Worcester Polytechnic Institute

Civil Engineering Program

MQP Report

# Pavement Analysis and Design:

# Incorporating RAP into Hot Mix Asphalt Design

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# Chapter 1

# Introduction

As the world becomes more connected than ever, highways and roads have become essential for any developed country to maintain the flow of people, food, and commodities across long distances. The U.S currently contains over four million miles of road according to the Federal Highway Administration.[1] Over 200,000 miles of this road make up the National Highway System, which accounts for a significant portion of interstate travel and commerce.[2] More than ninety percent of these roads are constructed with Hot Mix Asphalts (HMA). HMA is composed of a combination of aggregates of different sizes and asphalt binder, which are mixed at high temperature of approximately 150$^{o}$C. HMA pavements are often used because of their relatively low cost, lower noise and smoothness.[3]

However, there is room for the optimization of HMA design by using reclaimed asphalt pavements, abbreviated as RAP, that have been milled up already. By recycling these aged pavements and incorporating them into new mixes, pavement manufacturers can save money on purchasing virgin materials such as aggregate and binder. The environmental benefits of recycling pavements are just as significant. Instead of occupying landfill space, recycled RAP materials reduce the consumption of

[1] "Highway Finance Data Collection." U.S. Department of Transportation/Federal Highway Administration. Accessed March 22, 2021. https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/chapter1.cfm.
[2] "Frequently Asked Questions." The American Road & Transportation Builders Association (ARTBA), May 15, 2020. https://www.artba.org/about/faq/.
[3]"Hot Mix vs Cold Mix Asphalt - Advantages and Disadvantages." Colorado Pavement Solutions, December 4, 2019. https://copavementsolutions.com/hot-mix-vs-cold-mix-asphalt.

natural nonrenewable resources and reduce greenhouse gas emissions. This will become more important as our country grows increasingly vulnerable to the effects of climate change. Increasing temperatures brought on by the greenhouse gas effect will flood major cities in states such as New York, New Jersey and Florida, as well as exacerbate natural disasters like hurricanes, droughts and forest fires.[4]

Newly mixed asphalt pavements in the US currently contain approximately 20% of RAP.[5] There are multiple reasons preventing this number from rising higher, but the most significant reasoning is the degradation of the asphalt binder through aging, and its effect on the recycled mixture. For RAP content to reach its full potential, recycling agents must be added to the mix design process to restore the vitality of the reclaimed asphalt binders.

The objective of this Major Qualifying Project (MQP) was to analyze the environmental and economic effects of high RAP content HMA pavements. The scope of work consisted of a literature review, creation of an excel spreadsheet to facilitate mix design of recycled mixes, and evaluation of total cost, materials used, energy used, and emissions released during production of six different HMA mixes.

[4]How can climate change affect natural disasters? Accessed March 22, 2021. https://www.usgs.gov/faqs/how-can-climate-change-affect-natural-disasters-1.
[5]Williams, Brett A, Audrey Copeland, and T Carter Ross. “Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2017.” TRID, June 30, 2018. https://trid.trb.org/view/1526267.

# Chapter 2

# Literature Review

## 2.1

## What are Reclaimed Asphalt Pavements and why are they important?

Reclaimed Asphalt Pavement (RAP) or excavated Hot Mix Asphalt (HMA) from old pavements contain reusable asphalt, aggregates, and binders. It is the most consistently recycled material in the United States, with 99% of material put to beneficial use. These recycled materials can be used in new hot mix asphalts, reducing the amount of virgin aggregate and virgin binders that need to be produced. This is especially important as the demand for these nonrenewable pavement materials has been steadily increasing in the past few decades, causing costs to increase while supplies have been dwindling. For example, in 2006 and in 2008 there were sharp increases in asphalt binder costs as well as diminishing supplies of quality aggregate.[6] Since the asphalt binder is the most expensive ingredient in the hot mix asphalt, pavement engineers have found significant cost savings using RAP in surface and intermediate layers, where the reused asphalt binders can replace virgin asphalt binders. The same applies to virgin aggregates, which can be replaced to a certain extent by recycled aggregates. Another place where cost savings occurs is through lowered transportation costs since less demand for new materials leads to less

[6] Rathore, M. “Asphalt Recycling Technologies: A Review on Limitations and Benefits.” IOP Conference Series, 2019. https://iopscience.iop.org/article/10.1088/1757-899X/660/1/012046/pdf.

shipping. There are extraneous costs that come with using RAPs, however. One must factor in the reclamation process, the transportation and storage of the RAP materials, and the milling and crushing operation. However, taking all of these into account, studies have shown that a hot mix asphalt with a 50% RAP content can reduce costs by 35%.[7]

There are also environmental benefits from incorporating RAP into hot mix asphalts. With the growing concerns of pollution and climate change, reducing the environmental impacts of the pavement industry is essential to preserve the planet for future generations. Recycling old pavements reduces the use of new materials, which leads to a considerable reduction in the consumption of nonrenewable natural resources. This also results in a reduction in energy associated with manufacturing, as well as emissions during manufacturing. Another aspect of the environmental advantages of RAP is the landfill space savings ordinarily taken up by pavement disposal. In a survey conducted in 2018 by the National Asphalt Pavement Association, 61.4 million cubic yards of landfill space have been saved through the recycling of asphalt pavements.[8] It is important to recognize the significant emissions that arise from the plant production of high RAP mixtures; however numerous technological advancements have been developed to counteract this. For example, advances in asphalt production plant technology have allowed manufacturers to shield RAP from contact with the dryer burner flame and get overly oxidized, and modern air pollution

[7] Rathore, M. “Asphalt Recycling Technologies: A Review on Limitations and Benefits.” IOP Conference Series, 2019. https://iopscience.iop.org/article/10.1088/1757-899X/660/1/012046/pdf.
[8]Redling, Adam. “RAP Use in New Asphalt Pavement at All-Time High, According to Report.” Waste Today, September 17, 2019. https://www.wastetodaymagazine.com/article/recycled-asphalt-pavement-napa-report.

control technologies can be used to filter emissions before releasing into the atmosphere.

## 2.2

## What are the limitations for using RAP?

The average estimated percentage of RAP content in asphalt mixtures has increased from 15.6 percent in 2009 to 20.1 percent in 2017.[9] However, since RAP has such demonstrable benefits, what keeps the average from being as high as 40-50%? There are a few significant limitations that must be overcome to make high RAP hot mix asphalts universally applicable. It is imperative that RAP HMAs must be of equivalent quality to conventional mixtures, or else the maintenance work and associated costs will be prohibitive.

One issue of RAPs comes from the milling process, where the reclaimed pavement material is obtained from the existing pavement using specialized milling machines. This process can sometimes produce excessive fine aggregate through breakdown of larger aggregates, creating inconsistencies in the aggregate fraction.[10] To maintain gradation requirements, the RAP aggregate fractions must be equivalent to that of the virgin aggregate fractions.

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[9]Brett A. "Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage." Information Series 138. National Asphalt Pavement Association, 2017.

[10]Zaumanis, Martins. "How to Reduce Reclaimed Asphalt Variability: A Full-Scale Study." Researchgate.net, November 2018. https://www.researchgate.net/publication/327306385_How_to_reduce_reclaimed_asphalt_variability_A_full-scale_study.

Another limiting factor is related to the blending of the RAP asphalt with the virgin binder. When a perfect blend is achieved, the blended RAP and virgin binder create a homogenous film that coats the virgin aggregate completely. However, what often occurs is a partial blend, in which the inner layer of the RAP binder remains on the RAP aggregate without interacting with the virgin binder, and instead of coating the virgin aggregate it is considered to be part of the aggregate or “black rock”.[11]

Finally, asphalt binder becomes significantly stiffer over time, due to oxidation. The aged binder that comes with reclaimed pavement can lead to fatigue and block cracking if it is not mixed properly with the virgin binder and/or binder rejuvenators[12]. However, if the aged binder is softened too much by virgin binder and rejuvenators, it can cause rutting.[13] Therefore, it is of the utmost importance to characterize the RAP through testing before designing the new asphalt mix to create the optimal blend.

## 2.3

## What are the relevant properties of RAP and the corresponding testing methods?

The first physical property of RAP that is recorded is the gradation of the RAP aggregate after the milling process. This is done by sieve analysis, in which the milled

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[11] Gottumukkala, Bharath, and Sudhakar Reddy Kusam. “Estimation of Blending of Rap Binder in a Recycled Asphalt Pavement Mix.” Journal of Materials in Civil Engineering. American Society of Civil Engineers, May 31, 2018. https://ascelibrary.org/doi/10.1061/%28ASCE%29MT.1943-5533.0002403#e_1_2_4_7_1.

[12] Rejuvenators are recycling agents used to restore the properties of aged asphalt binder. More information can be found in Chapter 2.5.

[13] Rathore, M. “Asphalt Recycling Technologies: A Review on Limitations and Benefits.” IOP Conference Series, 2019. https://iopscience.iop.org/article/10.1088/1757-899X/660/1/012046/pdf.

RAP material is passed through mesh sieves (Figure 1), separating the particles by size, as demonstrated by AASHTO T30, Mechanical Analysis of Extracted Aggregate.[14] RAP is separated into at least two sizes, typically a coarse fraction (+1/2 or +3/8 inches (+12.5 or +9.5 mm)) and a fine fraction (-1/2 or -3/8 inches (-12.5 or -9.5 mm)) With this information, the aggregate gradation can be determined.[15] The angularity of the aggregate (ASTM D 5821), as well as the flat and elongated requirements (ASTM D 4791) are recorded by a visual inspection of a sample of RAP.

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[14] "AASHTO T 30." AASHTO T 30 - Standard Method of Test for Mechanical Analysis of Extracted Aggregate | Engineering360. Accessed March 22, 2021. https://standards.globalspec.com/std/9945238/aashto-t-30.

[15]Sunarjono, Sri. "Physical Properties of Reclaimed Asphalt Pavement." Researchgate.net, November 2019. https://www.researchgate.net/publication/337259788_Physical_properties_of_reclaimed_asphalt_pavement.

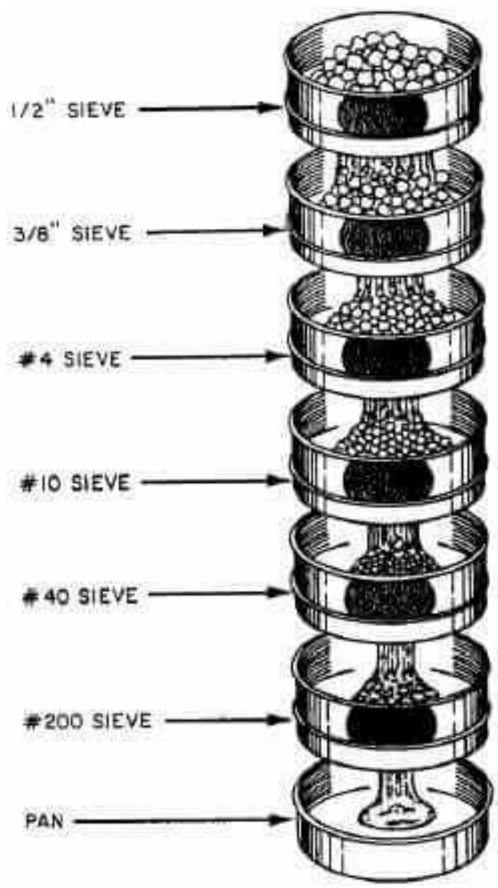


*Figure 1. Mechanical sieve analysis of aggregates*[16]

After the aggregate size distribution and shape are evaluated, the asphalt content is determined by separating the binder from the aggregate. This can be done by either ignition test or solvent extraction. However, note that the ignition test renders the binder unusable.[17] The most common solvent extraction method (Figure 2) is the Rotary Evaporator method of recovery, using TCE, methylene chloride, or nPB as reagents for extraction. The extraction is performed in a rotating drum, where the solvent comes in

[16] "How to Perform a Sieve Analysis." Mineral Processing & Metallurgy, July 1, 2018. https://www.911metallurgist.com/blog/perform-test_sieves-analysis.

[17] To perform the ignition method, the hot mix asphalt is heated in an oven sufficiently to burn off the asphalt binder within the mixture. The difference in weight before and after burning in the ignition oven gives a measure of asphalt binder content.

contact with the asphalt mixture. The extract is vacuum filtered through a two-stage filtering process to remove most of the aggregate fines. The extract is then transferred to a rotary evaporator where the solvent is vacuum distilled, separating the binder from the aggregate.[18] This procedure can be found in AASHTO T 319.[19] Once this is completed, the percentage of the asphalt binder compared to the percentage of aggregate within the RAP can be recorded. In most cases, aggregate makes up between 93-97%, while binder makes up between 3-7% of the mix.[20]

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[18] Wakefield, Amma. "A Review of Solvent Extraction-Recovery Procedures and Their Effect on Recovered Asphalt Binder Properties." Canadian Technical Asphalt Association, November 2018. https://www.researchgate.net/publication/328996268_A_Review_of_Solvent_Extraction-Recovery_Procedures_and_their_Effect_on_Recovered_Asphalt_Binder_Properties.

[19]"AASHTO T 319." AASHTO T 319 : Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures. Accessed March 22, 2021. https://global.ihs.com/doc_detail.cfm?document_name=AASHTO+T+319&item_s_key=00489225&csf=ASA.

[20] "User Guidelines for Waste and Byproduct Materials in Pavement Construction." U.S. Department of Transportation/Federal Highway Administration. Accessed March 22, 2021. https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap131.cfm.

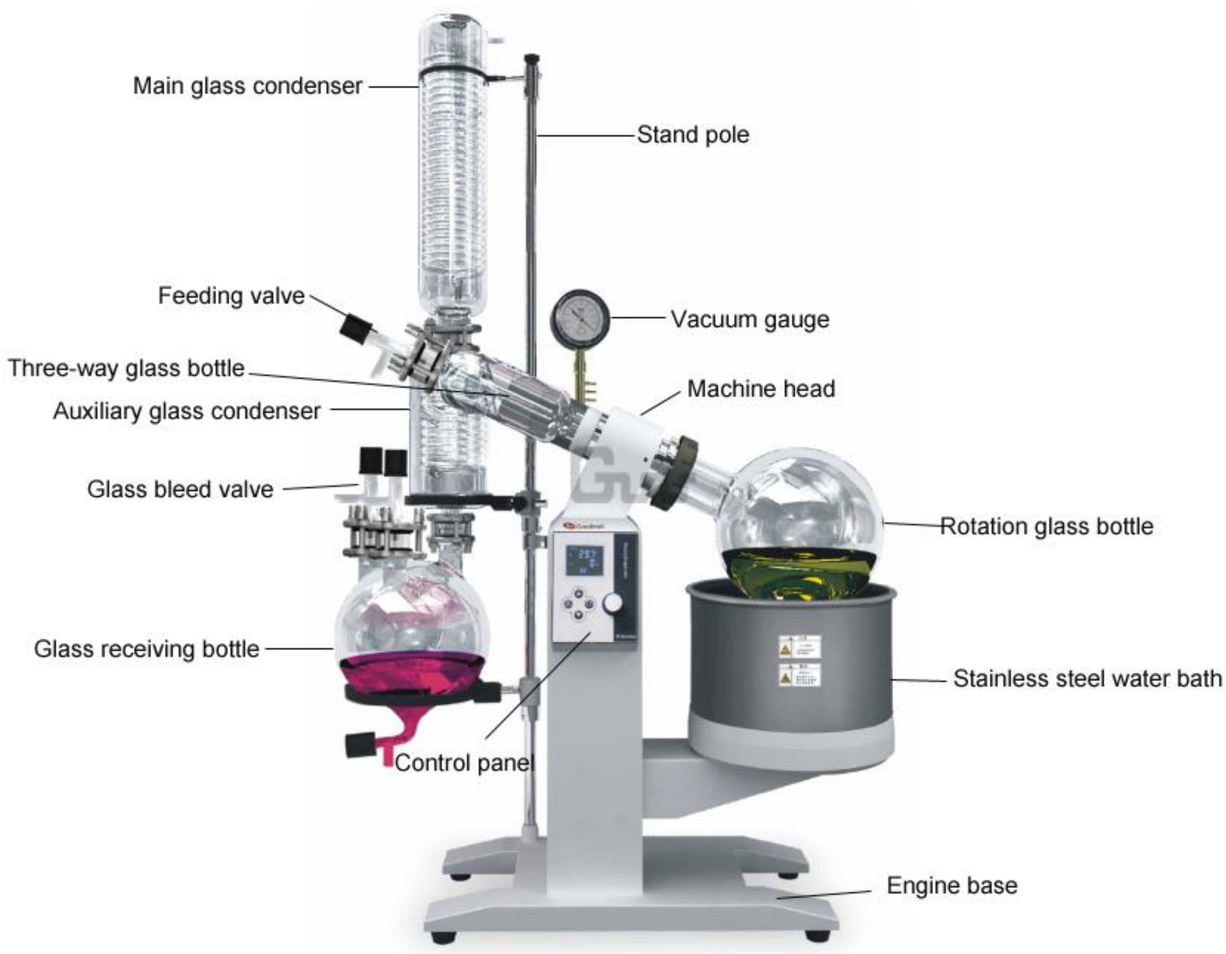


*Figure 2: Rotary Evaporator*[21]

Once the asphalt binder is separated, the viscosity and/or penetration properties of the asphalt binder are tested to estimate the amount and grade of virgin asphalt binder required in the mix design. The viscosity is measured by a vacuum capillary viscometer (Figure 3), as seen in AASHTO T 202.[22] The sample is poured down the tube at 60 °C, and viscosity is calculated by multiplying the flow time in seconds by the

[21] "10L High Quality Laboratory Rotary Evaporator with Patented Vacuum Distillation Sealing." Bio-equip. Accessed March 22, 2021. https://bio-equip.cn/enshow1equip.asp?equipid=5224.
[22] "AASHTO T 202." AASHTO T 202 : Standard Method of Test for Viscosity of Asphalts by Vacuum Capillary Viscometer. Accessed March 22, 2021. http://global.ihs.com/doc_detail.cfm?document_name=AASHTO+T+202&item_s_key=00489082.

viscometer calibration factor.[23] The penetration is tested by lowering a 100 gram needle into the binder at 25° C (Figure 4) and letting it sink in for five seconds, and recording the depth of penetration in dmm.

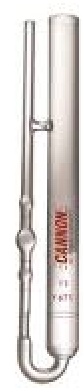


*Figure 3 and 4: Vacuum Capillary Viscometer and Penetration Test Equipment*[24]

Finally, the critical high, intermediate and low temperatures of the binder must be tested. The critical high and intermediate temperature ($T_c$(High)) is tested using a dynamic shear rheometer (Figure 5). A thin asphalt binder sample is placed between a fixed lower plate and an oscillating upper plate swinging back and forth across the sample at 10 rad/sec (1.59 Hz) to create a shearing action, as specified in AASHTO T 315.[25] The critical low temperature ($T_c$(S)) is tested using a bending beam rheometer

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[23]"Bitumen and Bituminous Binders – Determination of Dynamic Viscosity by Vacuum Capillary." EuroBitume, April 2020. https://www.eurobitume.eu/public_downloads/Technical/EB_Technical_Information_Dynamic_Viscosity__English_.pdf.

[24] "Bitumen and Bituminous Binders – Determination of Dynamic Viscosity by Vacuum Capillary." EuroBitume, April 2020. https://www.eurobitume.eu/public_downloads/Technical/EB_Technical_Information_Dynamic_Viscosity__English_.pdf.

[25] "AASHTO T 315." AASHTO T 315 - Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR) | Engineering360. Accessed March 22, 2021. https://standards.globalspec.com/std/14316806/aashto-t-315.

(Figure 6). The asphalt binder sample is formed into a simply supported beam and immersed in a cold liquid bath. A load is applied to the center of the beam and its deflection is measured against time. Stiffness is calculated based on the measured deflection. How the asphalt binder relaxes to the load induced stresses is also measured. The critical low temperature can also be calculated based on the "m-value"[26], or the slope of the stiffness versus time curve at 60 seconds. These critical temperatures are variables in the equation to calculate virgin binder grade necessary to balance the aged RAP binder.

