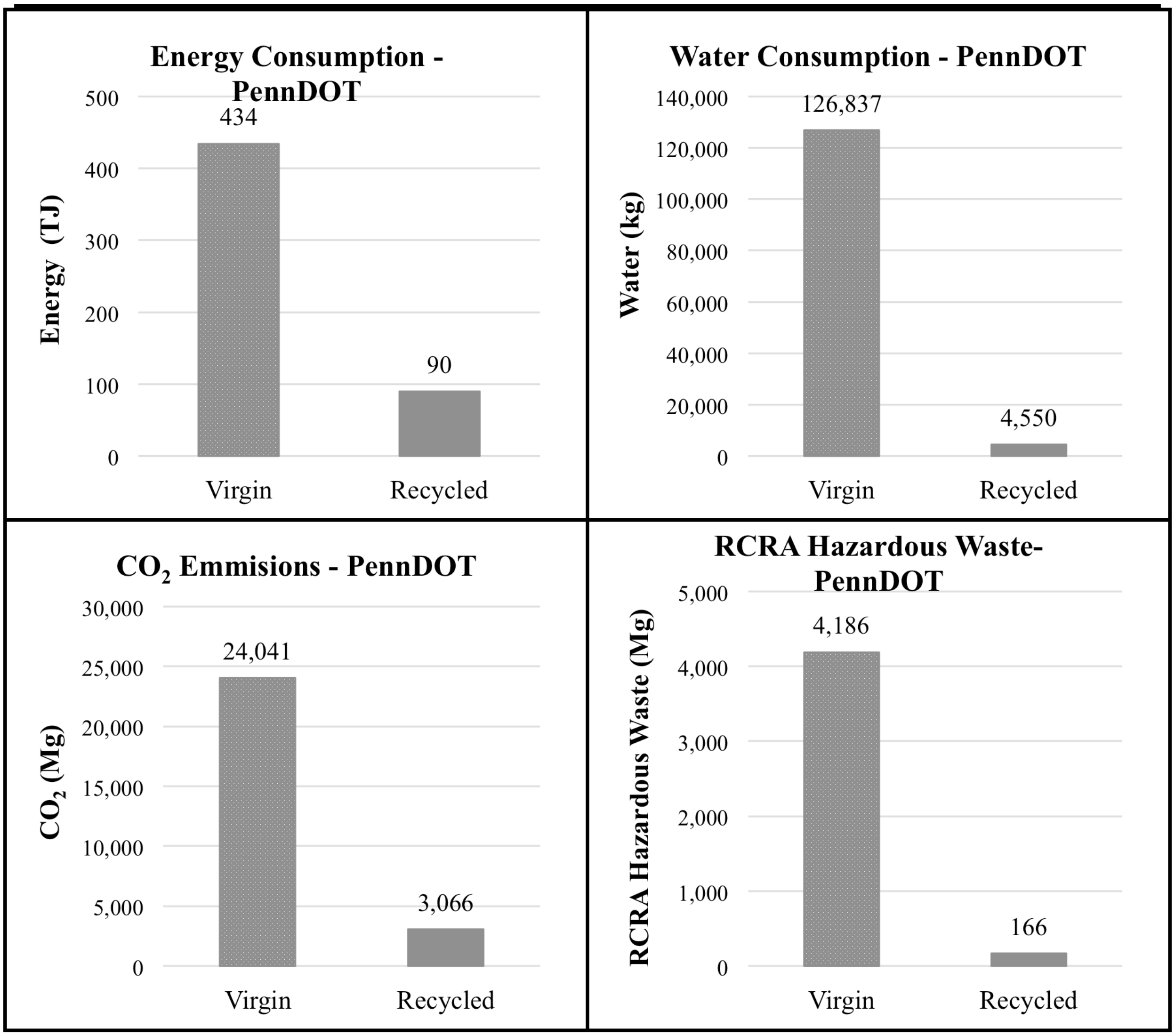
Figure 11-3 Reported Recycled Material Used in 2013 by PennDOT



11.2 Environmental Analysis Results

The use of recycled material reduced the environmental impact in all the impact criteria; as seen in Figure 11-4. It is important to recall that these savings were calculated based on a one to one volume replacement of raw material with recycled material, i.e. these are the environmental savings because of the use of recycled materials. For a list of assumptions made in the LCA, reference Sections 4 and 5, as well as the assumptions listed in the previous section.

Figure 11-4 Environmental Benefits as a Result of PennDOT Using Recycled Materials in 2013



The greatest reductions are seen in water consumption, followed by hazardous waste production, CO_2 emissions and finally energy production. To put these environmental savings into perspective:

- PennDOT could fill 718 bath tubs with the total amount of water saved[1],
- the amount of RCRA hazardous waste saved is equivalent to the average amount produced by 443,219 U.S. households in one year[2],

[1] The total mass of water to fill one tub is 179 kilograms. (PWB, 2016)
[2] The average U.S. household produces 9.07 kilograms of hazardous waste per year. (EPA, 2016)

- PennDOT's CO_2 savings are equivalent to the emissions of 4,463 cars in one year[3], and
- the energy savings are equal to the average energy use of 8,740 U.S. household in one year[4].

Table 11-2 lists the savings and percent reductions of each environmental impact category.

Table 11-1 Summary of Environmental Benefits Accumulated by PennDOT in 2013

Impact Category	*Virgin*	*Recycled*	*Savings*	*Percent Reduction*
Engergy (TJ)	434	90	344	79%
Water consumption (kg)	126,837	4,550	122,287	96%
CO_2 (Mg)	24,041	3,066	20,975	87%
RCRA hazardous waste (Mg)	4,186	166	4,020	96%

Another parameter to measure environmental savings by using recycled materials is social carbon cost (SCC). While not a PaLATE output, SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This can include, agricultural productivity, human health, property damages from increased flood rise and the value of ecosystem services due to climate change, (EPA, 2013). Based on EPA estimates for SCC in 2013, 34 in 2007 dollars per metric ton CO_2, at a 3 percent discount rate (future values equated to present values), PennDOT saved about 786 thousand in 2007 dollars in SCC. If inflation is considered, PennDOT saved about 884 thousand in 2013 dollars and 902 thousand in 2016 dollars in SCC.

11.3 Economic Analysis Results

The estimated cost savings of using recycled material in 2013 is shown in Table 11-2. It should be noted that these savings reflect only the price of the material and do include the potential price of hauling to the construction site, hauling to a landfill or any landfilling disposal fees. A description of assumptions made in each materials unit cost savings can be found below as well as in Sections 4 and 6 of this report. For a more detailed explanation of virgin material replacement by recycled material reference the recycled material in Section 2 Common Recycled Materials.

[3] The average car emits 4,700 kilogram of CO_2 per/year. (EPA, 2008)
[4] The average U.S. household consumes 0.03936 terajoules of energy per year. (EIA, 2015)

Table 11-2 Calculated PennDOT FY 2013 Cost Savings			
Recycled Material	***Quantity (Tons)***	***Savings($/ton)***	***Total Savings ($)***
RAP in HMA	403,334	$7.37	$2,973,725
Fly Ash	15,158	$8.97	$135,935
RAP in Base	158,706	$1.46	$231,854
Total	**577,198**		**$3,341,515**

The unit price of almost all material is given in dollars per ton (weight) of material. The unit weights of recycled materials and their corresponding virgin materials are not equal, i.e. the weight of one cubic yard of RCA does not equal the weight of one cubic yard of aggregate/gravel. For this reason, the volume of the known tonnage of recycled material was calculated using a known unit weight. The calculated volume of recycled materials was then assumed equal to the volume of the corresponding virgin material. The weight of the equal volume of virgin material was then calculated and used in a cost analysis to compare the prices of recycled and virgin material. Total savings and unit savings per ton of recycled material were then estimated for PennDOT in FY 2013.

The unit cost of virgin materials in the state of Pennsylvania was estimated using Engineering News-Record (ENR) material price lists for the cities of Pittsburgh and Philadelphia, as well as the total average price of the twenty cities tracked by ENR. Prices were averaged for both lists in a time period ranging from July 2012 and January 2014, in order to account for both the fiscal and calendar 2013 year. While there was not a significant change in average price for the twenty city average during this time period, prices among the individual cities varied and had a greater tendency for change. For this reason the two price lists were averaged in determining the final purchasing price of the virgin materials. Because of the fluctuation in price, PennDOT keeps a price index of asphalt cement which was found to be a better representation of binder prices. This was used instead of ENR to determine the price of liquid asphalt cement.

The unit cost of recycled materials was determined by contacting suppliers and state pavement associations and an average for the price of one ton of recycled material was determined. Suppliers were contacted in the second phase of data collection, sometimes one year or more after 2013. When available the 2013 pricing was used, but in some instances only the current price or pricing trends could be given.

Once both the purchasing price of both the virgin and recycled materials was determined, the cost of the total quantity of recycled material and the calculated quantity of virgin material were determined. The cost savings of using each recycled material was then calculated as the difference between the two. A unit savings could be found by dividing the total savings by the quantity of recycled material as shown in Table 11-2. All pricing data can be found in Appendix A.

11.4 PennDOT Overall Findings

As stated in the overview section, there were 4,956 miles of road improved by PennDOT in 2013. The total estimated savings of about $3.3 million equates to about $670 saved per improved mile of road in 2013. This estimation does not take into account potential future savings of using recycled materials. Future costs include hauling to a landfill, a disposing fee and potential higher rehabilitation costs. If the total cost savings were added to the highway related spending in FY 2013, it would account for 0.09% of funding. In other words, 0.09% of costs were cut to the state highway programs by using recycling materials.

Table 11-3 details the environmental savings per mile of road in FY 2013. To put this into perspective per mile PennDOT is saving, (using the same conversions as in Section 11.2):

- the energy use of 1.8 U.S. households in one year,
- the water it would take to fill 0.15 bath tubs,
- the CO_2 emissions of 0.90 cars in one year, and
- the RCRA hazardous waste produced by 89 households in one year.

Table 11-3 PennDOT Environmental Savings per Improved Mile in 2013

Impact Category	***Savings Per Mile***
Energy (MJ)	69,411
Water consumption (kg)	25
CO_2 (kg)	4,232
RCRA hazardous waste (kg)	811

12 VDOT ANALYSES – ENVIRONMENTAL AND ECONOMIC

12.1 VDOT Overview

VDOT 2016 Road and Bridge Specifications details the use of recycled materials in both rigid and flexible pavements, base course applications and bridges and structures. VDOT recently updated the 2007 Road and Bridge Specification to a 2016 version. The 2016 Road and Bridge Specifications allows for the use of RAS in asphalt concrete unlike the earlier 2007 version. Table 12-1 lists the recycled materials permitted for use in highway pavements and their uses.

Table 12-1 Acceptable Recycled Materials as listed in VDOT 2016 Road and Bridge Specifications

Recycled Material	*Use*
RCA	Coarse aggregate in production of hydraulic cement, asphalt concrete, stone matrix asphalt concrete and asphalt surface treatments[1]
Blast Furnace Slag	• Coarse aggregate in production of hydraulic cement, asphalt concrete and asphalt surface treatments • Subbase and aggregate base material • Penetrating surface course aggregate • Stone matrix asphalt concrete
Fly Ash	Hydraulic cement concrete, stone matrix asphalt concrete
RAP	Asphalt concrete and stone matrix asphalt concrete
RAS	Asphalt concrete and stone matrix asphalt concrete
Crushed Glass	Coarse aggregate in drainage applications

Source: (VDOT, 2015)
[1] RCA not permitted in reinforced cement concrete

Section 203 of the specifications covers material used as coarse aggregate in the production of hydraulic cement concrete, asphalt concrete, stone matrix asphalt concrete and asphalt surface treatments. RCA and blast furnace slag are acceptable course aggregate, given they meet the physical requirements and conform to the specified tests detailed in Section 203.

Blast furnace slag is permitted to be used in subbase as part of mixtures of natural or crushed gravel, crushed stone, natural or crushed sand, with or without soil mortar. Blast furnace slag is also permitted to be used in aggregate base material. Aggregate base material can be designated as Type I or Type II, both mixtures allow the use of slag. The physical requirements for all three mixtures are specified in Section 208.

Section 211 of the specifications details the material requirements for asphalt material. This includes the acceptable use and requirements of RAP and both tear-off RAS and tabs RAS materials. RAP and RAS may be used separately or in combination with each other. Table 12-2 shows the recommended performance grade of asphalt cement mixes based upon the allowable percentages of RAP in the mix, by weight. A mix may not contain more than 5%, by weight, of

RAS. The combined percentages by weight of RAP and RAS when used together shall not contribute more than 30% by weight of the total asphalt content of the mixture and are required to use the following maximum binder replacement criteria;

5% RAS and 0% RAP

4% RAS and 5% RAP minimum

3% RAS and 10% RAP minimum

2% RAS and 20% RAP minimum

The exception of the listed requirements is Type E mixtures. E designated mixtures shall not contain more than 15% RAP material or 3% RAS material, by weight.

Table 12-2 Recommended Performance Grade of Asphalt Cement Containing RAP

Mix Type	***%RAP ≤ 25.0%***	***25.0%< %RAP ≤ 30.0%***	***25.0% < %RAP ≤ 35.0%***
SM-4.75A, SM-9.0A, SM-9.5A, SM-12.5A	PG 64S-22	PG 64S-22	
SM-4.75D, SM-9.0D, SM-9.5D, SM-12.5D	PG 64H-22	PG 64S-22	
IM-19.0A	PG 64S-22	PG 64S-22	
IM-19.0D	PG 64H-22	PG 64S-22	
BM-25.0A	PG 64S-22		PG 64S-22
BM-25.0D	PG 64H-22		PG 64S-22

Source: (VDOT, 2015)

A 2014 study was conducted by VDOT to investigate the potential use of RAP material for road base and subbase applications. The study recommended VDOT allow for the use of RAP in base applications based on practices adopted by other state transportation agencies.

The permitted use of fly ash and ground granulated blast furnace slag in hydraulic cement concrete is detailed in Section 217of the specifications. Total Class F fly ash and ground granulated blast furnace slag contents shall not exceed 30% and 50% as a portion of the cementitious material. The conformance requirements of fly ash and ground granulated blast furnace slag are detailed in Sections 215 and 241 of the specifications.

VDOT LCCA computation guidelines are detailed in the VDOTs Manual of Instructions (MOI) Chapter V1: Pavement Design and Evaluation. VDOT does not have a standard LCCA program and therefore provides a set of procedures to use in analysis. VDOT's LCCA procedure to select the most cost-effective pavement is based upon the Federal Highway Administration (FHWA) Technical Bulletin, *Life Cycle Cost Analysis in Pavement Design*. An LCCA is required for a project if multiple pavement types need to be considered. The following criteria, as listed in Section 606 of the MOI, should be considered when determining if multiple pavements should be considered; new alignment, reconstruction and major rehabilitation

Once it is determined multiple pavements are to be considered, VDOT's technical guidance outlines three major components needed to perform an LCCA. These include (1) Economic Analysis, (2) Cost Factors and (3) Construction/Rehabilitation Options.

The economic analysis component consists determining an analysis period, discount rate, evaluation methods and sensitivity analysis when conducting an LCCA. The VDOT MOI recommends using a present worth (PW) or the equivalent uniform annual cost (EUAC) method when conducting an LCCA over a set analysis period. The PW method provides a total dollar amount (at the present dollar value) of initial and future pavement related costs. The EUAC method provides an average cost, distributed evenly, an agency will pay per year over the analysis period. The equations for both methods can be seen below.

$$PW = Initial\ cost + \sum_{k=1}^{n} Rehab\ Cost_k * \left[\frac{1}{(1+i)^n}\right] \tag{12-1}$$

$$EUAC = PW * \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{12-2}$$

Where:

i	=	discount rate
k	=	year of activity
n	=	analysis period

The VDOT MOI states that a 50-year analysis period and 4% discount rate should be used when performing the economic analysis. A 50-year analysis period was selected to account for the service life of initial construction and several rehabilitation activities. A 4% discount rate was found to be consistent with the recommendations of the FHWA and other state agencies. The discount rate represents the rate needed to discount future costs to present values. Historically, discount rates have ranged from 2% to 5%.

The MOI also recommends performing a sensitivity analysis to determine the effects of inputs on the calculated PW or EUAC of a project to ensure the inputs used are reasonable. These inputs include cost factors, analysis period and timing of activities.

The costs associated with pavement alternatives that should be considered when performing an LCCA include:

- Initial costs
- Rehabilitation costs
- Structural/functional improvement costs

In general VDOT disregards the maintenance costs and salvage value of pavements when conducting an LCCA. This is due in part to the generally high performance levels of major highways which require low routine reactive maintenance costs. Also, the difference between salvage values of alternative pavements when discounted 50 years is generally found to be negligible.

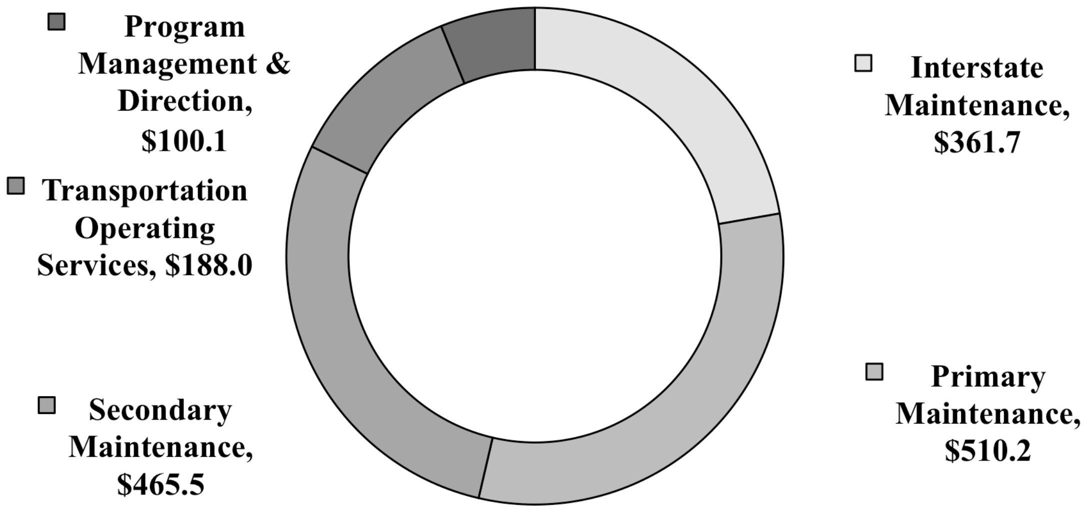
VDOT has defined six pavement options to be used in LCCA analysis in order to have consistent LCCA analyses throughout the state. These options include:

- Asphalt Concrete Construction/Reconstruction
- Jointed Plain Concrete Construction/Reconstruction with Tied PCC Shoulders
- Jointed Plain Concrete Construction/Reconstruction with Wide Lane and AC Shoulders
- Continuously Reinforced Concrete Pavement Construction/Reconstruction with Tied PCC Shoulders
- Continuously Reinforced Concrete Pavement Construction/Reconstruction with Wide Lane and AC Shoulders
- Major Rehabilitation

Predicted pavement activities and service life tables can be found in Appendix F. It should be noted that actual rehabilitation and other pavement activities preformed may be different than those listed. The tables represent the current practices of VDOT and should be treated as assumptions.

