Assessing the Life Cycle Benefits of Recycled Material Used in Roadways

Final Report

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16. Abstract

This is a small project to dovetail with a prior RMRC study of recycled materials use by DOTs. The main objective of this study is to quantify the life-cycle benefits associated with the use of recycled materials in highway pavement construction. This is an extension project specifically for the North Carolina Department of Transportation (NCDOT) to a prior study for RMRC-3G member DOTs. To quantify these benefits, data on the recycled materials quantities used by NCDOT will be collected and analyzed. The determined life-cycle benefits of the NCDOT will then be compared with the life-cycle benefits study of RMRC member states conducted in 2016. A second objective of this study is to compare two LCA tools, SimaPro and PaLATE to assess the compatibility of performing roadway LCAs on each tool. The purpose of both objectives is to validate the life-cycle benefit results of NCDOT's recycled material use in fiscal year (FY) 2018 and eliminate bias from pavement LCAs. The recycled materials utilized by NCDOT included RAP and RAS in HMA, RCA as base course and fill, fly ash in Portland cement and fill, and recycled glass beads as pavement markers. RAP and RAS in HMA made up the majority of materials, accounting for about 70.5% and 29.3%, respectively, of the total tons of recycled material reported by the NCDOT. The remaining 0.2% of recycled materials included fly ash, RCA and glass beads. As a state DOT program, concrete is not heavily used which is why the reported weight is low for both fly ash and RCA materials. Overall, the recycled materials life-cycle inventories for both SimaPro and PaLATE estimate significant environmental benefits in all categories when compared to the equivalent virgin materials life-cycle inventories. The percent reduction by impact category demonstrated that PaLATE and SimaPro estimate similar energy and water reductions (i.e., more than 80%). However, the reduction of CO_2 varied drastically between the two programs with SimaPro estimating a 45% reduction in CO_2 emissions and PaLATE estimating an 81% reduction. We consider this discrepancy is due to how the LCA tools calculate CO_2 emissions for the production of HMA. SimaPro lacks an input for HMA production. Similar percent reduction trend (44%) for CO_2 emissions when using RAP compared to energy consumption was found for Georgia DOT in a SimaPro LCA. These results further confirmed the 87% energy and 45% CO_2 reductions determined for NCDOT as SimaPro consistently underestimated CO_2 emission percent reductions for RAP in HMA when compared to PaLATE CO_2 emission percent reductions. A comparison with other states indicated that of the four measured parameters based on the PaLATE methodology, water consumption saw the highest percent reductions (94 to 99%), followed by RCRA waste production (92 to 99%), energy consumption (78 to 83%) and lastly CO_2 emissions (74 to 81%). Overall, the resulting impacts trend was very similar for all four categories of impact for all states. The estimated total cost savings for NCDOT was \$117.5 million. A comparison of the states ranged from \$3 to \$117.5 million. There are several reasons for the large difference in savings. Estimated cost savings per ton of recycled materials was about \$1,500/mile for NC, one of the highest among the states. Estimated cost savings per ton of recycled materials was \$99 based on all recycled materials used.

17. Key Words. Life cycle assessment (LCA), life cycle cost analysis (LCCA), recycled materials

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1. Introduction

Natural aggregates make up the largest non-fuel mineral materials used in the United States each year. Many of these mined materials are used to create concrete, asphalt and base course for the more than 164,000 miles of roadway in the National Highway System [1,2]. These highways are continuously being constructed and rehabilitated, requiring large amounts of natural raw materials, producing waste and consuming energy [3,4]. On average, 1.3 billion tons of natural aggregate such as gravel and crushed stone is used every year, two-thirds of which is used in road construction, and 90% of that is virgin aggregate. This equates to 680 million tons of virgin aggregate used in road construction each year. This large amount of virgin aggregate not only depletes a finite resource, but also has impacts on climate change due to the release of greenhouse gases, solid waste generation, energy consumption and water use [5].

To reduce these environmental and economic costs, state Departments of Transportations (DOTs) have been reusing highway construction materials in various DOT projects. Once past the initial life (i.e., through roadway reconstruction and/or maintenance), road construction materials such as asphalt, concrete and other fill materials *can be reclaimed and properly reused*. Reusing these materials can greatly add economic value and reduce environmental impacts for any state highway road program [6].

Therefore, it is useful that states to understand how the reuse of materials to make new roads can be both environmentally and economically beneficial for any state infrastructure program. Conducting a life cycle assessment, or LCA, quantifies the reduction in greenhouse gas emissions or CO_2, solid waste production, energy consumption, and water consumption achieved when using recycled materials in place of the virgin material equivalents. A life cycle cost analysis (LCCA) is used to quantify the economic benefits of using recycled materials. The following research presents the recycled material benefits through both LCA and LCCA analyses for North Carolina in the context of seven DOTs.

2. Objectives

The main objective of this study is to quantify the environmental and economic benefits of using recycled materials in highway pavement construction by state DOTs. From an environmental lens, a life cycle assessment is conducted to determine the environmental impacts of a given product, system, process or project. Prior research conducted in 2016 for DOTs in the states of Wisconsin, Minnesota, Illinois, Virginia, Pennsylvania and Georgia demonstrated over 50% reduction in four LCA categories (water consumption, energy consumption, solid waste generation, and carbon dioxide emissions) when recycled materials were substituted for virgin materials [7]. This research project will quantify benefits for a new LCA conducted for the North Carolina Department of Transportation (NCDOT), and present results alongside the prior research for other DOT programs.

In addition to environmental benefits, reusing recycled materials in lieu of mining new aggregates can be fiscally responsible. According to the same study above, the estimated total cost savings for six state DOTs ranged from \$3 to \$17.5 billion dollars [7]. These savings come from recycled materials being used in road construction applications in a variety of ways to offset the mining, creation, and transport of new materials. For example, recycled concrete aggregate (RCA) can be used as an aggregate, eliminating the need to mine and transport virgin aggregate for the roadway construction. Similarly, recycled asphalt pavement (RAP) can be used as an alternate aggregate both in base course and in the production of new asphalt. Recycled asphalt shingles (RAS) can also be used in asphalt pavement production. Coal combustion fly ash, a readily available by-product of coal combustion, can be used as an additive in concrete, partially eliminating the need for Portland cement; in turn, using the fly ash saves both the environmental impacts and economic costs of using Portland cement [7]. Many other recycled materials are available and have been used as additives and replacements for the traditional energy and resource taxing methods of roadway construction and maintenance.

This sustainability analysis also included the economic impact evaluation. The economic impacts of products can be assessed through a life cycle cost analysis, or LCCA. An LCCA will demonstrate the economic savings from utilizing recycled materials in place of traditional virgin materials in roadways. The outcome of the research will help demonstrate and quantify the triple bottom line that the use of recycled materials achieves by showing that recycled materials use in roads can benefit the environment, economy, and improve public safety.

3. Pavement Life Cycle

The pavement life cycle is a useful means to describe the stages that a pavement or road goes through, from the initial materials creation and sourcing, to the end of the road's useful life. An LCA looks at the environmental impacts over that entire pavement life cycle, which is illustrated in Figure 1.

Figure 1 – A simplified highway single-use life cycle without reuse at end-of-life.

A major goal for several DOT road programs is to avoid costly disposal of materials once the road has reached its useful life. To avoid disposal by reusing spent pavement materials, there are a few major considerations to understand so that the reuse is both *Safe,* from an environmental standpoint, and *Wise,* from an engineering standpoint. To make these determinations, it has been widely researched that many of the road materials can be reused to create new roads rather than disposal of such materials [6,7]. In fact, there are well-known engineering properties (wise), environmental benefits (safe) as well as economic benefits (wise) that these recycled materials can bring to new roads [6-8]. A preferred pavement life cycle to maximize material reuse should show the upcycling or reuse into new material production at the end-of-design life. Therefore, our research suggests a circular model that reduces the amount of end-of-life disposal as much as possible, and then increase the use of recycled materials as much as possible in various areas of the process. We show our circular model as Figure 2.

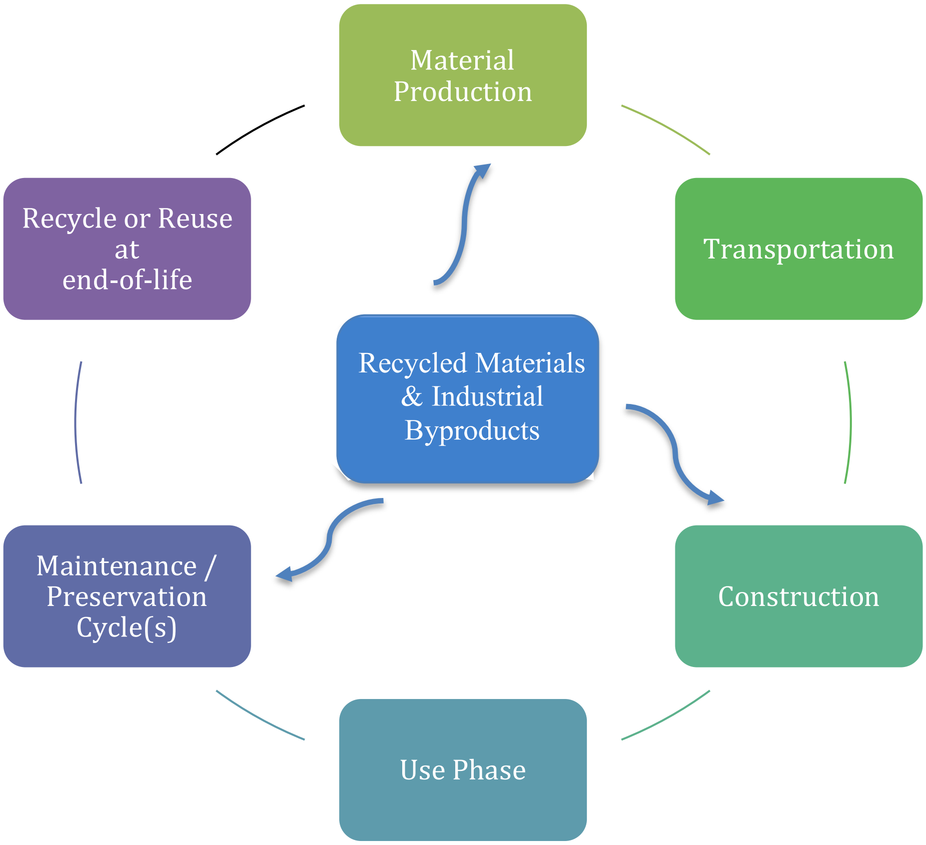


Figure 2 – Beneficial reuse of end-of-design life for road materials. This is a suggested pavement cycle in stages to maximize material reuse and avoid mining finite materials.

- ***Material production***. Material production includes all processes used in the acquisition (e.g., mining and crude oil extraction) and processing (e.g., refining, manufacturing and mixing) of pavement materials.
- ***Transportation***. The transportation stage refers to the process of moving all pavement materials, including aggregates, asphalt or concrete, to the construction site as well as the equipment to transport such materials.
- ***Construction***. The construction stage includes all processes and equipment associated with the construction of the initial pavement.
- ***Use Phase***. The use phase refers to the period during which the pavement is in service and is interacting with vehicles and the environment.
- ***Maintenance/Preservation***. These are activities applied at various times throughout the life of the pavement to maintain its overall serviceability. Some road designs include two or three cycles.
- ***Recycle/Reuse at End-of-Life (vs. Disposal)***. The final use of the road ideally provides useful materials that can be processed on site into a new material used for the next road, essentially starting the *Material Production* phase all over again. It is of great benefit that the prior end-of-life stage goes directly into subsequent reuse, processing, or recycling of the pavement after it has reached the end of its useful life and avoids costly landfill disposal.

- ***Recycled Materials & Industrial Byproducts***. These materials are often reclaimed materials that can be "upcycled" into something else after their initial life. Examples include tire crumb rubber, used roofing shingles, recycled asphalt pavement, recycled concrete pavement, recycled glass, or industrial process byproducts such as coal combustion fly ash/bottom ash and foundry sands.

4. Recycled Materials Defined

4.1 Fly Ash

Fly ash is a fine-grained, powdery particulate by-product of burning coal [8]. Fly ash is collected from coal plants through electrostatic precipitators and filter fabric baghouses [9]. When fly ash is used as an additive to concrete mixes, it is classified as either Class F or Class C based upon its chemical composition [10]. Class F fly ash is a by-product of burning bituminous and anthracite coals and is deficient in calcium. Class C fly ash is a by-product of burning sub-bituminous coals, enriched in calcium and has self-cementing properties, making Class C fly ash the more common and versatile fly ash in road construction [9].

