Designing and Constructing Strong and Durable Recycled Pavement with High Percentage of Reclaimed Asphalt Pavement (RAP)

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Approved:

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Abstract

The project focuses on designing and constructing the reclaimed asphalt pavement with improvement in the performance: durability, strength and fatigue & thermal cracking. The condition of recycled materials, design of pavement and binder that combines recycled materials and new materials were tested and constructed into HMA, Hot Mix Asphalt, to explore improved design. The result of the project showed the overall performance of RAP determined by RAP content ratio and rejuvenator.

Capstone Design Experience

The Project fulfill the capstone design experience requirement by conducting an analysis and design study to determine the optimal design of reclaim asphalt pavement to obtain a desired range of tensile strain and compression stress due to traffic loading for 20 years. Several designs were considered and analyzed until a desired design was obtained. The final structure was selected on the basis of several factors which included environmental consideration, manufacturability and cost.

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Introduction

The project is designing and constructing the improved model of Hot Mix Asphalt made of high ratio of reclaimed asphalt pavement (RAP). Currently, most highway agencies allow asphalt mixtures containing low percentages of RAP (i.e., less than 25 percent by weight of aggregate).[1] The result of this project will report how road can be designed with high ratio of RAP. This would increase in use of recycled material to construct road pavements that benefits economy and environment.

RAP uses recycled material of Hot-Mixed Asphalt (HMA) pavement as the primary material and remixed with new material for a new and re-graded pavement. The RAP then treated by adding rejuvenators to lower the viscosity and increase ductility to become an asphalt mix material. The benefit of using RAP is the asphalt pavement can perform as well as using the asphalt mix of virgin material. The process of fixing or repaving the road usually done by using the RAP, which increases the life expectancy of the pavements

The main properties that are going to determine the RAP asphalt mix design are rutting and fatigue cracking. The rutting of asphalt mix could be prevented through rotational viscosity test in order to find PG grade of the RAP binder. The high viscosity measurement means the RAP asphalt mix has high stiffness. The fatigue crack on RAP will be also determined through PG grade. Also, the location weather and traffic information will determine the cracking amount.

The method of increasing the ratio of recycled material is to replace the virgin materials with recycled materials. The (Appendix) experiment uses used oil or environment friendly materials as rejuvenators to soften hundred percent RAP binders. Then the construction method will be analyzed in different proportions of RAP content to design the road

The report introduces the results of different RAP contents. The main focuses of results are energy consumption, human toxicity and final expected cost. The final design is chosen one out of each proportion: 0% RAP, 10% RAP…, and 100% RAP. Although the performance may same even with 100% RAP binder, the economic and environmental efficiency must be concerned as well.

Background

RAP, reclaimed asphalt pavement, is the type of material for asphalt mix known for environmental and economic improvements. Using RAP asphalt mix also conserves aggregate, binders and energy. RAP consists of pre-processed road- building materials in order to avoid new production of asphalt pavement. As a result, engineers start to use RAP asphalt mix that has various types depends on countries, states and roads. Since the materials are generated when asphalts are removed for construction, resurfacing and access of utilities, they are limited in resource.

The history of use in RAP is not too long, but according to National Asphalt Pavement Associations, twenty years of industry experience has proven that hot-mix asphalt(HMA) can be recycled for use in roadways over time. In the mid-1970s, HMA recycling grew significantly and engineers discover that the recycled asphalt pavement has much more advantage in economy and environment.[2] Over ninety percent of American highway and roads are constructed with hot-mix asphalt and as infrastructures ages, these roads must be maintained or rehabilitated. A Federal Highway Administration, FHWA, report on pavement recycling indicates that long-term pavement performance of recycled HMA that is designed and controlled during production performs comparably to conventional HMA.[3] In fact, it can improve material properties of the existing pavement layer. Even though RAP is widely used, there are plenty of possibilities that RAP can be modified even further.