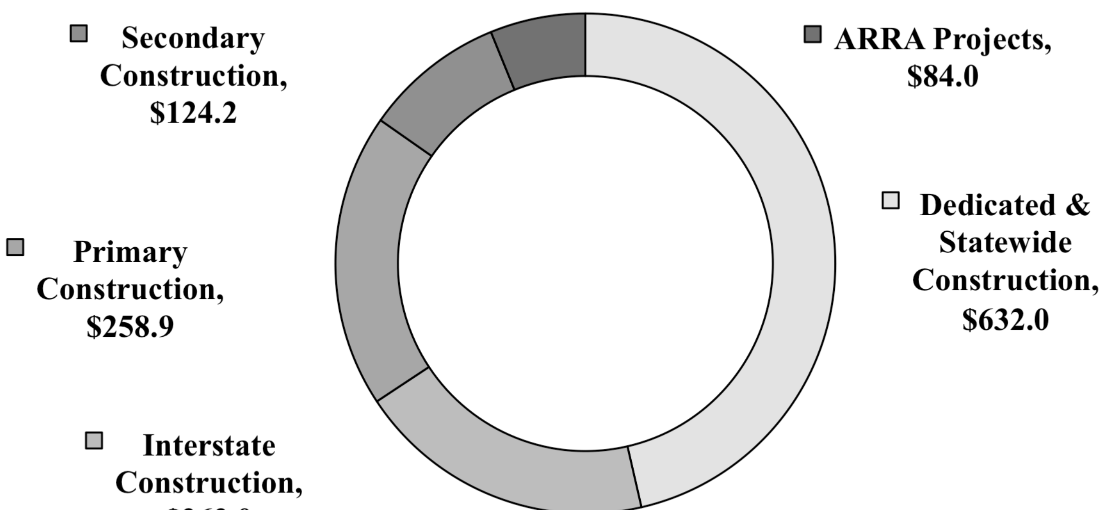
The VDOT FY 2013 operating budget totaled $4.5 billion but had an expenditures total of $4.25 billion as reported in the *2013 VDOT Annual Report*. Due to the nature of this report, the portion of the operating budget relating to only state-maintained highways will be summarized. The total FY 2013 operating budget and expenditures can be found in Figure F-1 in Appendix F. In 2013 the VDOT highway system comprised 58,000 centerline miles of interstate, primary and secondary roads, as well as one toll road (VDOT, 2013). Total spending relating to construction and maintenance of these highways can be seen in Figure 12-1and Figure 12-2. The total maintenance related spending was $1.6 billion and the total construction related spending was $1.4 billion. The total number of improved centerline miles using the FY 2013 budget was not available for this report.

Figure 12-1 VDOT FY 2013 Maintenance Program Spending ($ millions)



Source: **(VDOT, 2013)**

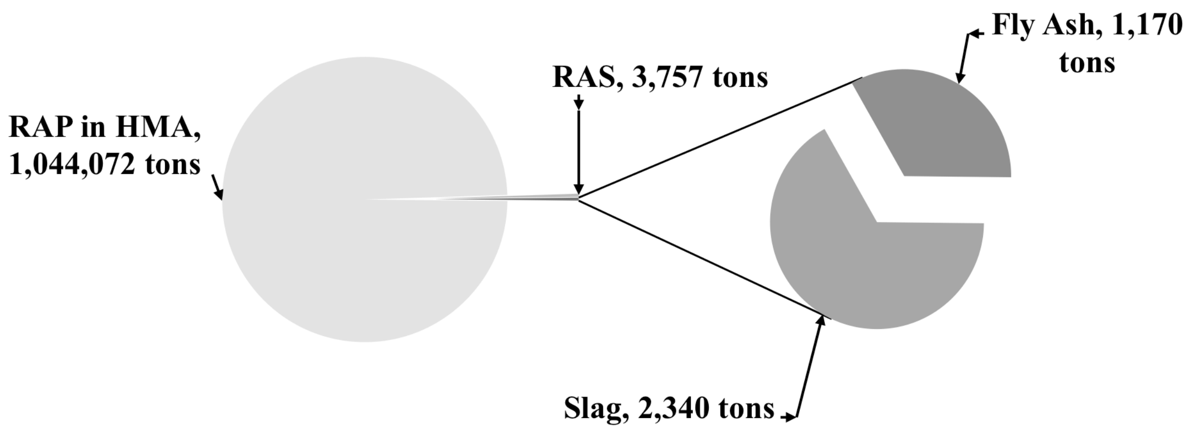
Figure 12-2 VDOT FY 2013 Construction Program Spending ($ millions)



Source: **(VDOT, 2013)**

Recycled material used by VDOT in 2013 included RAP in HMA, RAS, slag and fly ash. It should be noted that other recycled materials, such as crushed glass and RCA are being used by VDOT, but the quantities of such recycled materials were either not reported or tracked. Figure 12-3 shows the total reported recycled material used in 2013 by VDOT, by weight. RAP in HMA was the most widely used, comprising about 99%, by weight, of the total recycled materials used. The recycled materials were reported directly by the DOT, so there were no assumptions made by the RMRC in calculating quantities. Comparing materials by weight is somewhat misleading because RAP has a higher density than the other materials.

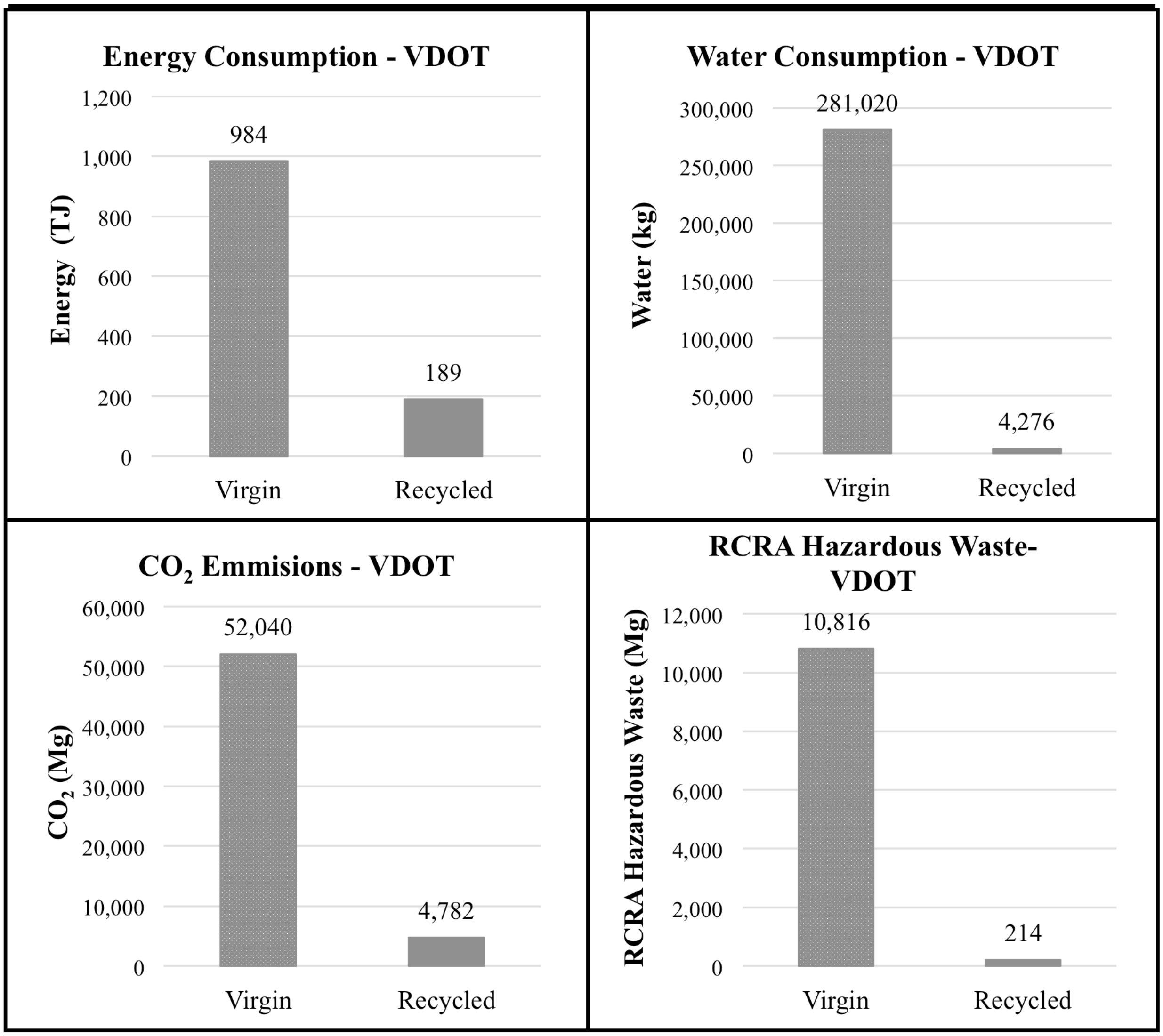
Figure 12-3 Reported Recycled Material Used in 2013 by VDOT



12.2 Environmental Analysis Results

The use of recycled material reduced the environmental impact in all the impact criteria; as seen in Figure 12-4. It is important to recall that these savings were calculated based on a one to one volume replacement of virgin material with recycled material, i.e. these are the environmental savings because of the use of recycled materials. For a list of assumptions made in the LCA, reference Sections 4 and 5.

Figure 12-4 Environmental Benefits as a result of VDOT using recycled materials in 2013



The most reductions are seen in water consumption and hazardous waste production, CO_2 emissions and finally energy consumption. To put these environmental savings into perspective:

- VDOT could fill 1,625 bath tubs with the total amount of water saved[1],
- the amount of RCRA hazardous waste saved is equivalent to the average amount produced by 1,168,908 U.S. households in one year[2],

[1] The total mass of water to fill one tub is 179 kilograms. (Portland Water Bureau, 2016)
[2] The average U.S. household produces 9.07 kilograms of hazardous waste per year (U.S. EPA, 2015)

- VDOT's CO_2 savings are equivalent to the emissions of 10,055 cars in one year[3], and

- the energy savings are equal to the average energy use of 20,198 U.S. household in one year[4].

Table 12-3 lists the savings and percent reductions of each environmental impact category.

Table 12-3 Summary of Environmental Benefits Accumulated by VDOT in 2013

Impact Category	*Virgin*	*Recycled*	*Savings*	*Percent Reduction*
Engergy (TJ)	984	189	795	81%
Water consumption (kg)	281,020	4,276	276,744	99%
CO_2 (Mg)	52,040	4,782	47,258	91%
RCRA hazardous waste (Mg)	10,816	214	10,602	98%

Another parameter to measure environmental savings by using recycled materials is social carbon cost (SCC). While not a PaLATE output, SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This can include, agricultural productivity, human health, property damages from increased flood rise and the value of ecosystem services due to climate change, (EPA, 2013). Based on EPA estimates for SCC in 2013, 34 in 2007 dollars per metric ton CO_2, at a 3 percent discount rate (future values equated to present values), VDOT saved about 1.77 million in 2007 dollars in SCC. If inflation is considered, VDOT saved about 1.99 million in 2013 dollars and 2.03 million in 2016 dollars in SCC.

12.3 Economic Analysis Results

The estimated cost savings of using recycled material in 2013 is shown in Table 12-4. It should be noted that these savings reflect only the price of the material and do include the potential price of hauling to the construction site, hauling to a landfill or any landfilling disposal fees. A description of assumptions made in each materials unit cost savings can be found below as well as in Sections 4 and 6 of this report. For a more detailed explanation of virgin material replacement by recycled material reference the recycled material in Section 2 Common Recycled Materials.

[3] The average car emits 4,700 kilogram of CO_2 per/year. (U.S. EPA - Office of Transportation and Air Quality, 2014)
[4] The average U.S. household consumes 0.03936 terajoules of energy per year. (U.S EIA, 2015)

Table 12-4 Calculated VDOT FY 2013 Cost Savings			
Recycled Material	***Quantity (Tons)***	***Savings($/ton)***	***Total Savings ($)***
RAP in HMA	1,044,072	$16.26	$16,972,895
RAS	3,757	$44.93	$168,809
Slag	2,340	$70.71	$165,468
Fly Ash	1,170	$66.18	$77,425
Total	**1,051,339**		**$17,384,598**

The unit price of almost all material is given in dollars per ton (weight) of material. The unit weights of recycled materials and their corresponding virgin materials are not equal, i.e. the weight of one cubic yard of RCA does not equal the weight of one cubic yard of aggregate/gravel. For this reason, the volume of the known tonnage of recycled material was calculated using a known unit weight. The calculated volume of recycled materials was then assumed equal to the volume of the corresponding virgin material. The weight of the equal volume of virgin material was then calculated and used in a cost analysis to compare the prices of recycled and virgin material. Total savings and unit savings per ton of recycled material were then estimated for VDOT in FY 2013.

The unit cost of virgin materials in the state of Virginia was estimated using Engineering News-Record (ENR) material price list for the city of Baltimore and the total average price of the twenty cities tracked by ENR. Prices were averaged for both lists in a time period ranging from July 2012 and January 2014, in order to account for both the fiscal and calendar 2013 year. While there was not a significant change in average price for the twenty city average during this time period, prices among the individual cities varied and had a greater tendency for change. For this reason the two price lists were averaged in determining the final purchasing price of the virgin materials. Because of the fluctuation in price, VDOT keeps a price index of asphalt cement which was found to be a better representation of binder prices. This was used instead of ENR to determine the price of liquid asphalt cement.

The unit cost of recycled materials was determined by contacting suppliers and state pavement associations and an average for the price of one ton of recycled material was determined. Suppliers were contacted in the second phase of data collection, sometimes one year or more after 2013. When available the 2013 pricing was used, but in some instances only the current price or pricing trends could be given.

Once both the purchasing price of both the virgin and recycled materials was determined, the cost of the total quantity of recycled material and the calculated quantity of virgin material were determined. The cost savings of using each recycled material was then calculated as the difference between the two. A unit savings could be found by dividing the total savings by the quantity of recycled material as shown in Table 12-4. All pricing data can be found in Appendix A.

12.4 VDOT Overall Findings

As stated in the overview section, there were 58,000 miles of road managed by VDOT in 2013. It should be noted these are the total miles of road throughout the state, not the number of miles of improved road in 2013. The total estimated savings of about $17.5 million equates to about $300 saved per mile of road in 2013. This estimation does not take into account potential future savings of using recycled materials. Future costs include hauling to a landfill, a disposing fee and potential higher rehabilitation costs. If the total cost savings were added to the highway related spending in FY 2013, it would account for 0.58% of funding. In other words, 0.58% of costs were cut to the state highway programs by using recycling materials.

Table 12-5 details the environmental savings per mile of road in FY 2013. To put this into perspective per mile VDOT is saving, (using the same conversions as in Section 12.2):

- the energy use of 0.35 U.S. households in one year,
- the water it would take to fill 0.03 bath tubs,
- the CO_2 emissions of 0.17 cars in one year, and
- the RCRA hazardous waste produced by 20 households in one year.

Table 12-5 VDOT Environmental Savings per Mile

Impact Category	*Savings Per Mile*
Energy (MJ)	13,707
Water consumption (kg)	5
CO_2 (kg)	815
RCRA hazardous waste (kg)	183

13 WISDOT ANALYSES – ENVIRONMENTAL AND ECONOMIC

13.1 WisDOT Overview

WisDOT Standard Specifications 2015 detail the requirements to be followed when incorporating recycled materials in a pavement mix design and as a base aggregate. WisDOT allows for the use of both crushed concrete (recycled concrete aggregate, RCA) and reclaimed asphalt pavement (RAP) as a base aggregate and provide the following classifications for the two materials based on weight percentages.

Crushed concrete (RCA)	>= 90 percent crushed concrete that is free of steel reinforcement and includes < 10 percent asphaltic pavement or surfacing, base, or a combination of asphaltic pavement, surfacing and base, incorporated during the removal operation.
Reclaimed asphaltic pavement (RAP)	>= 75 percent asphaltic pavement or surfacing.

RAP can only be used as a dense 1 ¼-inch and dense 3-inch base type while RCA may be used in any type of base-aggregate. The following by-product materials may be mixed with crushed gravel or stone and RCA up to the listed maximum percentages, by weight.

Glass 12%

Foundry slag 7%

Steel mill slag 75%

Bottom ash 8%

Pottery culls 7%

The standards provide base aggregate requirements, classifications, uses and physical properties for RCA and RAP in Sections 301.2.4.2, 301.2.4.3, 301.2.4.4, 301.2.4.5 and 305.2.2.2.

The use of RAP, recycled asphaltic shingles (RAS) and fractionated RAP (FRAP) are allowed in HMA mixtures according to the standard specification 460.2.5. Table 13-1 displays the required percent binder replacement, the ratio of recovered binder to the total binder.

Table 13-1 Maximum Allowable Percent Binder Replacement		
Recycled asphaltic material	***Lower layers***	***Upper layers***
RAS if used alone	25	20
RAP and FRAP in any combination	40	25
RAS, RAP and FRAP in combination[1]	35	25

Source: (WisDOT, 2015a)

[1] When used in combination the RAS component cannot exceed 5 percent of the total weight of the aggregate blend.

LCCA computation parameters as detailed in Section 14-15-10 of the WisDOT Facilities Design Manual outline the LCCA process and parameters used in the selection of pavement type. It is standard to include both a HMA pavement and a concrete pavement options in the pavement type selection. The following are exempt from LCCA:

- Jurisdictional transfer
- Highway safety improvement program
- Transportation economic assistance
- Preventative maintenance
- Local force account
- Bridge approaches
- Crossovers
- Pavements between new bridge approaches and existing roadway
- Pavements under bridges requiring work to allow for proper clearance
- Intersection improvements
- Temporary pavements
- Limited service pavements
- Ramps
- Auxiliary lanes
- Roundabouts

The WisPave parameters include: (1) two or more structurally equivalent alternative pavements, (2) bid item quantities, (3) estimated bid item costs and (4) future rehabilitation and maintenance costs. The pavements to be compared must include a HMA pavement and concrete pavement. The pavement structures may be also classified as drained or un-drained, but a drained pavement should not be compared to an un-drained pavement. WisPave uses WisDOT standard bid items and the costs of the bid items should account for both the quantity of materials and the location of the project.

The typical rehabilitation scenarios and standard sequences used in estimating future costs can be found in Table G-1and Table G-2. Cost and service life estimates used by WisDOT can also be found in Appendix G.

The WisDOT 2011-13 biennial budget had total revenue and spending values of $6,552 million and $6,501 million respectively, as reported in “Keep Wisconsin Moving: Smart Investments Measureable Results.” The breakdown of spending and funding sources can be found in Figure G-1and Figure G-2 in Appendix G. The report details the research and recommendations of the

Wisconsin Transportation Finance and Policy Commission. The focus of the Commission was to develop policy changes and financing options to balance projected transportation needs with revenues over the next 10 years. The issues examined by the Commission included:

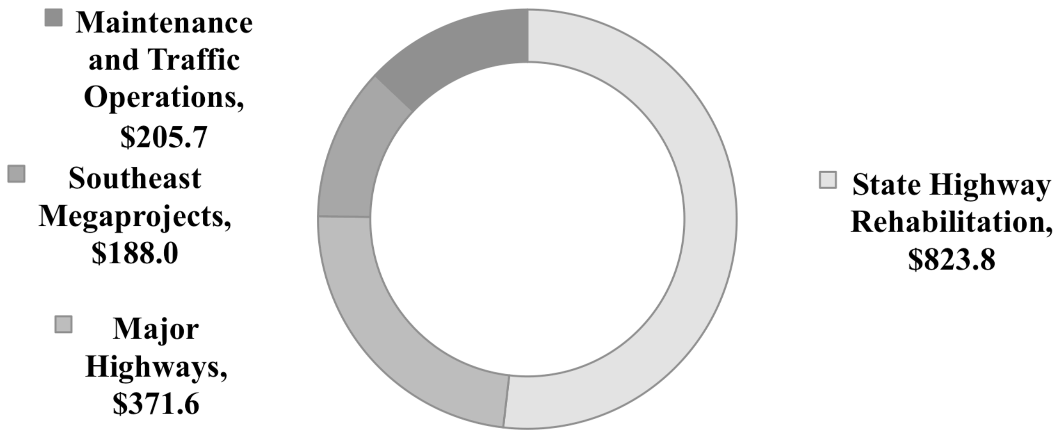
- state highway programs;
- local road, bridge and aid programs, including bicycle-pedestrian facilities and transit;
- freight and multimodal programs, including airports, harbors and railroads;
- Transportation Fund revenue projections and debt service; and
- revenue and finance alternatives.