Fly ash is added most commonly to cement mixes as a partial substitute to Portland cement. Although less common, fly ash can be used as a stabilizing agent for subgrade soils and recycled pavement sections due to its cementitious properties [9].

4.2 Recycled Asphalt Pavement

Recycled asphalt pavement, also known as RAP, is generated when existing asphalt pavement is removed by milling or by full-depth removal [10]. If RAP is properly processed, it will consist of high-quality, well-graded aggregates coated by asphalt cement [6]. This material can then be recycled into future hot mix asphalt paving mixtures as an aggregate, asphalt binder supplement or be used as an aggregate in base course and fill material [10].

According to the 2018 North Carolina Standard Specification, RAP can be incorporated up to 45 percent in intermediate and base course mixes and up to 40 percent in surface mixes [11]. There is current research being conducted at UW-Madison by Professor Hussain Bahia to test asphalt mixes using 30- and 50- percent recycled content [12]. In 2017, the asphalt industry recycled more than 99 percent of reclaimed asphalt pavement [13]. However, the percentage of RAP in new asphalt mixtures nationwide is 20.1 percent, meaning there is still a significant portion of roadways being paved with HMA mixes using virgin aggregates [13].

Overall, RAP used as a base or subbase aggregate performs satisfactory to excellent [10]. When properly incorporated x, RAP aggregates show adequate bearing capacity, good drainage properties and durability [10]. If RAP is not properly processed to specification and incorporated incorrectly, pavement performance will be poor [10].

4.3. Recycled Asphalt Shingles

Recycled Asphalt Shingles, also referred to as RAS, may be produced from two main sources. The first source is called tear-off roofing shingles [10]. Tear-off roofing shingles are created when an existing roof is demolished or replaced. The quality of tear-off roofing shingles varies due to the different exposures between post-consumer roofing shingles. The second source is called roofing shingle tabs [10]. Roofing shingle tabs are created during the production of new asphalt shingles when they are trimmed to meet specifications.

Roofing shingles are produced by interweaving fibers with a hot saturant asphalt, coating with more asphalt, and surfacing with mineral granules [10]. RAS created from post-consumer roofing shingles is processed by shredding and grading tear-off roofing shingles to specifications. NCDOT processing specifications specify ambient grading or granulating methods such that 100% of the particles will pass the 9.50 mm (3/8 inch) sieve when tested in accordance with AASHTO T27 [11]. RAS that meets NCDOT 2018 Standard Specifications shall contain no more than 0.5% by total cumulative weight of deleterious materials. These materials include, but are not limited to, excessive dirt, debris, concrete, metals, glass, paper, rubber, wood, plastic, soil, brick, tars, or other contaminating substances [11].

RAS incorporation in a hot mix asphalt (HMA) mix is generally less than that of RAP. According to NCDOT Standard Specifications, RAS material may constitute up to 6% by weight of the total mixture, excluding Open Graded Friction Course (OGFC) mixes, which are limited to 5% RAS by weight of total mixture. RAS may be incorporated up to 23% in intermediate and base mixes, and up to 20% in surface mixes [11].

RAS use in roadways occurs to a far lesser extent mainly because of a lack of knowledge regarding recycling and re-processing protocol [14]. However, in recent years there has been an increase in RAS incorporation in HMA mixes. During the 2017 construction season, nearly 79 million tons of recycled materials, the majority being RAP and RAS, were used in new HMA mixes [13].

The implementation of RAS in pavement mixtures can induce premature cracking in relatively new asphalt pavements [10]. Many state DOTs require that RAS be generated solely from scrap manufacturer tabs due to the high variability of tear-off roofing shingles. It is also important to note that states in warmer climates are less susceptible to pavement cracking from brittleness [10].

4.4 Recycled Concrete Aggregate

Reclaimed concrete material, also referred to as RCA, consists of high-quality, well-graded aggregates coated by hardened cementitious paste [10]. RCA is generated through the crushing of concrete structures and roadways. After the initial crushing and excavation, RCA is transported to an aggregate processing center, landfill or reused on-site [10]. At the aggregate processing center, any steel can be removed via a magnetic separation process and then crushed and screened to the desired gradation using aggregate processing equipment [10]. Some state agencies also require the washing of RCA aggregates to remove dust and reduce potential tufa formation [10].

RCA can be used as coarse- and fine-grained aggregate in granular bases [10]. Lower-quality RCA can be used as a subgrade or fill material [10]. Other less common applications of RCA are as an aggregate in HMA and surface treatments. RCA can also be used in embankment or fill, however due to its high quality as an aggregate in base courses, RCA use in embankment or fill is unlikely [6].

RCA contains residual cementitious material which provides good load transfer when placed on weaker subgrade [10]. The effects of RCA in granular base applications have shown increased stability in wet, soft, underlying soils during early construction stages. RCA has good durability, bearing strength and drainage characteristics in granular base applications. RCA demonstrates an increased resistance to freeze-thaw than natural aggregates making it more suitable in base course for states with harsh winters [6].

4.5 Glass Beads

Glass is a product of the supercooling of a melted liquid mixture of sand (silicon dioxide), soda ash (sodium carbonate) and/or limestone to a rigid solid. The supercooled material does not crystallize and retains the organization and internal structure of the melted liquid mixture. Glass can be recycled without any loss of its original quality and is therefore 100% recyclable. Recycled waste glass has been used successfully as an aggregate substitute in concrete, roadbeds, pavements and in the production of glass beads. Glass beads are transparent, sand-sized, solid glass microspheres made from recycled glass cullet. The glass beads are often applied to the surface of pavement markings or used in reflective paint for highways to increase the nighttime visibility of these markings and increase public safety on roadways.

Recycled glass has a lower melting point than the temperature needed to produce new glass, demonstrating that money, energy and raw materials are saved when recycled glass is used to produce glass beads versus using virgin glass in pavement markings [15]. While the use of glass beads in pavement markings is not new technology, the tracking of this use is a newer form of reuse for some states including North Carolina. Due to the newer tracking, glass beads were not included in the analyses because a process for analyzing glass bead production does not exist in either of the LCA models used. Overall, glass beads make up less than 0.1% of the total tons by weight of recycled material used, but increased use is assumed to produce even better LCA and LCCA results.

5. Life Cycle Assessment Tool Overview

To quantify the environmental benefits of using recycled materials in roadways, publicly available LCA tools were considered. Life cycle assessments are crucial in gaining insight and increased understanding of the environmental impacts of materials and processes throughout the entire life cycle, cradle-to-grave, of a product or process. An LCA provides relevant data to make informed decisions regarding environmental outcomes of a given process or product. The International Organization for Standardization (ISO) 14040 series provides a foundation for conducting an LCA study which details the four phases of an LCA:

1) definition of goals and scope
2) inventory analysis
3) impact assessment
4) interpretation

The process of conducting an LCA is similar regardless of the LCA tool used [16]. For this research project, two LCA tools, SimaPro and PaLATE, were used to assess the environmental effects of recycled materials in roadways. SimaPro is a well-known LCA software with a wide range of applications for determining environmental impacts. PaLATE, the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects, is an LCA modeling tool developed specifically for conducting roadway LCAs. With prior funding from the Recycled Materials Resource Center (RMRC) [17], PaLATE was designed by the Consortium on Green Design and Manufacturing, and since inception, PaLATE has been updated as data sets or other models (i.e., fuel consumption) change. PaLATE can be used to assess both the environmental and economic effects of road construction. By performing an LCA for both virgin and recycled materials on PaLATE and SimaPro, a comparison can be made between the relative impacts of virgin and recycled material use on each LCA tool. There is an annual fee to use the SimaPro software, but PaLATE is a free program available on the RMRC website at www.RMRC.wisc.edu.

5.1 Methodology

The scope of the research life cycle assessment included carbon dioxide (CO_2) emissions, energy consumption and water consumption from material acquisition, transportation, and processing. The PaLATE LCA also includes RCRA solid waste generation; SimaPro does not produce this information but it's important to note the efforts done to avoid landfilling materials. The life cycle inventories were created from recycled material data for FY18 provided by the NCDOT. North Carolina's recycled material use results have been compared with other RMRC member states from a prior study. States included in that study are Wisconsin, Minnesota, Georgia, Illinois, Pennsylvania and Virginia. These comparisons have allowed the data to be verified as well as gain further knowledge for the use of recycled materials in highway construction.

Data reporting for the recycled material quantities for FY18 was collected from the NCDOT's HiCAMS. The recycled material quantities along with prior research on recycled material utilization in roadways [6], [14] was used to build a recycled materials and equivalent virgin materials life cycle inventory for both the SimaPro and PaLATE LCAs. These inventories represent the environmental effects of producing the recycled and virgin materials, processing HMA and cement mixes, and transportation all these materials and mixes to a plant and to a site. Both the virgin and recycled life cycle inventories were analyzed using SimaPro and PaLATE.

5.2 SimaPro

SimaPro is an international LCA software that is used to perform an LCA for a wide variety of processes and products [18]. SimaPro allows the user to build a life cycle inventory that emulates a given product or process. A life cycle inventory is built by custom made inputs or by the selection of pre-existing inputs available in life cycle inventory databases within SimaPro. Once an inventory is created, the user may perform an LCA of the inventory. The user may select from several LCA methods that represent different regions of interest and provide outputs for a wide range of environmental impacts. SimaPro does not analyze life cycle costs.

SimaPro Methodology

For this research, the SimaPro LCA considered the environmental impacts of the material and mix production, transportation of materials, and processing. It should be mentioned that there are some limitations in using the SimaPro software exclusively. Initial construction involves the paving and rolling of the road, which are processes that are not included within the SimaPro database. SimaPro does not include all the necessary equipment used for roadway production, maintenance, and demolition. To perform a full roadway LCA that addresses the cradle-to-grave environmental effects of a roadway, the SimaPro database would need to be expanded to include the correct processes and equipment used when building, maintaining, and demolishing a roadway. However, in knowing these limitations, one can use the SimaPro outputs to inform resulting impacts of using reclaimed and recycled materials in the material and mix production, transportation, and processing activities.

For this project, two LCAs were performed on SimaPro. The first LCA was to address the environmental effects of recycled materials and the second LCA was to address the environmental effects of equivalent virgin materials. First, the life cycle inventories for the reported recycled materials and equivalent virgin materials were generated in SimaPro. Pre-existing inputs within the ecoinvent3 and USLCI databases were used to create the inventories. The ecoinvent3 database contains inputs for materials such as bitumen, glass and gravel which were used for the material production inputs. These pre-existing inputs include the impacts of mining, transporting, and producing such materials. For inputs not included in pre-existing databases, such as RAP, RAS and RCA, inputs were created through alternative methods. To account for the environmental impact of milling and crushing required to produce RAP, the impact of the hypothetical amount of diesel used by equipment when milling RAP was determined. To account for the environmental impacts of grinding shingles to produce RAS, the same amount of hypothetical diesel was determined and used as the SimaPro input for RAS. To account for the impacts of processing concrete to produce RCA, an onsite rock crushing input was added to the recycled materials inventory. These methodologies for simulating RAP, RAS and RCA impacts in SimaPro were used in past research including Assessing the Life Cycle Benefits of Recycled Material in Road Construction [7] and followed herein.

The recycled and virgin life-cycle inventories were both analyzed using the following single issue impact assessment methods: Cumulative Energy Demand V1.09, Selected LCI Results, additional V1.03, Selected LCI Results V1.04. Cumulative Energy Demand V1.09 will calculate the amount and sources of the energy used by the recycled and virgin life-cycle inventories. Similarly, Selected LCI Results versions V1.03 and V1.04 will calculate the amount and sources of water used and CO_2 released respectively.

SimaPro's ecoinvent3 database also contains an input for Portland cement production with and without fly ash. These inputs account for the varying environmental impacts of producing Portland cement with varying amounts of fly ash substitution. However, all databases in SimaPro lack an input for HMA production of any variety. RAP and RAS were a large quantity of the recycled materials utilized by the NCDOT and the production of HMA mixes required an input to account for the impact of producing HMA. Therefore, the electricity use from equipment used to produce HMA was calculated using the equation below taken from the PaLATE model. The result of the equation was the kWh required to produce a given amount of HMA, and was used as an input to both the recycled and virgin life cycle inventories as electricity, medium voltage.

$$Electricity\ Use = (quantity\ of\ RAP\ or\ RAS\ in\ tons\ ) * 227\frac{MJ}{ton} * 0.27778\frac{kWh}{MJ}$$

SimaPro Assumptions

Given the nature of the research project, a direct comparison between the recycled material quantities and their respective virgin materials, some assumptions had to be made. Because determining specific design parameters (such as the weight percent substitution of fly ash for Portland cement) for every DOT project over the annual period was impractical, certain standard practice assumptions were made. These assumptions were based on the input from Ms. Alyson Tamer, State Value Management Engineer, lead NCDOT contact for this project, and from references from similar prior research [6], [14]. Listed below are the assumptions used when constructing the SimaPro life cycle inventories for the recycled and equivalent virgin materials.