There are two ways to reclaim the RAP on the road, Milling and Full-depth removal. The full-depth removal is simply removing the whole asphalt layer, reconstruct the RAP and pave back with improved asphalt. When engineers pave asphalt by milling, only top part of damaged asphalt is removed and paved with thin virgin layer. Depends on the condition of the road and economic concern, both ways are equally beneficial.[4]

As an improved design of Asphalt, RAP is still investigated by Engineers who are searching for cost-efficient materials. Therefore, there has been much improvement in creating higher recycled material in RAP. There are not many of American roads which have 100% RAP road design. The main reasons for that are not enough historical evidence of using 100%RAP, requirement of recycled materials and risk of design failure. The project aims for the high proportion of recycled materials in RAP, which means even 100% RAP can be designed if it is efficient. Designing 100% RAP hot asphalt mix will be a great contribution to design higher RAP content road.

Objectives

The main objective of this project is to prove that high proportion of RAP is viable for actual design. There have been many researches to use high content of recycled asphalt. For example, RAP Technologies, LLC produced 100% RAP, but with the air pollution challenge. Unfortunately, testing on actual road requires over ten years of time and has design failure risk. By analyze the long term failure result, the project will find new way to design RAP.

Literature Review

Summary

Designing the improved model of asphalt mix using RAP requires full understanding of knowledge in use of RAP, super pave performance grading of binder, rejuvenator and physical properties such as *rutting and cracking.* This section of report explains the requirements and their necessity for designing RAP asphalt mix.

Rutting


Figures 1, 2 Rutting

The pavement is rut due to the tire loadings. Rutting is failure of asphalt pavement due to the too much compression loading. When the asphalt rut, the surface of pavement creates cracks shape of floor depression. Rutting usually happens in heavy traffic or intersection where many tire loading happens. In order to prevent rutting, the pavement has to be designed stiff enough to support heavy tire loading. There are two types of rutting failure; mix rutting and subgrade rutting. Mix rutting is common rut failure when the pavement surface is rut due to mixing and compaction problems. The rutting failure mainly happens due to design failures such as unstable mix design, high pavement temperature and insufficient stiffness. Subgrade rutting occurs when even the subgrade ruts and cause section of pavement to collapse.[5] When the subgrade also fails, it explains that the asphalt layer and base layers were not enough to protect subgrade layer. Subgrade layer is overstressed if the upper layers are not thick enough or stiff enough to prevent subgrade to be stressed.

Preventing rutting is important role in designing HMA, because the rutting determines the stiffness of the pavement. Prevent rutting will increase traffic safety, pavement age and etc..

Fatigue Cracking

The pavement fatigue cracking commonly happens to old pavements. When the crack reaches certain point, the top layer (HMA) needs to be replaced. Therefore, engineers test for fatigue cracking to determine the pave lifecycle. Fatigue cracking is caused by the tensile stress at the bottom of the layer during tire loading, which mean cracking happens after long time of period. When the asphalt layer is malleable and thick enough, the layer will last long duration. However, other than initial design and traffic loading, there are water drainage, thermal cracking, and environment factors that determine fatigue cracking. When the asphalt fails in result of fatigue cracking, the pavement may go through crack as shown in Figure 3.

Figure 3 Cracking on road

The important factors that are considered during designing are traffic loading and thermal cracking. The long periods of pressure on the surface of road gives tension at the bottom of the asphalt layer, which means cracking usually happens on highway or busy roads. If road is always busy or experience high traffic, the road requires maintenance. After long period of time, the road starts to experience cracking which cause from the tension. The shrinkage of material and freezing of road will cause crack road much faster. The road should not be frozen at any condition or the road may experience the design failure. The performance grade of binder is majorly concerned for preventing freezing.

PG Grade

The Performance Grade (PG) system is the method which determines the performance of asphalt cement binder used in asphalt pavement at different temperatures in terms of rutting, fatigue cracking and thermal cracking. Performance grading is based on the concept that the asphalt binder properties are related to the conditions of the binder.