Due to the nature of this report we will focus on the state highway programs base funding, as reported by the Commission, which are managed by WisDOT. As of 2013, there were 11,800 centerline miles of road that were maintained by WisDOT. The number of centerline miles improved in the FY 2013 was not available for this report. The base funding budget for the state highway programs is broken into four categories:

State Highway Rehabilitation (SHR)	Funds highway and bridge improvements of state trunk and connecting highways, including the Interstate system.
Maintenance and Traffic Operations	Funds general maintenance and upkeep of state trunk highways. This includes reimbursement to counties for labor, machinery costs and materials supplied for winter snow control.
Major Highway Development (Majors)	Funds high-cost rehabilitation and large capacity projects outside of Southeast Megaprojects.
Southeast Wisconsin Freeway Megaprojects	Freeway projects in the seven-county southeast region of the state, whose busy complex infrastructure is among the most expensive to replace. Federal, bond and state funds combine to provide for an estimated average cost of $250-$300 million annually till 2033.

Figure 13-1 shows the base funding for the 2013 fiscal year. A total of $1.6 billion dollars was allotted to highway construction and maintenance in 2013; rehabilitation of state highways was a little more 50 percent of the highway funded budget.

Figure 13-1 2013 WisDOT Highway Construction and Maintenance Budget ($ millions)

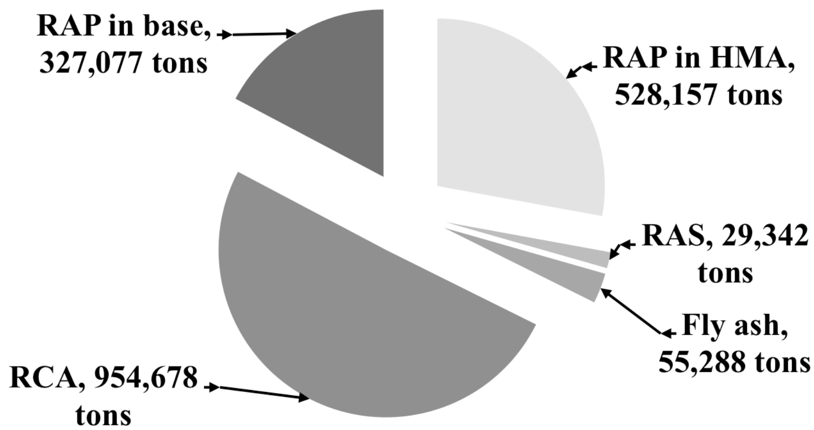


Source: **(WTFPC, 2013)**

Recycled materials used by WisDOT in 2013 included RAP in HMA, RAP in base course, RAS, RCA and fly ash. It should be noted that recycled materials other than RCA, RAP, fly ash and RAS such as slag, are being incorporated into pavements, but the quantities of such recycled materials are not being tracked by WisDOT. Figure 13-2 shows the total reported recycled material used in 2013 by WisDOT, by weight. RCA was incorporated the most and comprised about 50% of the total tonnage of recycled material. WisDOT's use of RAP in HMA and as a base course aggregate also comprises a large portion of the tracked recycled material at 45% of the total tonnage. The assumptions made in calculating the recycled materials used include those listed in Section 4.1, unless otherwise contradicted below, and the following:

- The average amount of RAP in HMA pavement was assumed to be 18%, by weight.
- For Pulverized and Relay, and Mill and Relay bid items, the assumed average depth of base course layers was 4 inches, when calculating asphalt in base course.
- For the Salvaged Asphaltic Pavement Base bid item, the assumed average depth of base course layers was 10 inches.
- The assumed density of RAP in base course was 138 lbs/CF.
- The average percent of projects that use RAS in HMA is 5%.
- For Concrete Removal and Rubblization bid items, the assumed average pavement thickness was 10 inches and the assumed pavement density was 142 lbs/CF.
- The assumed pavement thickness was 10 inches and the assumed unit quantity of fly ash in concrete was 170 lbs/CY.

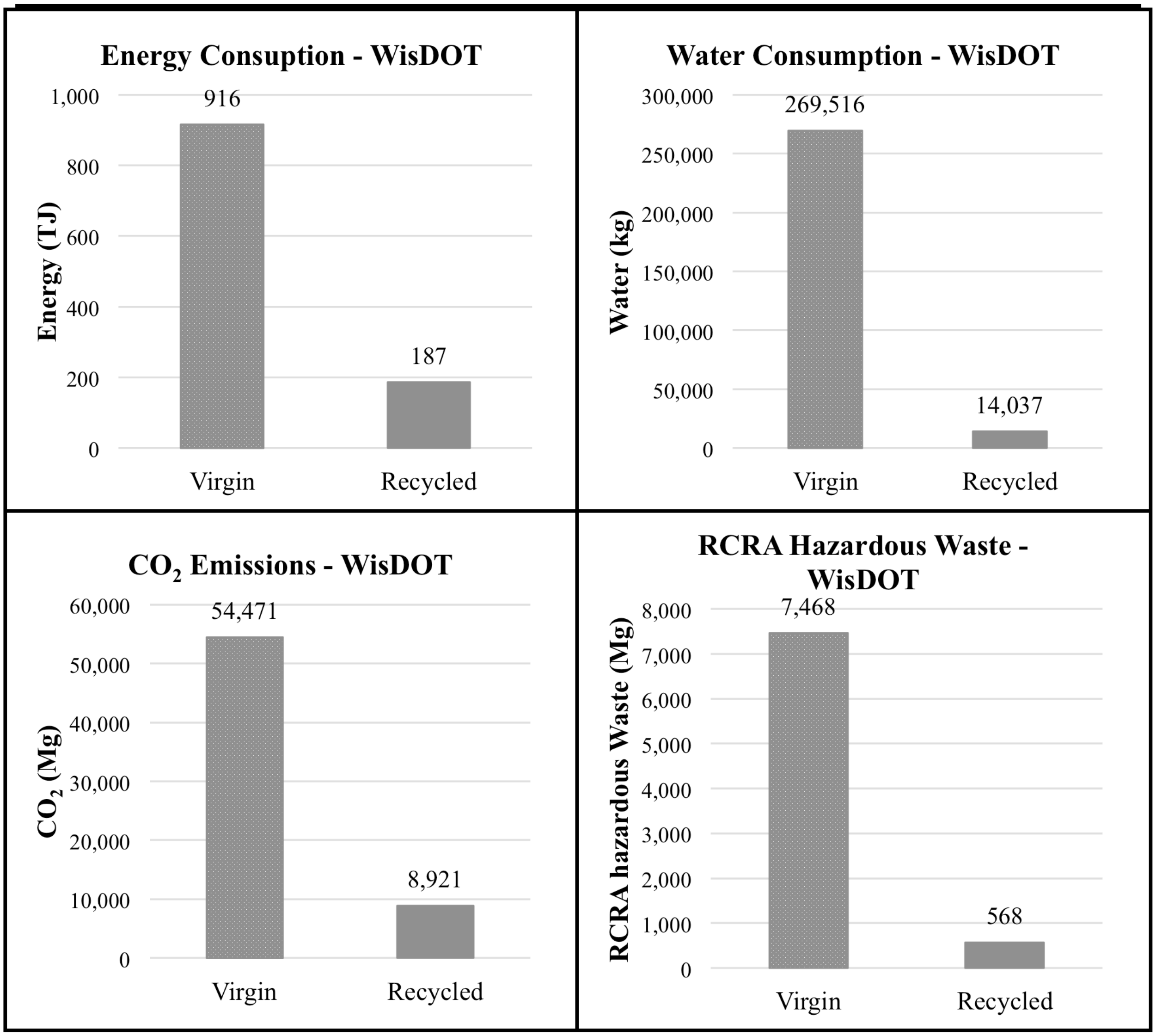
Figure 13-2 Reported Recycled Material Used in 2013 by WisDOT



13.2 Environmental Analysis Results

The use of recycled material reduced the environmental impact in all the impact criteria; as seen in Figure 13-3. It is important recall that these savings were calculated based on a one to one volume replacement of virgin material with recycled material, i.e. these environmental savings would be realized because of the use of recycled material. For a list of assumptions made in the LCA, reference Sections 4 and 5, as well as the assumptions listed in the previous section.

Figure 13-3 Environmental Benefits as a Result of WisDOT Using Recycled Materials in 2013



The greatest reductions are seen in water consumption, followed by hazardous waste production, CO_2 emissions and finally energy production. To put these environmental savings into perspective:

- WisDOT could fill 1,500 bath tubs with the total amount of water saved[1],
- the amount of RCRA hazardous waste saved is equivalent to the average amount produced by 760,750 U.S. households in one year[2],

[1] The total mass of water to fill one tub is 179 kilograms. (PWB, 2016)
[2] The average U.S. household produces 9.07 kilograms of hazardous waste per year. (EPA, 2016)

- WisDOT's CO_2 savings are equivalent to the emissions of 9,691 cars in one year[3], and

- the energy savings are equal to the average energy use of 18,521 U.S. household in one year[4].

Table 13-2 lists the savings and percent reductions of each environmental impact category.

Table 13-2 Summary of Environmental Benefits Accumulated by WisDOT in 2013

Impact Category	*Virgin*	*Recycled*	*Savings*	*Percent Reduction*
Engergy (TJ)	916	187	729	80%
Water consumption (kg)	269,516	14,037	255,479	95%
CO_2 (Mg)	54,471	8,921	45,550	84%
RCRA hazardous waste (Mg)	7,468	568	6,900	92%

Another parameter to measure environmental savings by using recycled materials is social carbon cost (SCC). While not a PaLATE output, SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. This can include, agricultural productivity, human health, property damages from increased flood rise and the value of ecosystem services due to climate change, (EPA, 2013). Based on EPA estimates for SCC in 2013, 34 in 2007 dollars per metric ton of CO_2, at a 3 percent discount rate (future values equated to present values), WisDOT saved about 1.71 million in 2007 dollars in SCC. If inflation is considered, WisDOT saved about 1.92 million in 2013 dollars and 1.96 million in 2016 dollars in SCC.

13.3 Economic Analysis Results

The estimated cost savings of using recycled material in 2013 is shown in Table 13-3. It should be noted that these savings reflect only the price of the material and do include the potential price of hauling to the construction site, hauling to a landfill or any landfilling disposal fees. A description of assumptions made in each materials unit cost savings can be found below as well as in Sections 4 and 6. For a more detailed explanation of virgin material replacement by recycled material reference the recycled material in Section 2 Common Recycled Materials. All pricing data can be found in Appendix A.

[3] The average car emits 4,700 kilogram of CO_2 per/year. (EPA, 2008)
[4] The average U.S. household consumes 0.03936 terajoules of energy per year. (EIA, 2015)

Table 13-3 Calculated WisDOT FY 2013 Cost Savings			
Recycled Material	***Quantity (Tons)***	***Savings ($/ton)***	***Total Savings ($)***
RAP in HMA	528,157	$5.72	$3,018,417
RAS	29,342	$98.00	$2,875,516
Fly Ash	55,288	$30.00	$1,658,640
RCA	954,678	$4.50	$4,296,051
RAP in Base Course	327,077	$4.00	$1,308,308
Total	**1,894,542**		**$13,156,932**

RAP in HMA cost savings were calculated based on the input of Brandon Strand of the Wisconsin Asphalt Pavement Association. The unit cost saving ($5.715/ton) was calculated by subtracting the average price of an HMA mix with 16% RAP in the mix design ($43.75/ton) from the average price of an HMA mix without RAP in the mix design ($49.47/ton). It was estimated that the average WisDOT HMA mix design included 16% RAP.

RAS cost savings were calculated based on input from Kent Hansen of the National Asphalt Paving Association and cost data provided by Steve Krebs of WisDOT. Of the total quantity of RAS used in HMA mixes, 20% is estimated to act as a binder and 80% as aggregate. The cost savings of RAS can then be estimated by calculating the total cost of the replaced virgin materials, (K. Hansen). The assumed unit cost of binder and aggregate in 2013 were $450/ton and $10.00/ton respectively. If one ton of RAS is used, then the cost savings are;

$$\left(.80\times {}^{\$10}/_{ton}\right)+\left(.2\times {}^{\$450}/_{ton}\right)={}^{\$98}/_{ton\ RAS} \tag{13-1}$$

Fly ash cost savings were calculated based on the input of Kevin McMullen of the Wisconsin Concrete Pavement Association. The price of fly ash in 2013 was found to be 30% less than that of traditional Portland cement ($100/ton), giving an estimate cost savings of $30/ton.

RCA cost savings were calculated based on the input of Kevin McMullen also, and aggregate cost data was again provided by Steve Krebs of WisDOT. Any RCA used was assumed to be recycled on-site and the estimated unit cost of recycling concrete on-site was taken as $5.50/ton. Given an average aggregate cost of $10/ton, the estimated unit cost savings of using RCA was found to be $4.50/ton.

RAP in base course cost savings were calculated based on WisDOT average unit prices provided by Steve Krebs. Given an average unit price of $6.00/ton for salvaged asphaltic pavement and an average unit price of aggregate of $10/ton, the unit costs savings of using RAP in base course was found to be $4/ton.

13.4 WisDOT Overall Findings

As stated in the overview section, there were 11,800 miles of road managed by WisDOT in 2013. It should be noted these are the total miles of road throughout the state, not the number of miles of improved road in 2013. The total estimated savings of about $13 million equates to about $1,100 saved per mile of road in 2013. This estimation does not take into account potential future savings of using recycled materials. Future costs include hauling to a landfill, a disposing fee and potential higher rehabilitation costs. If the total cost savings were added to the base funding for state highway programs in FY 2013, it would account for 1% of funding. In other words, 1% of costs were cut to the state highway programs by using recycling materials.

Table 13-4 details the environmental savings per mile of road in FY 2013. To put this into perspective per mile WisDOT is saving, (using the same conversions as in Section 13.2):

- the energy use of 1.6 U.S. households in one year,
- the water it would take to fill 0.13 bath tubs,
- the CO_2 emissions of 0.82 cars in one year, and
- the RCRA hazardous waste produced by 64 households in one year.

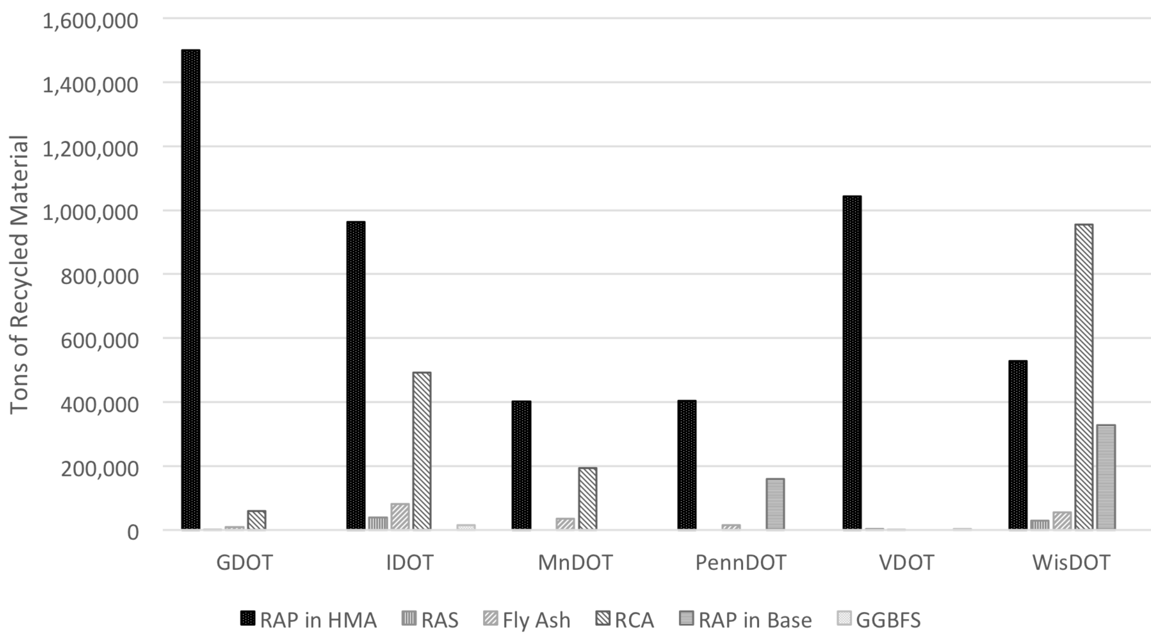
Table 13-4 WisDOT Environmental Savings per Mile

Impact Category	***Savings Per Mile***
Energy (MJ)	61,780
Water consumption (kg)	22
CO_2 (kg)	3,8600
RCRA hazardous waste (kg)	588

14 STATE RESULTS COMPARISON

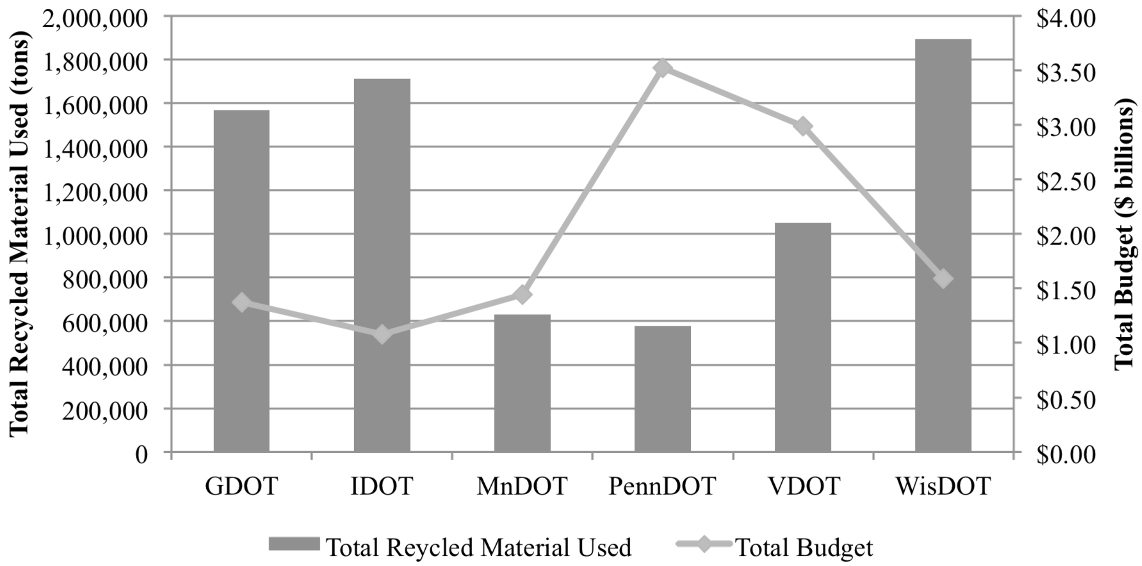
RAP in HMA and fly ash were utilized by all six member state DOTs, while RAS and RCA were utilized by at least four of the member state DOTs. Figure 14-1 shows the tonnage of each recycled material used per state in the LCA and economic analyses of this report. Crumb rubber was not included in the economic analysis. A table of values and averages for the data in Figure 14-1 can be found in the Appendix.