1. The scope of the SimaPro LCAs is limited to the impacts of initial material production and transportation.
2. A 1:1 replacement weight of virgin with recycled material was assumed, despite the known varying mechanical properties.
3. All densities of materials are assumed to be the listed densities in PaLATE.

4. All fly ash was assumed to be used as a replacement for Portland cement in concrete pavement and an average of 25% substitution of the total quantity of Portland cement.
5. All RAP was assumed to be used only in HMA, 6% by weight was assumed to be used as binder replacement with the remaining 94% by weight used as aggregate in the mix.
6. All RAS was assumed to be used only in HMA, 20% by weight was assumed to be used as binder replacement with the remaining 80% used as aggregate in the mix.
7. All RCA was assumed to be used on site in base course, and therefore, used as a replacement to virgin aggregate with a transportation distance of zero miles.
8. The process of producing HMA was assumed to be the same for HMA mixes with and without recycled material.
9. All materials, HMA and cement mixes were assumed to be delivered by diesel trucks.
10. Exact transport distances and quantities of cement and fly ash could not be determined for every DOT project. An average one-way distance of 200 miles from the processing site to the asphalt or concrete mix plant was assumed because fly ash use was significantly less than RAP and RAS, and the likelihood of a cement plant being close was low. Past research also used an assumed value of 200 miles for cement and fly ash transport [6].
11. All other materials were assumed to be delivered over a one-way distance of 25 miles from the processing site to the asphalt or concrete mix plant.
12. All HMA and cement mixes were assumed to be transported over a one-way distance of 25 miles from the asphalt or concrete mix plant to the site.

5.2 PaLATE

PaLATE is a unique program specifically designed for analyzing the pavement and roadway construction environmental impacts. PaLATE also can analyze the project's life cycle cost. Within PaLATE, a user can input volumes of a material within different wearing courses, subbases and embankments and the transport distance of these materials. PaLATE uses the volume inputs and corresponding equipment processing/constructing impacts to determine the environmental effects of material production, initial construction, maintenance, and transportation. PaLATE can generate outputs for energy use, water consumption, CO_2 emissions among other environmental impacts. For this research project, we used PaLATE to analyze the environmental benefits of using recycled materials versus conventional road construction materials. We also then compared the outputs between the two selected LCA software programs, SimaPro and PaLATE, to determine discrepancies between both software methods.

PaLATE Methodology

The PaLATE LCAs consider the environmental impacts of material production, transportation, and initial construction of a roadway, and analyze for energy consumption, water consumption, CO_2 emissions and RCRA waste generation. Resource Conservation and Recovery Act (RCRA) is enforced by the EPA by controlling the entire life cycle of waste with properties that make it dangerous or potentially harmful to human health or the environment [5]. For the LCA, material production includes the processes associated with extracting or generating the materials, such as mining or quarrying virgin aggregate and grinding asphalt pavement to generate RAP. Material transportation includes the impacts associated with transporting each material the specified distance in a chosen vehicle. Construction processes consider the impacts associated with installing the material, such as paving, placing and compaction. These aspects focus on the impact of the equipment used to produce the roadway.

The reported recycled materials quantities were in tons. To make an accurate comparison between the PaLATE and SimaPro LCA tools, the same tons must be used for each input between the two LCA tools. PaLATE requires a volume input whereas SimaPro requires a weight input. The assumed PaLATE densities were used to convert the tons of material in SimaPro to the equivalent volume in PaLATE, ensuring the differences in results were due to the differences in the LCA tools themselves.

PaLATE Assumptions

Some assumptions were required to perform an LCA. The assumptions used for the PaLATE LCAs were developed with reference to similar past research assumptions [6], [14] and nature of this specific project. The assumptions are as follows:

1. A 1:1 comparison between the tons of virgin and recycled materials in SimaPro to the volume of virgin and recycled materials in PaLATE was assumed, despite the known varying mechanical properties.
2. All comparisons between SimaPro and PaLATE materials were made on weight basis using the assumed actual density of the materials in PaLATE.
3. All materials were assumed to be utilized in initial construction operations.
4. Exact transport distances and quantities of cement and fly could not be determined, so an average one-way distance of 200 miles from the processing site to the asphalt or concrete mix plant was assumed because fly ash use was significantly less than RAP and RAS and the likelihood of a cement plant being close was low. Prior research also used an assumed value of 200 miles for cement and fly ash transport [6].
5. All RCA was assumed to be processed and reused on site with a transportation distance of zero miles.
6. All other materials included in HMA, ready-mix concrete and the base course were assumed to be delivered by dump trucks over a one-way distance of 25 miles from the processing site to the asphalt or concrete mix plant.
7. All HMA was assumed to be delivered by dump truck over a one-way distance of 25 miles from the asphalt plant to the site.
8. All ready-mix concrete was assumed to be delivered by mixing trucks over a one-way distance of 25 miles from the concrete mix plant to the site.
9. All equipment is assumed to be the default equipment type for each process in PaLATE.
10. All densities of materials are assumed to be the listed densities in PaLATE.

6. Economic Impact Analysis Overview

6.1 Life Cycle Cost Analysis Methodology

The purpose of conducting an LCCA before beginning construction is to estimate the life-cycle cost of the project. In the case of a highway LCCA, we estimate the life-cycle cost of an individual highway or section of roadway, not the entire length of the highway. Two LCCAs, one of a road using recycled materials and the second of the same road without recycled material use, would need to be performed on each individual project where recycled materials were used to calculate the total life cycle costs savings in North Carolina. The cost savings of North Carolina's DOT in FY18 were estimated by comparing the prices of recycled and virgin materials. To estimate the economic savings achieved, a cost savings in \$/ton was estimated for the usage of a given recycled material in place of the equivalent virgin material. Savings in \$/ton were determined through personal contact with (J. Weathersbee, personal communication, 2019) and (G. Dean, personal communication, 2019). The actual materials data used by NCDOT is discussed in a later section, and can be found in Appendix A.

6.2 Life Cycle Cost Analysis Assumptions

To estimate the economic savings of constructing a roadway with recycled materials in comparison to one with traditional virgin materials, some assumptions were made. The economic impact analysis only considers the initial cost savings in materials and does not include the costs of rehabilitating or maintaining the roadway after initial construction. The general assumptions made in the analysis are listed below.

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.
3. The cost savings of using recycled materials in replacement of virgin materials was assumed to be an average cost savings.
4. The rehabilitation costs of two roadways, one made with recycled materials, and one made without, was assumed to be the same.

7. North Carolina DOT Background

North Carolina is one of the largest state-maintained highway systems in the nation with about 80,000 miles of roads, and more than 13,500 bridges. This includes more than 15,000 miles of primary highways (interstate, U.S. and NC routes) and nearly 65,000 miles of secondary roads [11]. Within this large network, NCDOT utilizes a variety of recycled materials in roadway construction and maintenance to achieve environmental and economic savings. One main objective for this research project is to conduct an LCA and LCCA for NCDOT, and to show those results alongside prior research for other state DOT programs. The following sections provide details specific to NCDOT specifications, recycled materials used, design for life cycle methodology and the NCDOT operating budget.

7.1 NCDOT Standard Specifications

The NCDOT 2018 Standard Specifications for Roads and Structures detail the requirements for using recycled materials in roadways in North Carolina [11]. Recycled materials used by NCDOT according to the Standard Specifications is discussed in the following section.

NCDOT allows for the use of RCA in base course and fill applications. Fly ash is used as a fill material and as a concrete mix additive. Table 1 below outlines the fly ash additive use for concrete mix. Class F fly ash may be substituted for Portland cement in a mix up to 30% by weight at a rate of 1.0 lb. of fly ash to each pound of cement replaced.

Table 1. Supplementary Cementitious Material for use in Portland Cement Concrete

Supplementary Cementitious Material	Rate
Class F Fly Ash	20% - 30% by weight of required cement content with 1.0 lb. Class F fly ash per lb. of cement replaced

Source: Standard Specifications for Roads and Structures, 2018

If fly ash is used in the mixture, type IP (Portland-Pozzolan Cement) [19] blended cement should be used for that portion of the mix. Type IP blended cement that meets AASHTO M 240, except that the pozzolanic content is limited to between 17 and 23% by weight and the constituents shall be interground.

Recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) may be incorporated into asphalt mixes. Like fly ash in concrete, there are limits to the use of RAP and RAS in hot mix asphalt as outlined below.

1. The use of RAP material is not allowed in Open Graded Friction Course mixes or Ultra-thin Bonded Wearing Course (UBWC) mixes.
2. RAS material is not allowed in (UBWC) Mixes.

General guidelines for the inclusion of RAP and RAS in HMA mixes are as follows and included in Table 2:

RAP

- If the percentage of RAP exceeds 30% by weight of the total mixture, use Fractionated RAP (FRAP) meeting the requirements of Sub article 1012- 30 1(F)(c).

RAS

- RAS material may constitute up to 6% by weight of total mixture
- Graded Friction Course (OGFC) mixes are limited to 5% RAS by weight of total mixture.

Table 2. Maximum Recycled Binder Replacement Percentage (RBR%)

Recycled Material	Intermediate & Base Mixes	Surface Mixes	Mixes Using PG 76-22
RAS	23%	20%	18%
RAP or RAP/RAS Combination	45%	40%	18%

Source: Standard Specifications for Roads and Structures, 2018

7.2 Recycled Materials used by NCDOT

It's worth noting that each DOT has different ways of tracking their recycled materials use, and not all materials are tracked from state to state. For this research project, the recycled materials that were analyzed and compared included fly ash, recycled asphalt pavement, recycled asphalt shingles and recycled concrete aggregate. These items are the most widely used and most commonly tracked recycled materials by most state DOTs [6-8]. This is likely due to the volume and weight of these materials causing the largest beneficial impacts from a financial standpoint. For DOTs interested in tracking more recycled materials on individual projects, a free, downloadable spreadsheet has been developed for highway projects [17].

NCDOT materials engineering provided a complete list of recycled materials used by NCDOT. Table 3 includes all reclaimed or recycled materials used by NCDOT from July 2017 through June

2018; source data was taken from within their HiCAMS database as presented in Appendix A. The analyses presented in the following sections used the material quantities listed in sections 1, 3, 4 and 5 of Table 3. This data was then converted for the appropriate units of measure as inputs into both LCA programs. Estimates for 1:1 (virgin:recycled) materials replacements were used consistent with prior DOT studies. Tables for all LCA inputs are provided in Appendix B.

Table 3. Type, quantity and use of reclaimed or recycled materials used in road construction by NCDOT in FY18. Items listed in categories 7 and 8 include NCDOT Recycled Products & Solid Waste Utilization in Construction & Maintenance Projects this same period.

Product Category and Description	Use	Quantity	Units
1-Asphalt:			
Reclaimed Asphalt Pavement (RAP)	Asphalt Mix Additive	5,510,00*	Tons
Reclaimed Asphalt Shingles (RAS)	Asphalt Mix Additive	2,290,00*	Tons
2-Organics:			
Mulch	Wood	4,500	Cubic Yards
Mulch	Hydromulch	8,600	Bales
Compost Material	Soil Amendment	5,100	Cubic Yards
3-Coal Combustion Products:			
Fly Ash	Concrete Mix Additive/Fill	8,800*	Tons
4-Concrete:			
Recycled Concrete	ABC/Fill Material/Base Materials	3,200	Tons
5-Glass:			
Glass Beads	Pavement Markings	6,800*	Tons
6-Plastic:			
Recycled Plastic Offset Blocks	Guardrail Offset Blocks	280,000*	Each
Recycled Plastic Pipe (All Types & Sizes)	Pipe	144,000*	Linear Feet
Plastic Jugs	Recycled Herbicide Containers	650	Each
Type III Barricades		34,300*	Linear Feet
7-Scrap Tires:			
Tire Sidewalls	Traffic Drum Ballast	58,900*	Each
8-Misc. Materials:			
Guardrail		184,000*	Tons
Wood Posts		15	Each
Signs		209,000	Square Feet
Steel Beams		91	Each
Signal Heads		50	Each
Silt Fence Posts		11,900	Each
Sheet Piles		5,500	Square Feet
Cable Guiderail		991,000	Linear Feet
Sign Posts		9,500	Each
Paint Totes		4	Tons
Recycled Metal Pipe		160	Tons
Scrap Metal		260	Tons
** Data taken from HiCAMS – see Appendix A*			

NCDOT's Resource Conservation Program promotes solid waste recycling from Construction and Maintenance activities, collecting data and reporting data on an annual basis. More information can be found at the NCDOT website link: https://connect.ncdot.gov/resources/Materials/Resource-Conservation/Pages/default.aspx

7.3 NCDOT Life Cycle Design Methodology

NCDOT uses the NCDOT Pavement Design Procedure AASHTO 1993 Method to analyze the life-cycle cost of a roadway during the preconstruction design phase. There are several factors considered within this method including using FHWA software, Real Cost, to include user delay costs and the increase in vehicle operating costs associated with work zone delays. The following table gives a general guideline that NCDOT (and other DOTs) use during the design phase to predict life cycle maintenance and preservation scheduling. For more explicit details on LCCA procedure in North Carolina, reference the NCDOT Pavement Design Procedure AASHTO 1993 Method.