The equation for critical high temperature is as follows:

$$T_{c(High)} = \left(\frac{Log(1.00) - Log(G_1)}{a}\right) + T_1$$

Where $G_1$ = the $G^*/\sin \boldsymbol{\delta}$ value at a specific temperature $T_1$

And a = the slope of the stiffness-temperature curve as $\Delta$ Log(G*/sin δ)/ΔT [27]

The equation for critical intermediate temperature is as follows:

$$T_{c(Intermediate)} = \left(\left(Log(5000) - \frac{Log(G_1)}{a}\right)\right) + T_1$$

The equation for critical low temperature is as follows:

[26] A lower m-value is indicative of slower relaxation of the thermal stresses. The slope can be calculated as Δm-value/ΔT

[27] As temperature increases, stiffness decreases. The slope can be calculated as Δ Log(G*/sin δ)/ΔT

$$T_{c(Low_S)} = \left(\left(Log(300) - \frac{Log(S_1)}{a}\right)\right) + T_1$$

Where $S_1$ = the S-value at a specific temperature, $T_1$

And a = the slope of the stiffness-temperature curve as $\Delta$ Log(S)/$\Delta$T

$$T_{c(Low_m)} = \left(\left(Log(.300) - \frac{Log(m_1)}{a}\right)\right) + T_1$$

$m_1$ = the m-value at a specific temperature, $T_1$

a = slope of the m-value-temperature curve as $\Delta$m-value/$\Delta$T


*Figure 5 and 6: Dynamic Shear Rheometer and Bending Beam Rheometer*[28]

[28] "Binder Tests Dynamic Shear Rheometer." Accessed March 21, 2021. https://pavementinteractive.org/reference-desk/testing/binder-tests/dynamic-shear-rheometer/https:/www.pavementinteractive.org/wp-content/uploads/2011/04/Bbr.jpg.

The bulk specific gravity and absorption value of the RAP aggregate are two characteristics that cannot be measured through tests, so they are estimated using original construction records or mathematical equations.

The formula for Bulk Specific Gravity ($G_{sb}$) of RAP aggregate is calculated in two steps:

1) $G_{se}(\text{effective specific gravity}) = \frac{100-P_b}{\left(\frac{100}{G_{mm}}\right)-\left(\frac{P_b}{G_b}\right)}$

Where Pb is asphalt content of RAP mixture, $G_b$ is asphalt specific gravity (assumed to be 1.02) and $G_{mm}$ is maximum specific gravity[29]

2) $G_{sb}(Bulk\ Specific\ Gravity) = \frac{G_{se}}{\left(\frac{P_{ba}-G_{se}}{100G_b}\right)+1}$

Where $P_{ba}$ is the asphalt absorption value, which must be estimated using historical records of the original mix design. If historical data are not available, a value for $P_{ba}$ may be estimated as a percentage of the typical water absorption value, usually 60-65%.[30]

[29] "ALTERNATIVE METHOD FOR DETERMINING BULK SPECIFIC GRAVITY OF RECLAIMED ASPHALT PAVEMENT." VOLUMETRIC HOT MIX ASPHALT PRODUCER PROGRAM, May 2017. https://www.in.gov/indot/div/mt/itm/pubs/596_testing.pdf.

[30] "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of The Practice." U.S. Department of Transportation/Federal Highway Administration. Accessed March 22, 2021. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/11021/003.cfm.

## 2.4

## What is the current mix design method for including RAP in hot mix asphalts?

The Superpave performance grade binder and volumetric mix design system has become the most widely accepted design system for asphalt mixtures in the US. The standard practices and specifications for designing asphalt mixtures according to the Superpave® mix design system are AASHTO M 323 and AASHTO R 35.[31] AASHTO M 323 specifies the quality requirements for binder, aggregate, and HMA for Superpave® volumetric mix design, while AASHTO R 35 is a standard for mix design evaluation based on volumetric properties, air voids, VMA, and voids filled with asphalt of the HMA.

The mix design process for mixes incorporating RAP is similar to the mix design for all virgin materials and can be found in AASHTO M 323 and NCHRP 429.[32]

**Step 1: Collection of RAP**

RAP is collected from the existing road during rehabilitation or reconstruction, generally through cold milling. After being transported to a hot mix asphalt (HMA) plant, it is processed and stockpiled to be stored for later usage.

**Step 2: Characterization of RAP**

[31]"AASHTO M 323." AASHTO M 323 : Standard Specification for Superpave Volumetric Mix Design. Accessed March 22, 2021. https://global.ihs.com/doc_detail.cfm?document_name=AASHTO+M+323&item_s_key=0048865.
[32] Geotechnical Information Practices in Design-Build Projects. Accessed March 22, 2021. http://www.trb.org/Publications/Blurbs/167098.aspx.

When it becomes time for the stockpiled RAP to be used, the RAP binder is separated and recovered with solvent extraction. After the separation, the necessary physical properties are determined (aggregate gradation, asphalt content, asphalt viscosity, bulk specific gravity, absorption value). DSR testing can be used to determine the high and intermediate critical temperature while BBR testing is used to determine the low critical temperature.

**Step 3: Determination of virgin binder grade using approximate RAP binder ratio OR Determination of Max RAP binder ratio using known virgin binder grade**

The required critical temperature for virgin asphalt binder can be calculated with three variables: 1) $T_c$(need): Final critical temperature the blended mixture needs to be 2) $T_c$(RAP Binder): Critical temperature of recovered RAP binder 3) RBR: RAP Binder Ratio

The equation for critical temperature for virgin asphalt binder is as follows:

$$T_c(virgin) = \frac{T_c(need) - \left(RBR * T_c(RAP\ Binder)\right)}{(1 - RBR)}$$

Alternatively, the equation can be manipulated to find the max RAP Binder Ratio.

$$RBR_{max} = \frac{T_c(need) - T_c(virgin)}{(T_c(RAP\ Binder) - T_c(virgin))}$$

**Step 4: Three trial blends are established**

After selecting the virgin aggregate and virgin binder, three trial RAP mixtures are selected. Each trial should have a unique RAP percentage. The batch weights for both gyratory samples and maximum theoretical specific gravity samples are calculated. Next, the trial blend specimens are mixed and compacted.

**Step 5: Trial blends are evaluated**

The trial blends are evaluated according to different statistical standards: including dust proportion, percent of air voids (Voids in Total Mix, VTM), percent of voids in the mineral aggregate (VMA), percent of voids filled with asphalt (VFA). One blend is selected and four different trials are mixed with .5% binder content intervals. The blend that passes the densification standards is selected.[33]

**Step 6: Mix designs are verified**

The final mixture design is checked to ensure that it is not susceptible to moisture damage. It is also checked to ensure it still has at least 2 percent air voids present after compacting to the maximum number of gyrations, or $N_{Max}$.

## 2.5

## How can recycling agents or rejuvenators improve the Superpave mix design?

Recycling agents, otherwise known as rejuvenators, are a hydrocarbon product that restores the functionality of aged asphalt binders. As discussed in chapter 2.3, one of the major limitations of RAP is the stiffening of asphalt binders over time. Binders are

[33] As the number of gyrations increases, the density will increase as well. To pass the densification standards, the density must be less than 89% after initial gyrations, equal to 96% at the design level of gyrations, and less than 98% after maximum gyration.

made up of asphaltenes and maltenes, the former being much more viscous than the latter. The binder’s stiffening is a result of oxidation converting the maltene oil and resin into asphaltenes. A rejuvenator reverses this effect by restoring the balance between asphaltenes and maltenes. It has a few other benefits as well. For example, when sprayed on a pavement, it seals it from air and water, slowing down the oxidation process. It also increases the penetration value of the binder on the surface level, increasing its lifespan significantly. Rejuvenators can be used in a number of ways, including sealing new pavements, maintaining aging pavements and the reconstruction of unusable pavements. In this literature review, rejuvenators refer to softening agents that are utilized to reinvigorate aged binder and allow for a higher RAP content when creating a new mix.

# Chapter 3

# Overview of Work and Timeline

In order to select a mix design with the greatest economic and environmental benefits, multiple mix design trials with different percentages of RAP will be designed. The process of designing the hot mix asphalts is described in the literature review. The equations necessary to calculate the mix design were programmed in an excel spreadsheet. The purpose of the excel spreadsheet is to allow the user to input all the required variables and determine to an accurate hot mix asphalts design. After the Superpave method is transformed into the excel format, it can be modified separately to incorporate the addition of recycling agents into the mix design procedure. Three new mix design trials will be calculated, but these will contain recycling agents. After all the mix designs are calculated, they must be verified to make sure they are of sufficient quality. Once the mix designs pass the standard requirements, they will be evaluated on the following parameters: total cost, materials used, energy used, and emissions released. By comparing these parameters across mix designs with various percentages of RAP content, the most desirable mix design can be selected. An overview of the methods is indicated in Figure 7. A time schedule of this MQP is presented in Figure 8.

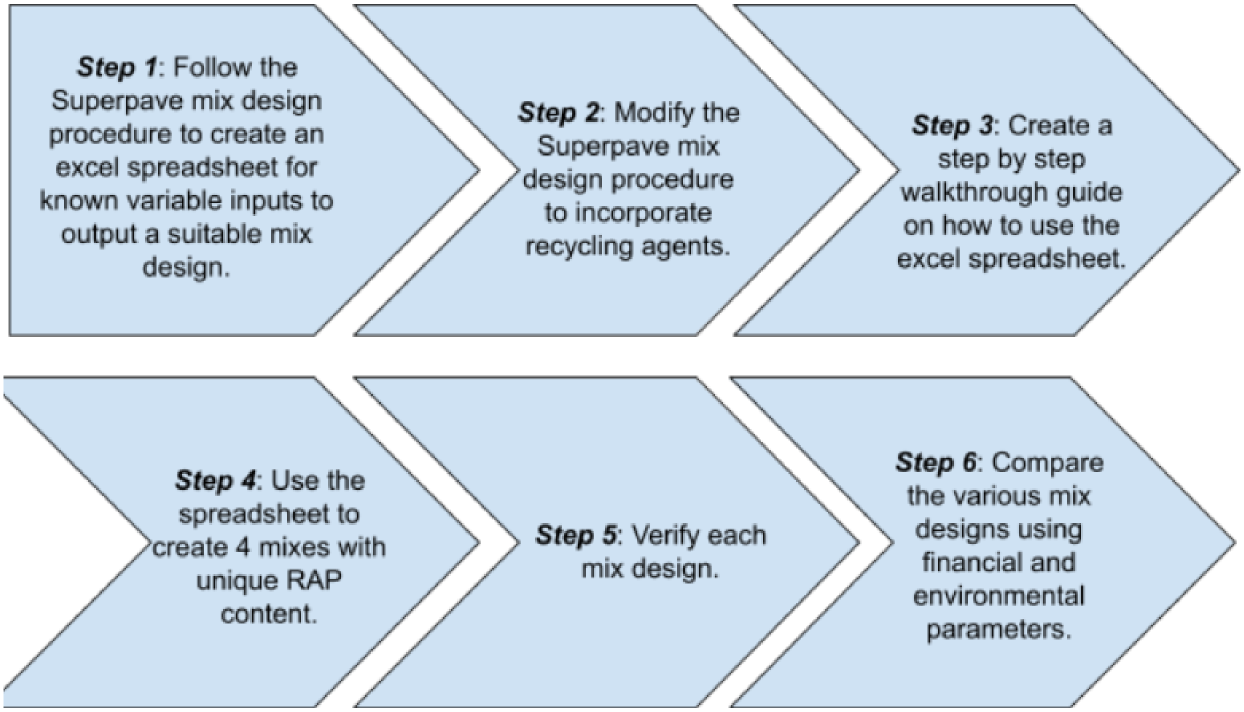
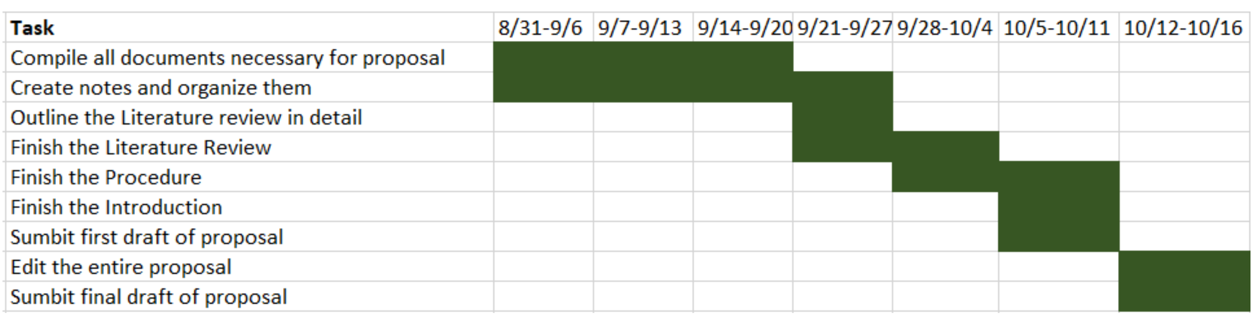
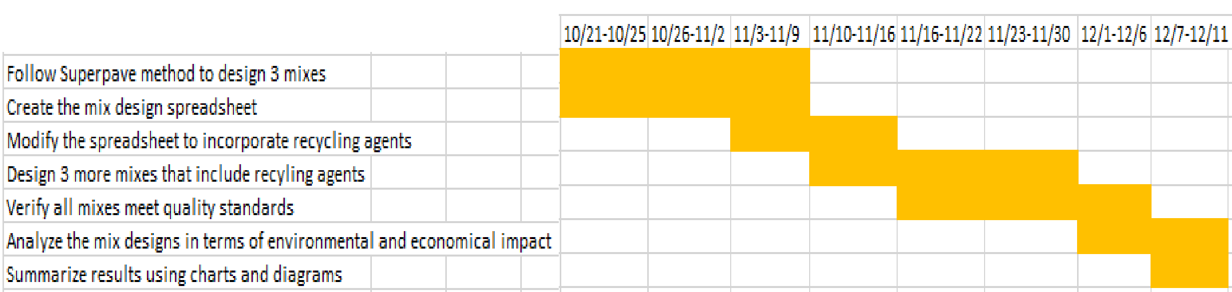



*Figure 7: Methods Overview*



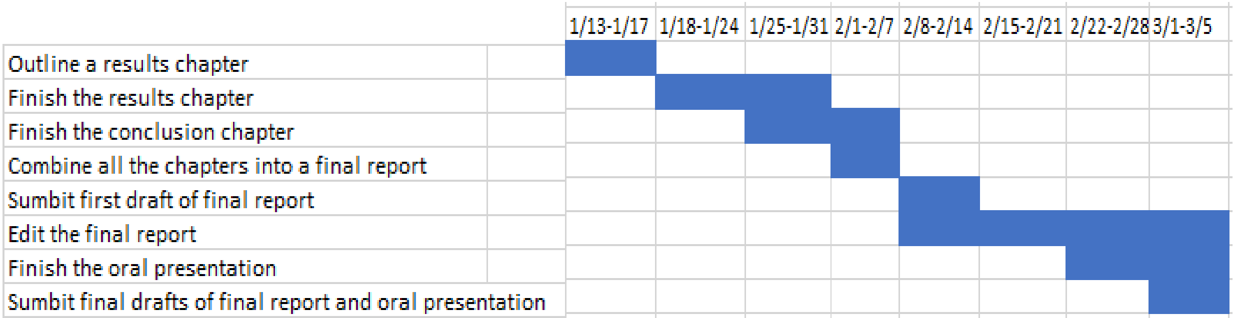


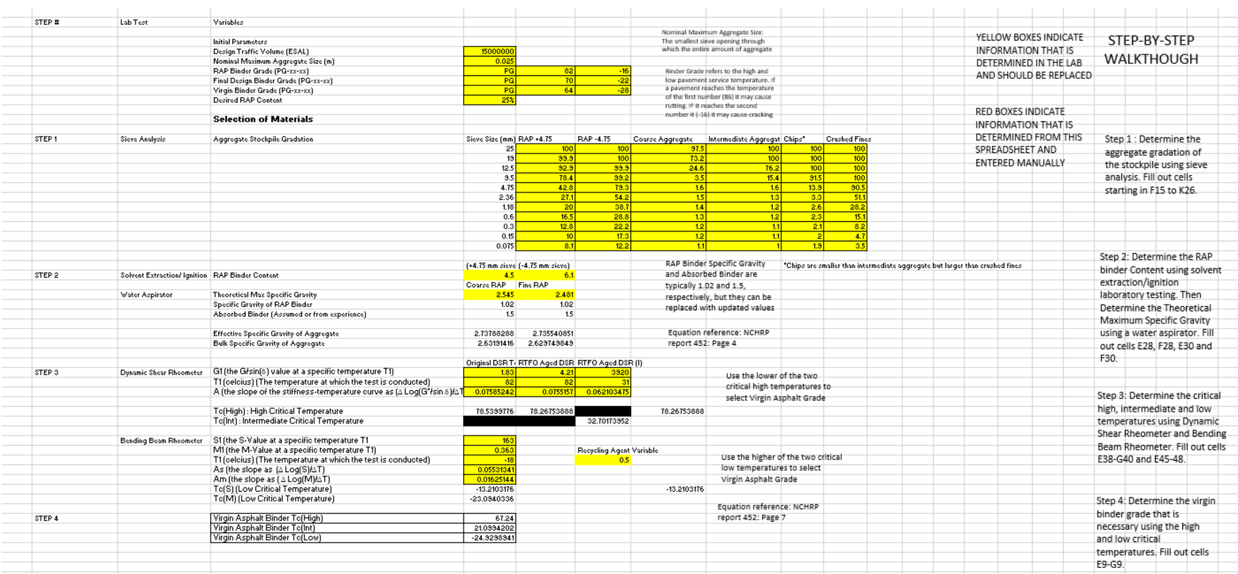

*Figure 8: Estimated Timeline*

# Chapter 4

# Results

## 4.1 Reclaimed Asphalt Pavement Mix Design Spreadsheet

The four mix design trials that were selected are with 0% RAP, 25% RAP, 35% RAP and 50% RAP. In order to calculate the necessary proportions of materials for each mix, a Reclaimed Asphalt Pavement Mix Design Spreadsheet was created using Microsoft Excel. Figure 9 shows page 1 of the excel spreadsheet, titled “Determine Properties”.



| STEP # | Lab Test | Variables | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Initial Parameters | | | | | | | |
| | | Design Traffic Volume (ESAL) | 15000000 | | | | | | |
| | | Nominal Maximum Aggregate Size (m) | 0.025 | | | | | | |
| | | RAP Binder Grade (PG-xx-xx) | PG | 82 | -16 | | | | |
| | | Final Design Binder Grade (PG-xx-xx) | PG | 70 | -22 | | | | |
| | | Virgin Binder Grade (PG-xx-xx) | PG | 64 | -28 | | | | |
| | | Desired RAP Content | 25% | | | | | | |
| | | **Selection of Materials** | | | | | | | |
| STEP 1 | Sieve Analysis | Aggregate Stockpile Gradation | Sieve Size (mm) | RAP +4.75 | RAP -4.75 | Coarse Aggregate | Intermediate Aggregat | Chips* | Crushed Fines |
| | | | 25 | 100 | 100 | 97.5 | 100 | 100 | 100 |
| | | | 19 | 99.9 | 100 | 73.2 | 100 | 100 | 100 |
| | | | 12.5 | 92.9 | 99.9 | 24.6 | 76.2 | 100 | 100 |
| | | | 9.5 | 78.4 | 99.2 | 3.5 | 15.4 | 91.5 | 100 |
| | | | 4.75 | 42.8 | 79.3 | 1.6 | 1.6 | 13.9 | 90.5 |
| | | | 2.36 | 27.1 | 54.2 | 1.5 | 1.3 | 3.3 | 51.1 |
| | | | 1.18 | 20 | 38.7 | 1.4 | 1.2 | 2.6 | 28.2 |
| | | | 0.6 | 16.5 | 28.8 | 1.3 | 1.2 | 2.3 | 15.1 |
| | | | 0.3 | 12.8 | 22.2 | 1.2 | 1.1 | 2.1 | 8.2 |
| | | | 0.15 | 10 | 17.3 | 1.2 | 1.1 | 2 | 4.7 |
| | | | 0.075 | 8.1 | 12.2 | 1.1 | 1 | 1.9 | 3.5 |
| | | | (+4.75 mm sieve | (-4.75 mm sieve) | | | | | |
| STEP 2 | Solvent Extraction/ Ignition | RAP Binder Content | 4.5 | 6.1 | | | | | |
| | | | Coarse RAP | Fine RAP | | | | | |
| | Water Aspirator | Theoretical Max Specific Gravity | 2.545 | 2.481 | | | | | |
| | | Specific Gravity of RAP Binder | 1.02 | 1.02 | | | | | |
| | | Absorbed Binder (Assumed or from experience) | 1.5 | 1.5 | | | | | |
| | | Effective Specific Gravity of Aggregate | 2.73788288 | 2.735540851 | | | | | |
| | | Bulk Specific Gravity of Aggregate | 2.63191416 | 2.629749849 | | | | | |
| | | | Original DSR T | RTFO Aged DSR | RTFO Aged DSR (I) | | | | |
| STEP 3 | Dynamic Shear Rheometer | G1 (the G/sin(δ) value at a specific temperature T1) | 1.83 | 4.21 | 3920 | | | | |
| | | T1 (celcius) (The temperature at which the test is conducted) | 82 | 82 | 31 | | | | |
| | | A (the slope of the stiffness-temperature curve as (Δ Log(G*/sin δ)/ΔT | 0.07585242 | 0.0755157 | 0.062103475 | | | | |
| | | Tc(High) : High Critical Temperature | 78.5399776 | 78.26753888 | | 78.26753888 | | | |
| | | Tc(Int) : Intermediate Critical Temperature | | | 32.70173952 | | | | |
| | Bending Beam Rheometer | S1 (the S-Value at a specific temperature T1 | 163 | | | | | | |
| | | M1 (the M-Value at a specific temperature T1) | 0.363 | | Recycling Agent Variable | | | | |
| | | T1 (celcius) (The temperature at which the test is conducted) | -18 | | 0.5 | | | | |
| | | As (the slope as (Δ Log(S)/ΔT) | 0.05531341 | | | | | | |
| | | Am (the slope as (Δ Log(M)/ΔT) | 0.01625144 | | | | | | |
| | | Tc(S) (Low Critical Temperature) | -13.2103176 | | | -13.2103176 | | | |
| | | Tc(M) (Low Critical Temperature) | -23.0940336 | | | | | | |
| STEP 4 | | Virgin Asphalt Binder Tc(High) | 67.24 | | | | | | |
| | | Virgin Asphalt Binder Tc(Int) | 21.0994202 | | | | | | |
| | | Virgin Asphalt Binder Tc(Low) | -24.9298941 | | | | | | |

Nominal Maximum Aggregate Size: The smallest sieve opening through which the entire amount of aggregate

Binder Grade refers to the high and low pavement service temperature. If a pavement reaches the temperature of the first number (86) it may cause rutting. IF it reaches the second number it (-16) it may cause cracking

YELLOW BOXES INDICATE INFORMATION THAT IS DETERMINED IN THE LAB AND SHOULD BE REPLACED

RED BOXES INDICATE INFORMATION THAT IS DETERMINED FROM THIS SPREADSHEET AND ENTERED MANUALLY

STEP-BY-STEP WALKTHOUGH

Step 1 : Determine the aggregate gradation of the stockpile using sieve analysis. Fill out cells starting in F15 to K26.