Figure 14-1 Total Recycled Material Utilized in 2013 (tons)



In general, RAP in HMA was utilized the most by weight and volume across all states (Table A-2 through Table A-7). Additionally, RAP in HMA use varies significantly with geography. In the southern states (GA and VA) HMA pavement is more widely used compared to the northern states (IL, MN and WI). HMA pavements' performance drops as the temperature decreases and the pavement becomes brittle. As a result northern states tend to use PCC pavement for their major highways. This is reflected in the recycled material use for each state. The northern states, where PCC is more common, use higher amounts of RCA, and the southern states, where HMA is widely utilized, use higher amounts of RAP, particularly in HMA.

Figure 14-2 Recycled Material and Total Budget for FY 2013 of Each State DOT



***IDOT total tonnage includes those materials not used in the LCA or economic analysis.**

IDOT used above average quantities of all four widely used recycled material (RAP in HMA, RAS, fly ash, and RCA), while WisDOT used more of RAS, fly ash and RCA. GDOT and VDOT used above average amounts of RAP in HMA, as expected since they are southern states, and MnDOT uses proportionately higher amounts of fly ash. As shown in Figure 14-2, WisDOT used the most recycled material (approximately 1.9 million tons), followed closely by IDOT and GDOT (approximately 1.6 million tons each). VDOT uses slightly more than half of the quantity of recycled material that WisDOT uses, while MnDOT and PennDOT use about one third of the quantity of WisDOT.

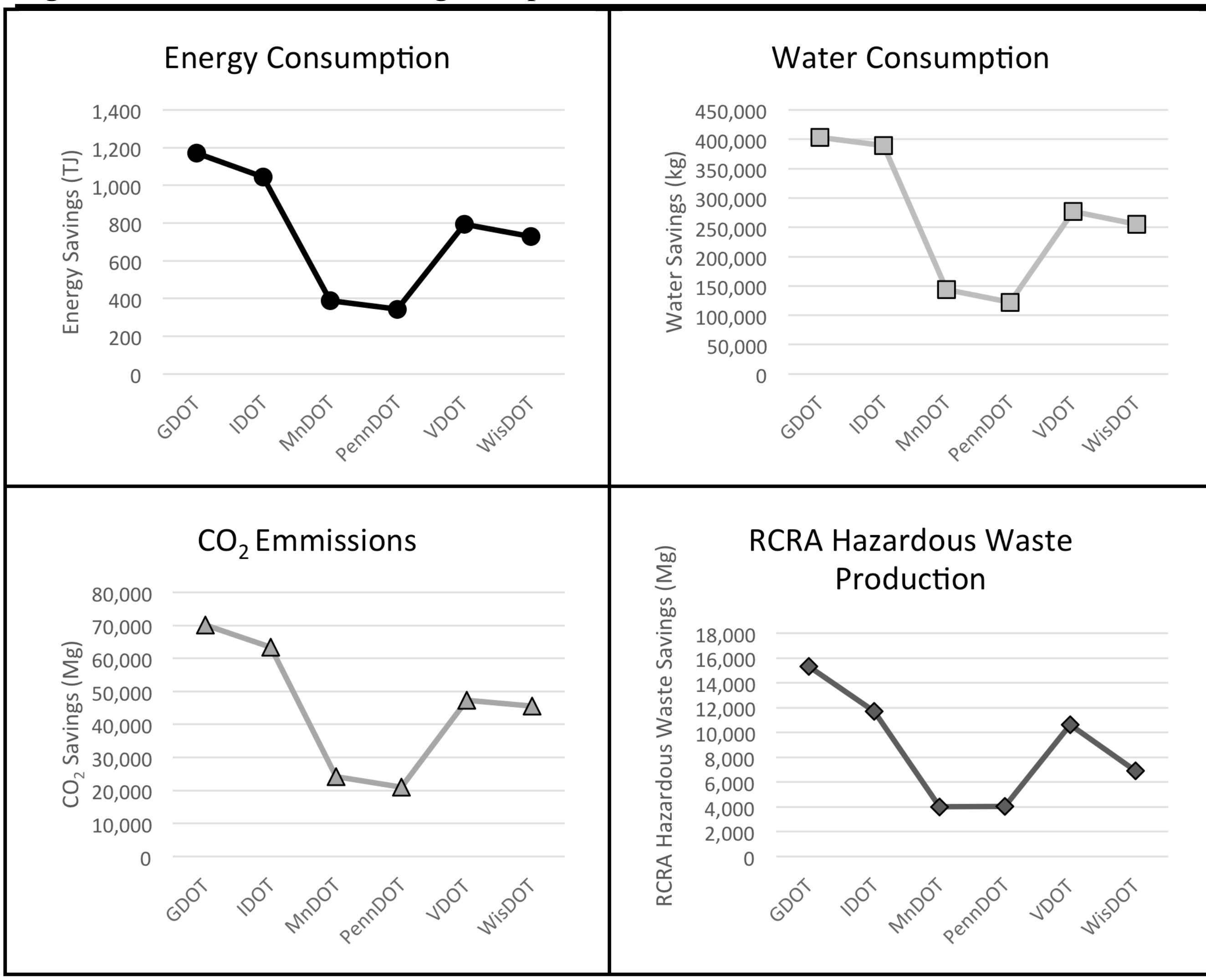
Figure 14-2 shows that member state DOTs with a higher budget usually indicated a lower use of recycled material, while member state DOTs with a lower budget had a higher usage of recycled material. PennDOT and VDOT have the highest budgets and use fewer quantities of recycled material than GDOT, IDOT, and WisDOT. An exception to this is MnDOT, which has a comparable budget to GDOT, IDOT, and WisDOT, but only used quantities of recycled material comparable to PennDOT.

It should be noted that miles managed or improved by each state in 2013 is not reflected in Figure 14-2. Additionally, in the following sections recycled material used per managed miles were not used as a comparison factor because improved miles could not be found for all states, only IDOT and PennDOT. A comparison using total managed miles in each state (i.e. to find tons of recycled material per mile) was not include in the analysis because the 2013 recycled material quantities were only used for improved miles in each state during that year. Normalization using total miles was determined to be an inaccurate representation of the total use of recycled material per mile in each state.

14.1 Overall Environmental Results

Environmental impacts of roadway construction are quantified through energy consumption, water consumption, CO_2 emissions, and RCRA hazardous waste production. The environmental savings from using recycled material is calculated as the difference between the recycled and virgin material scenarios for each impact category. Figure 14-3 shows these environmental savings.

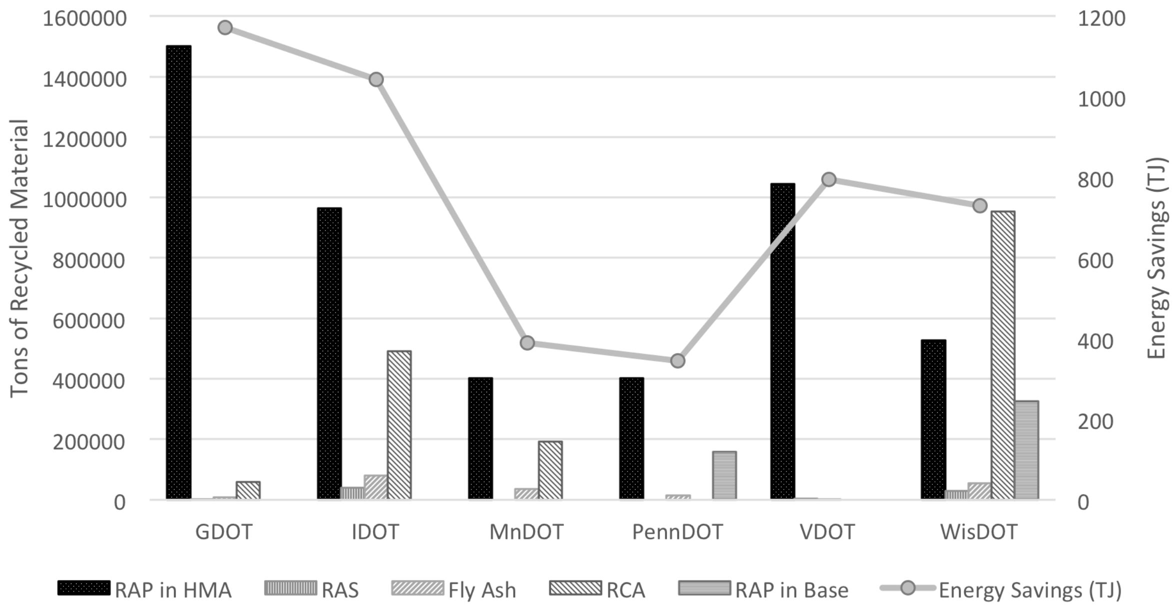
Figure 14-3 Environmental Savings Comparison



There are significant savings for all states in every environmental factor. Energy savings range from 344 TJ to 1,171 TJ, while savings in water consumption range from 122,287 kg to 402,829 kg. CO_2 savings span from 20,975 Mg to 70,178 Mg, and RCRA hazardous waste savings range from 4,014 Mg to 15,319 Mg. Additionally, the trends for all of the environmental savings are very similar. GDOT can expect the highest environmental savings across the board with IDOT expecting the second highest savings. VDOT and WisDOT are similar for all environmental factors except RCRA hazardous waste, where VDOT exceeds WisDOT in savings by a larger margin. MnDOT and PennDOT can expect the fewest environmental savings in all categories. Since the trends in environmental savings are similar for every state across all environmental factors, energy savings were used to examine other trends in the environmental impact data.

Figure 14-4 plots the tons of each recycled material used versus energy saved in every state. The figure demonstrates that states which use more recycled material should expect more energy savings. MnDOT and PennDOT use the least amount of recycled material, thus are shown to save the least energy. However, not all states follow this trend. WisDOT, which uses the most recycled material, does not see higher energy savings than GDOT and IDOT. This is because some materials have a larger energy savings than others. A trend between energy savings and RAP in HMA is observed. States which use large amounts of RAP in HMA see high environmental savings. RAP in HMA is the most widely used recycled material, accounting for about 66% of the total recycled material used by the six states studies. Hence, the energy savings reflected for each state is largely influence by the amount of RAP in HMA the state uses. However, total use of recycled materials has a significant effect as well. This balance can be seen by comparing WisDOT with MnDOT and PennDOT. These three states use a comparable amount of RAP in HMA, but WisDOT should expect significantly higher energy savings due to a much higher use of total recycled materials. Another example of the balance between RAP in HMA use and total recycled material is found when comparing WisDOT and VDOT. Both states see comparable energy savings despite differences in amount and type of recycled material used. VDOT used about 1 million tons of recycled material mainly consisting of RAP in HMA, while WisDOT uses about 1.9 million tons of a larger variety of recycled materials. WisDOT might expect higher total energy savings compared to VDOT, but the results do not show this conclusion.

Figure 14-4 Tonnage of Recycled Materials and Energy Savings



The large effect of RAP in HMA on energy savings is further illustrated in Figure 14-5, which shows recycled material use as a percent for each state and energy savings per ton. This figure, unlike Figure 14-4, does not consider the total amount of recycled materials used. It allows for a clearer view into which recycled materials have the highest potential for environmental savings. GDOT and VDOT have the highest percent of RAP in HMA (both over 90%) and see the highest energy savings per ton. The correlation can also be seen with WisDOT, which has the lowest percent RAP in HMA of the recycled materials used and the lowest energy savings per ton. This trend shows that RAP in HMA has a significant influence on energy savings of the materials studied. This is likely because RAP in HMA is a binder replacement. Producing the binder for a pavement is extremely energy intensive and using RAP in HMA reduces the need for the asphalt binder. RAS and fly ash, both binder replacements, would likely see the same influence on environmental savings. However, they are not recycled to the extent that RAP in HMA is and their effects are therefore overshadowed.

Figure 14-5 Percent of Material and Energy Savings Per Ton

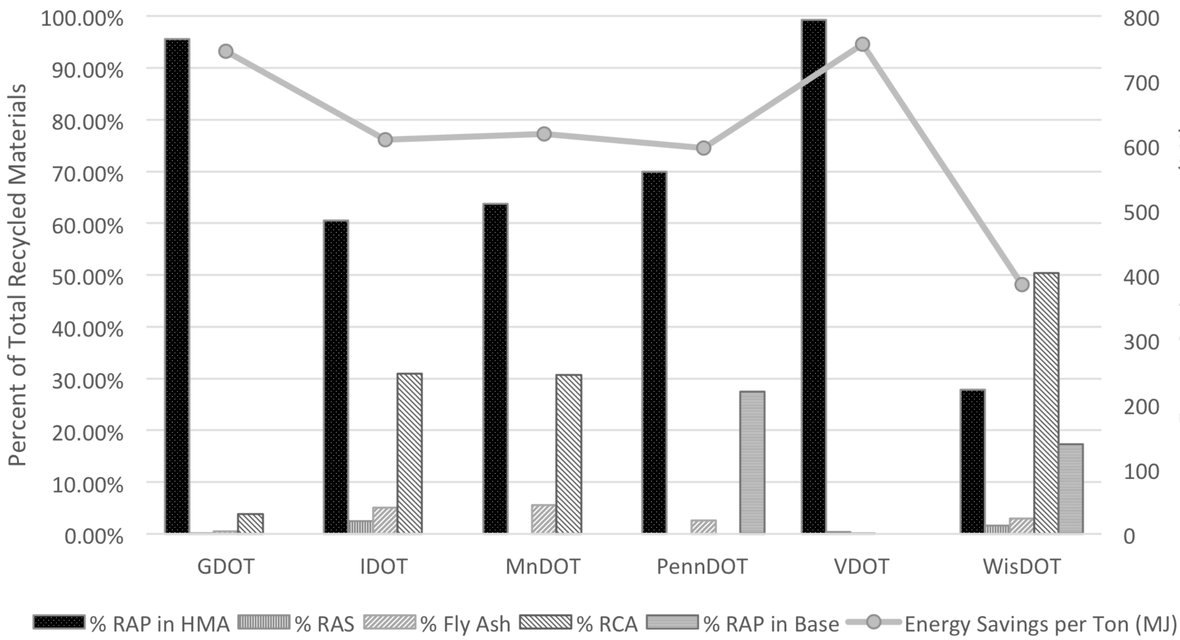
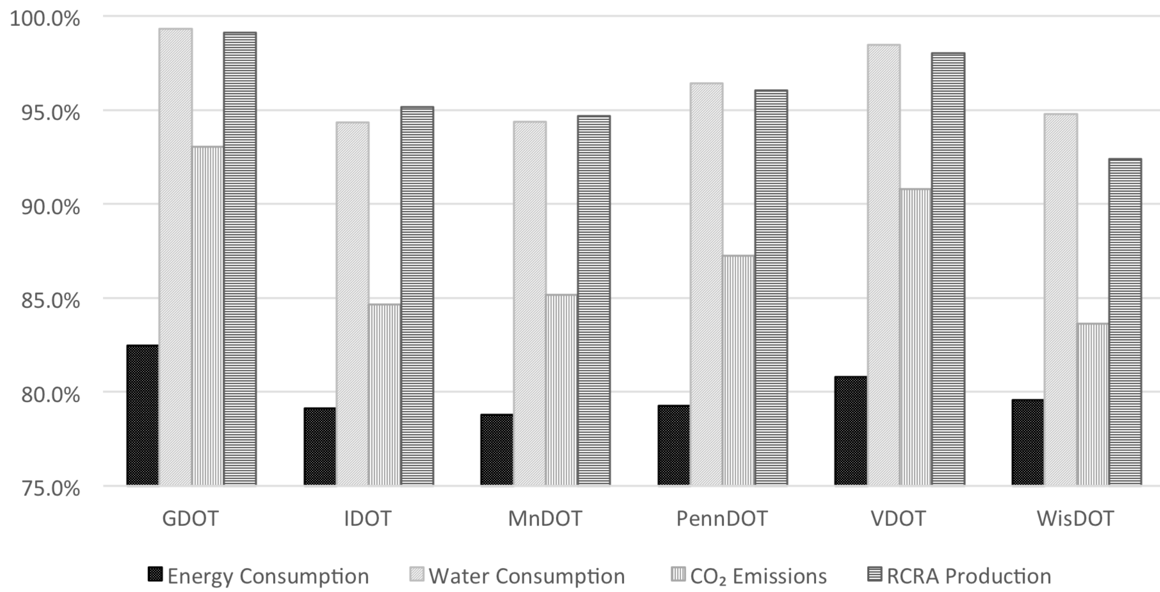


Figure 14-6 shows the percent reductions in environmental factors for each state due to 1:1 replacement of virgin materials with recycled materials. High percent savings are expected for all environmental factors, with water consumption savings having the highest (94% - 99%) and energy savings having the lowest (78% - 83%). Despite energy consumption showing the lowest savings of the four environmental factors, reducing the energy needed for road construction by at least 78% from the use of recycled materials is significant. It can therefore be concluded that utilizing recycled materials in roadway construction, in all the states studied, greatly reduces the environmental strain associated with road construction.

Figures 14-4 and 14-5 examine energy savings compared to recycled material use. From Figure 14-3 it was determined that all environmental categories display similar trends. Therefore, energy savings are representative of all the environmental categories (water consumption, CO_2 emissions, and RCRA hazardous waste production) and the trends discussed between energy savings and recycled material use hold true for the other environmental categories.

Figure 14-6 Percent Reduction in Environmental Impacts

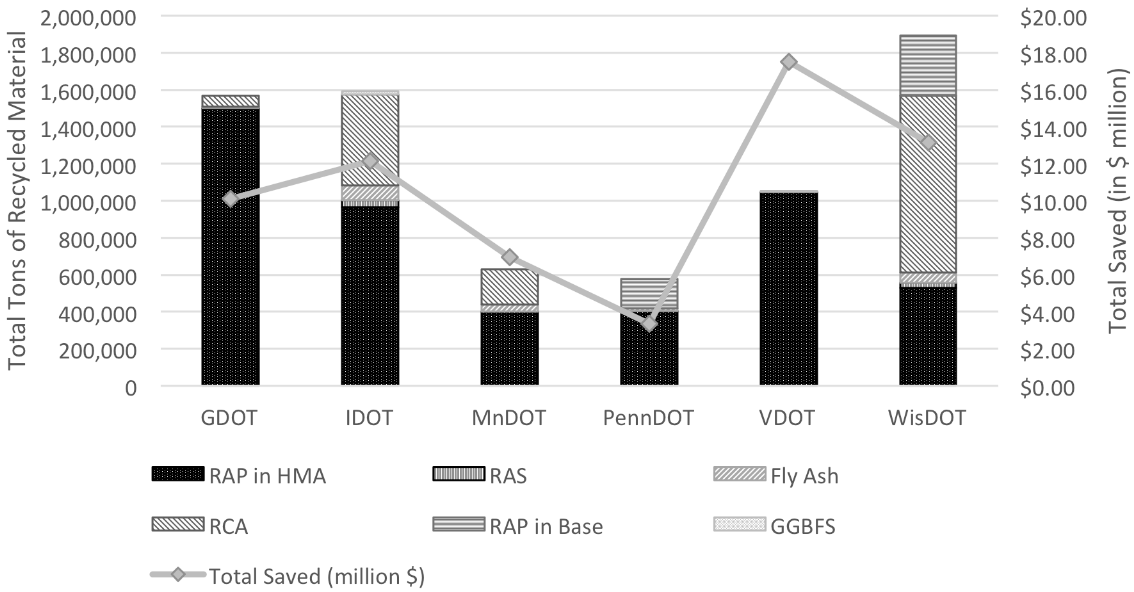


Note that the axis is scaled to start at 75%

14.2 Overall Economic Results

The estimated cost savings of each state ranged from $3 to $17.5 billion, shown in Figure 14-7. As expected, the economic benefit of using RAP in HMA as a binder and aggregate replacement was the highest of all the recycled materials because it was used in large quantities in most states. RAS and fly ash also had high estimated cost savings. These three recycled materials all replace a percentage of virgin materials that act as binders. RAS and RAP can be used as asphalt binder replacement and fly ash can be used as a substitute for cement, a hydraulic binder. Binder for asphalt mixes was priced in 2013 (Table A-9), on average, at about $500/ton and cement was, on average, at about $110/ton, making these the most expensive materials in their respective pavements (excluding binder modifiers, which were not researched for this report).Recycled materials that replaced aggregates generally priced at a much lower cost between $10 and $20 per ton, thus did not have as large of an impact on total cost savings. Comparing GDOT and IDOT, both states use similar quantities of recycled material, however IDOT saves about $2 million more than GDOT. This discrepancy can be attributed to the difference in materials recycled. IDOT recycles more binder replacements, specifically RAS and fly ash, which accounts for the greater cost savings, compared to GDOT.