Table 4. Life Cycle Costs included in the Design Phase by NCDOT

Time to Treatment	Flexible Pavements	Rigid Pavement
0	Initial construction with 30-year design.	Initial construction with 30-year design.
12 years	Cost to mill and replace 1.5” of surface course and to fog seal shoulders.	
17 years		Cost to saw and reseal joints and patch 1% of travel lanes. Fog seal asphalt shoulders with 1% patching if asphalt shoulders are present.
23 years	Cost to mill and replace 1.5” of surface course, including shoulders.	
30 years		1% patching. Overlay with ultrathin bonded wearing course (10-year life); 1% patching with diamond grinding will be considered on concrete with dowels and 15 ft. joint spacing.
34 years	Cost to mill 3” and add structure to achieve 20 more years of life. For high volume, replace milling with intermediate course and overlay with 2 lifts of surface. For lower volume, replace milling with intermediate course and overlay with 1 lift of surface course. For curb and gutter, 5% full depth patching, mill 3” and replace with surface course.	
40 years		Cost for 5.5” asphalt overlay with a life of 20 years.
45 years	Salvage value of 45% of year 34 treatment.	Salvage value of 75% of year 40 treatment.

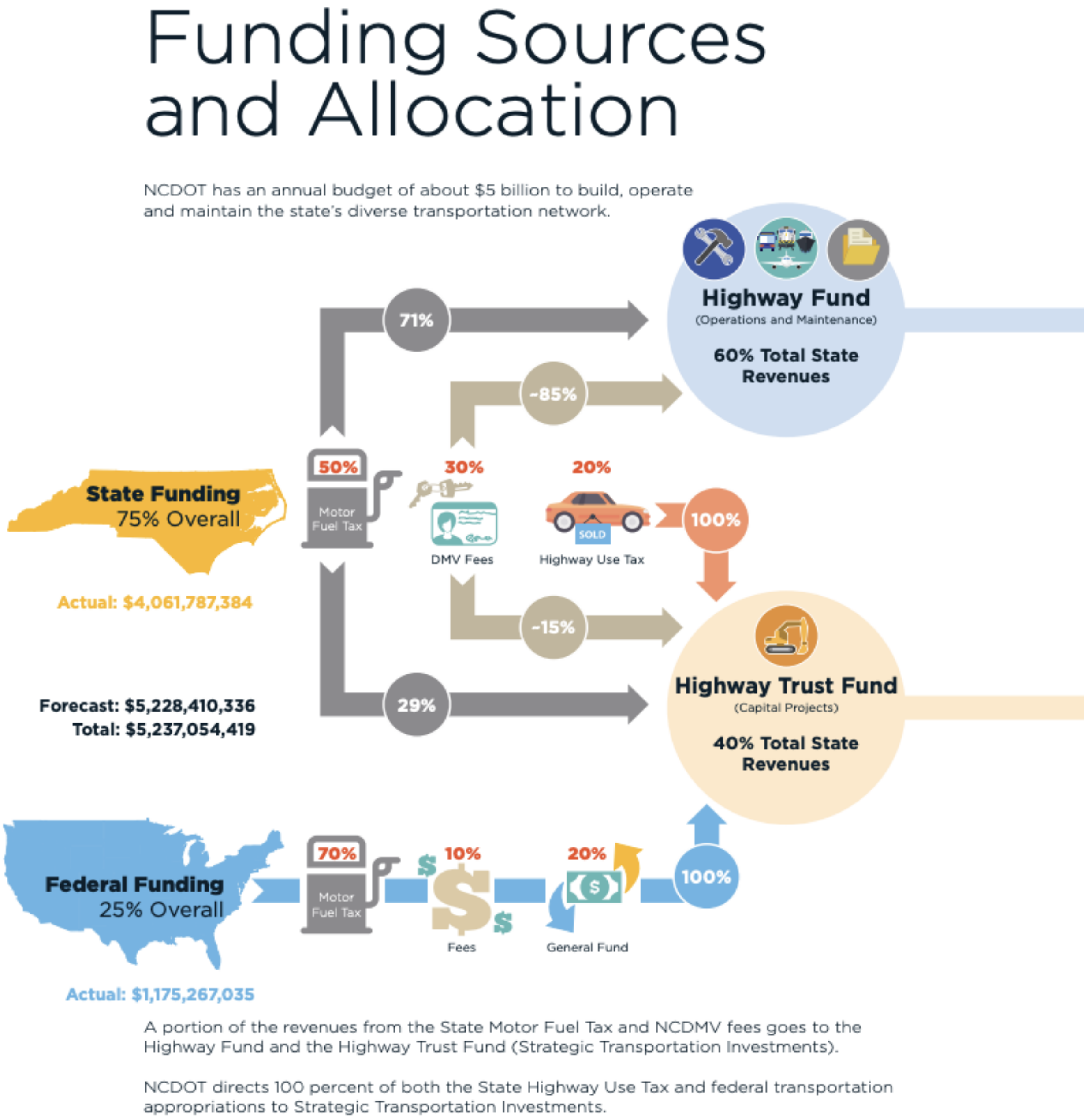
7.4 NCDOT Highway Budget

Typically, each DOT receives annual funding from their state as well as some federal funds. According to the NCDOT 2018 Annual Performance Report, the NCDOT road budget was $5.24 billion [20]. State funding made up 75% of the total budget at $4.06 billion. State funding consisted of the Motor Fuel Tax (50%), DMV fees (30%) and Highway Use Tax (20%). Federal Funding made up the other 25% of the total budget at $1.18 billion, and consisted of the Motor Fuel Tax, fees and the general fund.

NCDOTs Division of Highways is responsible for all aspects of the approximately 80,000-mile state-maintained highway system, including the safe and efficient movement of traffic. Each division oversees project planning, design, and construction, as well as all maintenance activities, such as mowing, pothole repair and resurfacing. Statewide units provide support and oversight for these functions.

Maintenance for the reporting year was $1.74B (29%), and primarily supported projects that help take care of the state's existing transportation system. This includes resurfacing highways, replacing bridges and paving unpaved secondary roads. Funds are distributed across North Carolina based on need. The construction budget was $3.11B (52%) and primarily funded new construction and expansion projects across all modes of transportation. Funding is allocated on local, regional and statewide levels based on data and input from local planning organizations and NCDOT divisions. Federal funding accounted for about 45% of NCDOT's available funding for these types of projects

Figure 3. NCDOT FY2018 Highway Budget Allocations



Funding Sources and Allocation

NCDOT has an annual budget of about $5 billion to build, operate and maintain the state's diverse transportation network.

A portion of the revenues from the State Motor Fuel Tax and NCDMV fees goes to the Highway Fund and the Highway Trust Fund (Strategic Transportation Investments).

NCDOT directs 100 percent of both the State Highway Use Tax and federal transportation appropriations to Strategic Transportation Investments.

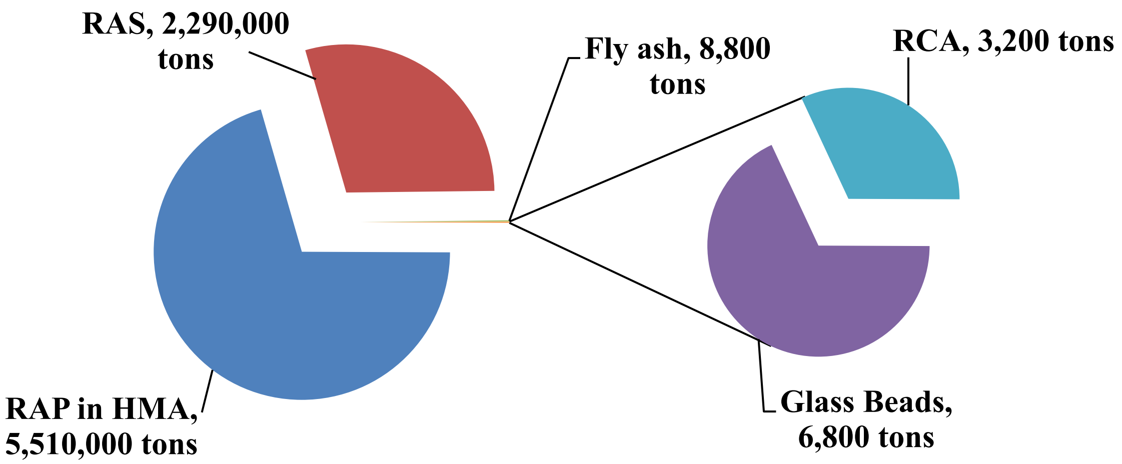
Source: NCDOT 2018 Annual Performance Report [20].

8. NCDOT Results and Discussion

8.1 NCDOT Environmental and Economic Results

The recycled materials utilized by NCDOT included RAP and RAS in HMA, RCA as base course and fill, fly ash in Portland cement and fill, and recycled glass beads as pavement markers. Figure 4 shows the total reported recycled materials by weight used. RAP and RAS in HMA made up the majority of materials, accounting for about 70.5% and 29.3%, respectively, of the total tons of recycled material reported by the NCDOT. The remaining 0.2% of recycled materials included fly ash, RCA and glass beads. Items lower than 0.2% by weight were not analyzed. As stated, most DOTs are tracking the use of RAP, RAS, fly ash and RCA in their road programs. As a state DOT program, concrete is not heavily used which is why the reported weight is low for both fly ash and RCA materials. Glass beads were not a material tracked by other DOTs analyzed, and glass beads could not be included in the analyses because a process for glass bead production does not exist in either LCA tool. Overall, glass beads make up less than 0.1% of the total tons by weight of recycled material used, however, increased use is assumed to produce even better LCA and LCCA results.

Figure 4. Most Common Recycled Material used in FY 2018 by NCDOT



8.2 NCDOT LCA - Environmental Results

Recall that certain inputs consider a 1:1 weight replacement of recycled materials with the equivalent virgin materials (i.e., RCA in place of virgin aggregate). Conversions are needed to calculate the difference in processing such as the productivity and fuel consumption of heavy equipment that can be avoided when a recycled material is available (i.e., fly ash to replace the production of Portland Cement). Table 5 below provides specific conversions used for energy, fuel consumption, water and emissions for materials production in this research.

Table 5. Standard units of conversion used to determine the environmental footprint outputs

Material	Energy Conversion	Water Conversion	CO_2 conversion	
Virgin Aggregate	154 MJ/ton	21 g/ton	10,922 g/ton	
Asphalt Bitumen	19,757 MJ/ton	8,292 g/ton	1,121,978 g/ton	
Cement	3,775 MJ/ton	1,871 g/ton	264,925 g/ton	
Gravel base agg	154 MJ/ton	21 g/ton	10,922 g/ton	

Material	Equipment (productivity, fuel consumption)	Energy Conversion	CO2 Conversion	Water
RAP Milling	Milling (1,100 tons/h, 156.2 l/h)	3.58e+07 J/l	852 g/l of diesel; 3.16 g of CO2/g of diesel	0
RAS Grinding	Grinding (115 tons/h, 161.1 l/h)	3.58e+07 J/l	853 g/l of diesel; 3.16 g of CO2/g of diesel	0
Coal Fly Ash	Energy, water and CO2 all zero			
RCA Aggregate Grinding	Excavator, wheel loader, dozer, generator all used	3.58e+07 J/l	853 g/l of diesel; 3.16 g of CO2/g of diesel	0
Crumb rubber	Tire recycling (3 tons/h, 104.73 kWh/ton)	<- 104.73 kWh/ton	1243.97 g/kWh	0.08 g/kWh

In both LCAs, the use of recycled materials reduces the environmental impact as shown in Table 6. The PaLATE results from the analysis demonstrate the environmental impact savings when the recycled materials, RAP, RAS, fly ash and RCA (not the entirety of all NCDOT's savings when constructing all roadways with all materials listed in Table 3) were used in lieu of conventional materials (sand, gravel and Portland cement).