RAP Binder Specific Gravity and Absorbed Binder are typically 1.02 and 1.5, respectively, but they can be replaced with updated values

*Chips are smaller than intermediate aggregate but larger than crushed fines

Equation reference: NCHRP report 452: Page 4

Step 2: Determine the RAP binder Content using solvent extraction/ignition laboratory testing. Then Determine the Theoretical Maximum Specific Gravity using a water aspirator. Fill out cells E28, F28, E30 and F30.

Use the lower of the two critical high temperatures to select Virgin Asphalt Grade

Step 3: Determine the critical high, intermediate and low temperatures using Dynamic Shear Rheometer and Bending Beam Rheometer. Fill out cells E38-G40 and E45-48.

Use the higher of the two critical low temperatures to select Virgin Asphalt Grade

Equation reference: NCHRP report 452: Page 7

Step 4: Determine the virgin binder grade that is necessary using the high and low critical temperatures. Fill out cells E9-G9.

*Figure 9: Determine Properties*

It is necessary to perform multiple laboratory tests to determine the physical properties of the RAP stockpile. Each test is listed on the left side next to each labeled step. The values that are collected from these tests should be entered into the yellow boxes. By the end of page 1, the user should know what binder grade is necessary for the virgin asphalt that will be mixed in with the RAP asphalt. Figure 10 shows page 2 of the excel spreadsheet, titled “Creating Trial Blends”.

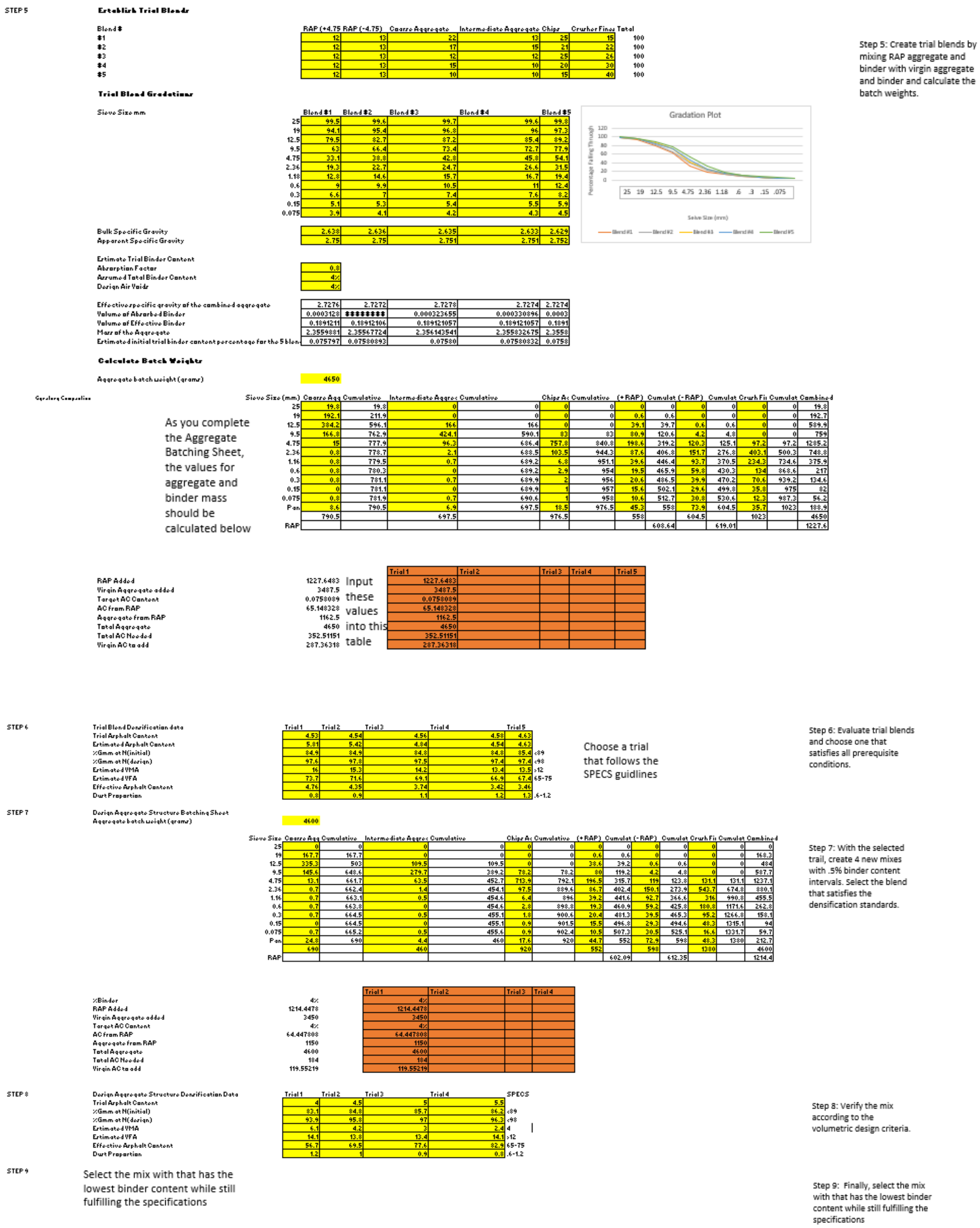



*Figure 10: Creating Trial Blends*

After the physical properties of the RAP and the virgin asphalt are determined, trial blends can be created to determine the optimal binder content for the final mix design. There are equations embedded in the excel spreadsheet that calculate the amount of RAP, aggregate and binder that are needed using data from batching sheets. The resulting densification data is used to eliminate any trials that do not pass the mix design specifications. At the end of the page, the user will be able to select a mix design that fits their needs, and it is suggested to choose the mix design with the lowest binder content while still fulfilling the design specifications, since this will be the least expensive option.

The four mix designs that were evaluated for their economic and environmental impacts were as follows: 0% RAP, 25% RAP, 35% RAP, and 50% RAP. Using the spreadsheet to calculate the batch weights, each mix design amounted to 6366.9 grams of total asphalt with a 4.5% binder content. The calculated proportions for the 0% RAP mix are 6080.4 grams of virgin aggregate added to 286.5 grams of bitumen (a type of binder). The 25% RAP mix was a combined 4582.8 grams of virgin aggregate, 202.2 grams of bitumen and 1581.9 grams of RAP. The 35% RAP mix was composed of 4065 grams of virgin aggregate, 173.7 grams of bitumen and 2128.2 grams of RAP. Finally, the 50% RAP mix was created with a combined 3065.55 grams of virgin aggregate, 117.9 grams of bitumen, and 3183.45 grams of RAP. The next chapter elaborates further on how to use the spreadsheet through a step-by-step walkthrough to calculate unique mix designs.

## 4.2 Step By Step Walkthrough for Reclaimed Asphalt Pavement Mix Design Excel Spreadsheet

This excel spreadsheet is intended to calculate an accurate and structurally sound hot mix asphalt mix design that incorporates RAP. There are a few laboratory tests that need to be performed in order to determine the properties of the RAP. Values from these tests will be entered into the spreadsheet, and then the equations are utilized to calculate the different parameters.

Note that the yellow boxes indicate areas that should be filled in with information determined through laboratory testing. They have been filled in as an example, but they should be replaced by the laboratory results. Red boxes indicate areas that should be filled in with information from calculations done by the spreadsheet (using copy and paste).

Step 1) Determine the aggregate gradation of the stockpile using sieve analysis (AASHTO T30). Fill out the cells starting in F15 to K26 from the spreadsheet (Table 1).

*Table 1. Aggregate Stockpile Gradation*

| Sieve Size (mm) | RAP +4.75 | RAP -4.75 | Coarse Aggregate | Intermediate Aggregate | Chips | Crushed Fines |
|---|---|---|---|---|---|---|
| 25 | 100 | 100 | 97.5 | 100 | 100 | 100 |
| 19 | 99.9 | 100 | 73.2 | 100 | 100 | 100 |
| 12.5 | 92.9 | 99.9 | 24.6 | 76.2 | 100 | 100 |
| 9.5 | 78.4 | 99.2 | 3.5 | 15.4 | 91.5 | 100 |
| 4.75 | 42.8 | 79.3 | 1.6 | 1.6 | 13.9 | 90.5 |
| 2.36 | 27.1 | 54.2 | 1.5 | 1.3 | 3.3 | 51.1 |
| 1.18 | 20 | 38.7 | 1.4 | 1.2 | 2.6 | 28.2 |
| 0.6 | 16.5 | 28.8 | 1.3 | 1.2 | 2.3 | 15.1 |
| 0.3 | 12.8 | 22.2 | 1.2 | 1.1 | 2.1 | 8.2 |
| 0.15 | 10 | 17.3 | 1.2 | 1.1 | 2 | 4.7 |
| 0.075 | 8.1 | 12.2 | 1.1 | 1 | 1.9 | 3.5 |

Step 2) Determine the RAP binder content using solvent extraction/ignition laboratory testing (AASHTO T 319). Then determine the theoretical maximum specific gravity using a water aspirator. Fill out cells E28, F28, E30 and F30 from the spreadsheet (Table 2).

*Table 2. RAP Binder Content and Theoretical Specific Gravity*

| | (+4.75 mm sieve) | (-4.75 mm sieve) |
|---|---|---|
| RAP Binder Content | 4.5 | 6.1 |
| | Coarse RAP | Fine RAP |
| Theoretical Max Specific Gravity | 2.545 | 2.481 |
| Specific Gravity of RAP Binder | 1.02 | 1.02 |
| Absorbed Binder (Assumed or from experience) | 1.5 | 1.5 |

Step 3) Determine the critical high, intermediate and low temperatures of the RAP binder using Dynamic Shear Rheometer and Bending Beam Rheometer (AASHTO T 315). Fill out cells E38-G40 and E45-48 from the spreadsheet. If you wish to add binder rejuvenators or recycling agents to soften the RAP binder, enter the modification variable into cell G47 (Table 3).

*Table 3. RAP Critical Temperatures*

| | | Original DSR Test | RTFO Aged DSR (H) | RTFO Aged DSR (I) |
|---|---|---|---|---|
| Dynamic Shear Rheometer | G1 (the G/sin(δ) value at a specific temperature T1) | 1.83 | 4.21 | 3920 |
| | T1 (celcius) (The temperature at which the test is conducted) | 82 | 82 | 31 |
| | A (the slope of the stiffness-temperature curve as (Δ Log(G*/sin δ)/ΔT) | 0.075852424 | 0.0755157 | 0.062103475 |
| | | | | |
| | Tc(High) : High Critical Temperature | 78.53997757 | 78.26753888 | |
| | Tc(Int) : Intermediate Critical Temperature | | | 32.70173952 |
| | | | | |
| Bending Beam Rheometer | S1 (the S-Value at a specific temperature T1 | 163 | | |
| | M1 (the M-Value at a specific temperature T1) | 0.363 | | Recycling Agent Variable |
| | T1 (celcius) (The temperature at which the test is conducted) | -18 | | 0.5 |
| | As (the slope as (Δ Log(S)/ΔT) | 0.055313407 | | |
| | Am (the slope as ( Δ Log(M)/ΔT) | 0.016251438 | | |
| | Tc(S) (Low Critical Temperature) | -13.2103176 | | |
| | Tc(M) (Low Critical Temperature) | -23.09403359 | | |

Step 4) Determine the virgin binder grade that is necessary using the high and low critical temperatures. Fill out cells E9-G9 from the spreadsheet (Table 4).

*Table 4. Virgin Binder Critical Temperatures*

| | |
|---|---|
| Virgin Asphalt Binder Tc(High) | 67.24 |
| Virgin Asphalt Binder Tc(Int) | 21.09942016 |
| Virgin Asphalt Binder Tc(Low) | -24.92989413 |

Step 5) Move to sheet two. Create trial blends by mixing RAP aggregate and binder with virgin aggregate and binder and calculate the batch weights. Fill out cells E5-J9, E14-I24, E26-I27 (Table 5) and the Aggregate Batching Sheet from E45-Q58 (Table 6).

*Table 5. Trial Blend Gradations*

| Sieve Size mm | Blend #1 | Blend #2 | Blend #3 | Blend #4 | Blend #5 |
|---|---|---|---|---|---|
| 25 | 99.5 | 99.6 | 99.7 | 99.6 | 99.8 |
| 19 | 94.1 | 95.4 | 96.8 | 96 | 97.3 |
| 12.5 | 79.5 | 82.7 | 87.2 | 85.4 | 89.2 |
| 9.5 | 63 | 66.4 | 73.4 | 72.7 | 77.9 |
| 4.75 | 33.1 | 38.8 | 42.8 | 45.8 | 54.1 |
| 2.36 | 19.3 | 22.7 | 24.7 | 26.6 | 31.5 |
| 1.18 | 12.8 | 14.6 | 15.7 | 16.7 | 19.4 |
| 0.6 | 9 | 9.9 | 10.5 | 11 | 12.4 |
| 0.3 | 6.6 | 7 | 7.4 | 7.6 | 8.2 |
| 0.15 | 5.1 | 5.3 | 5.4 | 5.5 | 5.9 |
| 0.075 | 3.9 | 4.1 | 4.2 | 4.3 | 4.5 |
| | | | | | |
| Bulk Specific Gravity | 2.638 | 2.636 | 2.635 | 2.633 | 2.629 |
| Apparent Specific Gravity | 2.75 | 2.75 | 2.751 | 2.751 | 2.752 |
| | | | | | |
| Estimate Trial Binder Content | | | | | |
| Absorption Factor | 0.8 | | | | |
| Assumed Total Binder Content | 4% | | | | |
| Design Air Voids | 4% | | | | |

*Table 6. Aggregate Batching Sheet*

| Sieve Size (mm) | Coarse Aggre | Cumulative | Intermediate Aggregate | Cumulative | Chips Agg | Cumulative | (+ RAP) | Cumulati | (- RAP) | Cumulati | Crush Fin | Cumulati | Combined |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 19.8 | 19.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19.8 |
| 19 | 192.1 | 211.9 | 0 | 0 | 0 | 0 | 0.6 | 0.6 | 0 | 0 | 0 | 0 | 192.7 |
| 12.5 | 384.2 | 596.1 | 166 | 166 | 0 | 0 | 39.1 | 39.7 | 0.6 | 0.6 | 0 | 0 | 589.9 |
| 9.5 | 166.8 | 762.9 | 424.1 | 590.1 | 83 | 83 | 80.9 | 120.6 | 4.2 | 4.8 | 0 | 0 | 759 |
| 4.75 | 15 | 777.9 | 96.3 | 686.4 | 757.8 | 840.8 | 198.6 | 319.2 | 120.3 | 125.1 | 97.2 | 97.2 | 1285.2 |
| 2.36 | 0.8 | 778.7 | 2.1 | 688.5 | 103.5 | 944.3 | 87.6 | 406.8 | 151.7 | 276.8 | 403.1 | 500.3 | 748.8 |
| 1.16 | 0.8 | 779.5 | 0.7 | 689.2 | 6.8 | 951.1 | 39.6 | 446.4 | 93.7 | 370.5 | 234.3 | 734.6 | 375.9 |
| 0.6 | 0.8 | 780.3 | 0 | 689.2 | 2.9 | 954 | 19.5 | 465.9 | 59.8 | 430.3 | 134 | 868.6 | 217 |
| 0.3 | 0.8 | 781.1 | 0.7 | 689.9 | 2 | 956 | 20.6 | 486.5 | 39.9 | 470.2 | 70.6 | 939.2 | 134.6 |
| 0.15 | 0 | 781.1 | 0 | 689.9 | 1 | 957 | 15.6 | 502.1 | 29.6 | 499.8 | 35.8 | 975 | 82 |
| 0.075 | 0.8 | 781.9 | 0.7 | 690.6 | 1 | 958 | 10.6 | 512.7 | 30.8 | 530.6 | 12.3 | 987.3 | 56.2 |
| Pan | 8.6 | 790.5 | 6.9 | 697.5 | 18.5 | 976.5 | 45.3 | 558 | 73.9 | 604.5 | 35.7 | 1023 | 188.9 |
| | 790.5 | | 697.5 | | 976.5 | | 558 | | 604.5 | | 1023 | | 4650 |
| RAP | | | | | | | | 608.639 | | 619.01 | | | 1227.65 |

Step 6) After completing step 5 and entering all the associated information, take the values from E64-71 (Table 7) and input them into the red table from cells G64-K71 (Table 8). Repeat step 5 and 6 for each trial blend.

*Table 7. Individual Trial Batching Weights*

| | |
|---|---|
| RAP Added | 1227.6483 |
| Virgin Aggregate added | 3487.5 |
| Target AC Content | 0.0758089 |
| AC from RAP | 65.148328 |
| Aggregate from RAP | 1162.5 |
| Total Aggregate | 4650 |
| Total AC Needed | 352.51151 |
| Virgin AC to add | 287.36318 |

Enter the values from Table 7 into Table 8 and repeat for all five trials.

*Table 8. Batching Weights of All Trials*

| Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|---|---|---|---|---|
| 1227.6483 | | | | |
| 3487.5 | | | | |
| 0.0758089 | | | | |
| 65.148328 | | | | |
| 1162.5 | | | | |
| 4650 | | | | |
| 352.51151 | | | | |
| 287.36318 | | | | |

Fill out cells E77-I84 with the proper densification data (Table 9). Evaluate the densification data for each trial blend and choose one that satisfies all prerequisite conditions.

*Table 9. Densification Data Table*

| Trial Blend Densification data | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 | |
|---|---|---|---|---|---|---|
| Trial Asphalt Content | 4.53 | 4.54 | 4.56 | 4.58 | 4.63 | |
| Estimated Asphalt Content | 5.81 | 5.42 | 4.84 | 4.54 | 4.63 | |
| %Gmm at N(initial) | 84.9 | 84.9 | 84.8 | 84.8 | 85.4 | <89 |
| %Gmm at N(design) | 97.6 | 97.8 | 97.5 | 97.4 | 97.4 | <98 |
| Estimated VMA | 16 | 15.3 | 14.2 | 13.4 | 13.5 | >12 |
| Estimated VFA | 73.7 | 71.6 | 69.1 | 66.9 | 67.4 | 65-75 |
| Effective Asphalt Content | 4.76 | 4.35 | 3.74 | 3.42 | 3.46 | |
| Dust Proportion | 0.8 | 0.9 | 1.1 | 1.2 | 1.3 | .6-1.2 |

Step 7) With the selected trail, create 4 new mixes with .5% binder content intervals. Fill out cells E90-Q103 (Table 10).