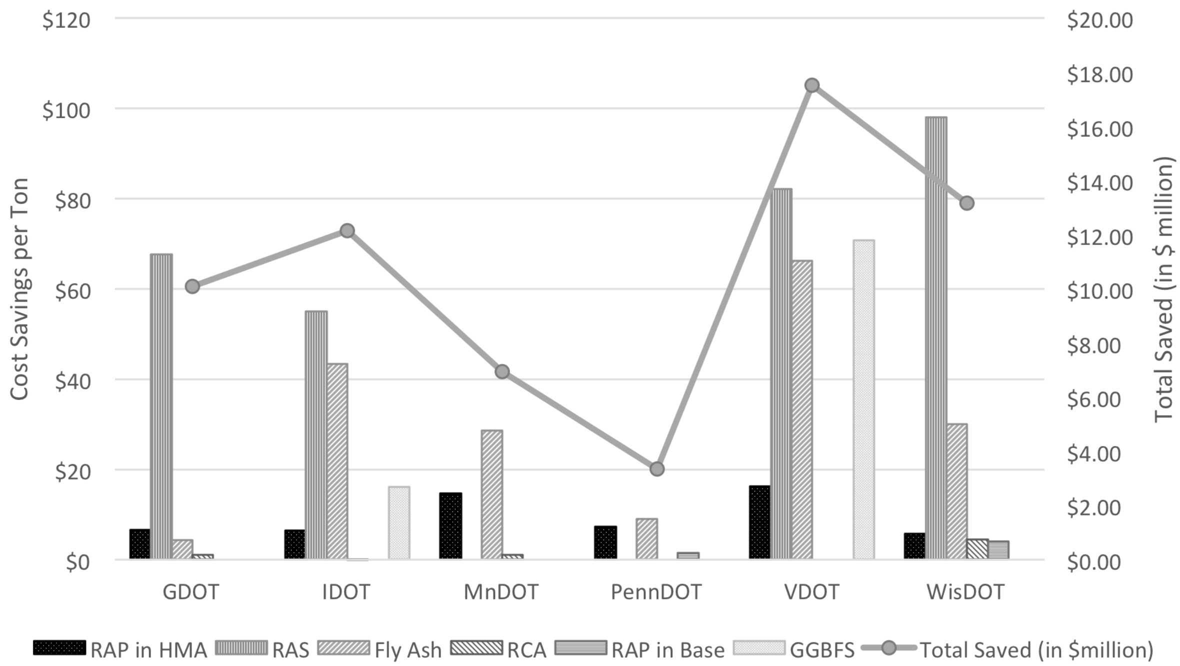
Figure 14-7 Cost Savings from Recycled Material Use



Variability in cost savings per material may account for some differences in total savings, but it does not account for the disproportionately higher savings seen by VDOT, shown in Figure 14-7. VDOT utilized only the fourth largest amount of total recycled material but saved the most by about $4.5 billion. In total, VDOT saved about $17.5 billion and WisDOT followed with a savings of about $13 billion. This disproportionality cannot be explained by the higher cost savings realized through the use of binder replacements because compared to VDOT, IDOT recycles the same amount of RAP in HMA and uses a significantly larger amount of material including more binder replacements. However, IDOTs savings are about $5.5 billion less. A possible explanation for this discrepancy is the differences in local cost structure.

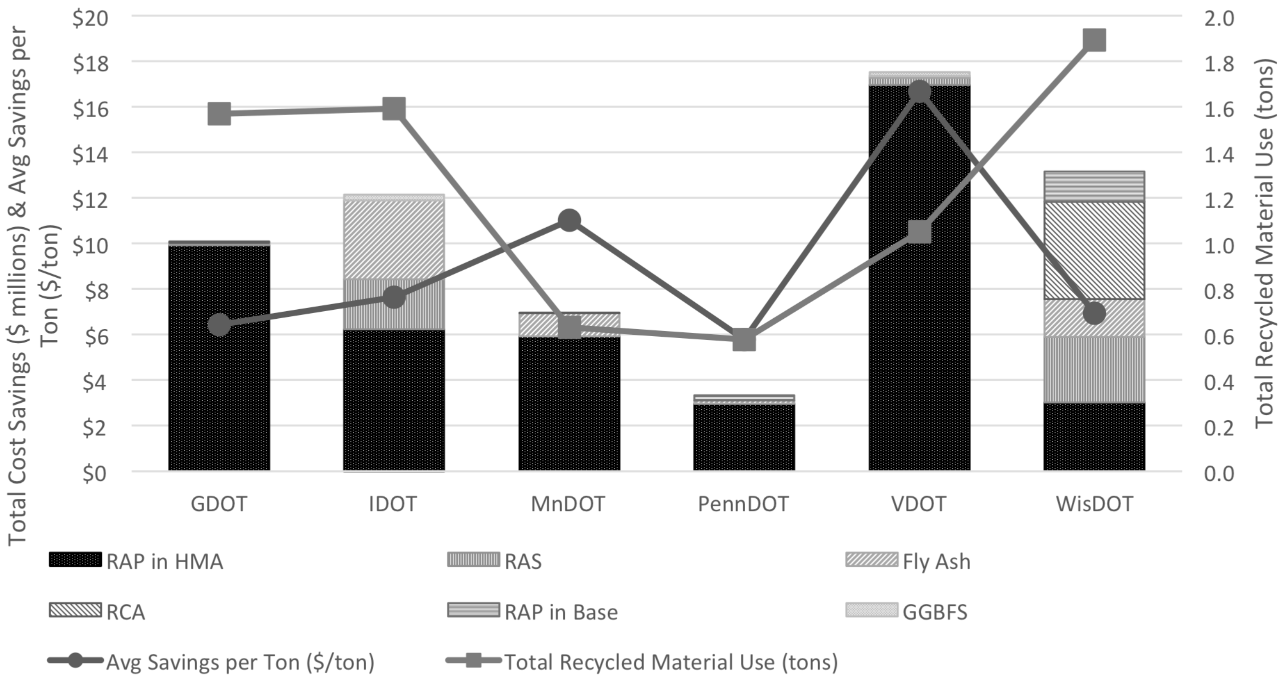
Savings per ton per material, as seen in the bars in Figure 14-8, is derived from the difference between the price of a ton of virgin material and the price of a ton of recycled material. The different savings per ton for each material in a given state is what determines that states local cost structure. As expected, the binder replacement materials, RAS, Rap and fly ash, show the greatest savings per ton in each state. However, Figure 14-8 also shows that savings per ton varies greatly from state to state. It can also be noted that there is a correlation between savings per ton and total savings, shown in the line graph on Figure 14-8. This can be explained by the fact that, certain materials, ones that replace expensive virgin materials, will have a greater impact on total cost savings than others. However, using more recycled material will, on average, lead to increased savings, increased savings that may vary depending on the quantity and material recycled. With its significantly greater total recycled material tonnage compared to other states, one would expect VDOT to see greater cost savings. However, this is not the case, an explanation for this discrepancy is VDOT’s utilization of a variety of materials, materials which have higher savings per ton in Virginia. The savings per ton realized utilizing RAP in HMA, although slightly higher than most states, is especially significant because RAP in HMA makes up 99% of Virginia’s total tonnage of recycled material. Moreover, this leads to the conclusion that savings are not simply derived from the amount of materials recycled, but also from the specific materials being recycled.

Figure 14-8 Savings per ton of Recycled Material ($)



Comparing, average savings, total tons of recycled material used and total cost savings, as seen in Figure 14-9, the previously stated conclusion is reiterated. The graph behaves as expected from previously discussed trends. For example GDOT, IDOT and WisDOT all display lower average savings per ton of recycled material but higher total recycled material usage. As a result, those states display intermediate total cost savings compared to the other states. On the other hand, VDOT displays the highest average savings per ton of recycled material and intermediate total tons of recycled material used compared to the other states; therefore, its total cost savings are the highest. This trend reiterates the conclusion that the economic impact realized through the use of recycled material is dependent on the type and quantity of recycled materials. However, it should be noted that all states experienced savings in the millions of dollars. While some materials may save more than others, all recycled material use results in a measureable amount of savings. In conclusion, the more recycled materials utilized, the greater the savings

Figure 14-9 Total Savings



15 SUMMARY AND CONCLUSIONS

The main objective of this report was to quantify the economic and environmental benefits of using recycled material in highway pavements in 2013.Most prior research on the use of recycled material in highway construction applications has been the engineering properties of these materials. Little research has been conducted on the sustainability assessment characteristic of these materials, including: CO_2 emissions, energy and water consumptions, RCRA hazardous waste production and life-cycle cost benefits.

In order to quantitatively determine the environmental benefits of using recycled materials, six member state DOTs of the RMRC reported their estimated recycled material usage in either the fiscal or calendar year of 2013. Once the different recycled materials and quantity of each used by the state DOTs was known, the resulting environmental benefits could be determined using life cycle assessment (LCA) software. Publically available LCA programs specific to highway construction were researched and the Excel based spreadsheet PaLATE was chosen as the best assessment tool for our data. Once the data was run through PaLATE, four environmental outputs were analyzed for each member state DOT: energy consumption, water consumption, CO_2 emissions and RCRA hazardous waste production.

The economic benefits were calculated by comparing the average price of virgin materials and recycled materials. Prices were determined by surveying material producers and examining available price lists for the year 2013. Due to the many factors involved in calculating the price of material (i.e. hauling costs, regulatory fees, region competition, etc.), this study determined the average purchase price per ton of both recycled materials and virgin materials without any other factors. The total savings and unit savings per ton of recycled material were then be estimated for each member state DOT.

The following conclusions were found after the described research and subsequent analysis:

- The recycled material used in pavement depends on the region in which construction is taking place. In the south, where flexible pavement is prevalent, RAP in HMA is more common. In the north, where rigid pavement is common, there are higher usages of RCA and fly ash.

- Life cycle cost analyses (LCCAs) are required in most large construction projects and recommended in smaller projects in each member state. Furthermore, each member state provides an LCCA tool to aid in project selection.

- Member states do not requires an LCA to be performed on any project. There are very few LCA tools specific to highways that can be used in an analysis.

- Many recycled materials allowable in highway construction, according to standard specifications, are either not being used or are not reported in many of the member states.

- If DOTs were required projects to report their recycled material usage, the total quantity of recycled materials would be known, and therefore a more accurate estimation of benefits could be made.

- The most utilized recycled material in highway construction in 2013 was RAP as a substitute for binder and aggregate in asphalt mixtures.

- The environmental assessment parameters used for this study, were driven by the usage rate of RAP in asphalt mixtures.

- Materials used as a partial replacement for traditional binders had relatively high cost savings compared to materials used in substitution to aggregates.

- Total costs savings were dependent on the usage rate of each material, as well as the estimated unit cost savings for each member state DOT.

Any future research into sustainability assessment measurements should consider real time collection of the data, particularly in relation to material prices. All of the data used in this study was collected in 2014 and 2015, which in turn resulted in significant assumptions being made when calculating recycled material quantities, average material unit prices and conducting the LCA in PaLATE for each member state DOT. Further case studies and developments using the RMRC developed material tracking tool can aide in determining project specific parameters and therefore more accurate future estimations of the economical and environmental of using recycled materials in highway pavements. Because PaLATE was used as the LCA tool in this research, any limitations associated with PaLATE must be taken into account. If PaLATE was to be used for future analyses and research, its databases should be updated.

The conducted research outlined in this report not only quantifies the economic benefits of using recycled materials in highway pavement construction, but also draws attention to the considerable economic benefits as well. Each member state DOT saw large reductions in the measured environmental outputs and positive total monetary saving as a result of using recycled materials and industrial by products in highways in 2013.

16 ACKNOWLEDGEMENTS

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18 APPENDICES

Appendix A Data Collection

Table A-1 2013 RMRC State DOT Survey Results[1]

Question	*Supplementary Question*	*Yes*	*No*	*Overall*
Do you feel that the availability of a RMRC recycled materials tracking tool would be useful in your agency?		5 (GA, WI, CO, IL, PA)	1 (MN)	Y
Does your State use Reclaimed Asphalt Pavement (RAP) in road construction?		All Yes		Y
	Are annual quantities of RAP in Hot Mix Asphalt (HMA) tracked?	3 (GA, WI, CO)	3 (MN, IL, PA)	?
	Are annual quantities of RAP in base course tracked?	1 (WI)	5 (MN, GA, CO, IL, PA)	N
Does your State use Recycled Asphalt Shingles (RAS) in road construction?		All Yes		Y
	Are annual quantities of RAS in Hot Mix Asphalt (HMA) tracked?	4 (GA, WI, CO, IL)	2 (MN, PA)	Y
	Are annual quantities of RAS in structural fill or sub-base tracked?		All No	N
Does your State use Recycled Concrete Aggregate in road construction?		All Yes		Y
	Are annual quantities of Recycled Concrete Aggregate used in base course tracked?	2 (GA, WI)	4 (MN, CO, IL, PA)	N
	Are annual quantities of Recycled Concrete Aggregate used in drainage tracked?		All No	N
Does your State use Recycled Glass Aggregate in road construction?		3 (MN, WI, PA)	3 (GA, CO, IL)	?
	Are annual quantities of Recycled Glass Aggregate used in concrete tracked?		All No (MN, WI, PA)	N
	Are annual quantities of Recycled Glass Aggregate used in drainage tracked?		All No (MN, WI, PA)	N

Question	*Supplementary Question*	*Yes*	*No*	*Overall*
Does your State use coal-combustion Fly Ash in road construction?		All Yes		Y
	Are annual quantities of coal-combustion Fly Ash used in concrete production tracked?	2 (WI, CO)	4 (MN, GA, IL, PA)	N
	Are annual quantities of coal-combustion Fly Ash used in soil stabilization tracked?	1 (WI)	5 (MN, GA, CO, IL, PA)	N
	Are annual quantities of coal-combustion Fly Ash used as structural fill tracked?		All No	N
Does your State use waste-incineration Fly Ash in road construction?			All No	N
	Are annual quantities of waste-incineration Fly Ash used in road construction tracked?		All No	N
Does your State use Bottom Ash in road construction?		3 (WI, IL, PA)	3 (MN, GA, CO)	?
	Are annual quantities of Bottom Ash used in base and sub-base tracked?		All No (WI, IL, PA)	N
	Are annual quantities of Bottom Ash used as asphalt or concrete aggregate tracked?		All No (WI, IL, PA)	N
	Are annual quantities of Bottom Ash used in drainage tracked?		All No (WI, IL, PA)	N
	Are annual quantities of Bottom Ash used in constructing working platform tracked?		All No (WI, IL, PA)	N
Does your State use Foundry Byproducts (foundry sand and slag) in road construction?		4 (WI, CO, IL, PA)	2 (MN, GA)	Y
	Are annual quantities of Foundry Byproducts (foundry sand and slag) used in base and sub-base tracked?		All No (WI, CO, IL, PA)	N
	Are annual quantities of Foundry Byproducts (foundry sand and slag) used as asphalt or concrete aggregate tracked?		All No (WI, CO, IL, PA)	N
	Are annual quantities of Foundry Byproducts (foundry sand and slag) used in drainage		All No (WI, CO, IL, PA)	N

Question	*Supplementary Question*	*Yes*	*No*	*Overall*
	tracked?			
	Are annual quantities of Foundry Byproducts (foundry sand and slag) used in constructing working platform tracked?		All No (WI, CO, IL, PA)	N
Does your State use Iron or Steel Slag in road construction?		4 (WI, CO, IL, PA)	2 (MN, GA)	Y
	Are annual quantities of Iron or Steel Slag used in base and sub-base tracked?		All No (WI, CO, IL, PA)	N
	Are annual quantities of Iron or Steel Slag used for drainage tracked?		All No (WI, CO, IL, PA)	N
	Are annual quantities of Iron or Steel Slag used in constructing working platform tracked?		All No (WI, CO, IL, PA)	N
Does your State use Rubber Derived Aggregate or Crumb Rubber in road construction?		3 (GA, IL, PA)	3 (MN, WI, CO)	?
	Are annual quantities of Rubber Derived Aggregate or Crumb Rubber used in HMA tracked?	2 (GA, PA)	1 (IL)	Y
	Are annual quantities of Rubber Derived Aggregate or Crumb Rubber used in drainage tracked?		All No (GA, IL, PA)	N
	Are annual quantities of Rubber Derived Aggregate or Crumb Rubber used in lightweight fill tracked?	1 (PA)	2 (GA, IL)	N
Does your State have a database for tracking as-let quantities for standard bid items on an annual basis?		4 (MN, WI, CO, IL)	2 (GA, PA)	Y
Do you feel that developing a tracking system similar to this, but adapted to your State's database characteristics, would be useful?		4 (GA, WI, IL, PA)	2 (MN, CO)	Y
Would you like to see RMRC-3G pursue developing such a tool for your State to use?		3 (WI, IL, PA)	3 (MN, GA, CO)	?