Table 6. Estimated Environmental Impacts and Benefits of NCDOT Recycled Materials based on Use

Material	*Energy Consumption (TJ)*	*Water Consumption (kg)*	*CO_2 Emissions (Mg)*	*Solid Waste Disposal (tons)*
Virgin	19,069	6,844,384	1,139,378	310,410
Recycled	2,516	138,003	214,993	5,077
Savings	16,553	6,706,381	924,385	305,333

To put these results into relative terms, the use of the recycled materials by NCDOT in one year accounted for:

- The energy savings equal to the annual average energy use of 442,155 U.S. households[1], or roughly a city the size of Raleigh, North Carolina,
- Water savings equal to 4,343,660 U.S. gallons which could fill the equivalent of 2,688 concrete trucks[2],
- A reduction in greenhouse gas (CO_2) emissions equivalent to the emissions of 200,953 cars in one year[3], and
- The reduction of solid waste NOT landfilled equal to the average amount of waste produced by about 31 million U.S. households in one year[4], or roughly all the homes in the states of North Carolina, Georgia and Virginia combined!

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[1] The average U.S. household consumes 0.037436 terajoules of energy per year [21]

[2] The most common truck capacity is 8 cubic yards (6.1 m^3) [22]

[3] The average car emits 4,600 kilogram of CO_2 per/year [23]

[4] The average U.S. household produces 9.07 kilograms of waste per year [24]

8.3 NCDOT SimaPro and PaLATE Comparison

One goal of this research project is to compare the SimaPro and PaLATE LCA tools which can aid in accuracy in analyzing and reporting. Not every LCA tool is perfect, but prior research identified strengths for both modeling programs used in this study [25]. After performing an LCA for the both the recycled materials and equivalent virgin materials, the results were combined below, by impact category, to assess any differences between the two LCA tools. It is important to note that the recycled and virgin material inputs to both SimaPro and PaLATE are equivalent. Any difference in outputs is a result of the difference in calculation within the models for the LCA tools. By percent, we considered the benefits of the NCDOT recycled materials used for each LCA tool, and those results are presented in Table 7.

Table 7. NCDOT LCA Environmental Impact Comparison and Reductions by Percent

LCA Tool	***Energy Consumption % Reduction***	***Water Consumption % Reduction***	***CO_2 Emissions % Reduction***	***Solid Waste Reduction %***
SimaPro	82%	99%	45%	not analyzed
PaLATE	87%	98%	81%	98%

Overall, the recycled materials life-cycle inventories for both SimaPro and PaLATE estimate a significant environmental impact in all categories when compared to the equivalent virgin materials life-cycle inventories. The percent reduction by impact category chart demonstrates that PaLATE and SimaPro estimate similar energy and water reductions as seen in Table 7. However, the reduction of CO_2 varies drastically between the two programs with SimaPro estimating a 45% reduction in CO_2 emissions and PaLATE estimating an 81% reduction. We consider this discrepancy is due to how the LCA tools calculate CO_2 emissions for the production of HMA. Recall that RAP and RAS use in HMA is the largest percentage of material reuse by NCDOT. PaLATE estimates approximately 2.7 times more CO_2 emissions due to the fact that SimaPro lacks an input for HMA production; therefore, the database model is likely underestimating the impacts of CO_2 emissions. We did include bitumen in the model, but as can be seen in Table 8, the bitumen emissions itself is low for the SimaPro output. This is one reason why using and comparing the results from two tools was useful for the research.

Table 8. CO2 emissions from Bitumen Production in HMA

LCA Tool	Material	CO_2 Emissions (Mg) from Bitumen
SimaPro	Virgin	333,056
PaLATE	Virgin	884,792

In prior research [6], PaLATE results for the percent reduction in the CO_2 and energy impact categories tend to parallel each other. For this study, SimaPro reported 45% reduction CO_2 emissions and an 87% reduction in energy usage. To further assess the anomaly of a 45% reduction in CO_2 emissions from the SimaPro LCA, a comparison between the prior DOT study and this one was performed. RAP had the largest influence on the NCDOT LCAs, so a comparison study was made between another state with a reported high use of RAP, Georgia DOT. A SimaPro analysis of only RAP usage from Georgia DOT was performed and the results are shown in Table 9.

Table 9. SimaPro LCA Results for Recycled Asphalt Pavement from Georgia DOT [6]

GA DOT SimaPro LCA	Virgin	Recycled	% Reduction
Energy Consumption (TJ)	5,984	1,376	77.%
CO2 Emissions (Mg)	136,626	77,075	44%

As seen above in Table 9, a similar percent reduction trend (44%) for CO_2 emissions when using RAP compared to energy consumption was found for Georgia DOT in a SimaPro LCA. These results further confirmed the 87% energy and 45% CO_2 reductions determined for NCDOT as SimaPro consistently underestimated CO_2 emission percent reductions for RAP in HMA when compared to PaLATE CO_2 emission percent reductions.

8.4 NCDOT LCCA - Economic Analysis Results

NCDOT estimated cost savings of using recycled materials is estimated at $117M as shown in Table 10. 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. Also note that a flat rate of RAP, RAS and fly ash could not be determined for each project that NCDOT managed because many prices are kept by Contractors. Instead, the cost savings presented here are the savings associated with an HMA mix containing either RAP or RAS, and a cement mix with approximately 20% fly ash substitution for Portland cement.

Table 10. Calculated NCDOT FY18 Materials Cost Savings between Recycled Materials and Virgin Materials per Ton

Recycled Material	Quantity (Tons)	Savings($/ton)*	Total Savings ($)
RAP in HMA	5,510,000	$15	$82,650,000
RAS in HMA	2,290,000	$15	$34,350,000
Fly Ash in Portland Cement	8,800	$50	$440,000
RCA	3,200	$15	$48,000
Total	*7,812,000*		*$117,488,000*

** Note: Savings obtained from personal communications with NCDOT personnel.*

9. State DOT Comparison

With the NCDOT LCA results complete, we can compare the program to prior research [6] results of six other state DOT's (Georgia, Illinois, Minnesota, Pennsylvania, Virginia and Wisconsin).

RAP in HMA and fly ash in concrete were utilized by all DOTs studied. RAS and RCA were reported by at least five of the seven DOTs. Table 11 presents the total recycled material quantities used by each DOT that were analyzed in the LCA. Table presents each DOT's percent reduction of energy, water, CO2 emissions and solid waste. More tables of values and averages for all data can be found in Appendix B.

Table 11. Summary of RMRC Member State Recycled Materials Tonnage by Major Categories

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
RAP in HMA	1,500,000	963,996	402,048	5,510,000	403,334	1,044,072	528,157	1,478,801
RAS	1,000	39,791		2,290,000		3,757	29,342	472,778
Fly Ash	8,600	80,440	35,474	8,800	15,158	1,170	55,288	29,276
RCA	59,334	491,835	193,541	3,200			954,678	340,518
RAP in Base					158,706		327,077	242,892
GGBFS		15,045				2,340		8,693
Crumb Rubber	840							840

Note: GGBFS = ground granulated blast furnace

Table 12. Estimated Percent Reductions for each RMRC Member State (%)

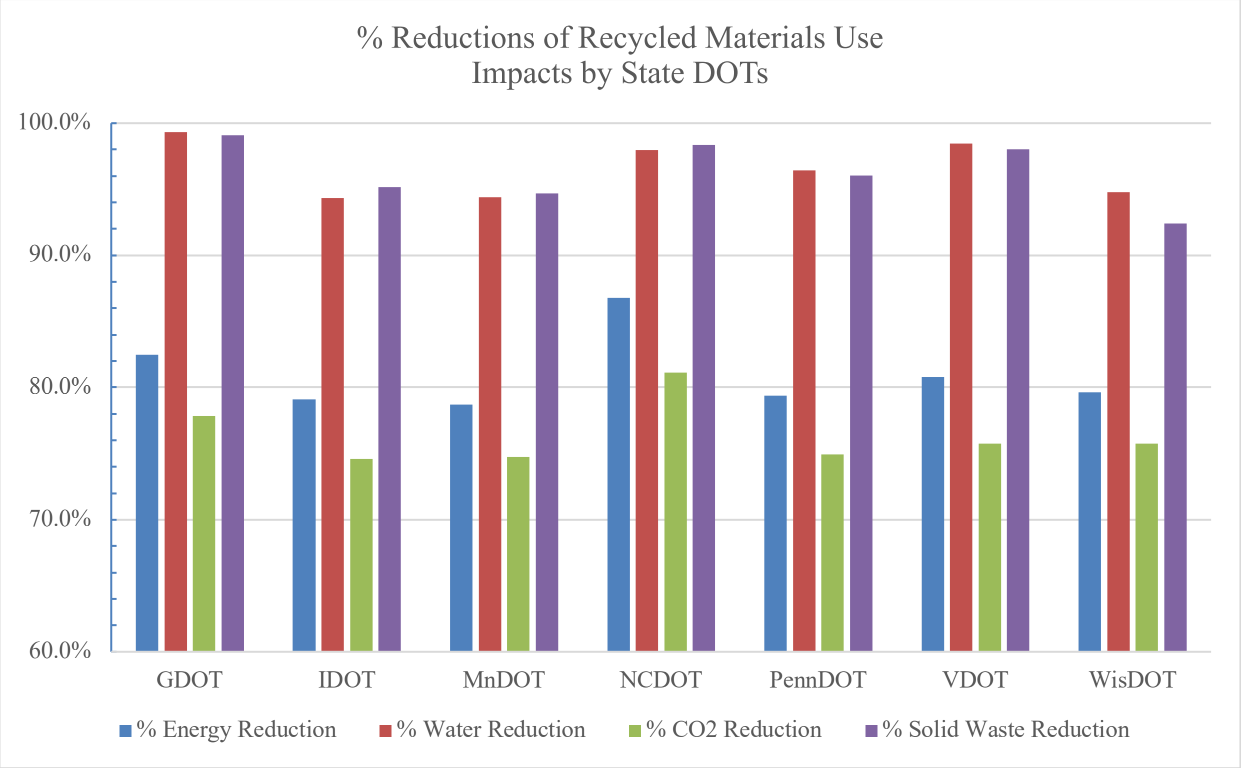
	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
Energy Consumption	82.5%	79.1%	78.8%	86.8%	79.3%	80.8%	79.6%	81.0%
Water Consumption	99.3%	94.4%	94.4%	98.0%	96.4%	98.5%	94.8%	96.5%
CO_2 Emissions	77.9%	74.6%	74.7%	81.1%	74.9%	75.8%	75.8%	76.4%
Solid Waste	99.1%	95.2%	94.7%	98.4%	96.0%	98.0%	92.4%	96.2%

RAP in HMA was used by all seven DOTs, and was utilized the most, by weight as well as volume in the southern states (GA, NC and VA) where flexible pavement is more prevalent. NCDOT used the most RAP and RAS in HMA of any state. In areas where concrete pavement is common (IL, MN, WI, and PennDOT), a greater amount of RCA is recycled. WisDOT used above average fly ash and used the most RCA of each DOT. GDOT used above average RAP in HMA and MnDOT used above average fly ash. IDOT utilized above average tonnage of RCA and used the most fly ash, crumb rubber and ground granulated blast furnace slag (GGBFS) of each state. (Not all states track or report the same recycled materials (i.e., glass beads, crumb rubber and GGBFS).

9.1 Comparison of States LCA Environmental Results

In general, percent reductions in all four environmental parameters estimated using PaLATE, were within 75 to nearly 100%, as shown in Figure 5. Of the four measured parameters, water consumption saw the highest percent reductions (94 to 99%), followed by RCRA waste production (92 to 99%), energy consumption (78 to 83%) and lastly CO_2 emissions (74 to 81%). It should be noted that these are the reduction of a 1:1 replacement of virgin material by recycled material. In other words, these are the environmental benefits seen when recycled materials are used in lieu of conventional materials. Overall, the resulting impacts trend very similar for all four categories of impact. See Appendix B, Table B-7 for Estimated % Reduction for all state DOTs.