*Table 10. Aggregate Batching Sheet*

| Sieve Size | Coarse Aggre | Cumulative | Intermediate Aggregate | Cumulative | Chips Agg | Cumulative | (+ RAP) | Cumulati | (- RAP) | Cumulati | Crush Fin | Cumulati | Combined |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 167.7 | 167.7 | 0 | 0 | 0 | 0 | 0.6 | 0.6 | 0 | 0 | 0 | 0 | 168.3 |
| 12.5 | 335.3 | 503 | 109.5 | 109.5 | 0 | 0 | 38.6 | 39.2 | 0.6 | 0.6 | 0 | 0 | 484 |
| 9.5 | 145.6 | 648.6 | 279.7 | 389.2 | 78.2 | 78.2 | 80 | 119.2 | 4.2 | 4.8 | 0 | 0 | 587.7 |
| 4.75 | 13.1 | 661.7 | 63.5 | 452.7 | 713.9 | 792.1 | 196.5 | 315.7 | 119 | 123.8 | 131.1 | 131.1 | 1237.1 |
| 2.36 | 0.7 | 662.4 | 1.4 | 454.1 | 97.5 | 889.6 | 86.7 | 402.4 | 150.1 | 273.9 | 543.7 | 674.8 | 880.1 |
| 1.16 | 0.7 | 663.1 | 0.5 | 454.6 | 6.4 | 896 | 39.2 | 441.6 | 92.7 | 366.6 | 316 | 990.8 | 455.5 |
| 0.6 | 0.7 | 663.8 | 0 | 454.6 | 2.8 | 898.8 | 19.3 | 460.9 | 59.2 | 425.8 | 180.8 | 1171.6 | 262.8 |
| 0.3 | 0.7 | 664.5 | 0.5 | 455.1 | 1.8 | 900.6 | 20.4 | 481.3 | 39.5 | 465.3 | 95.2 | 1266.8 | 158.1 |
| 0.15 | 0 | 664.5 | 0 | 455.1 | 0.9 | 901.5 | 15.5 | 496.8 | 29.3 | 494.6 | 48.3 | 1315.1 | 94 |
| 0.075 | 0.7 | 665.2 | 0.5 | 455.6 | 0.9 | 902.4 | 10.5 | 507.3 | 30.5 | 525.1 | 16.6 | 1331.7 | 59.7 |
| Pan | 24.8 | 690 | 4.4 | 460 | 17.6 | 920 | 44.7 | 552 | 72.9 | 598 | 48.3 | 1380 | 212.7 |
| | 690 | | 460 | | 920 | | 552 | | 598 | | 1380 | | 4600 |
| RAP | | | | | | | | 602.094 | | 612.354 | | | 1214.45 |

Fill out the red table from cells G108-J116 (Table 11) exactly the same way as step 6.

*Table 11. Batching Weights*

| | | | Trial 1 | Trial 2 | Trial 3 | Trial 4 |
|---|---|---|---|---|---|---|
| %Binder | 4% | | 4% | | | |
| RAP Added | 1214.4478 | | 1214.4478 | | | |
| Virgin Aggregate added | 3450 | | 3450 | | | |
| Target AC Content | 4% | | 4% | | | |
| AC from RAP | 64.447808 | | 64.447808 | | | |
| Aggregate from RAP | 1150 | | 1150 | | | |
| Total Aggregate | 4600 | | 4600 | | | |
| Total AC Needed | 184 | | 184 | | | |
| Virgin AC to add | 119.55219 | | 119.55219 | | | |

Fill out cells E120-H126 with the densification data. Select the blend that satisfies the densification standards (Table 12).

*Table 12. Densification Data Table*

| Design Aggregate Structure Densification Data | Trial 1 | Trial 2 | Trial 3 | Trial 4 | SPECS |
|---|---|---|---|---|---|
| Trial Asphalt Content | 4 | 4.5 | 5 | 5.5 | |
| %Gmm at N(initial) | 83.1 | 84.8 | 85.7 | 86.2 | <89 |
| %Gmm at N(design) | 93.9 | 95.8 | 97 | 96.3 | <98 |
| Estimated VMA | 6.1 | 4.2 | 3 | 2.4 | 4 |
| Estimated VFA | 14.1 | 13.8 | 13.4 | 14.1 | >12 |
| Effective Asphalt Content | 56.7 | 69.5 | 77.6 | 82.9 | 65-75 |
| Dust Proportion | 1.2 | 1 | 0.9 | 0.8 | .6-1.2 |

Step 8) Verify the mix according to the volumetric design criteria. The tensile strength ratio should be greater than 80 percent, and there should be a minimum of 2% air voids after compacting to $N_{max}$.

Step 9) Select the mix with the lowest binder content that still fulfills the specifications.

# Chapter 5

# Evaluation of Sustainability: Economic and Environmental Impacts

While the fiscal bottom line has always been a top priority in the construction of roads and highways, recently environmental sustainability has become more of a focus, especially considering the mounting evidence of the negative effects of climate change and pollution. To calculate the economic and environmental impacts of road building, the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects, (PaLATE)[34], developed by Professor Arpad Horvath at the University of California, Berkeley, was utilized. On the fiscal side, this spreadsheet accounts for the cost of producing the materials needed for asphalt, the transportation of the materials, and the equipment needed to complete the construction of the project. On the environmental side, it calculates the energy and water usage, many types of toxic emissions, a few types of groundwater pollution, waste generation and toxicity potential, all by factoring in the work done by the manufacturing plant, the work done by the trucks that transport the material and the work done by construction workers building the roads. All three of these activities produce emissions while consuming nonrenewable resources.

The first step in using PaLATE is to design the project. This is done by entering the length, width and height of the road layers in the table shown in below (Table 13).

---

[34] Horvath, Arpad. "PaLATE- Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects." PaLATE - Pavement Life-cycle Tool, June 2007. http://faculty.ce.berkeley.edu/horvath/palate.html.

*Table 13: Layer Specifications*

| Layer Specifications | | | | |
|---|---|---|---|---|
| Layer | Width [ft] | Length [miles] | Depth [inches] | Volume [yd^3] |
| Wearing Course 1 | | | | 0 |
| Wearing Course 2 | | | | 0 |
| Wearing Course 3 | | | | 0 |
| Subbase 1 | | | | 0 |
| Subbase 2 | | | | 0 |
| Subbase 3 | | | | 0 |
| Subbase 4 | | | | 0 |
| **Total** | | | 0 | 0 |

| Embankment and Shoulder Volume [yd^3]: | |
|---|---|

Next, for each material used to construct the pavement, the amount of material in cubic yards for each corresponding layer should be entered. Also, the one-way travel distance should be recorded to factor in transportation costs and emissions. This information should be entered in the table shown below (Table 14).

*Table 14: Initial Construction*

| | | Material | Density [tons/(yd^3)] | New Asphalt Pavement | New Concrete Pavement | New Subbase & Embankment Construction | Transportation | |
|---|---|---|---|---|---|---|---|---|
| | | | | Volume [yd^3] | Volume [yd^3] | Volume [yd^3] | One-way transport distance [mi] | Transportation mode |
| Wearing Course 1 | Materials | Virgin Aggregate | 2.23 | | 0 | | | dump truck |
| | | Bitumen | 0.84 | | | | | tanker truck |
| | | Cement | 1.27 | | 0 | | 0 | cement truck |
| | | Concrete Additives | 0.84 | | 0 | | 0 | tanker truck |
| | | RAP transportation | 1.85 | 0 | 0 | | 0 | dump truck |
| | | RCM transportation | 1.88 | 0 | 0 | | 0 | dump truck |
| | | Coal Fly Ash | 2.2 | 0 | 0 | | 0 | cement truck |
| | | Coal Bottom Ash | 2 | 0 | 0 | | 0 | dump truck |
| | | Blast Furnace Slag | 1.72 | 0 | 0 | | 0 | dump truck |
| | | Foundry Sand | 0.000 | 0 | 0 | | 0 | dump truck |
| | | Recycled Tires/ Crumb Rubber | 1.92 | 0 | 0 | | 0 | dump truck |
| | | Glass Cullet | 1.93 | 0 | 0 | | 0 | dump truck |
| | | Water | 0.84 | | 0 | | | |
| | | Steel Reinforcing Bars | 0.24 | | 0 | | 0 | dump truck |
| | | **Total: Asphalt mix to site** | 1.23 | **0** | | | 0 | dump truck |
| | | **Total: Ready-mix concrete mix to site** | 2.03 | | **0** | | 0 | mixing truck |
| | Waste material to landfill | RAP from site to landfill | 1.85 | 0 | | | 0 | dump truck |
| | | RCM from site to landfill | 1.88 | | 0 | | 0 | dump truck |
| | | Virgin Aggregate | 2.22889 | 0.0 | 0.0 | | 0 | dump truck |
| | | Bitumen | 0.84 | 0 | | | 0 | tanker truck |
| | | Cement | 1.27 | | 0 | | 0 | cement truck |

Finally, move to the page labeled cost and fill out the orange table (Table 15) by entering the total initial construction volume. The user may tweak the excepted cost of the raw materials to reflect the real cost; the ones provided are just a placeholder.

*Table 15: Costs*

| | Virgin Aggregate | | Bitumen | | Cement | | Concrete Additives | | Asphalt Emulsion | | RAP from Asphalt plant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Expected Cost: 9.33 | | Expected Cost: 0 | | Expected Cost: $100.00 /ton | | Expected Cost: 0 | | Expected Cost: 0 | | Expected Cost: $5.23 /ton | |
| | Total Initial Construction Volume [yd^3]: 0 | | Total Initial Construction Volume [yd^3]: 0 | | Total Initial Construction Volume [yd^3]: 0 | | Total Initial Construction Volume [yd^3]: 0 | | Total Initial Construction Volume [yd^3]: | | Total Initial Construction Volume [yd^3]: 0 | |
| | Total Maintenance Volume [yd^3]: 0 | | Total Maintenance Volume [yd^3]: 0 | | Total Maintenance Volume [yd^3]: 0 | | Total Maintenance Volume [yd^3]: 0 | | Total Maintenance Volume [yd^3]: 0 | | Total Maintenance Volume [yd^3]: 0 | |
| Year | Volume [yd^3] | Actual Cost [$] | Volume [yd^3] | Actual Cost [$] | Volume [yd^3] | Actual Cost [$] | Volume [yd^3] | Actual Cost [$] | Volume [yd^3] | Actual Cost [$] | Volume [yd^3] | Actual Cost [$] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

The results are shown in tables and charts on pages “$ Results” and “Env Results”. In this MQP, the results from the 0% RAP, 25% RAP, 35% RAP and 50% RAP mix designs were evaluated and presented in the following sections.

## 5.1 Economic and Environmental Impact Results

The four mix designs were used to complete two separate projects: one new pavement construction project and one replacement of an old pavement construction project. In the first case, the road consists of two lanes, with a lane width of 12 feet, as well as two 6-ft wide, with a total width of 36 feet. The road length is 10 miles, and the depth is 1.5 inches, creating a total volume of hot mix asphalt of 8,800 cubic yards. The distance from the asphalt manufacturing plant is 50 miles from the project site. The second project replaces a road of the same dimensions (36ft x 10mi x 1.5) and is the same distance from the manufacturing plant. In addition, the excavated old pavement that is not used in the new mix must be dumped in a landfill 20 miles away.

Tables 16 and 17 show the economic and environmental impact results from constructing new pavement that were calculated using PaLATE. On the economic side, this is represented by total cost in dollars. The environmental side has many different categories, including energy usage, water usage, carbon dioxide emissions, nitrogen oxide emissions, particulate matter emissions, sulfur dioxide emissions, carbon monoxide emissions, mercury pollution and lead pollution. These values can be found in Table 16. Table 17 covers three more environmental indicators: RCRA Hazardous Waste, Human Toxicity Potential (Non-cancer) and Human Toxicity Potential (Cancer). The non-cancerous toxicity potential is measured by the amount of aldehyde released, while the cancerous toxicity potential is measured by the amount of benzo[a]pyrene. Figure 11 to Figure 23 are bar charts that represent Tables 16 and 17 in a visual manner. Table 18 shows the comparison of how much cost and emissions are reduced percentagewise, while Figure 24 represents this data in a bar chart format.

*Table 16: Cost and Emissions per Mix Design from Constructing New Pavement*

| %RAP | Cost | Energy (MJ) | Water (kg) | CO2 (Mg) | NOx (kg) | PM10 (kg) | SO2 (kg) | CO (kg) | Hg (g) | Pb (g) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0% RAP | $195,907.29 | 13,613,958 | 3,446 | 727 | 11,095 | 4,573 | 184,302 | 2,411 | 13 | 661 |
| 25% RAP | $164,116.85 | 10,974,309 | 2,529 | 576 | 10,313 | 3,728 | 183,695 | 1,885 | 10 | 486 |
| 35% RAP | $153,337.63 | 10,076,416 | 2,218 | 524 | 10,047 | 3,436 | 183,490 | 1,707 | 8 | 427 |
| 50% RAP | $132,272.45 | 8,325,282 | 1,610 | 424 | 9,528 | 2,872 | 183,088 | 1,359 | 6 | 311 |