[1] Responses include those from Colorado DOT, VDOT provided a general response

Table A-2 GDOT Reported Recycled Materials and Equivalent Virgin Material Volumes

Reported Recycled Material	*Reported Recycled Material Quantity (tons)*	*Reported Recycled Material Volume (yd^3)*	*Equivalent Virgin Material*	*Equivalent Virgin Material Volume (yd^3)*
RAP in HMA	1,500,000	810,811	Aggregate	762,162
--	--	--	Binder	48,649
RAS	1,000	893	Aggregate	714
--	--	--	Binder	179
Fly Ash	8,600	3,909	Cement	3,909
RCA	59,334	31,561	Gravel	31,561
Crumb Rubber	840	438	Binder	438

Table A-3 IDOT Reported Recycled Materials and Equivalent Virgin Material Volumes

Reported Recycled Material	*Reported Recycled Material Quantity (tons)*	*Reported Recycled Material Volume (yd^3)*	*Equivalent Virgin Material*	*Equivalent Virgin Material Volume (yd^3)*
RAP in HMA	963,996	521,079	Aggregate	489,814
--	--	--	Binder	31,265
RAS	39,791	35,528	Aggregate	28,422
--	--	--	Binder	7,106
Fly Ash	80,440	36,564	Cement	36,564
RCA	491,835	261,614	Gravel	261,614
GGBFS	15,045	8,747	Cement	8,747

Table A-4 MnDOT Reported Recycled Materials and Equivalent Virgin Material Volumes

Reported Recycled Material	*Reported Recycled Material Quantity (tons)*	*Reported Recycled Material Volume (yd^3)*	*Equivalent Virgin Material*	*Equivalent Virgin Material Volume (yd^3)*
Fly Ash	35,474	16,125	Cement	16,125
RCA	193,541	102,947	Gravel	102,947
RAP in HMA	402,048	217,323	Aggregate	204,284
--	--	--	Binder	13,039

Table A-5 PennDOT Reported Recycled Materials and Equivalent Virgin Material Volumes

Reported Recycled Material	*Reported Recycled Material Quantity (tons)*	*Reported Recycled Material Volume (yd^3)*	*Equivalent Virgin Material*	*Equivalent Virgin Material Volume (yd^3)*
RAP in HMA	403,334	218,018	Aggregate	204,937
--	--	--	Binder	13,081
Fly Ash	15,158	6,890	Cement	6,890
RAP in Base Course	158,706	85,787	Gravel	85,787

Table A-6 VDOT Recycled Materials and Equivalent Virgin Material Volumes

Reported Recycled Material	*Reported Recycled Material Quantity (tons)*	*Reported Recycled Material Volume (yd^3)*	*Equivalent Virgin Material*	*Equivalent Virgin Material Volume (yd^3)*
RAP	1,044,072	564,363	Aggregate	530,501
--	--	--	Binder	33,862
RAS	3,757	3,354	Aggregate	2,684
--	--	--	Binder	671
Slag	2,340	1,360	Cement	1,360
Fly Ash	1,170	532	Cement	532

Table A-7 WisDOT Recycled Materials and Equivalent Virgin Material Volumes

Reported Recycled Material	*Reported Recycled Material Quantity (tons)*	*Reported Recycled Material Volume (yd^3)*	*Equivalent Virgin Material*	*Equivalent Virgin Material Volume (yd^3)*
RAP in HMA	528,157	285,490	Aggregate	268,361
--	--	--	Binder	17,129
RAS	29,342	26,198	Aggregate	20,959
--	--	--	Binder	5,240
Fly Ash	55,288	25,131	Cement	25,131
RCA	954,678	507,807	Gravel	507,807
RAP in Base Course	327,077	176,798	Gravel	176,798

Table A-8 ENR 2013 Virgin Material Individual and 20-City Average Prices ($/ton)

Material	*Atlanta*	*Baltimore*	*Chicago*	*Minneapolis*	*Philadelphia*	*Pittsburgh*	*20 City Average*
Cement	$107.19	$157.47	$109.58	$127.81	$108.46	$95.53	$109.92
Gravel, Crushed Stone	$10.31	$14.89	$10.21	$7.77	$11.69	$9.90	$10.65
Crushed Stone, Base Course	$10.26	$14.89	$10.45	$7.65	$9.74	$9.90	$10.39
Crushed Stone. Asphalt Course	$10.17	$15.84	$10.36	$7.47	$11.86	$9.90	$11.11

Source: (ENR, 1917)

Table A-9 ENR 2013 Virgin Material Averaged Individual and 20-City Average Prices used in Calculations ($/ton)

Material	*Atlanta*	*Baltimore*	*Chicago*	*Minneapolis*	*Philadelphia, Pittsburg*
Cement	$108.55	$133.69	$109.75	$118.86	$105.96
Asphalt[1]	$571.36	$574.84	$536.16	$536.16[2]	$556.82
Gravel, Crushed Stone	$10.48	$12.77	$10.43	$9.21	$10.72
Crushed Stone, Base Course	$10.33	$12.64	$10.43	$9.02	$10.11
Crushed Stone. Asphalt Course	$10.64	$13.47	$10.73	$9.29	$10.77

Source: (ENR, 1917)
[1]Taken from state DOT indices
[2]IDOT Asphalt Indices used

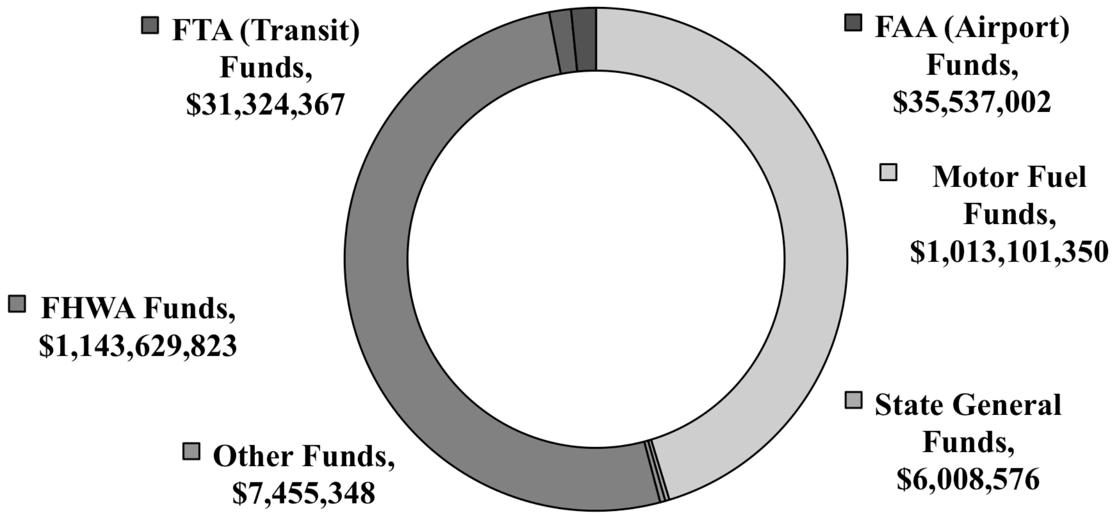
Table A-10 Estimated 2013 Recycled Material Unit Costs ($/ton)[1]

Material	*Georgia*	*Illinois*	*Minnesota*	*Pennsylvania*	*Virginia*
RAP in HMA	$21.00	$20.30	$10.42	$20.00	$14.67
RAS	$35.00	$42.50	--	--	$25.50
Fly Ash	$58.33	$20.00	$40.00	$52.20	$62.70
RCA	$6.50	$7.50	$6.50	--	--
Slag	--	$65.00	--	--	$28.00
RAP in Base	--	--	--	$5.92	--

[1]See Section 13.3 for WisDOT Cost Savings

Appendix B Georgia

Figure B-1 Total GDOT FY 2013 Budget



Source: **(GDOT, 2013a)**

Figure B-2 GDOT Total State Motor Fuel Budget for FY 2013

Source: **(GDOT, 2013a)**

Table B-1 Sample GDOT Decision Matrix

Alternatives	*Decision Factors*						*Total Score*	*Rank*
	Initial Agency Costs	Rehabilitation Costs	Annualized Agency Costs	Annualized User Costs	Initial Construction Duration	Duration of Rehabilitation Activities		
	55	**25**	**5**	**5**	**5**	**5**		
A	1.00 55.0	0.44 11.0	1.00 5.0	1.00 5.0	1.00 5.0	0.67 3.4	84.4	1
B	0.69 38.0	1.00 25.0	0.83 4.2	0.69 3.4	0.54 2.7	1.00 5.0	78.3	2

Source: (GDOT, 2005)

Each decision factor of the matrix is assigned a weight based on relative importance in the selection process and the sum of all the factor weights must equal 100. Factors assigned a higher weight have more certainty in prediction at the time of analysis.

For each alternative, a division is created per decision factor called the matrix element. Each matrix element is given a value called the element value, which is based on LCCA calculations and engineering judgment, i.e. an initial agency cost of $1.35 million. From the element value a ratio is calculated called the spread factor. The spread factor is a ratio ranging in value from 0.00 to 1.00 and it measures distributional differences in element values. In the example above the spread factor is the first value below the decision factor weight. The spread factor is based on the optimum value for each decision factor. The pavement with the optimum value will have a spread factor equal to 1.00. The spread factor of other pavement alternatives will be proportioned based on its particular value to the optimum value and will be lower than 1.00. The spread factor is calculated by dividing the optimal element value by the associated element value.

In the above example shown in Table B-1, the element value for the initial agency costs for Alternatives A and B are $1.35 million and $1.95 million respectively. The spread factor for initial agency costs in Alternative B is 0.69 which is calculated by dividing the element value for Alternative B (1.95) into the optimal value (element value of Alternative A, 1.35). The elemental score (shown below the spread factor) is then calculated as the product of the decision factor weight and the spread factor. The total score is then the sum of all the element score of each pavement. In general the alternative with the highest score is usually selected as the appropriate pavement.

Appendix C Illinois

Table C-1 IDOT Maintenance and Rehabilitation Activity Schedule JPCP and Unbonded JPC Overlay

Year (After Initial Construction)	*Activity*
10	• 0.10% Class B Pavement Patching
15	• 0.20% Class B Pavement Patching
20	• 2.0% Class B Pavement Patching • 0.50% Class C Shoulder patching • 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing
25	• 3.0% Class B Pavement Patching • 1.0% Class C Shoulder Patching
30	• 4.0% Class B Pavement Patching • 1.5% Class C Shoulder Patching • Policy HMA Overlay of Pavement and Shoulder
35	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random Crack Routing & Sealing[1] • 40% Reflective Transverse Crack Routing & Sealing • 0.10% Partial-Depth Pavement Patching (Mill & Fill Surface – Interstates; Mill & Fill 2.50 in. – Non-Interstates)
40	• 0.50% Class B Pavement Patching • 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Reflective Transverse Crack Routing & Sealing • 50% Random Crack Routing & Sealing[1] • 0.50% Partial-Depth Patching (Mill & Fill Surface – Interstates; Mill & Fill 2.50 in. – Non-Interstates)

Source: (IDOT, 2013)
[1] For random crack routing and sealing, assume 100 ft/station/lane.

Table C-2 IDOT Maintenance and Rehabilitation Activity Schedule for CRCP and Unbonded CRC Overlay

Year (After Initial Construction)	*Activity*
10	• 0.10% Class A Pavement Patching
15	• 0.20% Class A Pavement Patching
20	• 0.50% Class A Pavement patching • 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing
25	• 0.75% Class A Pavement Patching • 0.50% Class C Shoulder Patching
30	• 3.0% Class A Pavement Patching • 1.0% Class C Shoulder Patching • Policy HMA Overlay of Pavement and Shoulder
35	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random Crack Routing & Sealing[1] • 0.10% Partial-Depth Pavement Patching (Mill & Fill Surface)
40	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Crack Routing & Sealing • 50% Random Crack Routing & Sealing[1] • 0.50% Class A Pavement Patching • 0.50% Partial-Depth Patching (Mill & Fill Surface)

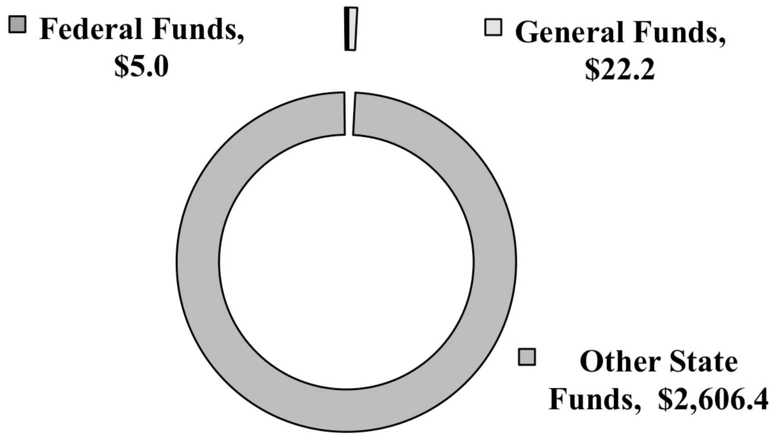
Source: (IDOT, 2013)
[1] For random crack routing and sealing, assume 100 ft/station/lane.

Table C-3 IDOT Maintenance and Rehabilitation Schedule Full-Depth HMA Pavement and HMA Overlay of Rubbilized PCC Pavement

Year (After Initial Construction)	*Activity*
5	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random/Thermal Crack Routing & Sealing* • 0.10% Partial-Depth Pavement Patching (Mill & Fill Surface)
10	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random/Thermal Crack Routing & Sealing* • 0.50% Partial-Depth Pavement Patching (Mill & Fill Surface)
15	• 2.00 in. Milling – Pavement & Shoulder • 1.0% Partial-Depth Pavement Patching (Mill & Fill Additional 2.00 in.) • 2.00 in. HMA Overlay – Pavement & Shoulder
20	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random/Thermal Crack Routing & Sealing* • 0.10% Partial-Depth Pavement Patching (Mill & Fill Surface)
25	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random/Thermal Crack Routing & Sealing* • 0.50% Partial-Depth Pavement Patching (Mill & Fill Surface)
30	***Interstate Standard Design:*** • 2.00 in. Milling – Pavement Only • 2.0% Partial-Depth Pavement Patching (Mill & Fill Additional 2.00 in.) • 1.0% Partial-Depth Shoulder Patching (Mill & Fill Surface) • 3.75 in. HMA Overlay Pavement • 1.75 in. HMA Overlay Shoulder ***Other State maintained Route Standard Design:*** • 2.00 in. Milling – Pavement & Shoulder • 2.0% Partial-Depth Pavement Patching (Mill & Fill Additional 2.00 in.) • 1.0% Partial-Depth Shoulder Patching (Mill & Fill Additional 2.00 in.) • 2.25 in. HMA Overlay Pavement & Shoulder ***All Limiting Strain Criterion Designs:*** • 2.00 in. Milling – Pavement & Shoulder • 2.0% Partial-Depth Pavement Patching (Mill & Fill Additional 2.00 in.) • 1.0% Partial-Depth Shoulder Patching (Mill & Fill Additional 2.00 in.) • 2.00 in. HMA Overlay Pavement & Shoulder
35	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random/Thermal Crack Routing & Sealing[1] • 0.10% Partial-Depth Pavement Patching (Mill & Fill Surface)
40	• 100% Longitudinal Shoulder Joint Routing & Sealing • 100% Centerline Joint Routing & Sealing • 50% Random/Thermal Crack Routing & Sealing[1] • 0.50% Partial-Depth Pavement Patching (Mill & Fill Surface)

Source: (IDOT, 2013)
[1] For random crack routing and sealing, assume 100 ft/station/lane.

Figure C-1 Total FY 2013 IDOT Appropriations by Funding Source ($ in millions)



Source: **(OMB, 2015)**

Appendix D Minnesota

Table D-1 MnDOT Maintenance Schedule for PCC with 12' or 15' Joint Spacing, DL of 20 years

Pavement Age	*35 Year Analysis Treatment*	*50 Year Analysis Treatment*
0	Initial Construction	Initial Construction
20	1st CPR	1st CPR
35	End of Analysis (No Remaining Service Life)	Remove & Replace (PCC with 20-year Design Life)
50		End of Analysis Period (5/20 Remaining Service Life)

Source: (MnDOT, 2016)

Table D-2 MnDOT Maintenance Schedule for PCC with 12' or 15' Joint Spacing, DL of 35 years

Pavement Age	*35 Year Analysis Treatment*	*50 Year Analysis Treatment*
0	Initial Construction	Initial Construction
20	1st CPR	1st CPR
35	End of Analysis (No Remaining Service Life)	2nd CPR
50		End of Analysis Period (No Remaining Service Life)

Source: (MnDOT, 2016)

Table D-3 MnDOT Maintenance Schedule for PCC with 6' X 6' Joint Spacing, DL of 20 years, PCC thickness of 5.5 inches or Greater

Pavement Age	*35 Year Analysis Treatment*	*50 Year Analysis Treatment*
0	Initial Construction	Initial Construction
20	1st CPR	1st CPR
35	End of Analysis (No Remaining Service Life)	Remove & Replace (PCC with 20-year Design Life)
50		End of Analysis Period (5/20 Remaining Service Life)

Source: (MnDOT, 2016)

Table D-4 MnDOT Maintenance Schedule for PCC with 6' X 6' Joint Spacing, DL of 20 years, PCC thickness of 5.0 inches or Less

Pavement Age	*35 Year Analysis Treatment*	*50 Year Analysis Treatment*
0	Initial Construction	Initial Construction
20	1st CPR	1st CPR
30	Remove & Replace (PCC with 35-year Design Life)	Remove & Replace (PCC with 35-year Design Life)
35	End of Analysis (30/35 Remaining Service Life)	
50		End of Analysis Period (15/35 Remaining Service Life)

Source: (MnDOT, 2016)

Table D-5 MnDOT Maintenance Schedule for PCC with 6' X 6' Joint Spacing, DL of 35 years

Pavement Age	*35 Year Analysis Treatment*	*50 Year Analysis Treatment*
0	Initial Construction	Initial Construction
20	1st CPR	1st CPR
35	End of Analysis (No Remaining Service Life)	2nd CPR
50		End of Analysis Period (No Remaining Service Life)

Source: (MnDOT, 2016)

Table D-6 MnDOT Maintenance Schedule for New HMA Pavement over Aggregate Base, FDR, SFDR, CIR, or Rubbilized PCC, DL of 20 years

Pavement Age	*35 Year Analysis Treatment*	*50 Year Analysis Treatment*
0	Initial Construction	Initial Construction
8	Crack Treatment	Crack Treatment
12	Surface Treatment [1, 2]	Surface Treatment [1, 2]
20	Mill & Overlay (1st Overlay)	Mill & Overlay (1st Overlay)
23	Crack Treatment	Crack Treatment
27	Surface Treatment [2]	Surface Treatment [2]
35	End of Analysis (2/17 Remaining Service Life)	
37		Mill & Overlay (2nd Overlay)
40		Crack Treatment
44		Surface Treatment
50		End of Analysis (4/17 Remaining Service Life)

Source: (MnDOT, 2016)
[1] Delete when ultra-thin bonded wearing course is used
[2] Eliminate chip seal and fog seal when 20 year ESALs are > 7 million

Table D-7 Maintenance Schedule for HMA Overlay, DL of 13 to 17 years

Pavement Age	*50 Year Analysis Treatment*
0	Initial Construction (1st Overlay)
3	Crack Treatment
7	Chip Seal[1]
DL	Mill & Overlay (2nd Overlay)
DL+3	Crack Treatment
DL+7	Chip Seal[1]
2*DL-1	Mill & Overlay (3rd Overlay)
2*DL+2	Crack Treatment [2]
2*DL+6	Chip Seal[1, 3]
35	End of Analysis Period (Remaining Life of Last Overlay = [3*DL-38)/(DL-2)]

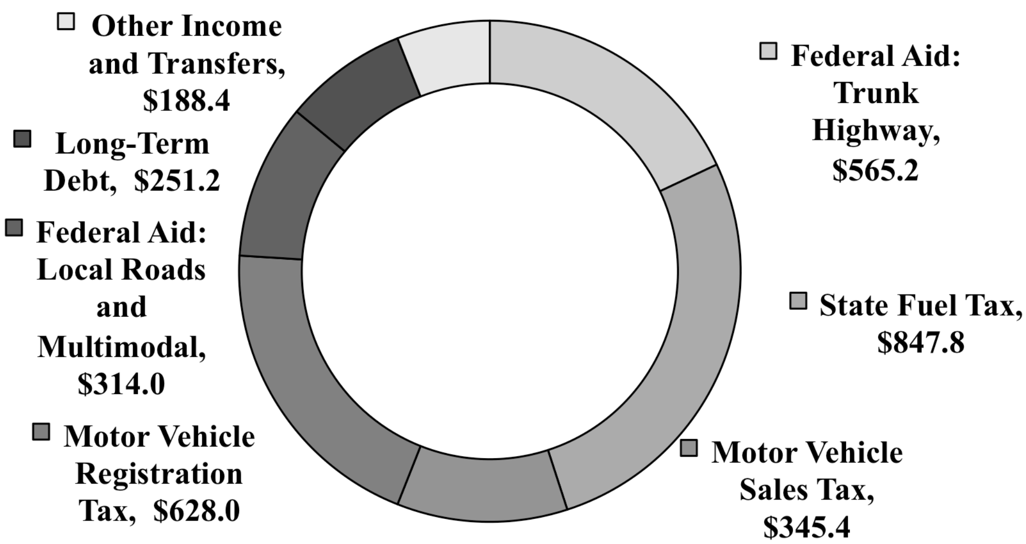
Source: (MnDOT, 2016)
[1] Eliminate chip seal and fog seal when 20 year BESALs are > 7 million
[2] Do not use when DL = 17
[3] Do not use when DL = 15, 16, 17