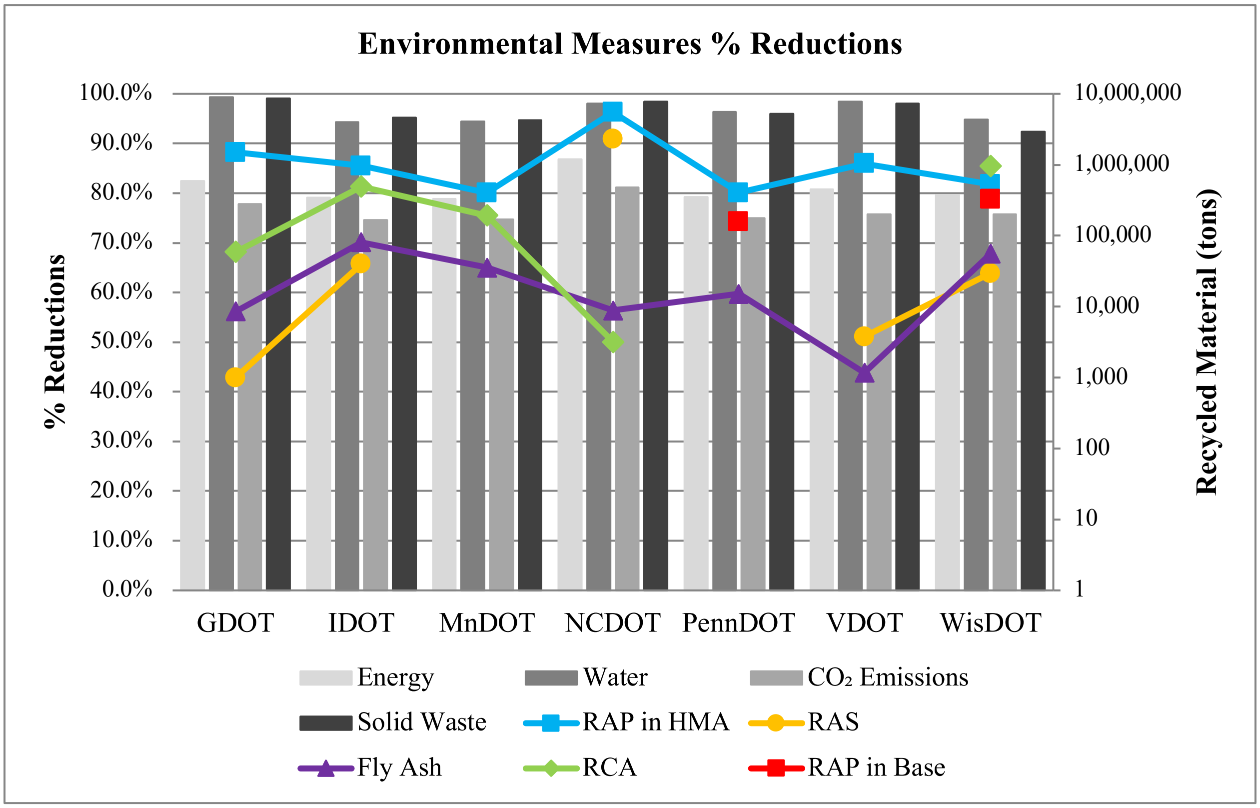
Figure 5. Environmental Benefits by Impact Category for Each State DOT based on PaLATE method.



When measured against total tonnage of recycled materials, the environmental benefit categories all tend to be driven by RAP in HMA usage. This is expected as RAP in HMA is the most heavily used recycled material in each state. NCDOT used the most RAP in HMA at 5.5 million tons. Comparatively, GDOT used about 1.5 million tons of RAP in HMA and IDOT and VDOT used around 1 million tons. All other member states, MnDOT, PennDOT and WisDOT, used less than 1 million tons of RAP in HMA.

Figure 6 presents combines the percent reductions for each environmental measure against the recycled material tons by state. The strong influence of RAP in HMA can be further demonstrated when examining the percent reductions seen by WisDOT, VDOT, PennDOT and NCDOT. PennDOT was in the lower half of states in terms of recycled material reported, but almost 95% of the material recycled by PennDOT was RAP. Of that 95%, about 70% was RAP in HMA. A similar trend in high reductions by using RAP in HMA can be seen by NCDOT. NCDOT tracked the most recycled materials, with 71% of its total recycled materials being RAP in HMA. NCDOT also saw the highest percent reductions in the energy and CO_2 categories, and the second highest percent reductions in the water and solid waste disposal impact categories.

Figure 6. Calculated Environmental Benefits by Impact Category with Tonnage of Recycled Materials



9.2 LCCA Economic Analysis Results

The estimated total cost savings of each state ranged from $3 to $117.5 million dollars, as shown in Figure 7. There are several reasons for the large difference in savings. First, not all states record and therefore reported all materials recycled. Overall, Illinois and North Carolina showed the largest inventories and materials tracking capabilities. The size (miles) and scale (scope) of highway programs by each state varies. Depending on the location within the U.S., certain recycled materials are not readily available, and transportation of those materials would be cost prohibitive. RAS and RAP can be used as an asphalt binder replacement, and although all states use HMA, warmer climates are driving the higher use or strict use of HMA in southern states. Fly as ash can be used as a substitute for Portland cement, a hydraulic binder. Fly ash weighs far less than RAP or RAS, so a strict weight comparison for the materials would not be representative of savings. Unit costs for the same material also varies across the borders. For example, unit cost savings for fly ash ranged between $4.33/ton (Georgia) to $50/ton (NCDOT). Even with the difference in reporting years, at present value this is still a large difference. Unit cost of replacement materials by state can be found in Appendix B, Table B-10.

On the other hand, recycled materials that replaced aggregates generally priced between $10 and $20 per ton, did not have a large impact on total cost savings. For example, the estimated total costs savings of MnDOT were about $7 million, 85% of which was due to RAP in HMA. The other 15% can be attributed to mostly fly ash, yet about 30% of the recycled material utilized by MnDOT in 2013 was RCA and only 6 percent was fly ash, by weight. For NCDOT, RAP and RAS cost savings as an HMA additive were significantly less than fly ash cost savings as a cement additive. Since RAP and RAS made up 70.5% and 29.3% of the NCDOT's total reported recycled material quantities, savings from other recycled materials used by NCDOT, fly ash and RCA, were not as prominent. Significant cost savings due to RCA and RAP in Base, both as aggregate replacements, were seen by WisDOT, showing the potential of each recycled material as a more economic aggregate option. WisDOT utilized more than double the amount of both materials and half as much RAP in HMA than most other member state DOTS.

Figure 7. Savings per Ton of Recycled Materials Recorded by Each State

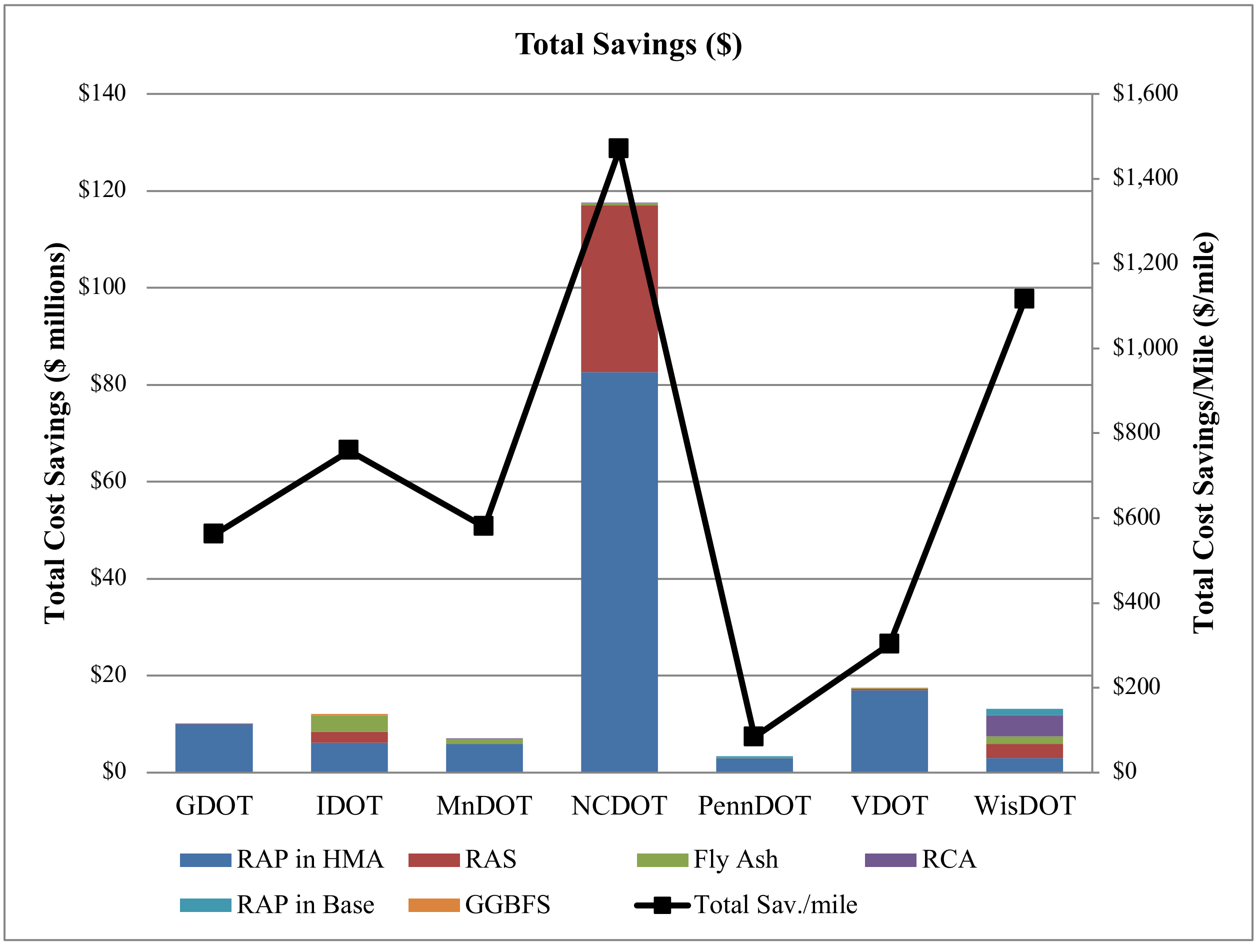
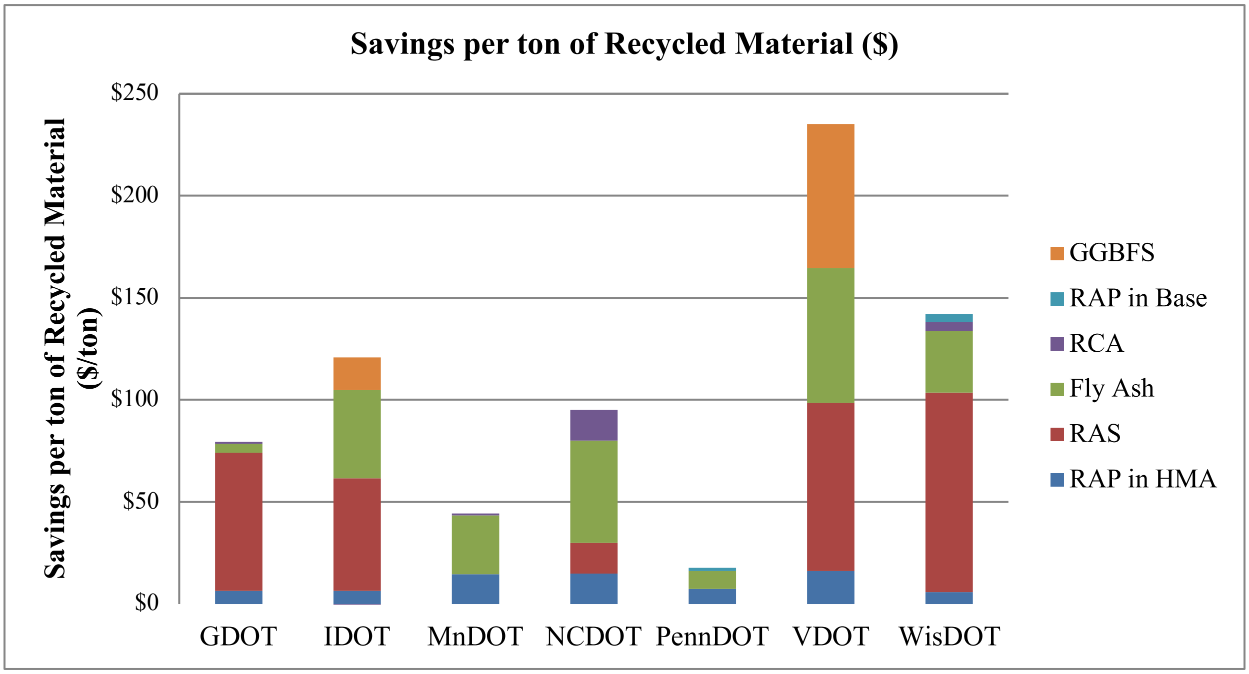


Figure 8 shows the estimated cost savings per ton of recycled material for each state. See Appendix B, Table B-11 for total cost savings by recycled materials per mile of road managed by each DOT.