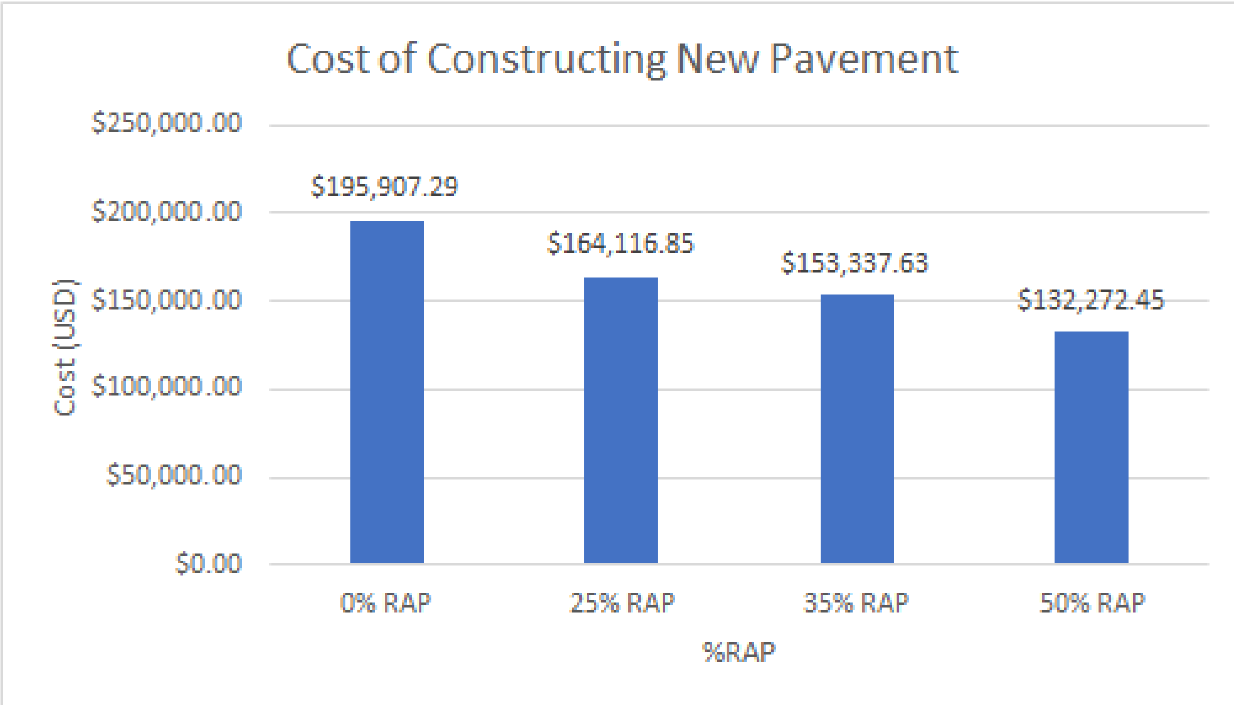



*Figure 11: Cost of Constructing New Pavement*

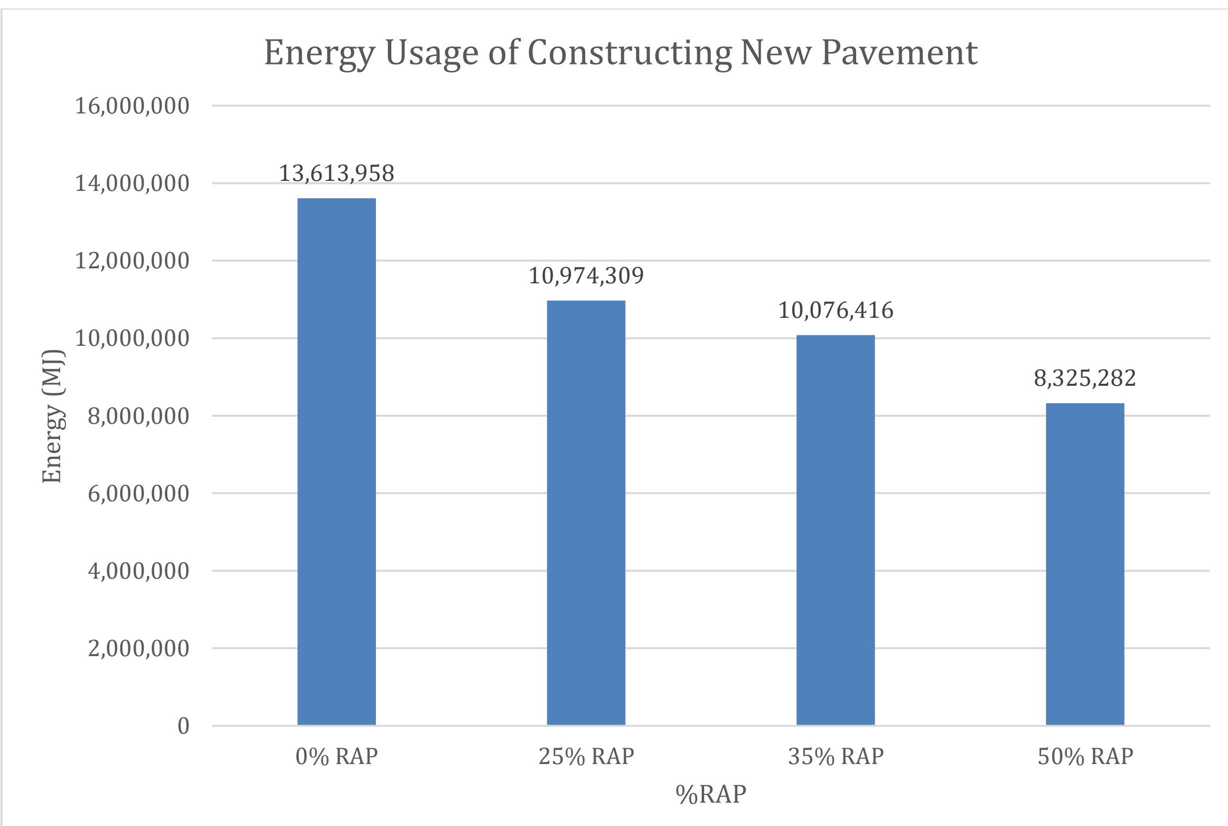



*Figure 12: Energy Usage of Constructing New Pavement*

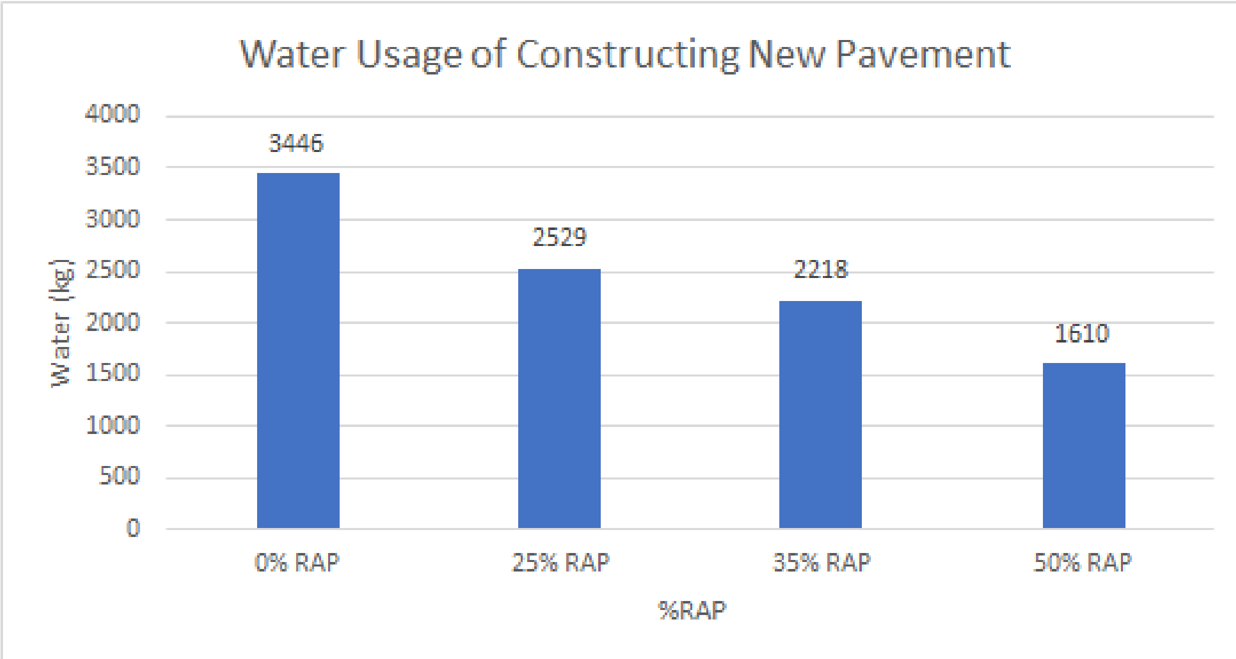



*Figure 13: Water Usage of Constructing New Pavement*

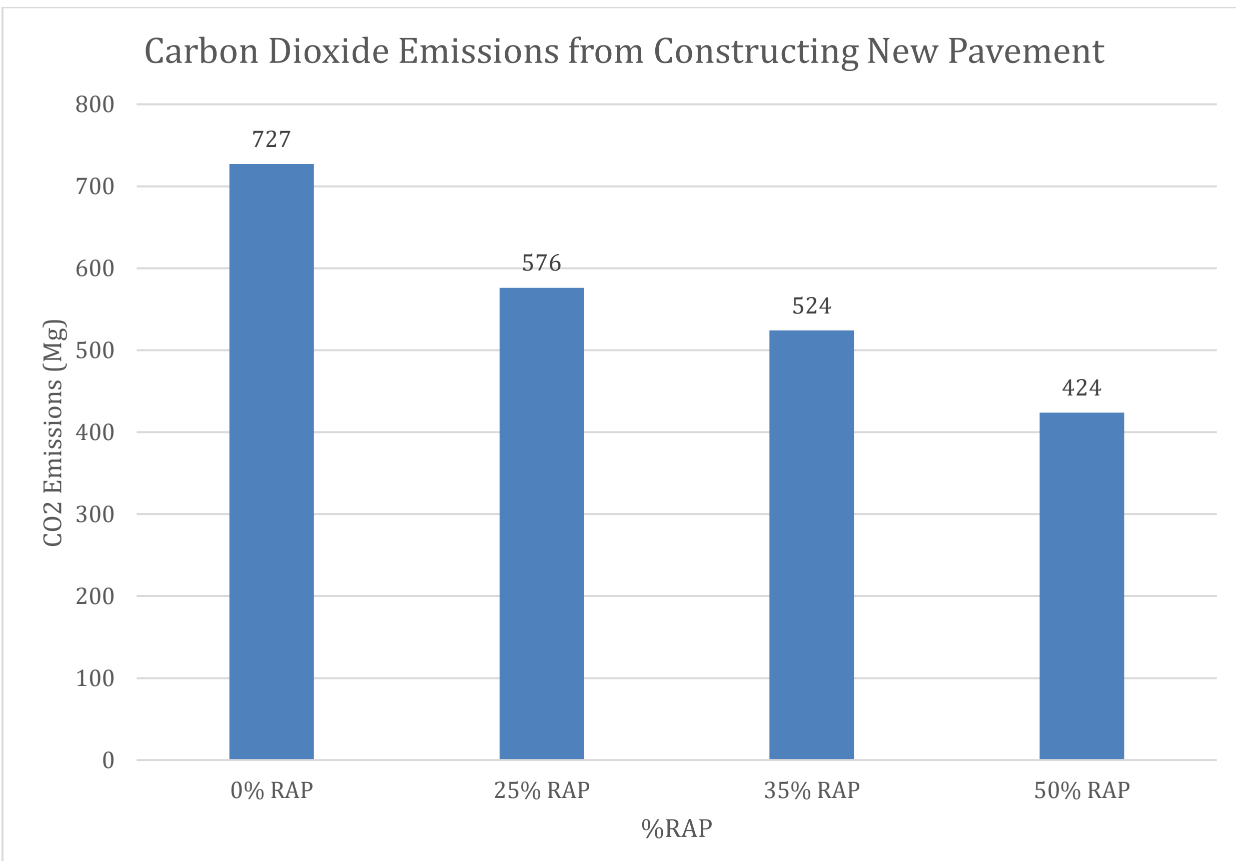



*Figure 14: Carbon Dioxide Emissions from Constructing New Pavement*

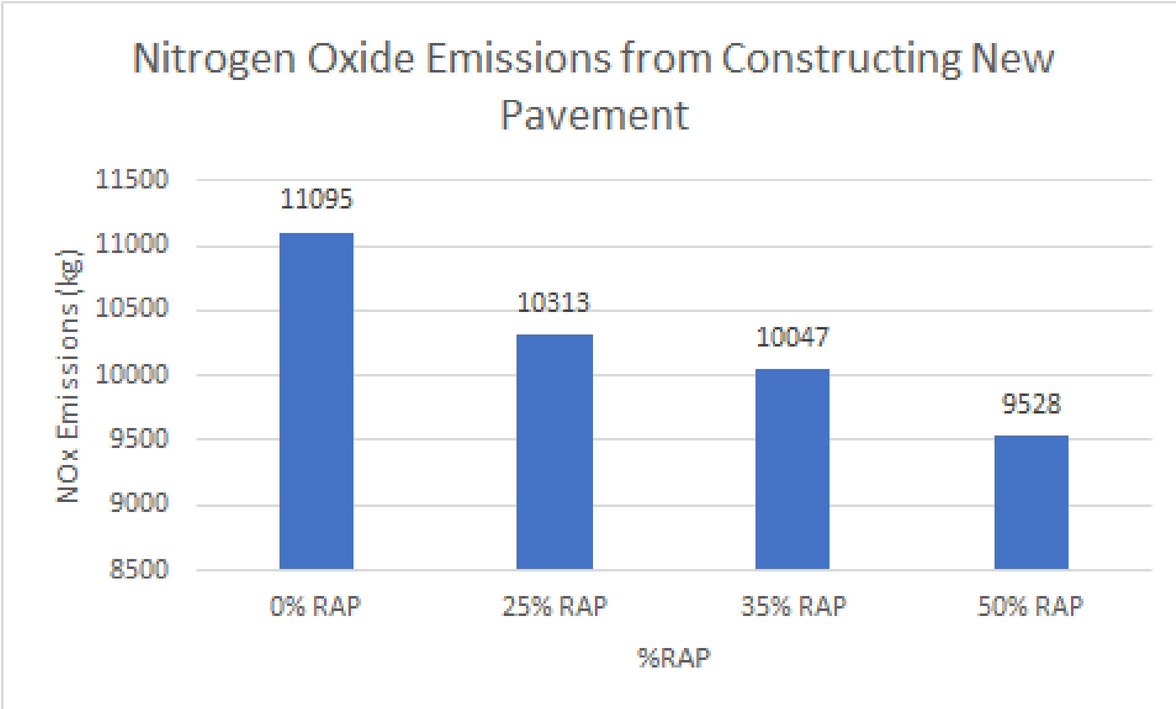



*Figure 15: Nitrogen Oxide Emissions from Constructing New Pavement*

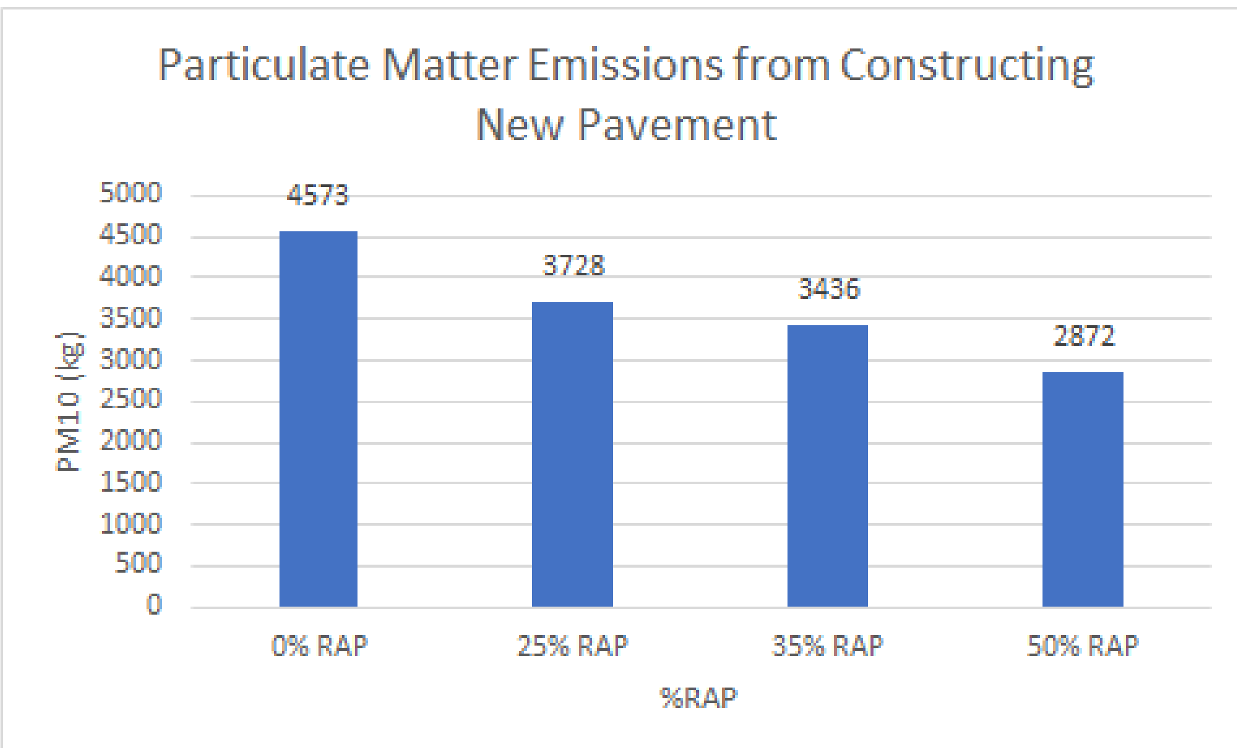



*Figure 16: Particulate Matter Emissions from Constructing New Pavement*

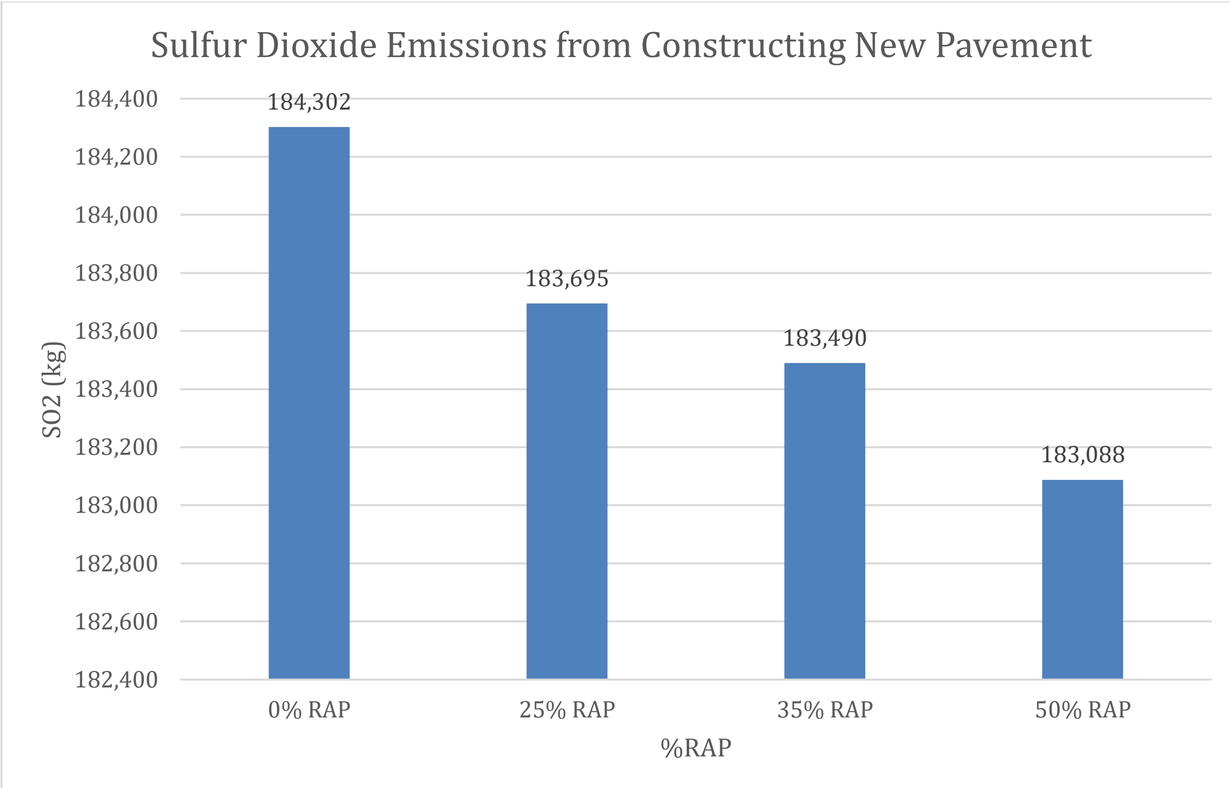



*Figure 17: Sulfur Dioxide Emissions from Constructing New Pavement*

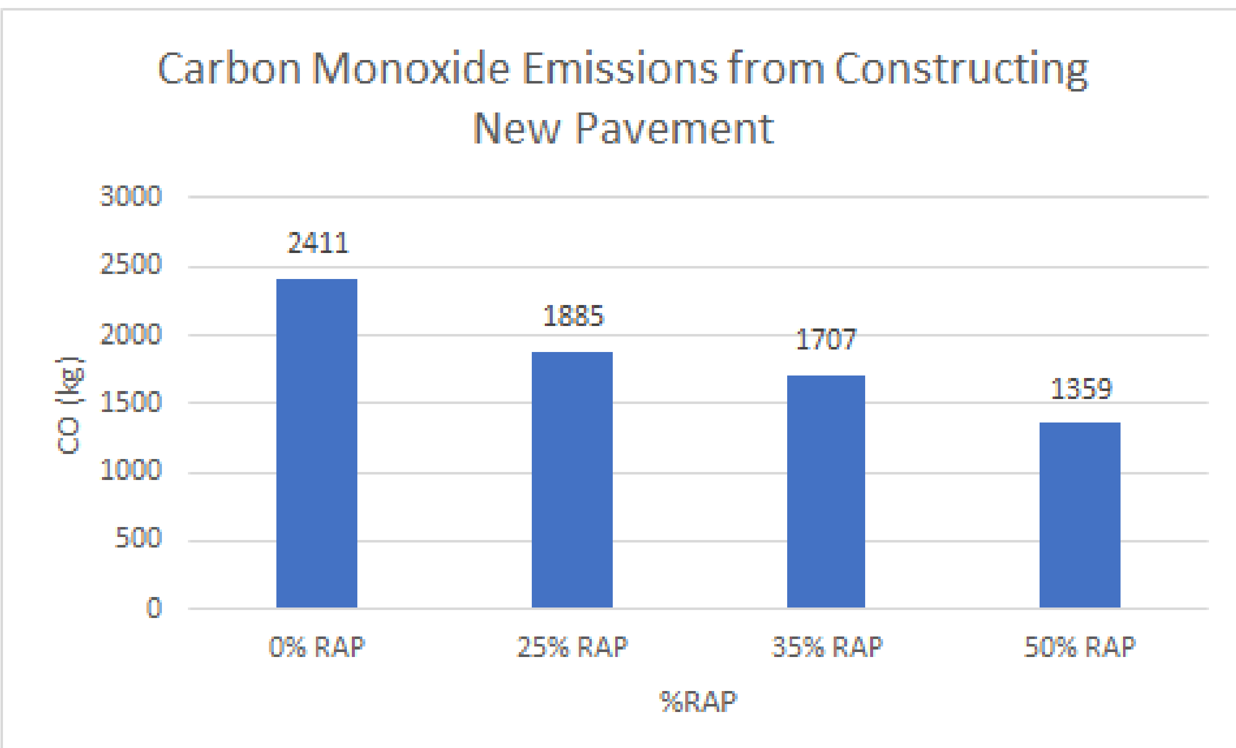



*Figure 18: Carbon Monoxide Emissions from Constructing New Pavement*

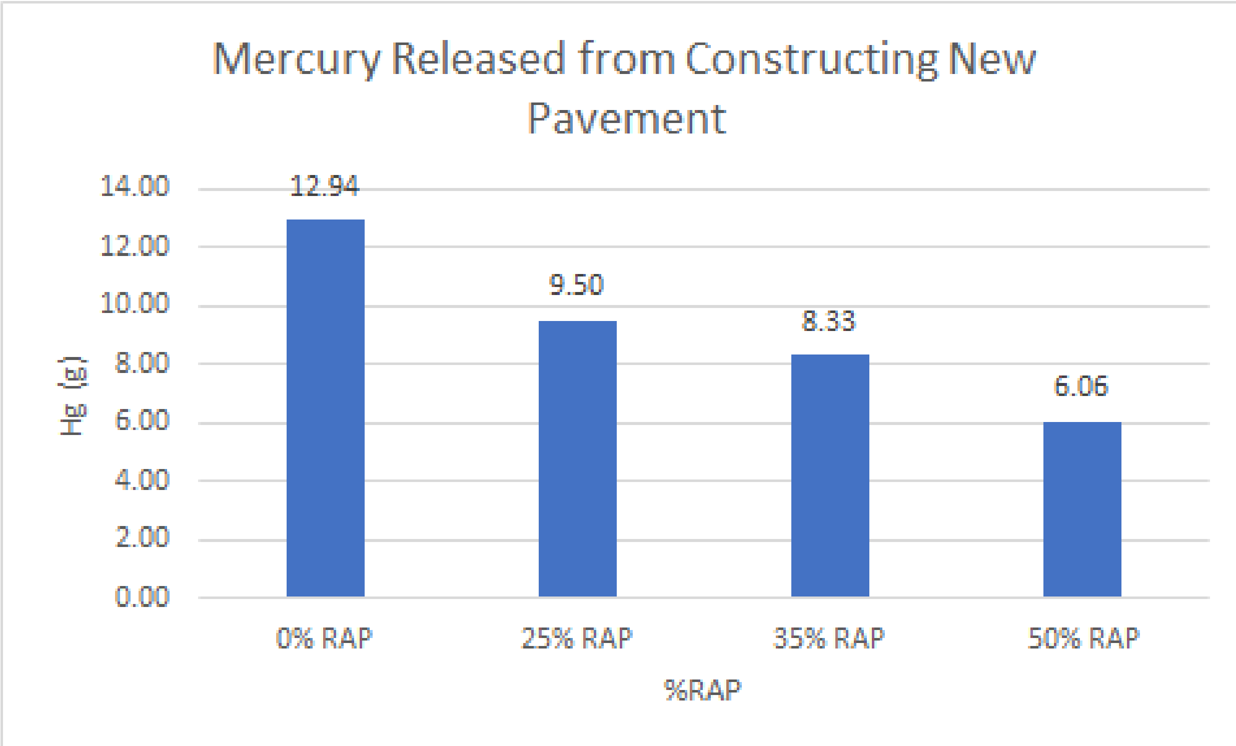



*Figure 19: Mercury Released from Constructing New Pavement*

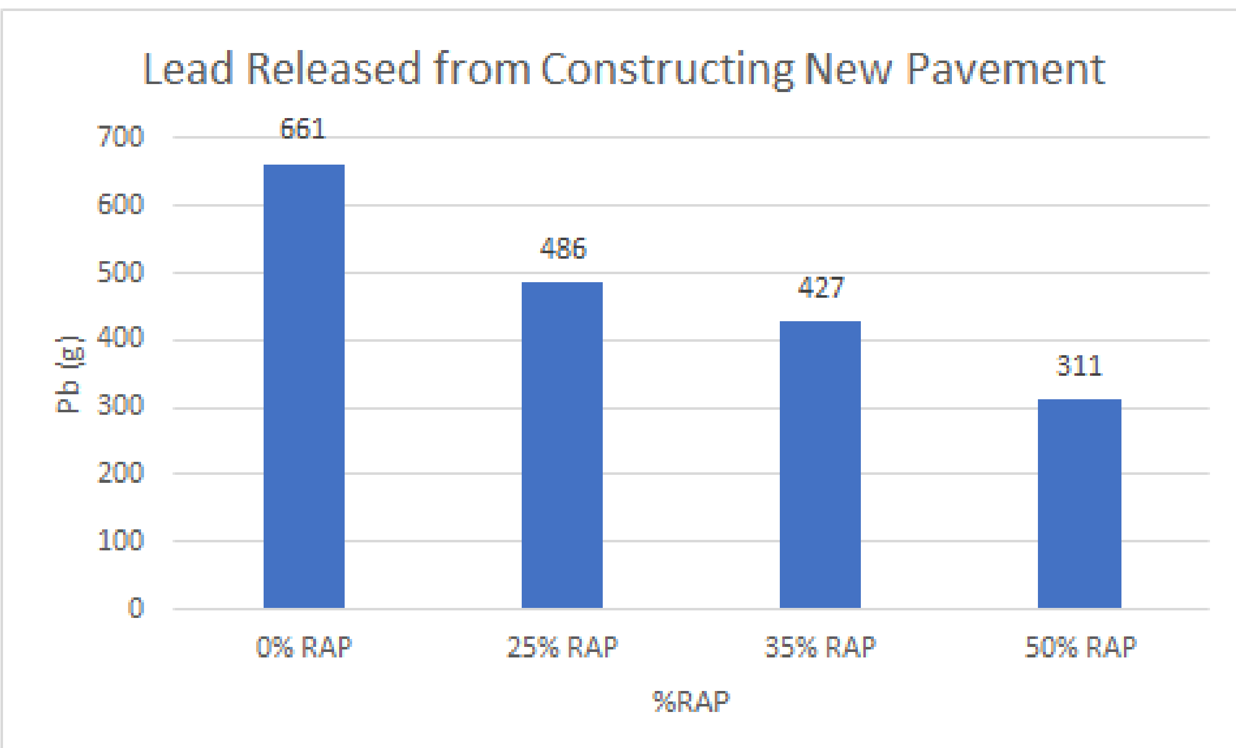



*Figure 20: Lead Released from Constructing New Pavement*

*Table 17: Alternative Measures of Environmental Impacts from Constructing New Pavement*

| RCRA Hazardous Waste Generated (kg) | Human Toxicity Potential (Cancer) | Human Toxicity Potential (Non-cancer) |
|---|---|---|
| 132,328 | 2,117,015 | 3,503,556,172 |
| 97,194 | 1,576,046 | 2,755,731,430 |
| 85,309 | 1,393,061 | 2,497,125,882 |
| 62,049 | 1,034,914 | 1,998,021,405 |