Table D-8 MnDOT Maintenance Schedule for HMA Overlay, DL > 17 years

Pavement Age	*50 Year Analysis Treatment*
0	Initial Construction (1st Overlay)
3	Crack Treatment
7	Chip Seal[1]
DL	Mill & Overlay (2nd Overlay)
DL+3	Crack Treatment
DL+7	Chip Seal[1]
35	End of Analysis Period (Remaining Life of Last Overlay = [2*DL-36)/(DL-1)]

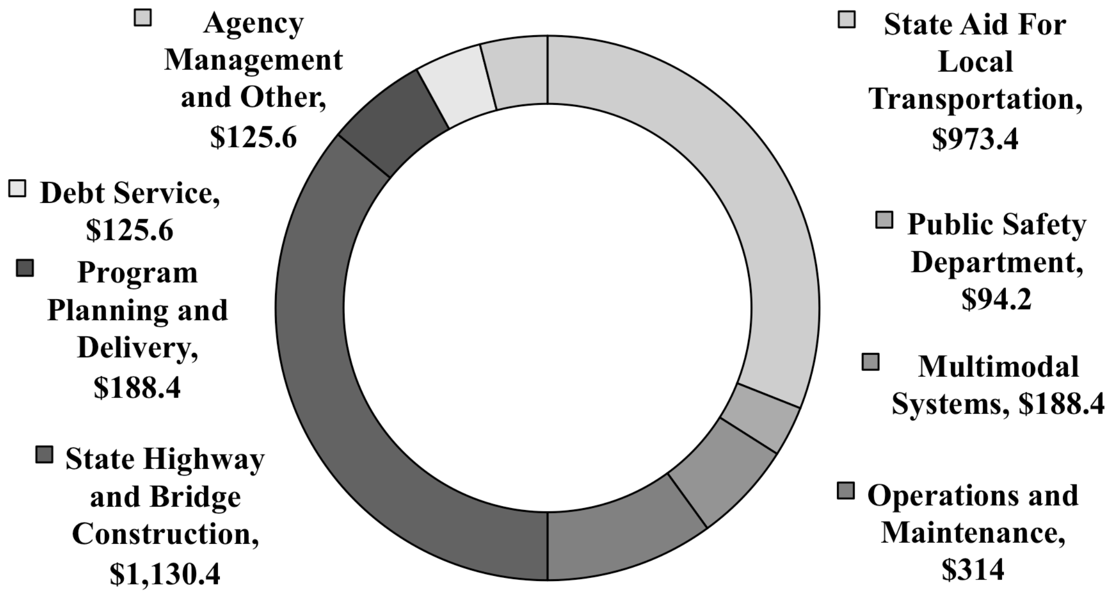
Source: (MnDOT, 2016)
[1] Eliminate chip seal and fog seal when 20 year BESALs are > 7 million
Do not use when DL = 17
Do not use when DL = 15, 16, 17

Figure D-1 Sources of MnDOT Funds for FY 2013 ($ in millions)



Source: **(MnDOT, 2013)**

Figure D-2 Uses of MnDOT Funds for FY 2013 ($ in millions)



Source: **(MnDOT, 2013)**

Appendix E Pennsylvania

Table E-1 PennDOT Bituminous New Construction or Reconstruction for 50 Year Analysis Period

Activity Year	*Activity*
5	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders if Type 1, 1S, 3, 4, 6, or 6S • Maintenance and Protection of Traffic • User Delay
10	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay
15	• Full Depth Patching, 2% of pavement area • Mill wearing course • Bituminous Inlay, 1.5 inches or 2.0 inches • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay
20	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay
25	• Full Depth Patching, 4% of pavement area • Mill wearing course • Bituminous Inlay, 1.5 inches or 2.0 inches • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay
30	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay
35	• Full Depth Patching, 4% of pavement area • Scratch Course, 60 pounds per square yard • Bituminous Overlay, 1.5 inches or 2.0 inches • Type 7 Paved Shoulders • Adjust guide rail and drainage structures, if necessary • Maintenance and Protection of Traffic • User Delay
40	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic

	• User Delay
45	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface roadway and shoulders • Partial Depth Asphalt Surface Patching, 2% of pavement area • Maintenance and Protection of Traffic • User Delay

Source: (PennDOT, 2016)

Table E-2 PennDOT Concrete New Construction, Reconstruction, Unbonded Concrete Overlay for 50 Year Analysis Period

Activity Year	*Activity*
10	• Clean and Seal, 25% of longitudinal joints including shoulders • Clean and Seal, 25% of transverse joints • Maintenance and Protection of Traffic • User Delay
15	• Concrete Patching, 2% of pavement area • Diamond Grinding, 50% of pavement area • Clean and Seal, all longitudinal joints including shoulders • Clean and Seal, all transverse joints • Maintenance and Protection of Traffic • User Delay
25	• Concrete Patching, 4% of pavement area • Diamond Grinding, 100% of pavement area (full width) • Clean and Seal, all longitudinal joints including shoulders • Clean and Seal, all transverse joints • Maintenance and Protection of Traffic • User Delay
35	• Concrete Patching, 6% of pavement area • Clean and Seal, all longitudinal joints including shoulders • Clean and Seal, all transverse joints • Scratch Course, 60 pounds per square yard • Bituminous Overlay, 4 inches or 4.5 inches • Saw and Seal, all transverse joints • Type 7 Paved Shoulders • Adjust guide rail and drainage structures, if necessary • Maintenance and Protection of Traffic • User Delay
40	• Clean and Seal, 25% of longitudinal joints • Clean and Seal, 25% of transverse joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay
45	• Crack Seal, 500 lineal feet per mile • Partial Depth Asphalt Surface Patching, 2% of pavement area • Clean and Seal, 25% of all longitudinal joints, including shoulders • Clean and Seal, 25% of all transverse joints • Micro Surface roadway • Maintenance and Protection of Traffic • User Delay

Source: (PennDOT, 2016)

Table E-3 PennDOT Bonded Concrete Overlay for a 30 Year Analysis Period

Activity Year	*Activity*
5	• Clean and Seal, 25% of longitudinal joints including shoulders • Clean and Seal, 25% of transverse joints • Seal Coat or Micro Surface shoulders, if bituminous • Maintenance and Protection of Traffic • User Delay
10	• Concrete Patching, 5% of pavement area • Diamond Grinding, 50% of pavement area • Clean and Seal, 25% of longitudinal joints including shoulders • Clean & Seal, 25% of transverse joints • Seal Coat or Micro Surface shoulders, if bituminous • Maintenance and Protection of Traffic • User Delay
15	• Clean and Seal, 25% of longitudinal joints including shoulders • Clean and Seal, 25% of transverse joints • Seal Coat or Micro Surface shoulders, if bituminous • Maintenance and Protection of Traffic • User Delay
20	• Concrete Patching, 8% of pavement area • Clean and Seal, all longitudinal joints including shoulders • Clean and Seal, all transverse joints • Scratch Course, 60 pounds per square yard • Bituminous Overlay, 4 inches or 4.5 inches • Saw and Seal, all transverse joints • Type 7 Paved Shoulders • Adjust guide rail and drainage structures, if necessary • Maintenance and Protection of Traffic • User Delay
25	• Clean and Seal, 25% of sawed and sealed joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay

Source: (PennDOT, 2016)

Table E-4 PennDOT Concrete Pavement Rehabilitation (CPR) & Bituminous Overlay for a 30 Year Analysis Period

Activity Year	*Activity*
10	• Mill Wearing Course • Bituminous Inlay, 1.5 inches or 2.0 inches • Saw & Seal, all transverse joints • Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S • Maintenance and Protection of Traffic • User Delay
15	• Clean & Seal, 25% of sawed & sealed joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S • Maintenance and Protection of Traffic • User Delay
20	• Concrete Patching, 2% of pavement area • Scratch Course, 60 pounds per square yard • Bituminous Overlay, 1.5 inches or 2.0 inches • Saw & Seal, all transverse joints • Type 7 Paved Shoulders • Adjust guide rail and drainage structures, if necessary • Maintenance and Protection of Traffic • User Delay
25	• Clean & Seal, 25% of longitudinal and transverse joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay

Source: (PennDOT, 2016)

Table E-5 PennDOT Bituminous Overlay on Bituminous Pavement for a 10 Year Analysis Period

Activity Year	*Activity*
5	• Clean and Seal, 25% of longitudinal joints • Crack Seal, 500 lineal feet per mile • Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S • Maintenance and Protection of Traffic • User Delay

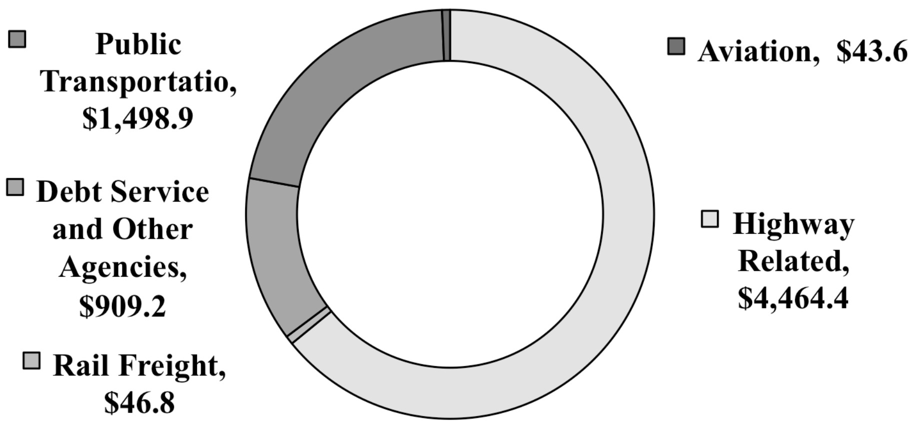
Source: (PennDOT, 2016)

Table E-6 PennDOT Ultra-Thin Whitetopping on Bituminous Pavements for a 10 Year Analysis Period

Activity Year	*Activity*
5	• Clean and Seal, 25% of longitudinal joints including shoulders • Clean and Seal, 25% of transverse joints • Seal Coat or Micro Surface shoulders • Maintenance and Protection of Traffic • User Delay

Source: (PennDOT, 2016)

Figure E-1 FY 2013 PennDOT Spending ($ in millions)



Source: **(PennDOT, 2013)**

Appendix F Virginia

Table F-1 VDOT LCCA Asphalt Pavement, Dense Graded Mixes Construction/Reconstruction Schedule

Year	*Section*	*Activities*
Year 0 – New Construction/Reconstruction	Mainline[1]	• AC Surface Material • AC Intermediate Material • AC Base Material • Stabilized Drainage Layer • CTA or DGA Subbase
	Shoulders[1]	• AC Surface Material • AC Intermediate Material • AC Base Material • Stabilized Drainage Layer • CTA or DGA Subbase
Year 12 – Functional Mill and Replace	Mainline	• Pre-overlay Repair – Patch – 1% (up to the top of base layer) • Mill – Surface Layer • Replace with AC Wearing Course – one layer
	Shoulders	• Surface Treatment
Year 22 – Functional Mill and Replace	Mainline	• Pre-overlay Repair – Patch – 1% (up to the top of base layer) • Mill – Surface Layer • Replace with AC Surface Materials – one layer
	Shoulders	• Surface Treatment
Year 32 – Major Rehabilitation	Mainline	• Pre-overlay Repair – Patch – 5% (full depth) • Deep Mill (All Surface and Intermediate Layers) • Replace with AC Base Material, AC Intermediate Material, AC Wearing Course
	Shoulders	• Overlay with AC Wearing Course
Year 44 – Functional Mill and Replace	Mainline	• Pre-overlay Repair – Patch – 1% (up to the top of base layer) • Mill – Surface Layer • Replace with AC Wearing Course – one layer
	Shoulders	• Surface Treatment
Year 50 – Salvage Value	N/A	• None

Source: (VDOT, 2011)
[1]As appropriate

Table F-2 VDOT LCCA Asphalt Pavement, SMA Surface Construction/Reconstruction Schedule

Year	*Section*	*Activities*
Year 0 – New Construction/Reconstruction	Mainline[1]	• AC Surface Material • AC Intermediate Material • AC Base Material • Stabilized Drainage Layer • CTA or DGA Subbase
	Shoulders[1]	• AC Surface Material • AC Intermediate Material • AC Base Material • Stabilized Drainage Layer • CTA or DGA Subbase
Year 15 – Functional Mill and Replace	Mainline	• Pre-overlay Repair – Patch – 1% (up to the top of base layer) • Mill – Surface Layer • Replace with AC Wearing Course – one layer
	Shoulders	• Surface Treatment
Year 28 – Major Rehabilitation	Mainline	• Pre-overlay Repair – Patch – 5% (full depth) • Deep Mill (All Surface and Intermediate Layers) • Replace with AC Base Material, AC Intermediate Material, AC Wearing Course
	Shoulders	• Overlay with AC Wearing Course
Year 43 – Functional Mill and Replace	Mainline	• Pre-overlay Repair – Patch – 1% (up to the top of base layer) • Mill – Surface Layer • Replace with AC Wearing Course – one layer
	Shoulders	• Surface Treatment
Year 44 – Functional Mill and Replace	Mainline	• Pre-overlay Repair – Patch – 1% (up to the top of base layer) • Mill – Surface Layer • Replace with AC Wearing Course – one layer
	Shoulders	• Surface Treatment
Year 50 – Salvage Value	N/A	• None

Source: (VDOT, 2011)
[1]As appropriate

Table F-3 VDOT LCCA Jointed Concrete Pavement with Tied PCC Shoulders Construction/Reconstruction Schedule

Year	*Section*	*Activities*
Year 0 – New Construction/Reconstruction	Mainline[1]	• Pavement Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase
	Shoulders[1]	• Pavement Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase • Soil Stabilization
Year 10 – Concrete Pavement Maintenance	Mainline	• Patching – 1.5% (of surface area) • Clean and Seal Joints – 100%
Year 20 – Concrete Pavement Restoration	Mainline	• Patching – 5% (of surface area) • Clean and Seal Joints – 100% • Grinding – 100%
Year 30 – Concrete Pavement Restoration and AC Overlay	Mainline	• Pre-overlay Repair – Patch – 5% (of surface area) • AC Overlay (Minimum two lifts) with: AC Surface Material, AC Intermediate Material, AC Base Material
	Shoulders	• AC Overlay (Minimum two lifts) with: AC Wearing Course, AC Intermediate Material, AC Base Material
Year 42 or 45[2] – Mill and Replace	Mainline	• Pre-overlay Repair – Patching AC Overlay (2.5% of surface area), Patching PCC Base (2.5% of surface area) • Mill – Surface Layer • Materials – one layer • Overlay with AC Wearing Course – one layer
	Shoulders	• Overlay with AC Wearing Course – one layer
Year 50 – Salvage Value	N/A	• None

Source: (VDOT, 2011)
[1]As appropriate
[2]If SMA mixes utilized at year 30

Table F-4 VDOT LCCA Jointed Concrete Pavement with Wide Lane (14 feet) and AC Shoulders Construction/Reconstruction Schedule

Year	*Section*	*Activities*
Year 0 – New Construction/Reconstruction	Mainline with 14' Lanes – Inside and Outside[1]	• Mainline Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase
	Shoulders[1]	• Shoulder Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase • Soil Stabilization
Year 10 – Concrete Pavement Maintenance	Mainline	• Patching – 1.5% (of surface area) • Clean and Seal Joints – 100%
	Shoulders	• Surface Treatment
Year 20 – Concrete Pavement Restoration	Mainline	• Patching – 5% (of surface area) • Clean and Seal Joints – 100% • Grinding – 100%
	Shoulders	• Surface Treatment
Year 30 – Concrete Pavement Restoration and AC Overlay	Mainline	• Pre-Overlay - Patch – 5% (of surface area) • AC Overlay (Minimum two lifts) with: AC Wearing Course, AC Intermediate Material, AC Base Material
	Shoulders	• AC Overlay (typically two lifts) with: AC Wearing Course, AC Intermediate Material, AC Base Material
Year 42 or 45[2] – Mill and Replace	Mainline	• Pre-overlay Patching AC Overlay (2.5% of surface area), • Pre-overlay Patching PCC Base (2.5% of surface area) • Mill – Surface Layer • Replace with AC Intermediate Materials – one layer • Overlay with AC Wearing Course – one layer
	Shoulders	• Overlay with AC Wearing Course – one layer
Year 50 – Salvage Value	N/A	• None

Source: (VDOT, 2011)
[1]As appropriate
[2]If SMA mixes utilized at year 30

Table F-5 VDOT LCCA Continuously Reinforced Concrete Pavement with Tied PCC Shoulders Construction/Reconstruction Schedule

Year	***Section***	***Activities***
Year 0 – New Construction/Reconstruction	Mainline[1]	• Mainline Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase
	Shoulders[1]	• Shoulder Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase • Soil Stabilization
Year 10 – Concrete Pavement Maintenance	Mainline	• Patching – 1% (of surface area) • Clean and Seal Longitudinal Joints – 100%
Year 20 – Concrete Pavement Restoration	Mainline	• Patching – 5% (of surface area) • Clean and Seal Joints – 100% • Grinding – 100%
Year 30 – Concrete Pavement Restoration and AC Overlay	Mainline	• Patching – 5% (of surface area) • AC Overlay (Typically two lifts) with: AC Surface Material, AC Intermediate or Base Material
	Shoulders	• AC Overlay (Typically two lifts) with: AC Wearing Course, AC Intermediate or Base Material
Year 42 or 45[2] – Mill and Replace	Mainline	• Patching AC Overlay (2.5% of surface area) • Patching PCC Base (2.5% of surface area) • Mill – Surface Course • Replace with AC Wearing Course – one layer
	Shoulders	• Surface Treatment
Year 50 – Salvage Value	N/A	• None