The analysis included the top recycled materials, RAP in HMA, RAP in base course, RAS, RCA, and fly ash. In addition, Illinois and Virginia have access to large quantities of GGBFS and tracking was reported so those were added to their overall materials reuse in the prior study.

Figure 8. Estimated Cost Savings per Ton of Recycled Materials



RAS had the highest average estimated cost savings per ton. Fly ash and slag (GGBFS) also have high estimated cost savings, mostly in part due to the high cost of cement and their relatively low cost to obtain these materials for reuse. Relative to the estimated unit cost savings of RAS and fly ash, RAP in HMA had a low estimated unit cost savings. However, RAP in HMA was the most used recycled material in all member state DOTs, except for WisDOT, in which it was the second most used recycled material. This further demonstrates the effect that a high recycled materials use has on the total cost savings. Overall tracking of materials varies from state to state. After cost savings and optimal engineering properties, highest use, available volumes and weight are the common added reasons for tracking and reporting by DOTs.

10. Summary and Conclusions

The purpose of this research study was to conduct a life cycle assessment (LCA) and life cycle cost analysis (LCCA) for North Carolina DOT and compare those results to the other six DOTs. For this research project, two LCA tools, SimaPro and PaLATE, were used to assess the environmental effects of recycled materials in roadways. Four LCA categories (water consumption, energy consumption, solid waste generation, and carbon dioxide emissions) were considered when recycled materials were substituted for virgin materials. By performing an LCA for both virgin and recycled materials on PaLATE and SimaPro, a comparison can be made between the relative impacts of virgin and recycled material use on each LCA tool. Additionally, the results from each of these two LCA tools were compared. The cost savings of North Carolina's DOT in FY18 were estimated by comparing the prices of recycled and virgin materials in the economic analysis. To estimate the economic savings achieved, a cost savings in $/ton was estimated for the usage of a given recycled material in place of the equivalent virgin material – a 1:1 replacement.

The recycled materials utilized by NCDOT included RAP and RAS in HMA, RCA as base course and fill, fly ash in Portland cement and fill, and recycled glass beads as pavement markers. RAP and RAS in HMA made up the majority of materials, accounting for about 70.5% and 29.3%, respectively, of the total tons of recycled material reported by the NCDOT. The remaining 0.2% of recycled materials included fly ash, RCA and glass beads. As a state DOT program, concrete is not heavily used which is why the reported weight is low for both fly ash and RCA materials in North Carolina.

Overall, the recycled materials life-cycle inventories for both SimaPro and PaLATE estimate a significant environmental impact in all categories when compared to the equivalent virgin materials life-cycle inventories. The percent reduction by impact category demonstrated that PaLATE and SimaPro estimate similar energy and water reductions (i.e., more than 80%). However, the reduction of CO_2 varied drastically between the two programs with SimaPro estimating a 45% reduction in CO_2 emissions and PaLATE estimating an 81% reduction. We consider this discrepancy is due to how the LCA tools calculate CO_2 emissions to produce HMA. SimaPro lacks an input for HMA production. Similar percent reduction trend (44%) for CO_2 emissions when using RAP compared to energy consumption was found for Georgia DOT in a SimaPro LCA. These results further confirmed the 87% energy and 45% CO_2 reductions determined for NCDOT as SimaPro consistently underestimated CO_2 emission percent reductions for RAP in HMA when compared to PaLATE CO_2 emission percent reductions.

A comparison with other states indicated that of the four measured parameters based on the PaLATE methodology, water consumption saw the highest percent reductions (94 to 99%), followed by RCRA waste production (92 to 99%), energy consumption (78 to 83%) and lastly, CO_2 emissions (74 to 81%). Overall, the resulting impacts trend was very similar for all four categories of impact for all states.

The estimated total cost savings for NCDOT was \$117.5 million. A comparison of the states ranged from \$3 to \$117.5 million. There are several reasons for the large difference in savings. Estimated cost savings per ton of recycled materials used was about \$1,500/mile for NCDOT, one of the highest among the states; and estimated cost savings per ton of recycled materials was \$99/ton based on all recycled materials used.

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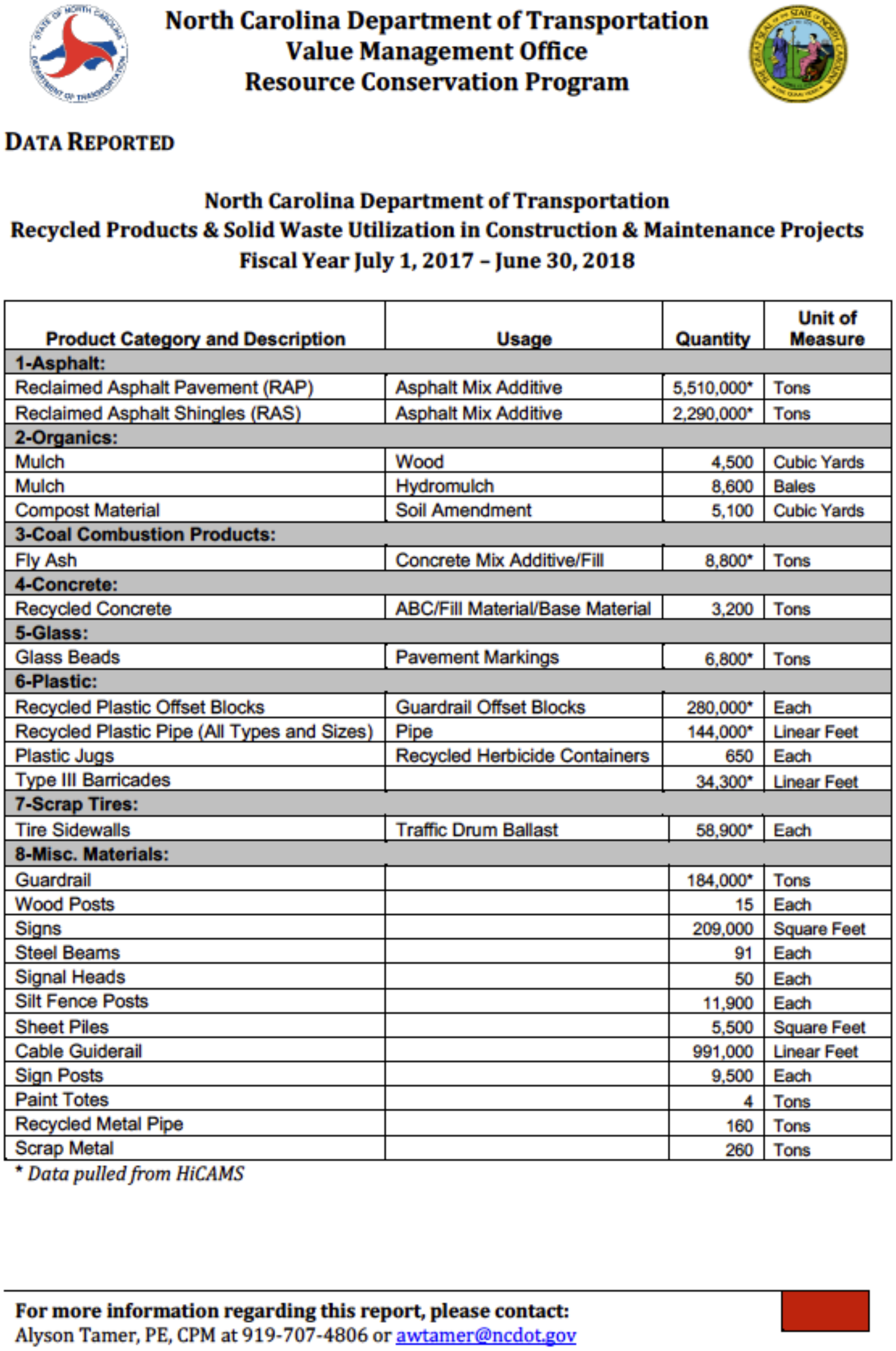
Appendix A



North Carolina Department of Transportation
Value Management Office
Resource Conservation Program

DATA REPORTED

North Carolina Department of Transportation
Recycled Products & Solid Waste Utilization in Construction & Maintenance Projects
Fiscal Year July 1, 2017 – June 30, 2018

Product Category and Description	Usage	Quantity	Unit of Measure
1-Asphalt:			
Reclaimed Asphalt Pavement (RAP)	Asphalt Mix Additive	5,510,000*	Tons
Reclaimed Asphalt Shingles (RAS)	Asphalt Mix Additive	2,290,000*	Tons
2-Organics:			
Mulch	Wood	4,500	Cubic Yards
Mulch	Hydromulch	8,600	Bales
Compost Material	Soil Amendment	5,100	Cubic Yards
3-Coal Combustion Products:			
Fly Ash	Concrete Mix Additive/Fill	8,800*	Tons
4-Concrete:			
Recycled Concrete	ABC/Fill Material/Base Material	3,200	Tons
5-Glass:			
Glass Beads	Pavement Markings	6,800*	Tons
6-Plastic:			
Recycled Plastic Offset Blocks	Guardrail Offset Blocks	280,000*	Each
Recycled Plastic Pipe (All Types and Sizes)	Pipe	144,000*	Linear Feet
Plastic Jugs	Recycled Herbicide Containers	650	Each
Type III Barricades		34,300*	Linear Feet
7-Scrap Tires:			
Tire Sidewalls	Traffic Drum Ballast	58,900*	Each
8-Misc. Materials:			
Guardrail		184,000*	Tons
Wood Posts		15	Each
Signs		209,000	Square Feet
Steel Beams		91	Each
Signal Heads		50	Each
Silt Fence Posts		11,900	Each
Sheet Piles		5,500	Square Feet
Cable Guiderail		991,000	Linear Feet
Sign Posts		9,500	Each
Paint Totes		4	Tons
Recycled Metal Pipe		160	Tons
Scrap Metal		260	Tons

** Data pulled from HiCAMS*

For more information regarding this report, please contact:
Alyson Tamer, PE, CPM at 919-707-4806 or awtamer@ncdot.gov

Appendix B

Table B-1 Recycled to Virgin Materials Equivalencies Calculation

Material	Recycled Material Inventory	Material Quantity (tons)	Equivalent Virgin Material Inventory	Weight %	Equivalent Virgin Material Quantity (tons)
RAP	RAP in HMA	5,510,000	Bitumen	6%	330,600
			Virgin Aggregate	94%	5,179,400
RAS	RAS in HMA	2,290,000	Bitumen	20%	458,000
			Virgin Aggregate	80%	1,832,000
Total Cement Mix	Fly Ash in Cement	8,800	Cement	100%	35,200
	Cement	26,400			
	RCA	3,200	Gravel	100%	3,200

Table B-2 PaLATE LCA Inputs for Recycled Materials

	PaLATE Process	Material Quantity (tons)	Material Volume Input (yd^3)	Transport Vehicle	Transport Distance (mi)
RAP in HMA	RAP	5,510,000	2,978,378	dump truck	25
RAS in HMA	RAS	2,290,000	2,044,643	dump truck	25
Fly Ash in Cement	Fly Ash	8,800	4,000	cement truck	200
Cement	Cement	26,400	20,787	cement truck	200
RCA	RCA Processing	3,200	1,702	n/a	0 (onsite)

Table B-3 PaLATE LCA Inputs for Virgin Materials

	Material	PaLATE Process	Material Quantity (tons)	Material Volume Input (yd^3)	Transport Vehicle	Transport Distance (mi)
RAP	Virgin Aggregate	Virgin Aggregate	5,179,400	2,323,753	dump truck	25
	Bitumen	Bitumen	330,600	393,571	dump truck	25
RAS	Virgin Aggregate	Virgin Aggregate	1,832,000	821,932	dump truck	25
	Bitumen	Bitumen	458,000	545,238	dump truck	25
	Cement	Cement	35,200	27,717	cement truck	200
	Gravel	Gravel	3,200	2,370	dump truck	25

Table B-4 SimaPro Inputs for Recycled LCA

Material	SimaPro Process	Material Quantity Input (kg)
RAP	Rock crushing | processing | Alloc Def, U	4,998,587,917
	Diesel | petroleum refinery operation | Alloc Def, U	1,138,247
RAS	Diesel | petroleum refinery operation | Alloc Def, U	2,706,585
Fly Ash	Cement, Portland {US}| production | Alloc Def, U	31,932,903
Gravel	Gravel, crushed | production | Alloc Def, U	2,902,991
Transportation	Transport, single unit truck, diesel powered/US	580,888,423
HMA Production	Electricity, medium voltage | market for | Alloc Def, U	491,390,639