The condition concerns air and pavement temperatures, and specific application for that specific facility, which determines rutting and thermal cracking.

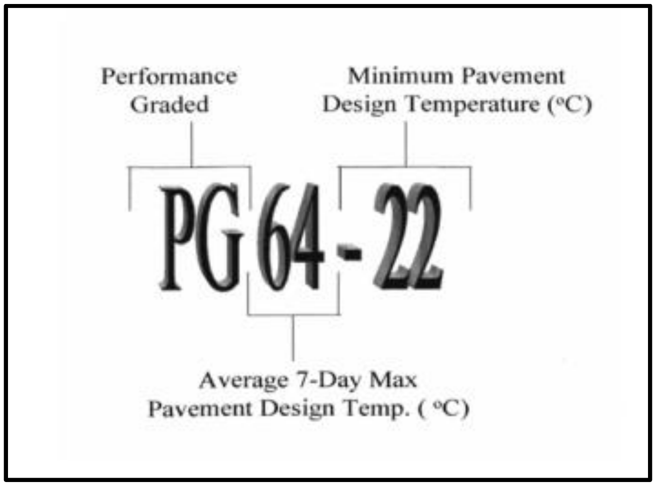

Figure 4 Performance Grade reading

The standard notation PG grade represents the design of asphalt, such as rutting, fatigue cracking, thermal cracking, cost expectation and life expectancy. PG system is based on project climate. The standard notation for PG binder uses maximum pavement temperature and minimum temperatures to represent the pavement grade. PG grade is written as PG XX-YY, where XX is the average-seven day maximum pavement design temperature and YY is the average-seven day minimum pavement design temperature.[6]

Since rutting occurs at high temperature, the maximum temperature of PG grade (XX)represents direct relation to rutting. Although actual rutting has to be tested and measured to find, engineers can overestimate design by choosing the right PG grade.

The minimum temperature (YY), on the other hand, provides thermal cracking. As one of the contributor of cracking result, thermal cracking is important factor to prevent. If the cracking result can be predicted, as mentioned in fatigue cracking chapter, the life expectancy of the asphalt can be determined

The range of maximum temperature and minimum temperature can be used to predict the price of the PG binder. When the range of maximum and minimum temperature is increased, price of binder also increases because modifiers such as polymers are used to meet the temperature requirement.

There are infinite grades of PG binders for each of the vast variations of project climatic conditions around the State. However, for practical applications of the PG System, Industry and Caltrans PG Task Group identified the number of PG grades that would meet the State needs. The Task Group also generated a climatic map for the State of California with the recommended PG grade for each of the climatic zone. [7]

Binder Performance Test

There are many methods to determine the performance grade of asphalt binder such as Dynamic Rheometer test, Rotational Viscometer test, Bending Beam Rheometer and Direct Tension Tester. Each method requires different machines and tools, but all the results are accurate. Also, it is common that every tests measure average maximum and minimum temperature for seven days. The method used for the project was viscometer test and all the PG grade of RAP binders with different rejuvenator.

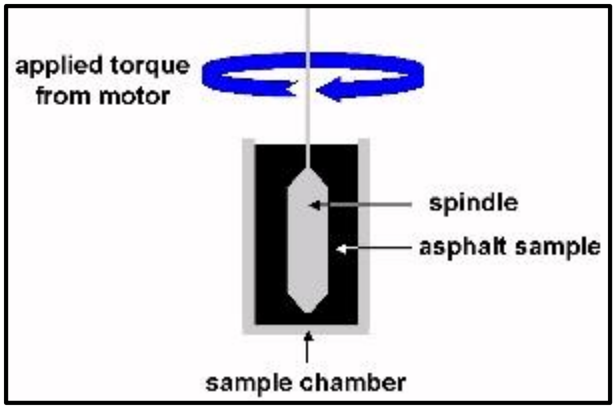

Figure 5 Rotational Viscometer test

The rotational viscosity is used to determine the flow characteristics of the asphalt binder. The rotational viscosity test measures the torque required to stay at a constant rotational speed of a cylindrical spindle while it is submerged in an asphalt binder (Figure 5). The torque is calculated into viscosity by the viscometer. The reasons performance grade of RAP binders determine by viscometer were faster procedure because the viscosity test requires constant temperature, and viscometer is capable of measuring modified and unmodified asphalt.[8]