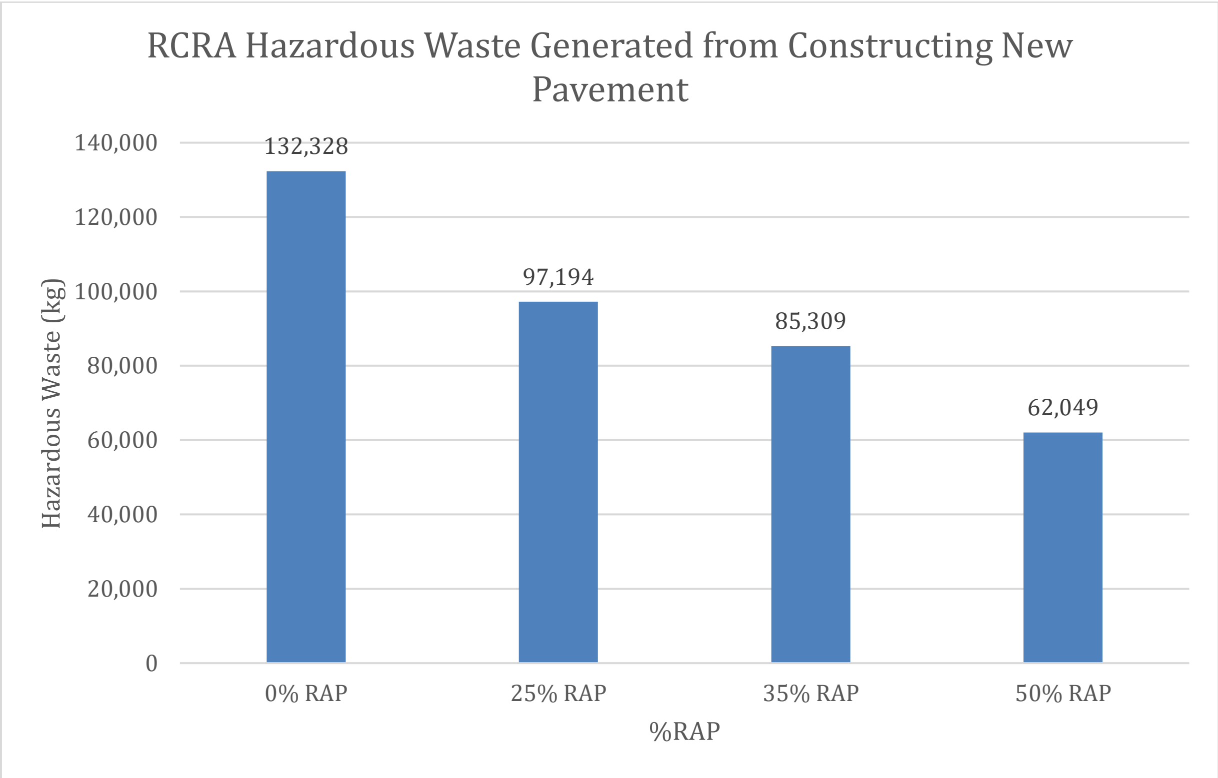



*Figure 21: RCRA Hazardous Waste Generated from Constructing New Pavement*

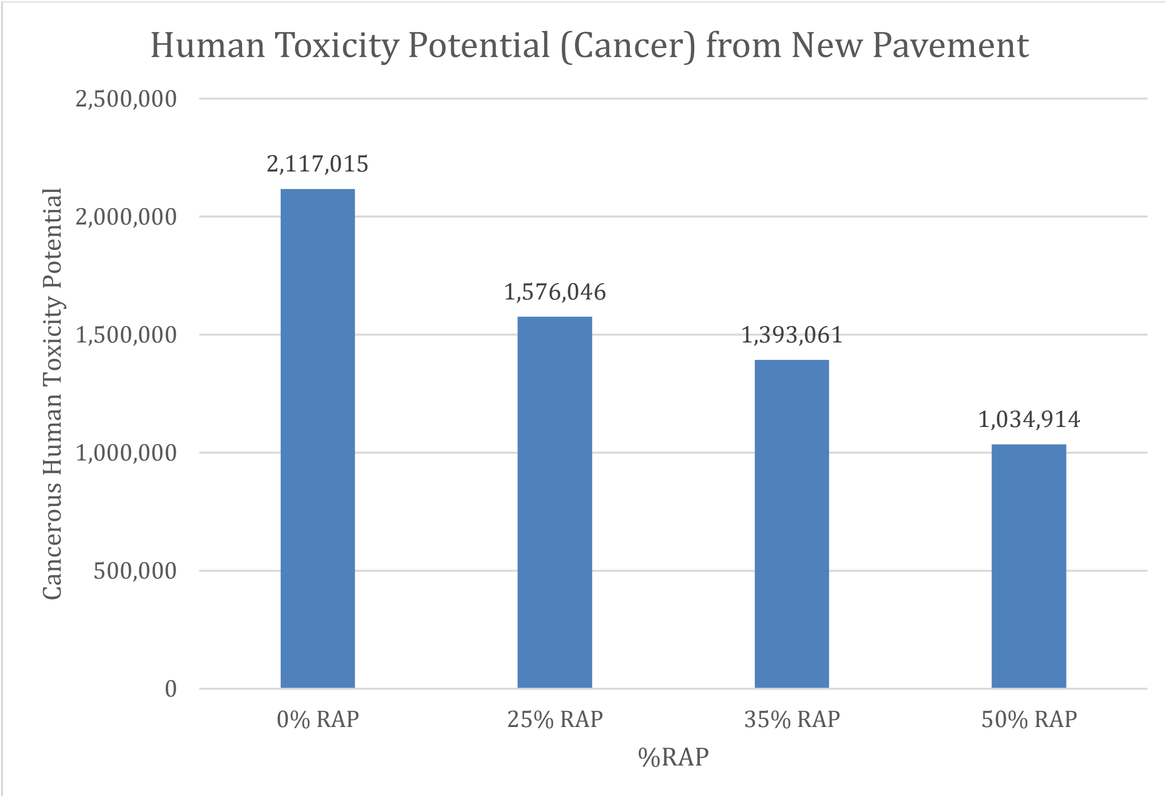



*Figure 22: Human Toxicity Potential (Cancer) from New Pavement*

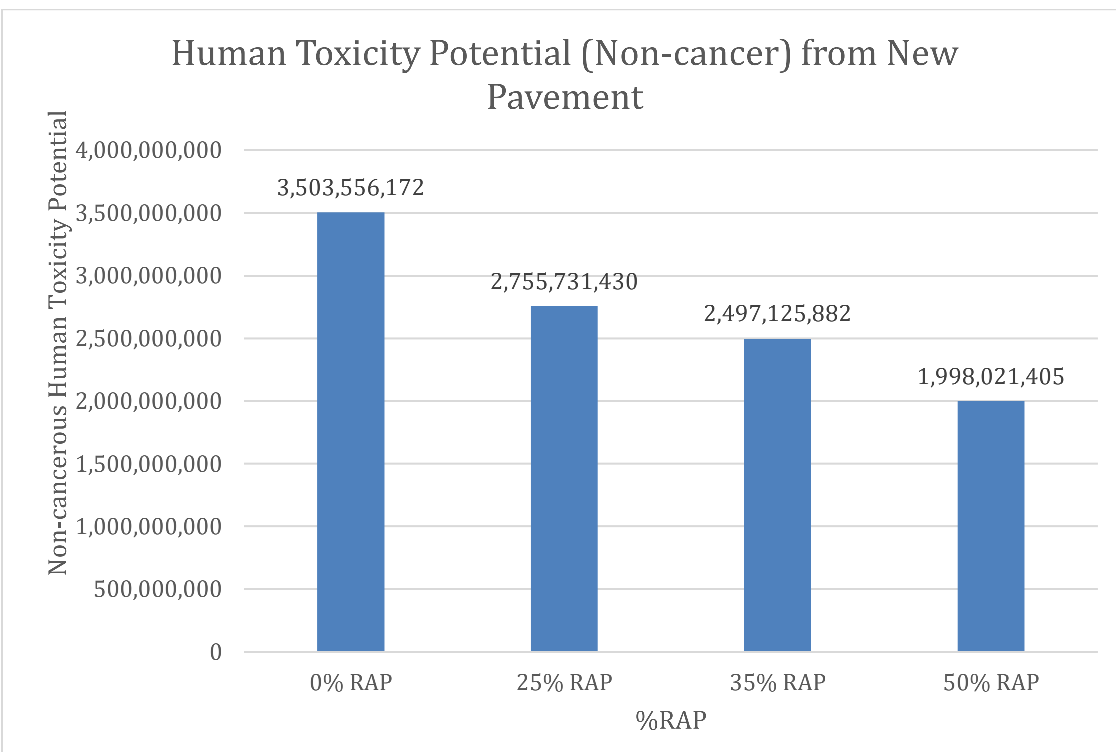



*Figure 23: Human Toxicity Potential (Non-cancer) from New Pavement*

*Table 18: Percentage Saved in Economic and Environmental Categories (New Pavement)*

| %RAP | Cost | Energy (MJ) | Water (kg) | CO2 (Mg) | NOx (kg) | PM10 (kg) | SO2 (kg) | CO (kg) | Hg (g) | Pb (g) | Hazardous Waste | Cancer Potential | Toxicity Potential |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0% RAP | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| 25% RAP | 16.23% | 19.39% | 26.61% | 20.77% | 7.05% | 18.48% | 0.33% | 21.82% | 26.58% | 26.48% | 26.55% | 25.55% | 21.34% |
| 35% RAP | 21.73% | 25.98% | 35.64% | 27.92% | 9.45% | 24.86% | 0.44% | 29.20% | 35.63% | 35.40% | 35.53% | 34.20% | 28.73% |
| 50% RAP | 32.48% | 38.85% | 53.28% | 41.68% | 14.12% | 37.20% | 0.66% | 43.63% | 53.17% | 52.95% | 53.11% | 51.11% | 42.97% |

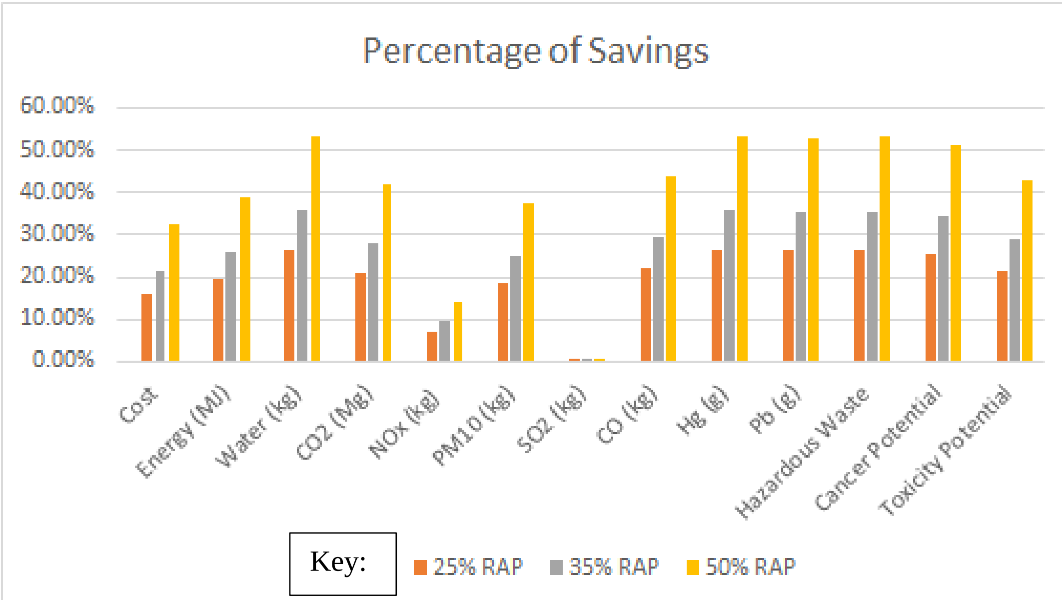



*Figure 24: Percentage of Savings from Constructing New Pavement*

Tables 19 and 20 show the economic and environmental impact results from replacing old pavement that were calculated using PaLATE, using the same categories that were used for the first case study of constructing new pavement. Figure 25 to Figure 37 are bar charts that represent Tables 19 and 20 in a visual manner. Table 21 shows the comparison of how much cost and emissions are reduced percentagewise, while Figure 38 represents this data in a bar chart format.

*Table 19: Cost and Emissions per Mix Design from Replacing Old Pavement*

| %RAP | Cost | Energy (MJ) | Water (kg) | CO2 (Mg) | NOx (kg) | PM10 (kg) | SO2 (kg) | CO (kg) | Hg (g) | Pb (g) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0% RAP | $1,293,178.87 | 13733319 | 3466 | 736 | 11571 | 4666 | 184330 | 2451 | 13.03 | 665 |
| 25% RAP | $988,929.59 | 11021003 | 2537 | 579 | 10499 | 3764 | 183706 | 1901 | 9.53 | 488 |
| 35% RAP | $832,677.57 | 10,015,574 | 2208 | 520 | 9805 | 3389 | 183475 | 1687 | 8.29 | 425 |
| 50% RAP | $642,487.65 | 7188991 | 1437 | 341 | 7459 | 1837 | 182925 | 1134 | 5.7 | 282 |