Table B-5 SimaPro Inputs for Virgin LCA

Material	SimaPro Process	Material Quantity Input (kg)
RAP Virgin Agg.	Gravel, crushed | production | Alloc Def, U	4,698,672,642
RAP Bitumen	Bitumen adhesive compound, hot | production | Alloc Def, U	299,915,275
RAS Virgin Agg.	Gravel, crushed | production | Alloc Def, U	1,661,962,444
RAS Bitumen	Bitumen adhesive compound, hot | production | Alloc Def, U	415,490,611
Cement	Cement, Portland {US}| production | Alloc Def, U	31,932,903
Gravel	Gravel, crushed | production | Alloc Def, U	2,902,991
Transportation	Transport, single unit truck, diesel powered/US	581,005,196
HMA Production	Electricity, medium voltage | market for | Alloc Def, U	491,390,639

Table B-6 Estimated Tons Recycled Material for each RMRC Member States

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
RAP in HMA	1,500,000	963,996	402,048	5,510,000	403,334	1,044,072	528,157	1,478,801
RAS	1,000	39,791	--	2,290,000	--	3,757	29,342	472,778
Fly Ash	8,600	80,440	35,474	8,800	15,158	1,170	55,288	29,276
RCA	59,334	491,835	193,541	3,200	--	--	954,678	340,518
RAP in Base	--	--	--	--	158,706	--	327,077	242,892
GGBFS	--	15,045	--	--	--	2,340	--	8,693

*Quantities listed are in short tons and does not include materials not used in analyses, i.e., glass beads

Figure B-1 Estimated Recycled Materials for each RMRC Member States

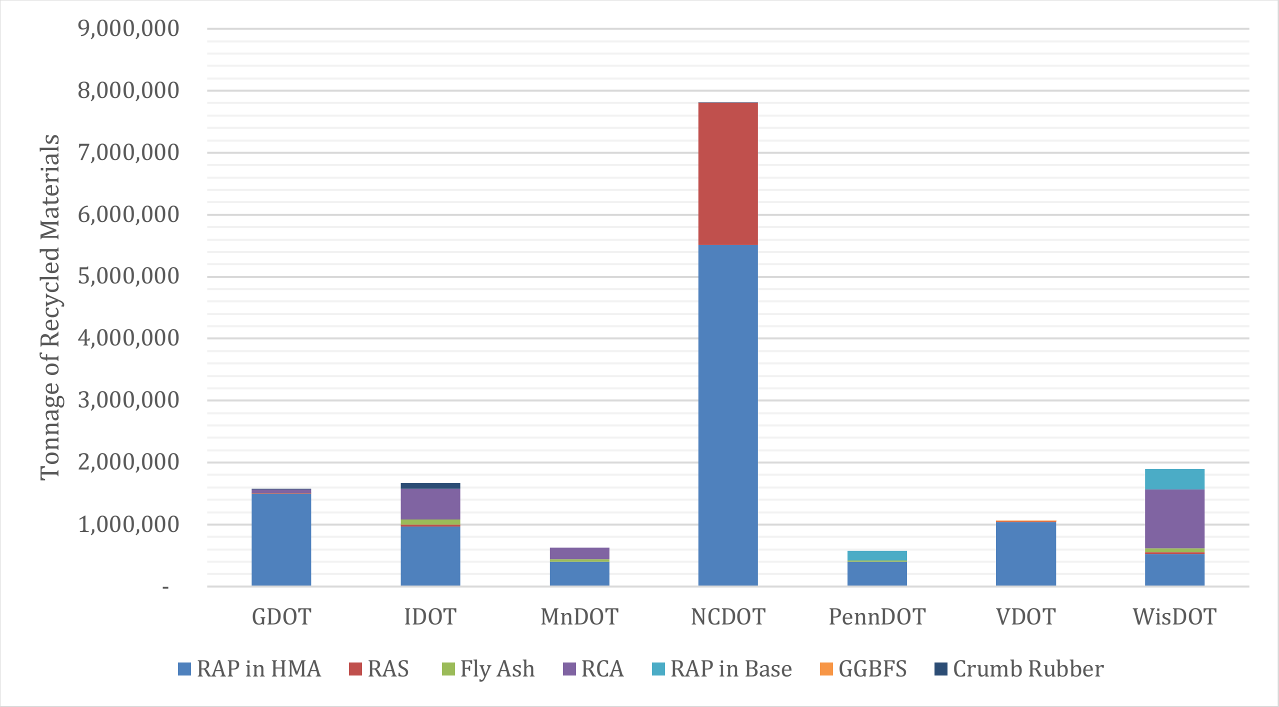


*Chart only includes materials used in current and prior analyses, i.e., glass beads are not included in total tonnage.

Figure B-2 Percent reduction of Environmental Measure in each RMRC Member States

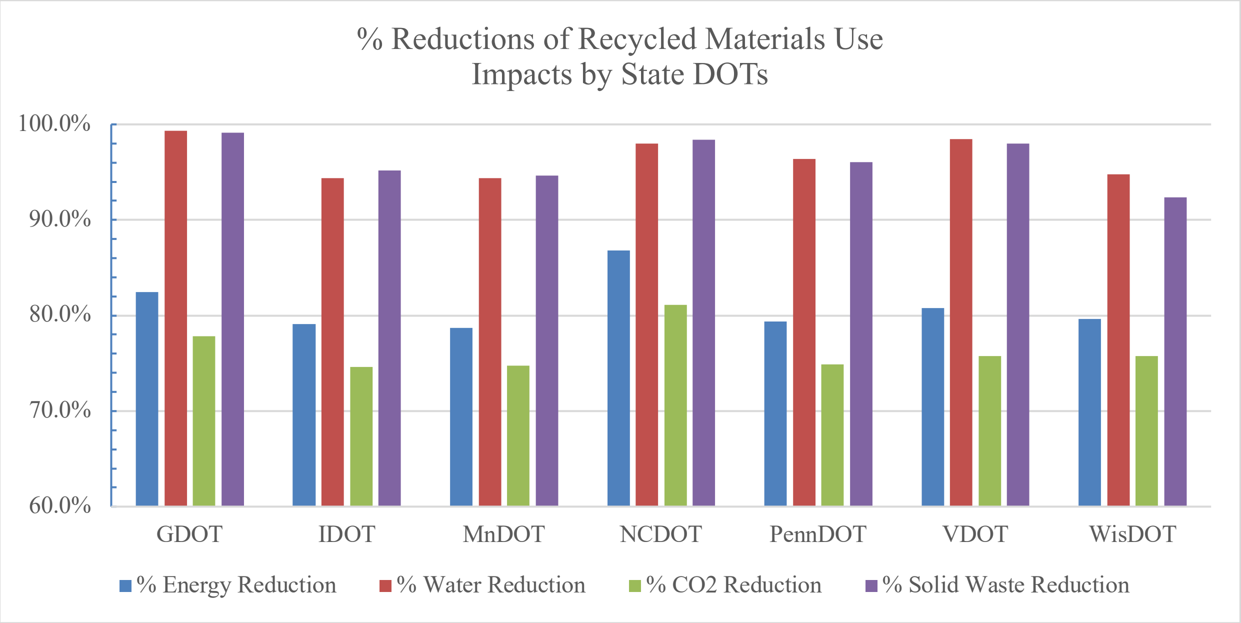


Table B-7 Estimated Percent Reductions for each RMRC Member State (%)

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
Energy Consumption	82.5%	79.1%	78.8%	86.8%	79.3%	80.8%	79.6%	81.0%
Water Consumption	99.3%	94.4%	94.4%	98.0%	96.4%	98.5%	94.8%	96.5%
CO_2 Emissions	77.9%	74.6%	74.7%	81.1%	74.9%	75.8%	75.8%	76.4%
Solid Waste	99.1%	95.2%	94.7%	98.4%	96.0%	98.0%	92.4%	96.2%

Figure B-3 Environmental Savings per Mile for Each RMRC Member State

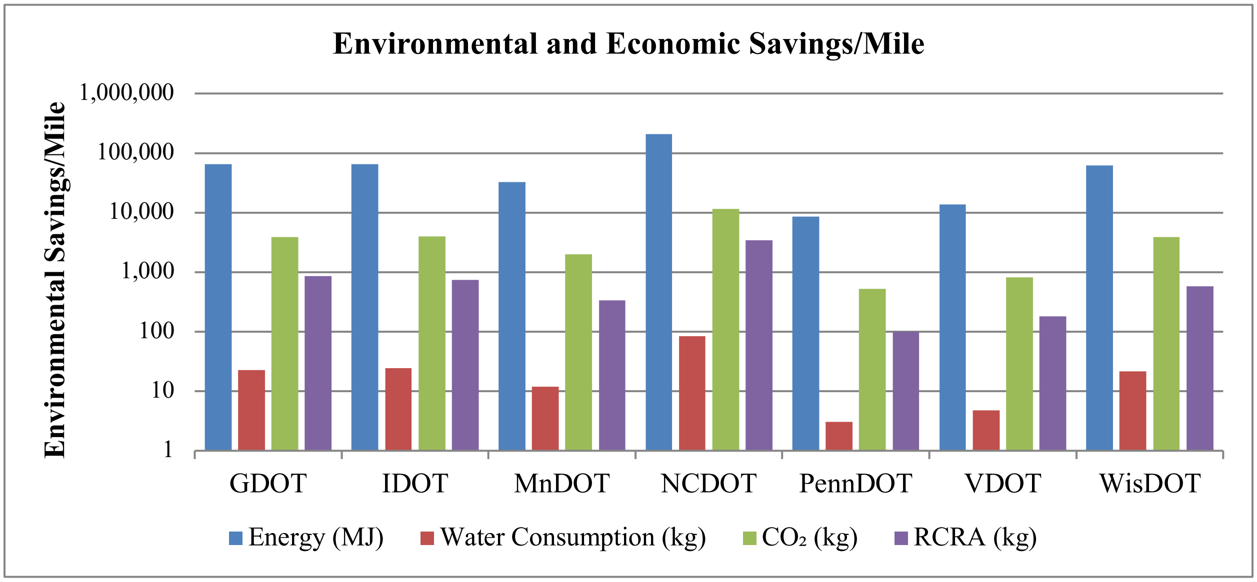


Table B-8 Environmental Savings for each RMRC Member State

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
Energy Consumption (TJ)	1,171	1,043	390	16,553	344	795	729	3,004
Water Consumption (kg)	402,829	389,331	144,200	6,706,381	122,287	276,744	255,479	1,185,322
CO_2 Emissions (Mg)	70,186	63,475	24,100	924,385	20,975	47,233	45,550	170,844
Solid Waste (Mg)	15,319	11,702	4,014	276,994	4,020	10,602	6,900	47,079

Table B-9 Environmental Savings per Total Managed Mile by State DOTs

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
Energy (MJ)	65,056	65,188	32,500	207,029	8,645	13,707	61,780	64,843
Water Consumption (kg)	22	24	12	84	3	5	22	25
CO_2 (kg)	3,899	3,967	2,008	11,561	527	814	3,860	3,805
Solid Waste (kg)	851	731	335	3,464	101	183	585	893

Table B-10 Estimated Unit Cost Savings per Ton of Recycled Material for State DOTs

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
RAP in HMA	$6.62	$6.46	$14.72	$15.00	$7.37	$16.26	$5.72	$10.31
RAS	$67.65	$55.02	--	$15.00	--	$82.18	$98.00	$63.57
Fly Ash	$4.33	$43.36	$28.61	$50.00	$8.97	$66.18	$30.00	$33.06
RCA	$1.03	-$0.01	$1.03	$15.00	--	--	$4.50	$4.31
RAP in Base	--	--	--	--	$1.46	--	$4.00	$2.73
GGBFS	--	$16.04	--	--	--	$70.71	--	$43.38

**Unit cost savings for NCDOT were from (J. Weathersbee, 2019) and (G. Dean, 2019); all other states are from sources [6-8]*

Table B-11 Total Savings for Recycled Material per Mile for each State DOT

	GDOT	IDOT	MnDOT	NCDOT	PennDOT	VDOT	WisDOT	Average
RAP in HMA	$9.93	$6.23	$5.92	$82.65	$2.97	$16.97	$3.02	$18.24
RAS	$0.07	$2.19	--	$34.35	--	$0.31	$2.88	$7.96
Fly Ash	$0.04	$3.49	$1.02	$0.44	$0.14	$0.08	$1.66	$0.98
RCA	$0.06	-$0.01	$0.02	$0.05	--	--	$4.30	$0.88
RAP in Base	--	--	--		$0.23	--	$1.31	$0.77
GGBFS	--	$0.24	--		--	$0.17	--	$0.20
Total (million)	$10.10	$12.14	$6.95	$117.49	$3.34	$17.52	$13.16	$25.82
Total Sav./mile	$561.01	$759.05	$579.48	$1,469.43	$83.97	$302.15	$1,114.99	$695.73