Rejuvenator

Figure 6 rejuvenator

There are many ways to restore the performance properties of recycled binder: such as increase the binder ratio by lowering void ratio, add rejuvenator, or just simply use softer binder. The rejuvenator, or recycled agent is treatment emulsion to make the binder much more malleable. While the rejuvenator reduces the stiffness of binder, it improves the mixture resistance to cracking, especially when using high proportion of RAP.

Although the rejuvenator sounds encouraging using high recycled binder contents, High ratio of RAP has not been used widely due to low efficiency. There are few disadvantages in using rejuvenators. The rejuvenator has uncertain effect, lack of adequate mixing of recycled binder and rejuvenator, and the required reaction time on performance properties of the recycled binders. However, if the right amount of rejuvenator is added and mixed properly, RAP with high proportion of the recycled materials can be made with improved cracking resistance without worsening the rutting.

Environment

The main concerns for environment when constructing the RAP are pollution, which has to with chemical emission, and energy consumption. As mentioned previously, RAP is much more environment friendly than new asphalt, but the project will analyze the environmental result for different proportion of recycled material for RAP.

The data received from assessment tool PaLATE, which contains energy consumption, water consumption, chemical emissions of Mg, NO2, SO2, CO, Hg, Pb and human toxicity prediction based on the geometric feature input of asphalt road. By analyzing the result of environmental effect, we can prevent high pollution and able to produce RAP that concerns both price and environment; the RAP proportion directly connected to cost.[9]

As example, carbon dioxide is one of the main environmental problem people concern. Carbon dioxide main causes the global warming and it generally produced from fossil fuels, asphalt production and many other related to industries. After major industrial revolution after World War 1, the amount of carbon dioxide exponentially increased as shown in figure 7. Reducing amount of carbon dioxide production can improve the world greener.