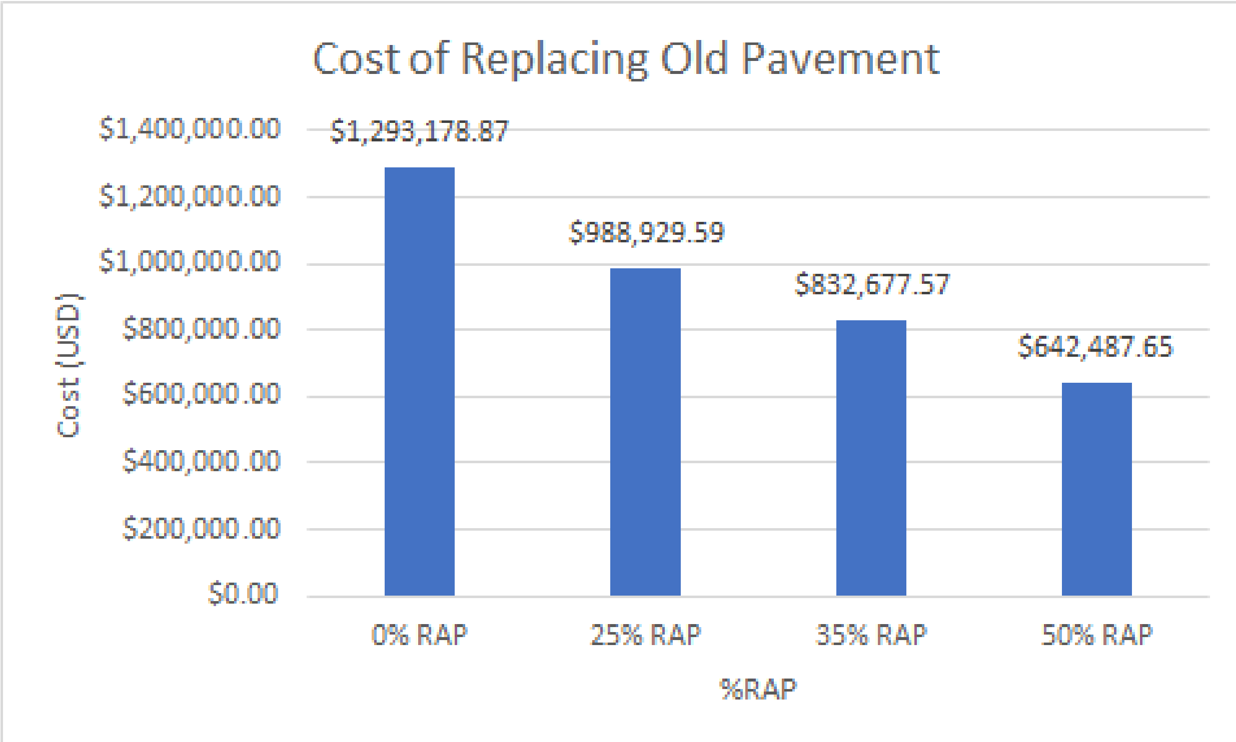



*Figure 25: Cost of Replacing Old Pavement*

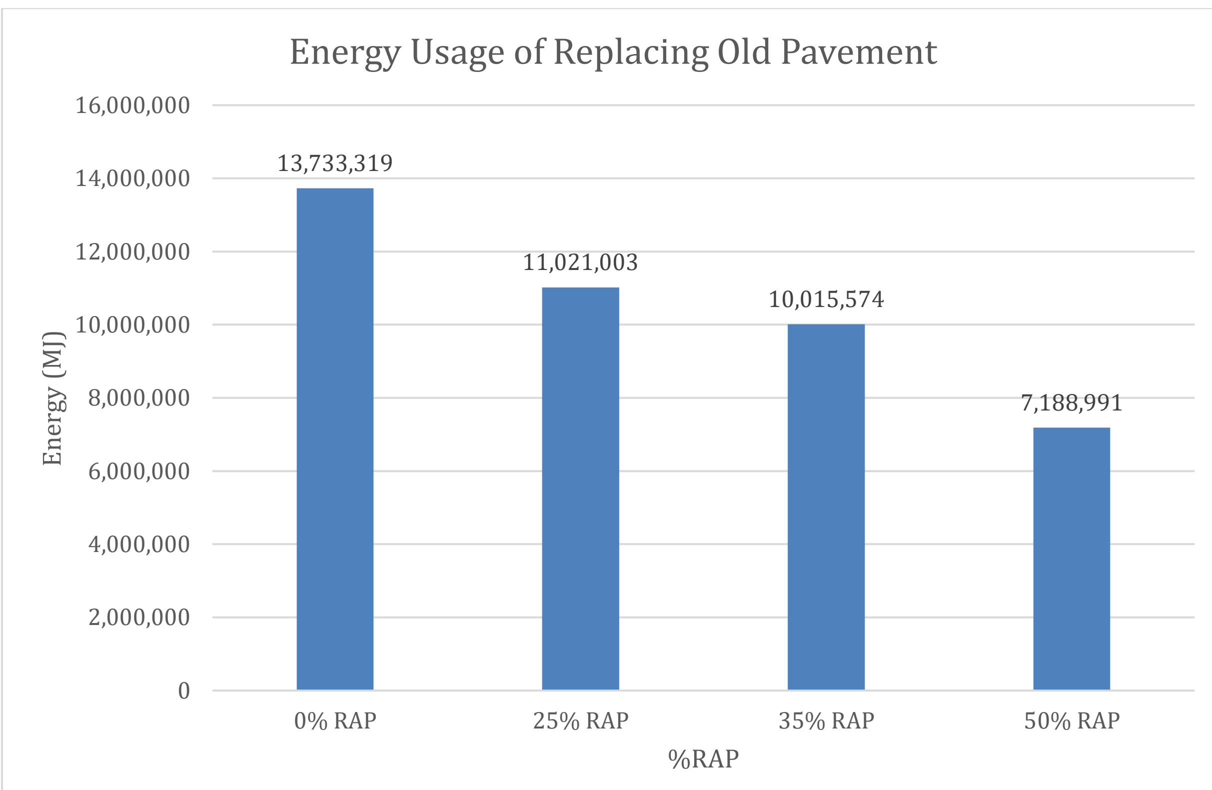



*Figure 26: Energy Usage of Replacing Old Pavement*

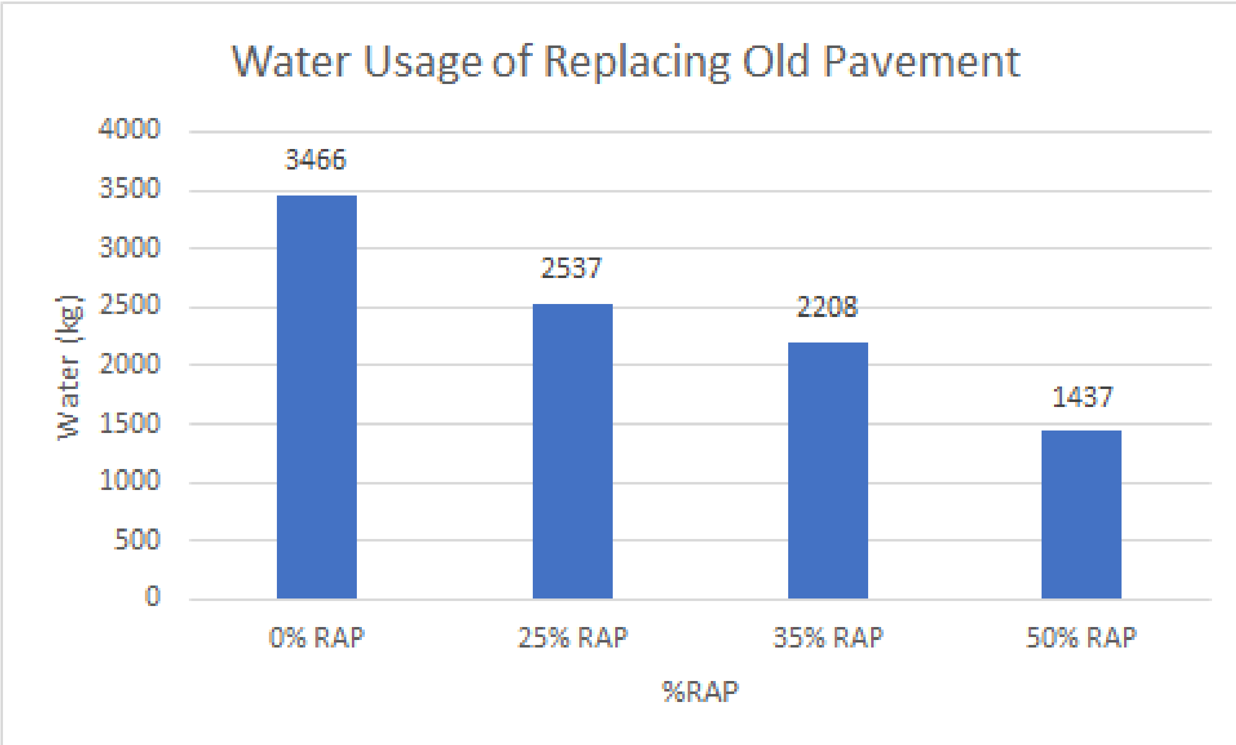



*Figure 27: Water Usage of Replacing Old Pavement*

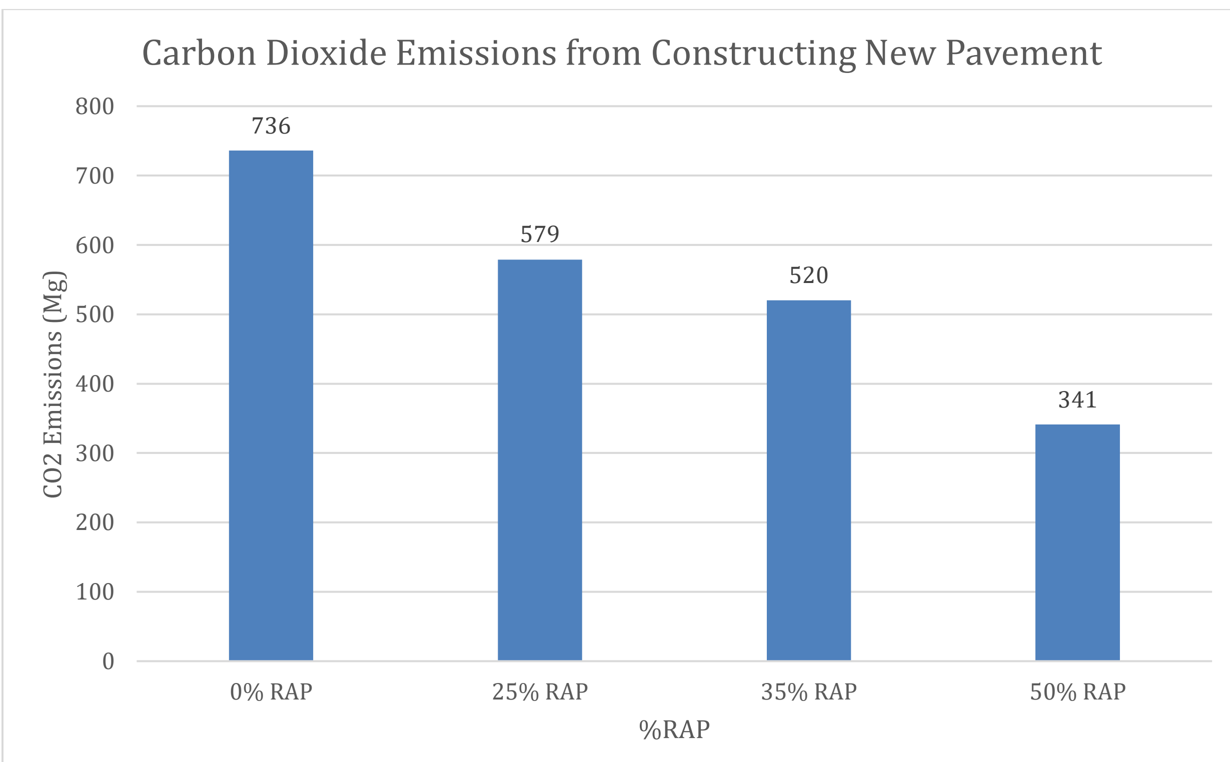



*Figure 28: Carbon Dioxide Emissions from Replacing Old Pavement*

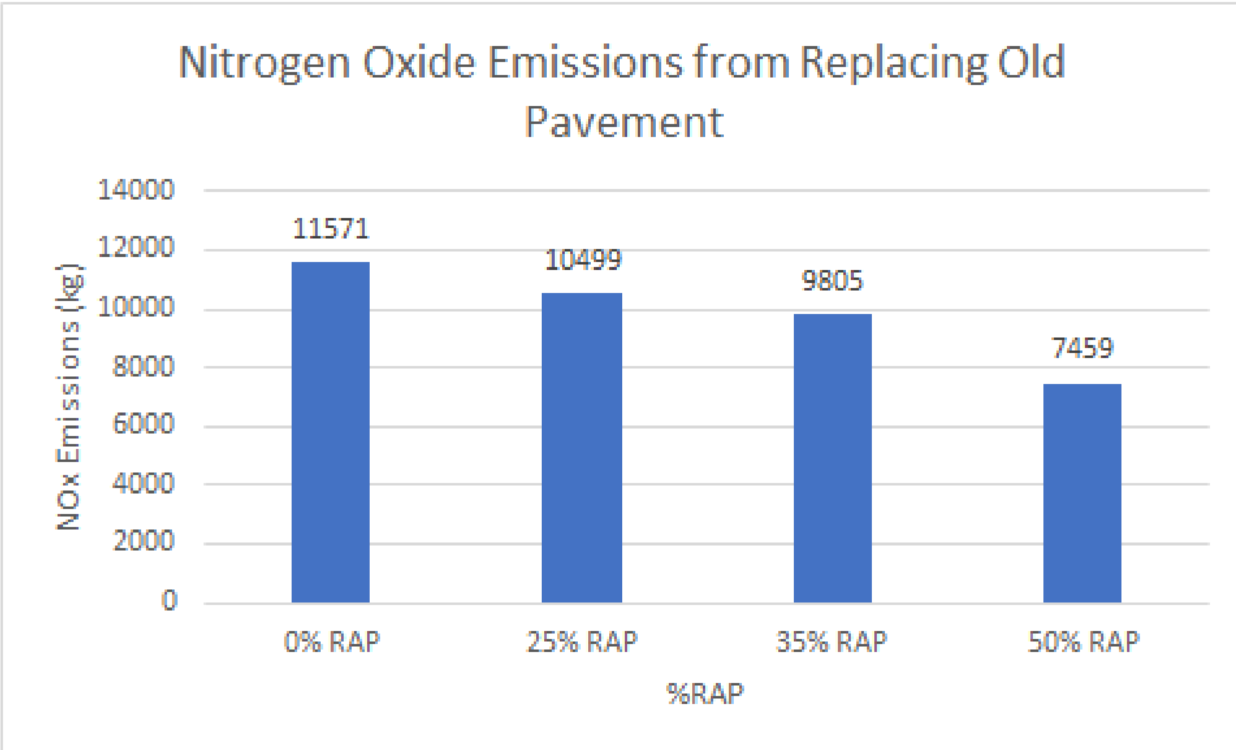



*Figure 29: Nitrogen Oxide Emissions from Replacing Old Pavement*

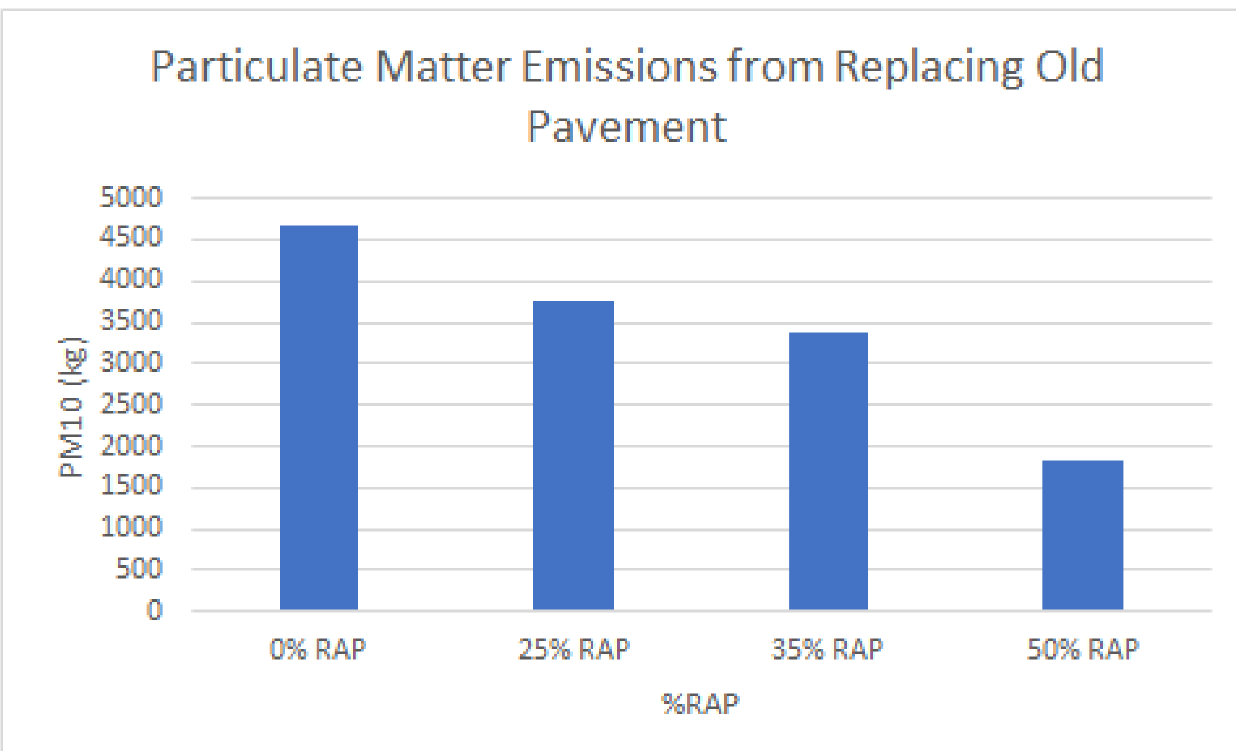



*Figure 30: Particulate Matter Emissions from Replacing Old Pavement*

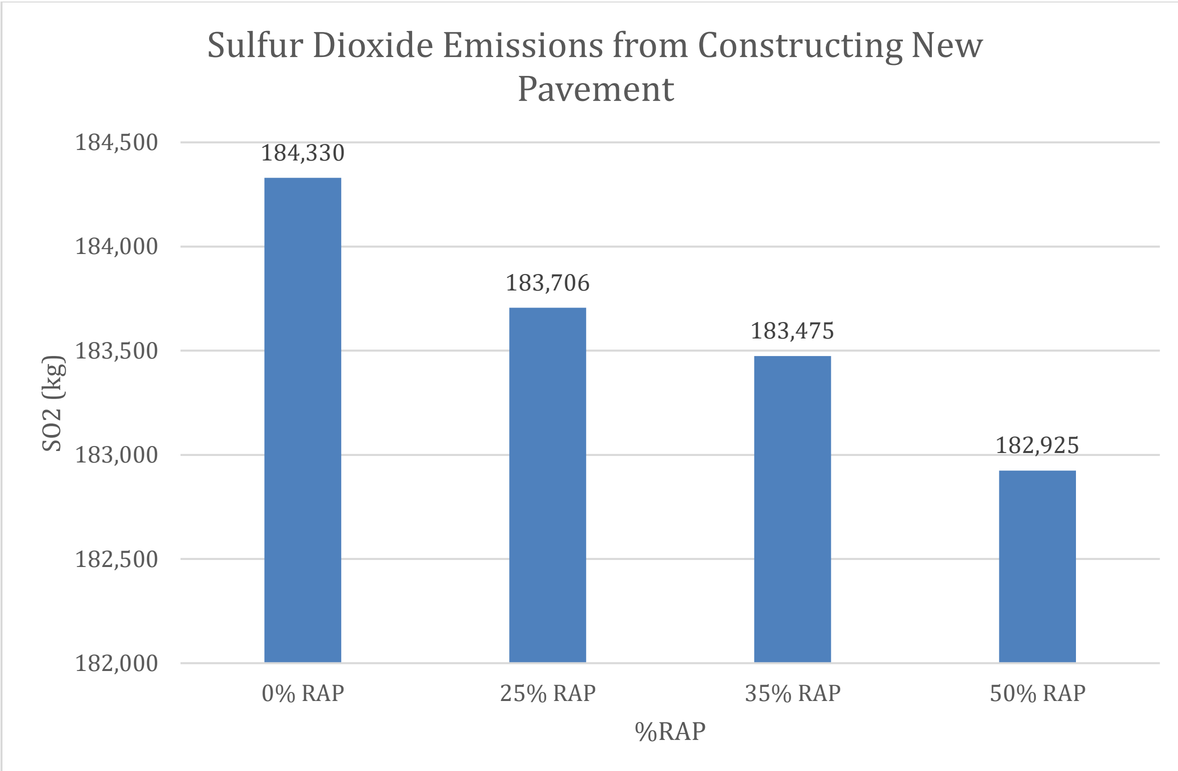



*Figure 31: Sulfur Dioxide Emissions from Replacing Old Pavement*

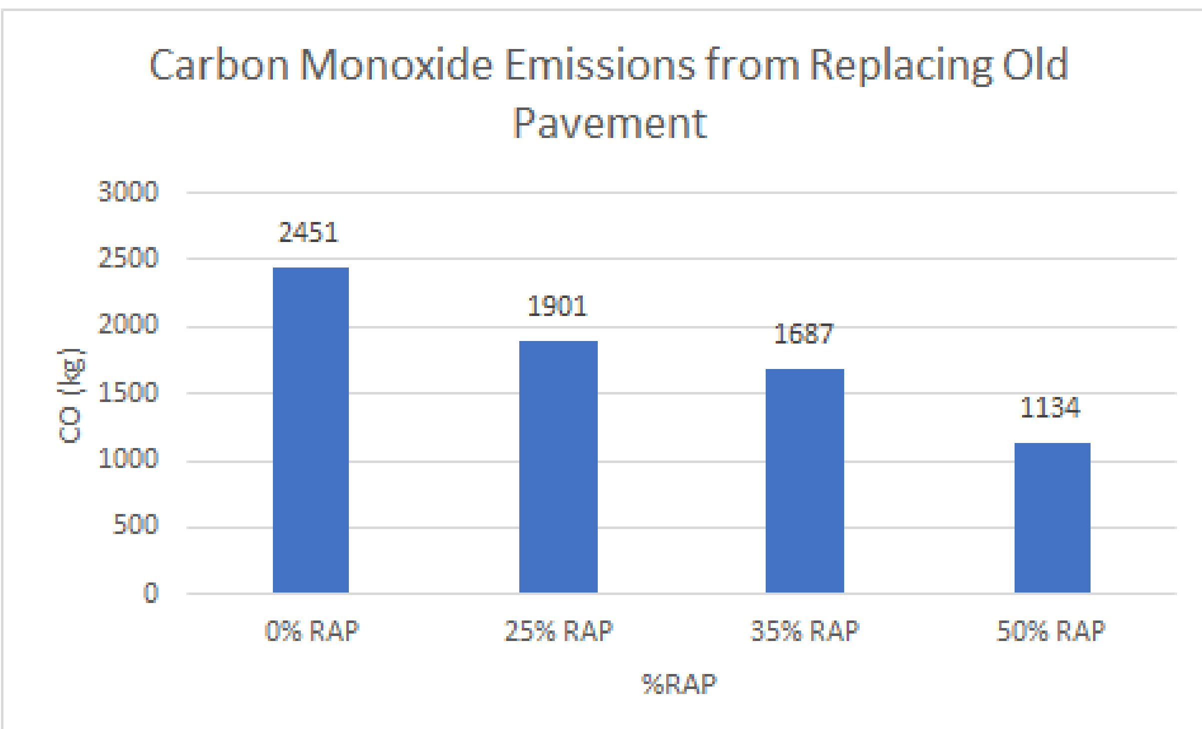



*Figure 32: Carbon Monoxide Emissions from Replacing Old Pavement*

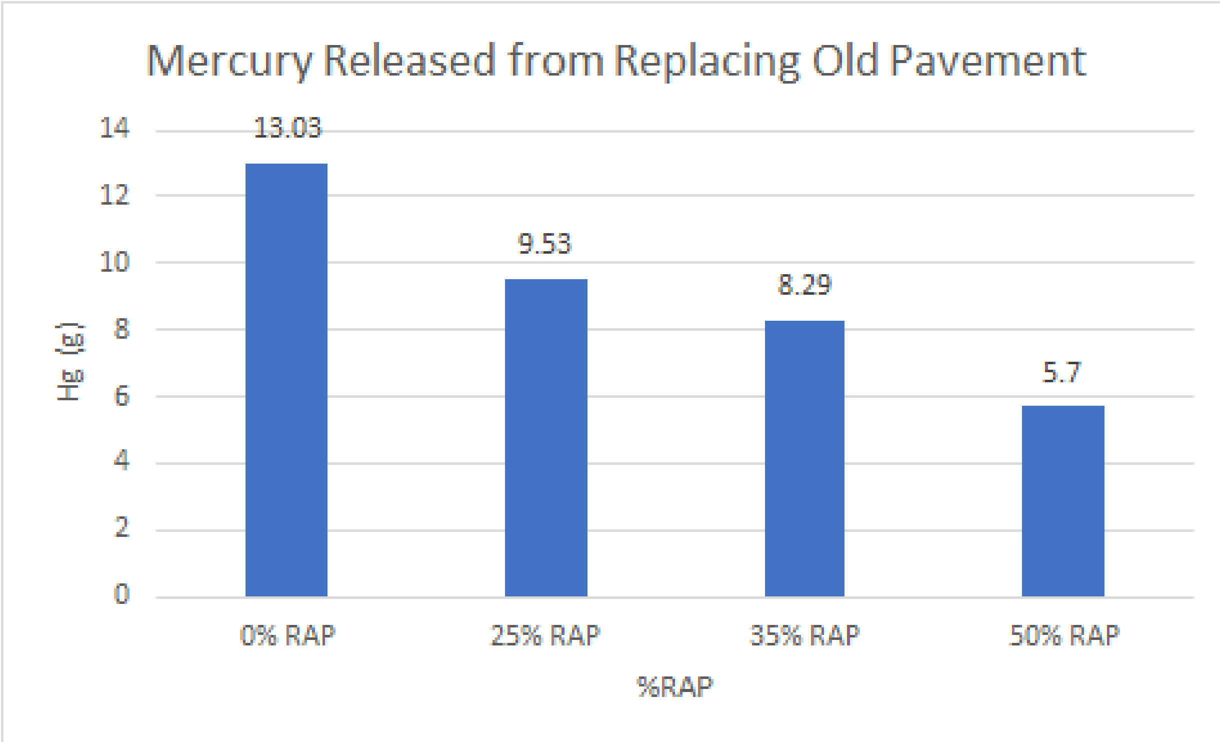



*Figure 33: Mercury Released from Replacing Old Pavement*

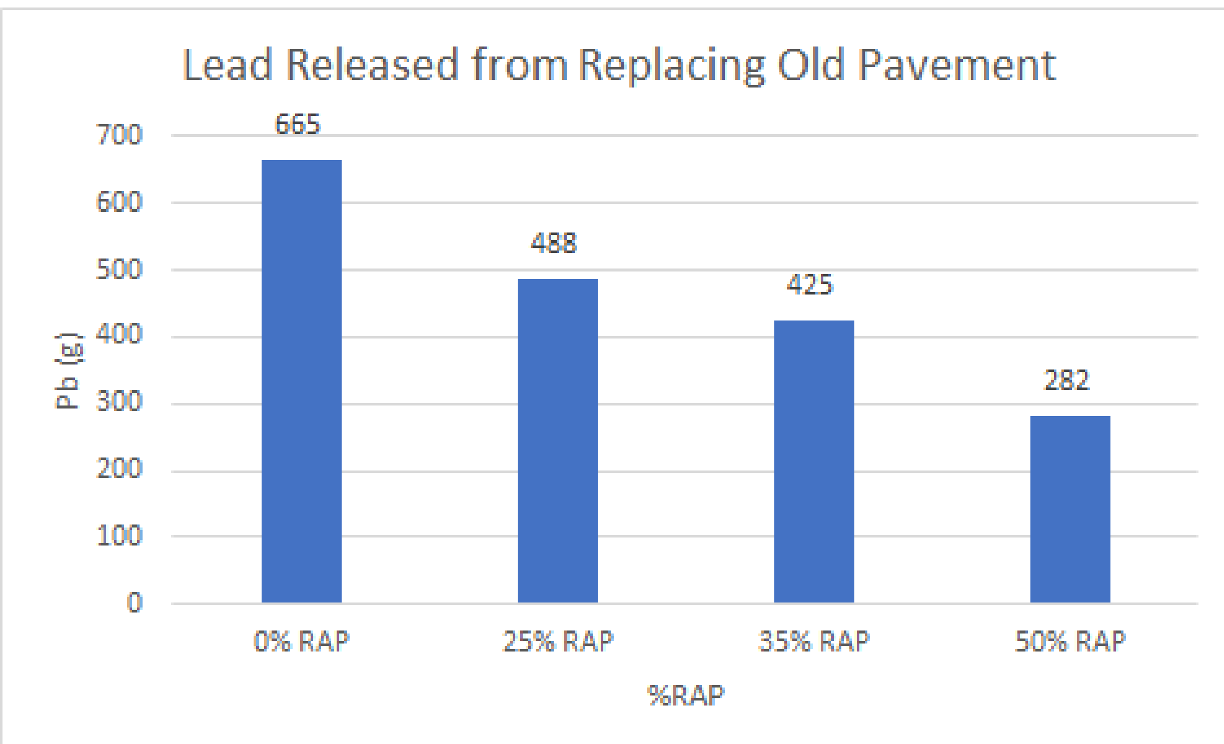



*Figure 34: Lead Released from Replacing Old Pavement*

*Table 20: Alternative Measures of Environmental Impacts from Replacing Old Pavement*

| RCRA Hazardous Waste Generated (kg) | Human Toxicity Potential (Cancer) | Human Toxicity Potential (Non-cancer) |
|---|---|---|
| 133,188 | 2,124,691 | 3,512,973,084 |
| 97,530 | 1,577,047 | 2,756,959,413 |
| 84,871 | 1,419,297 | 2,530,715,839 |
| 57,727 | 983,196 | 1,243,983,003 |

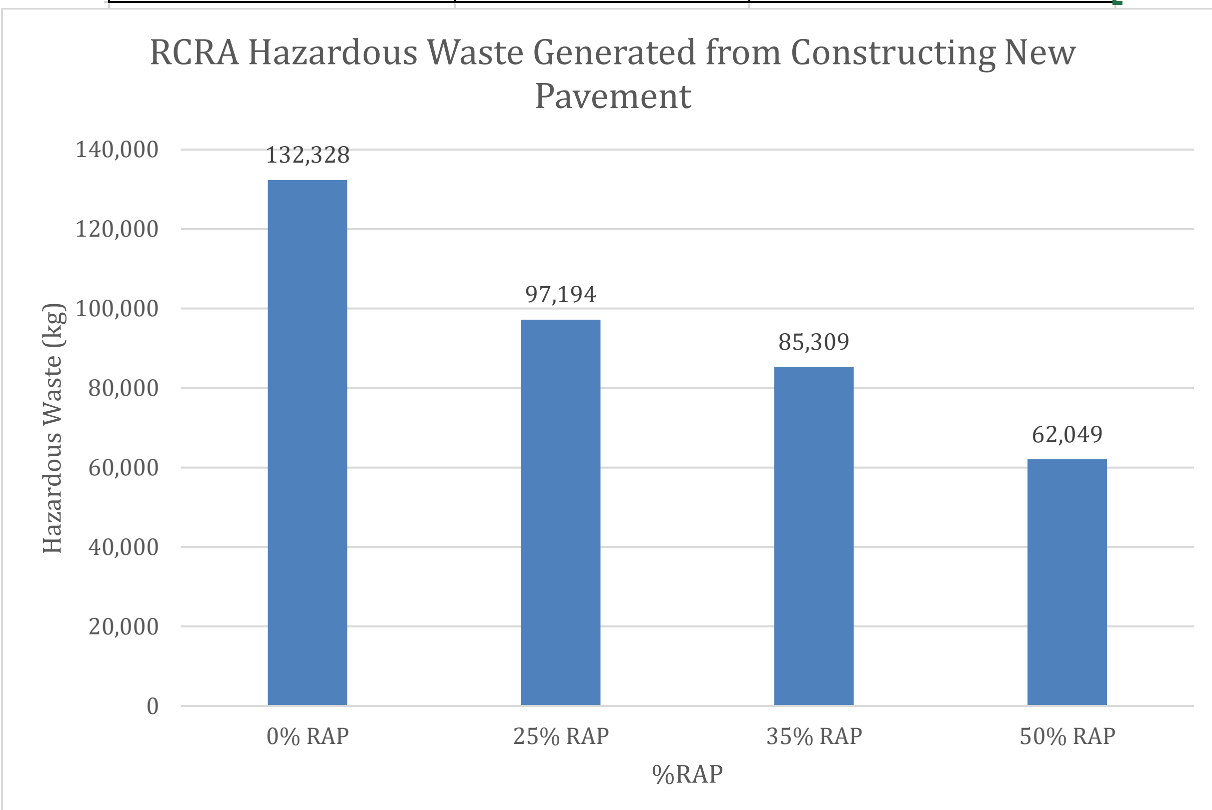



*Figure 35: RCRA Hazardous Waste Generated from Replacing Old Pavement*

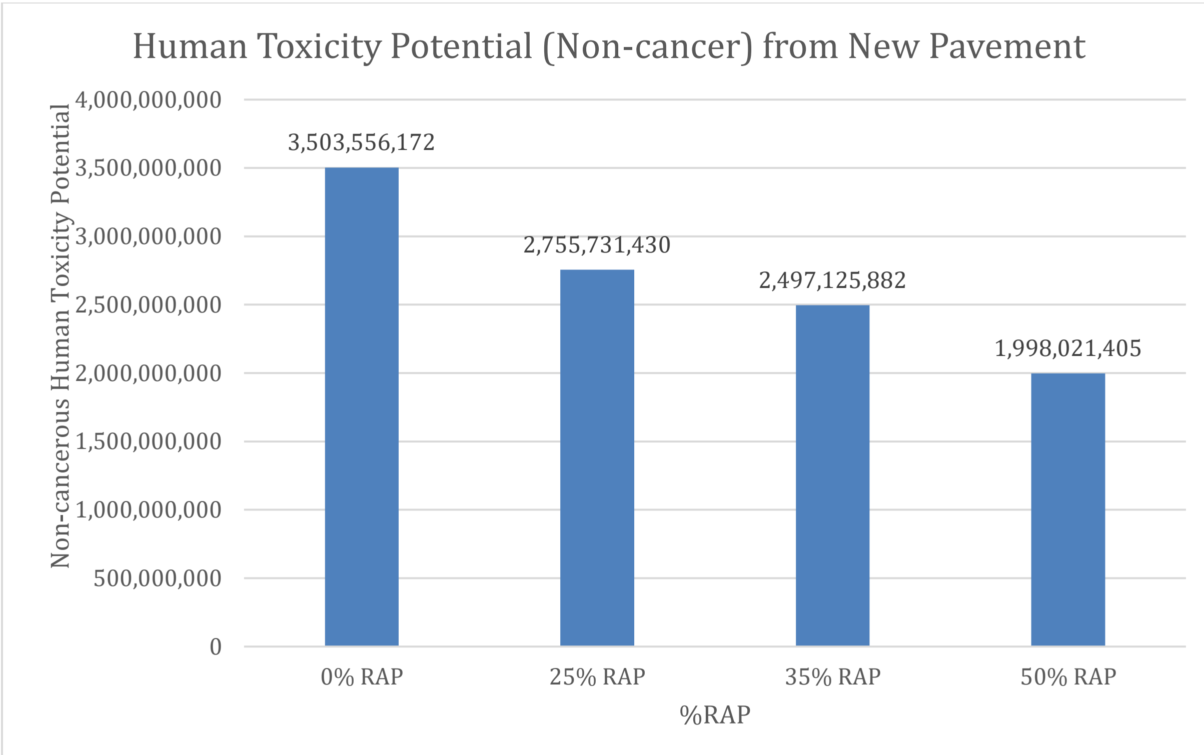



*Figure 36: Human Toxicity Potential (Non-cancer) from Replacing Old Pavement*

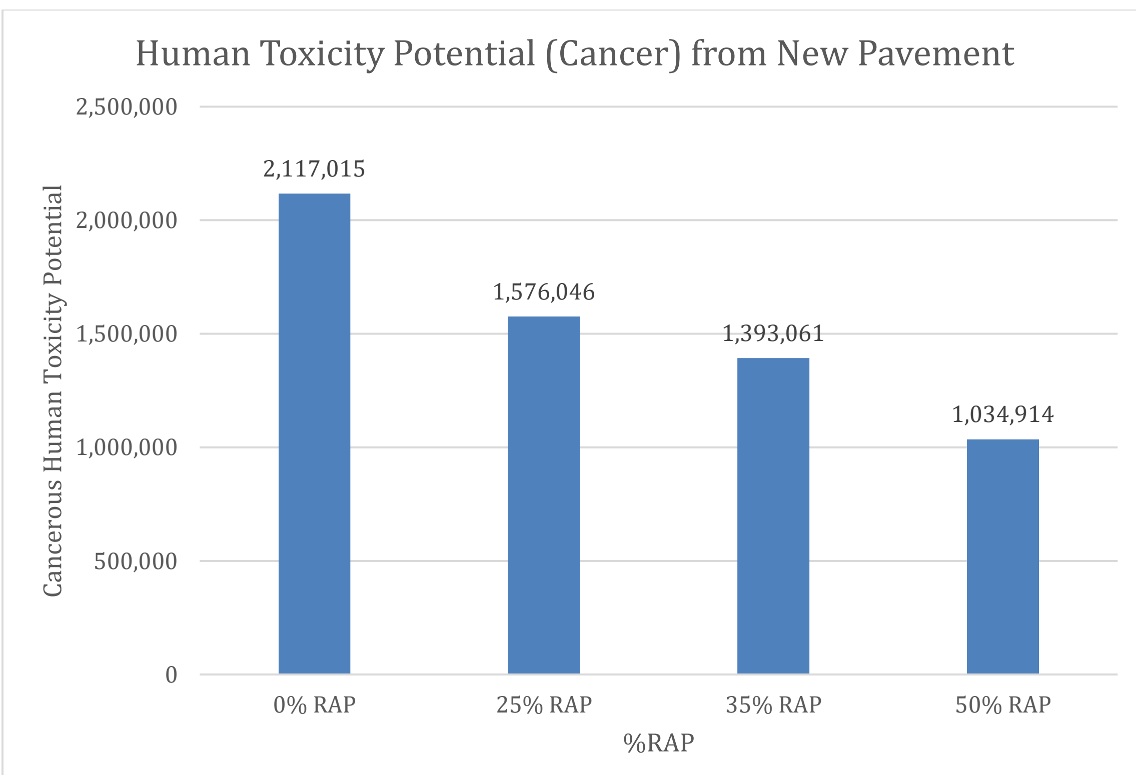



*Figure 37: Human Toxicity Potential (Cancer) Replacing Old Pavement*

*Table 21: Percentage Saved in Economic and Environmental Categories (Old Pavement)*

| %RAP | Cost | Energy (MJ) | Water (kg) | CO2 (Mg) | NOx (kg) | PM10 (kg) | SO2 (kg) | CO (kg) | Hg (g) | Pb (g) | Hazardous Waste | Cancer Potential | Toxicity Potential |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0% RAP | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| 25% RAP | 23.53% | 19.75% | 26.80% | 21.33% | 9.26% | 19.33% | 0.34% | 22.44% | 26.86% | 26.62% | 26.77% | 25.78% | 21.52% |
| 35% RAP | 35.61% | 27.07% | 36.30% | 29.35% | 15.26% | 27.37% | 0.46% | 31.17% | 36.38% | 36.09% | 36.28% | 33.20% | 27.96% |
| 50% RAP | 50.32% | 47.65% | 58.54% | 53.67% | 35.54% | 60.63% | 0.76% | 53.73% | 56.25% | 57.59% | 56.66% | 53.73% | 64.59% |

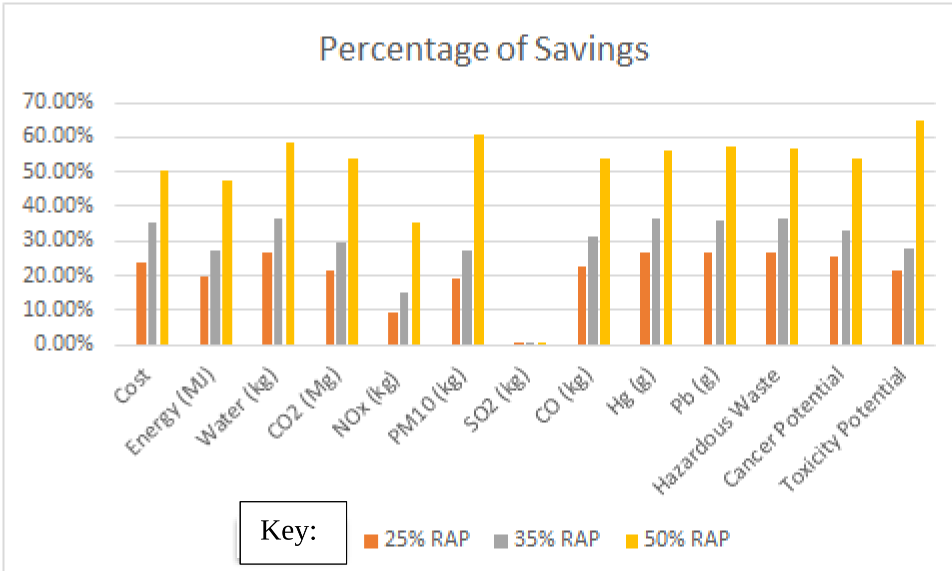



*Figure 38: Percentage of Savings from Replacing Old Pavement*

When considering the first case study, in which a new pavement is constructed without replacing an old one, the economic and environmental savings from using a high percentage of RAP in the mix design is significant. When considering the cost to manufacture the mix, ship the materials to the site, and operate all the necessary machines, there is up to 32.48% cost savings from switching from 0% RAP to 50% RAP (from $195,907.29 to $132,272.45). The environmental impact reduction was just as significant, with above 35% savings in all categories except nitrogen oxide emissions (14.12%) and sulfur oxide emissions (0.66%). Certain categories even reached above 50% in savings, such as water consumption, mercury pollution, RCRA hazardous waste generation, and human toxicity cancer potential. These statistics can be found in Table 18 in the results chapter, or Figure 24 if a bar graph version is desired. From this data it is evident that adopting high percentage RAP usage in the construction of new pavements would save a significant amount of money in the long run while being much more environmentally sustainable.