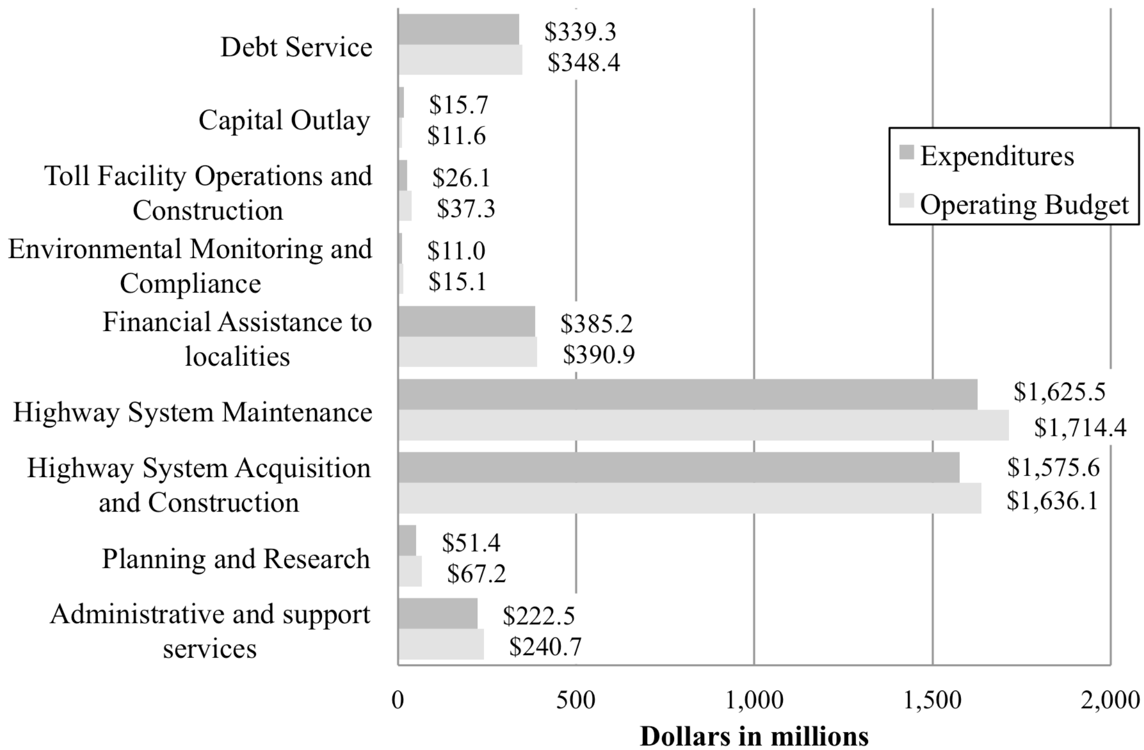
Source: (VDOT, 2011)
[1]As appropriate
[2]If SMA mixes utilized at year 30

Table F-6 VDOT LCCA Continuously Reinforced Concrete Pavement with Wide Lanes (14 feet) and AC Shoulders Construction/Reconstruction Schedule

Year	*Section*	*Activities*
Year 0 – New Construction/Reconstruction	Mainline with 14' lanes – Inside and Outside[1]	• Pavement Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase
	Shoulders[1]	• Shoulder Removal (Reconstruction) • PCC Slab • Stabilized Drainage Layer • CTA or DGA Subbase • Soil Stabilization
Year 10 – Concrete Pavement Maintenance	Mainline	• Patching – 1% (of surface area) • Clean and Seal Joints – 100%
	Shoulders	• Surface Treatment
Year 20 – Concrete Pavement Restoration	Mainline	• Patching – 5% (of surface area) • Clean and Seal Joints – 100% • Grinding – 100%
	Shoulders	• Surface Treatment
Year 30 – Concrete Pavement Restoration and AC Overlay	Mainline	• Patching – 5% (of surface area) • AC Overlay (Typically two lifts) with: AC Surface Material, AC Intermediate or Base Material
	Shoulders	• AC Overlay (Typically two lifts) with: AC Wearing Course, AC Intermediate or Base Material
Year 42 or 45[2] – Mill and Replace	Mainline	• Pre-overlay Repair - Patching AC Overlay (2.5% of surface area) • Pre-overlay Repair - Patching PCC Base (2.5% of surface area) • Mill – Surface Course • Replace with AC Surface Course – one layer
	Shoulders	• Surface Treatment
Year 50 – Salvage Value	N/A	• None

Source: (VDOT, 2011)
[1]As appropriate
[2]If SMA mixes utilized at year 30

Figure F-1 VDOT FY 2013 Total Spending



Source: **(VDOT, 2013)**

Appendix G Wisconsin

Table G-1 WisDOT HMA Pavement Life Cycle

Scenario	***Traditional HMA pavements***	***Deep-strength or perpetual HMA pavements***
Initial construction	New construction, reconstruction, or pavement replacement	New construction, reconstruction, or pavement replacement
First rehabilitation	HMA overlay or mill and HMA overlay	Mill top layer of HMA plus ½-inch and overlay a minimum of same thickness as removed
Second rehabilitation	HMA overlay or mill and HMA overlay	Mill top layer of HMA plus ½-inch and overlay a minimum of same thickness as removed
Third rehabilitation	HMA overlay or mill and HMA overlay	Mill top layer of HMA plus ½-inch and overlay a minimum of same thickness as removed
Reconstruction	Reconstruction or pavement replacement (including pulverization)	Reconstruction or pavement replacement (including pulverization)

Source: (WisDOT, 2015b)

Table G-2 WisDOT Concrete Pavement Life Cycle

Scenario	***Options***
Initial construction	New construction, reconstruction, or pavement replacement
First rehabilitation	Concrete repair and grind or concrete repair and HMA overlay
Second rehabilitation	Concrete repair and grind or concrete repair and HMA overlay or mill, concrete repair and HMA overlay
Third rehabilitation	Concrete repair and grind or concrete repair and HMA overlay or mill, concrete repair and HMA overlay
Reconstruction	Reconstruction or pavement replacement (including rubblization)

Source: (WisDOT, 2015b)

Table G-3 WisDOT Maintenance Costs

Pavement surface type	*Pavement surface age (years)*	*One time cost per lane mile*
HMA	1/3 of service life	$2000
HMA	2/3 of service life	$2500
Concrete	1/3 of service life	$4000
Concrete	2/3 of service life	$8000

Source: (WisDOT, 2015b)

Table G-4 WisDOT Initial Service Life

Initial Construction	*Service life (years)*
HMA – traditional or deep-strength	18
HMA (drained) – traditional or deep-strength	22
HMA – perpetual	16
HMA over pulverized HMA	18
HMA over rubbilized concrete	22
Concrete	25
Concrete (drained)	31
Concrete over rubbilized concrete	31

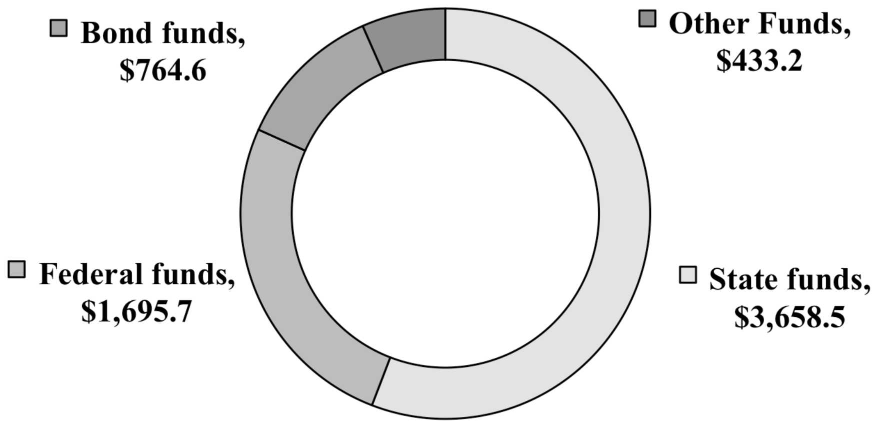
Source: (WisDOT, 2015b)

Table G-5 WisDOT Rehabilitation Service Life

Rehabilitation	*Service life (years)*
HMA overlay over traditional HMA Pavement	12
HMA overlay over continuous reinforced concrete pavement (CRCP)	8
HMA overlay over jointed reinforced concrete pavement (JRCP)	8
HMA overlay over JPCP	15
Mill and HMA overlay over traditional or deep-strength HMA pavement	12
Mill and 1st or 2nd HMA overlay over perpetual HMA pavement	16
Mill and 3rd HMA overlay over perpetual HMA pavement	12
Concrete pavement repair and grind	8

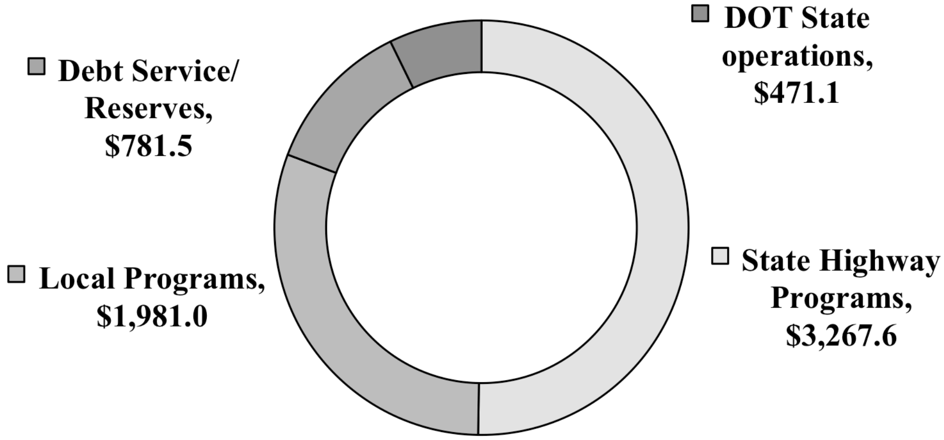
Source: (WisDOT, 2015b)

Figure G-1 WisDOT Revenues 2011-13 Biennial Budget ($ millions)



***Source*: (WTFPC, 2013)**

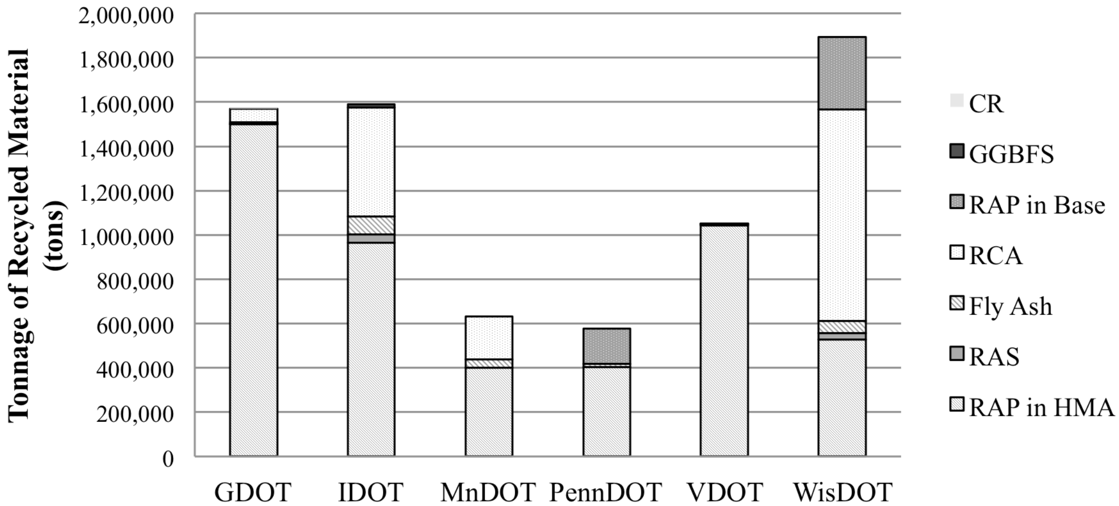
Figure G-2 WisDOT Total Spending 2011-13 Biennial Budget



Source: (WTFPC, 2013)

Appendix H Overall Results

Figure H-1 Estimated Recycled Materials For All Member States in 2013 (tons)



***Only includes materials used in analyses**

Table H-1 Estimated Total Recycled Material in 2013 (tons)

	GDOT	*IDOT*	*MnDOT*	*PennDOT*	*VDOT*	*WisDOT*	*Average*
RAP in HMA	1,500,000	963,996	402,048	403,334	1,044,072	528,157	806,935
RAS	1,000	39,791	--	--	3,757	29,342	18,473
Fly Ash	8,600	80,440	35,474	15,158	1,170	55,288	32,688
RCA	59,334	491,835	193,541	--	--	954,678	424,847
RAP in Base	--	--	--	158,706	--	327,077	242,892
GGBFS	--	15,045	--	--	2,340	--	8,693

Figure H-2 Percent Reductions of Environmental Measures in All States in 2013

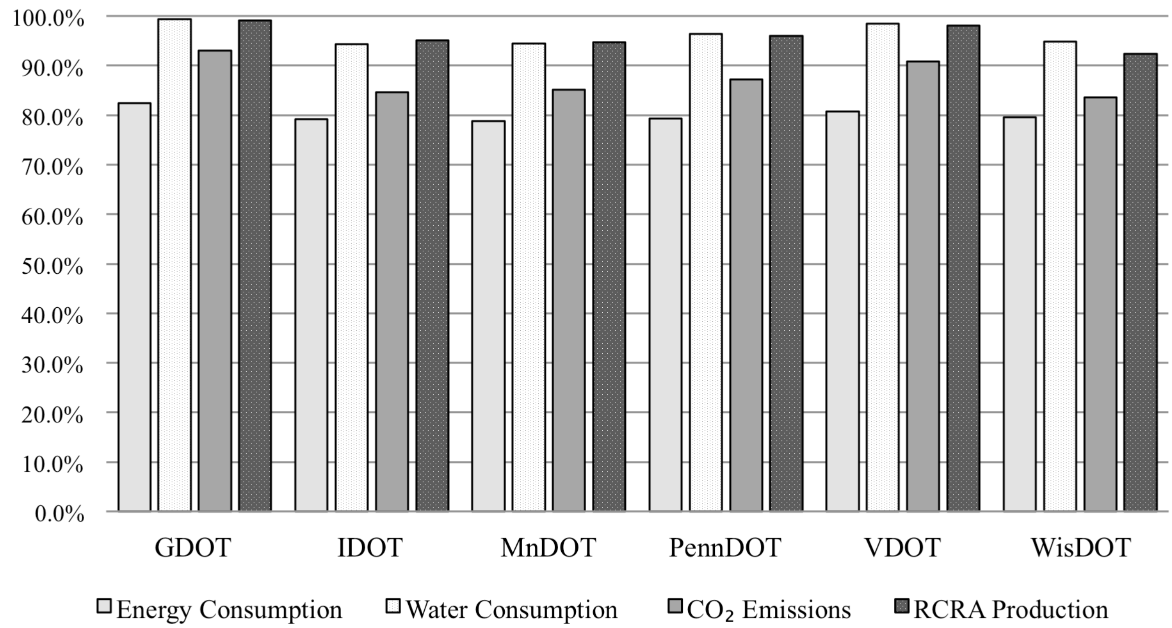


Table H-2 Estimated Percent Reductions for Each State in 2013 (%)

	GDOT	*IDOT*	*MnDOT*	*PennDOT*	*VDOT*	*WisDOT*	*Average*
Energy Consumption	82.5%	79.1%	78.8%	79.3%	80.8%	79.6%	80.0%
Water Consumption	99.3%	94.4%	94.4%	96.4%	98.5%	94.8%	96.3%
CO_2 Emissions	93.1%	84.7%	85.2%	87.2%	90.8%	83.6%	87.4%
RCRA Production	99.1%	95.2%	94.7%	96.0%	98.0%	92.4%	95.9%

Figure H-3 Environmental Savings per Mile in 2013 for All States

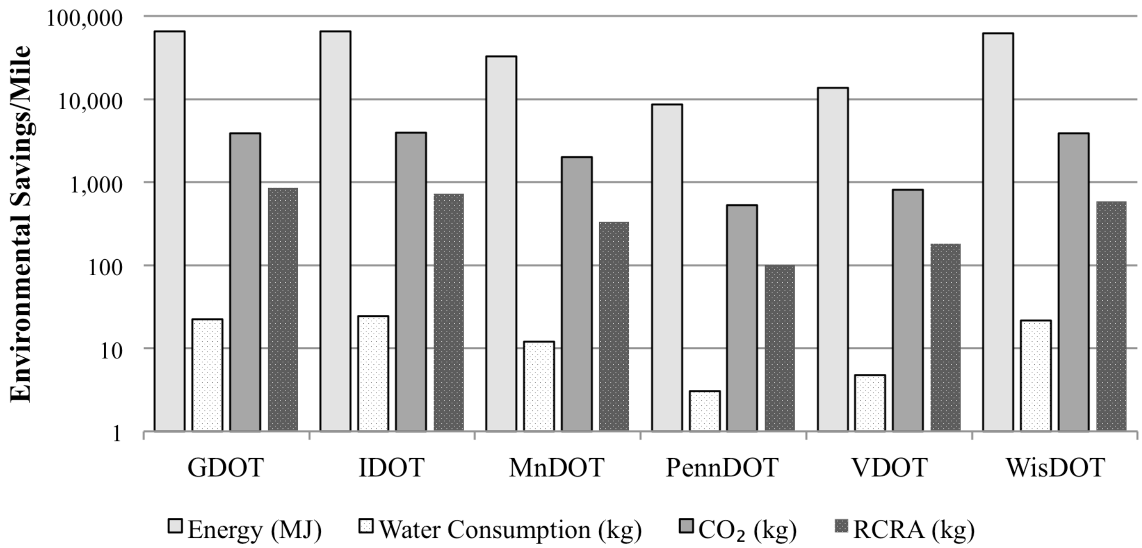


Table H-3 Estimated 2013 Environmental Savings

	GDOT	*IDOT*	*MnDOT*	*PennDOT*	*VDOT*	*WisDOT*	*Average*
Energy Consumption (TJ)	1,171	1,043	390	344	795	729	745
Water Consumption (kg)	402,829	389,331	144,200	122,287	276,744	255,479	265,145
CO_2 Emissions (Mg)	70,177	63,475	24,101	20,975	47,258	45,550	45,256
RCRA Production (Mg)	15,319	11,702	4,014	4,020	10,602	6,900	8,760
SCC Savings (2013 $)	$2,956,268	$2,673,940	$1,015,276	$883,590	$1,990,785	$1,918,834	$1,906,449

Table H-4 Estimated 2013 Environmental Savings per Total Managed Mile by Member State DOTs

	GDOT	*IDOT*	*MnDOT*	*PennDOT*	*VDOT*	*WisDOT*	*Average*
Energy (MJ)	65,056	65,188	32,500	8,645	13,707	61,780	41,146
Water Consumption (kg)	22	24	12	3	5	22	15
CO_2 (kg)	3,899	3,967	2,008	527	815	3,860	2,513
RCRA (kg)	851	731	335	101	183	585	464

Table H-5 Estimated 2013 Unit Cost Savings per Ton of Recycled Material for all Member State DOTs

	GDOT	*IDOT*	*MnDOT*	*PennDOT*	*VDOT*	*WisDOT*	*Average*
RAP in HMA	$6.62	$6.46	$14.72	$7.37	$16.26	$5.72	$9.53
RAS	$67.65	$55.02	--	--	$82.18	$98.00	$75.71
Fly Ash	$4.33	$43.36	$28.61	$8.97	$66.18	$30.00	$30.24
RCA	$1.03	-$0.01	$1.03	--	--	$4.50	$1.64
RAP in Base	--	--	--	$1.46	--	$4.00	$2.73
GGBFS	--	$16.04	--	--	$70.71	--	$43.38

Table H-6 Estimated 2013 Total Cost Savings of all Member State DOTs

	GDOT	*IDOT*	*MnDOT*	*PennDOT*	*VDOT*	*WisDOT*	*Average*
RAP in HMA	$9.93	$6.23	$5.92	$2.97	$16.97	$3.02	$7.51
RAS	$0.07	$2.19	--	--	$0.31	$2.88	$1.36
Fly Ash	$0.04	$3.49	$1.02	$0.14	$0.08	$1.66	$1.07
RCA	$0.06	-$0.01	$0.02	--	--	$4.30	$1.09
RAP in Base	--	--	--	$0.23	--	$1.31	$0.77
GGBFS	--	$0.24	--	--	$0.17	--	$0.20