The second case study requires a few more variables, since the old pavement must be excavated and shipped to the plant for processing. Any pavement that is not recycled must be stored in a landfill. Dumping pavement into a landfill adds additional costs and environmental impacts, so preventing as much pavement from reaching the landfill is desired. For this reason, the cost savings from the second case study exceeded that of the first, amounting to a decrease of 50.32% (from $1,293,178.87 to $642,487.65) from using 50% RAP instead of 0% RAP. In addition, the environmental impacts were also reduced more than the first case study. There was a greater than 35% reduction in all categories except sulfur oxide emissions, and in nine categories this reduction was greater than 50%. The non-cancerous human toxicity potential had the highest reduction percentage, at 64.59%. These statistics can also be found in the results chapter, in Table 21 and Figure 38. Not only is it evident that high percentage RAP mix designs are financially and environmentally beneficial, but also that the savings are greater when replacing pavement as opposed to simply constructing new pavement. This observation is significant because currently in the US, most pavement construction involves rehabilitation of old pavements.

# Chapter 6

# Summary

It is more important than ever to update the US's crumbling road and highway infrastructure. To do this effectively, it is important to consider alternatives to not only reduce the implementation costs but also to build sustainably. This major qualifying project aimed to quantify the economic and environmental impact reductions that can be achieved by incorporating binder rejuvenators, which allow a much higher percentage of RAP to be mixed with virgin materials. In order to do this, a Reclaimed Asphalt Pavement Mix Design Spreadsheet was created using Microsoft Excel® to design a 0% RAP mix, a 25% RAP mix, a 35% RAP mix, and a 50% RAP mix. Included with this excel is a step-by-step walkthrough on how to create a unique mix design using the spreadsheet if desired. Using these four mix designs into the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects software (PaLATE software) and using a consistent set of parameters for the scope of the construction, the economic and environmental impacts of both constructing new pavement and replacing old pavement were calculated. In the case of constructing new pavements, the cost savings amounted to almost 33% for a RAP percentage of 50, with significant reductions in emissions, pollution, energy and water usage and waste generation. In the case of replacing old pavements, the cost savings were even higher at slightly greater than 50%, along with even greater reductions in environmental categories across the board. The reason for this is because using RAP in a mix design prevents the old, excavated pavement from entering the landfill in such large amounts, as well as saves the manufacturing plant from having to produce so much raw materials such as aggregate and bitumen.

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