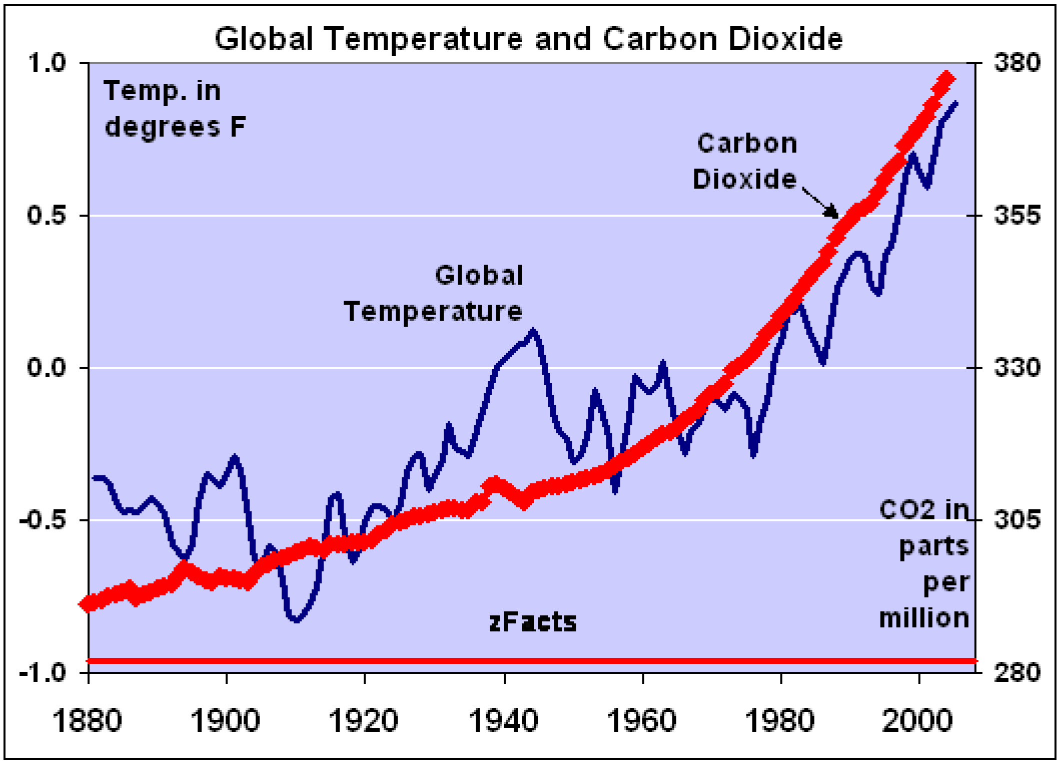

Figure 7 Global Temperature and Carbon Dioxide from 1880 to 2000

The energy, such as fossil fuels, are ones of the most important resources for human civilization to function. Energy is directly related to money and environment as well. The expectation of energy consumption will be majorly from transportation. The more transportation of RAP requires, the more energy will be consumed. There will be more discussion of energy in the Improvement section[10].

Programs

Since the performance of RAP binder will be graded with PG grade system, which overestimated performance of the asphalt pavement, the expectancy of performance of asphalt binder can be predicted.

The new method the project is design with softwares. Excavating, paving and repaving just to test the performance of RAP asphalt mix costs extreme amount of money. Also, long term performance such as fatigue cracking requires years of time to collect data. For design, I used two softwares which popularly used when designing road pavement design: MEPDG and PaLate.

M-E PDG (Mechanistic-Empirical Pavement Design Guide)

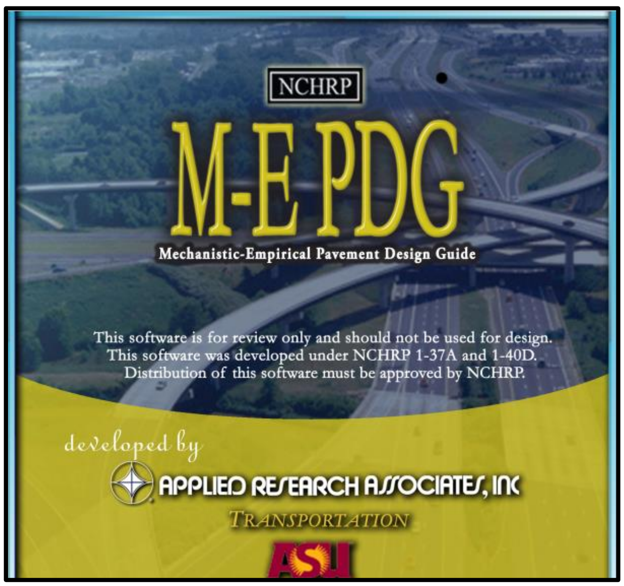

Figure 8 M-E PDG

The software ME PDG is great tool which predicts the performance of the asphalt design. MEPDG requires pavement design with structural characteristics of each layer: such as thickness, performance grade, gradation, void and etc., climate data of specific

State, and years to predict. As Figure 25 through 28[11] shown, the MEPDG analyzed expected value of rutting and fatigue crack on pavement is calculated annually for twenty years. The predicted results of rutting and fatigue cracking are very important when designing the asphalt pavement, because they are the main result of design failure. With the climate data given, MEPDG calculate complex calculation with annual different environmental temperatures.

PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects)

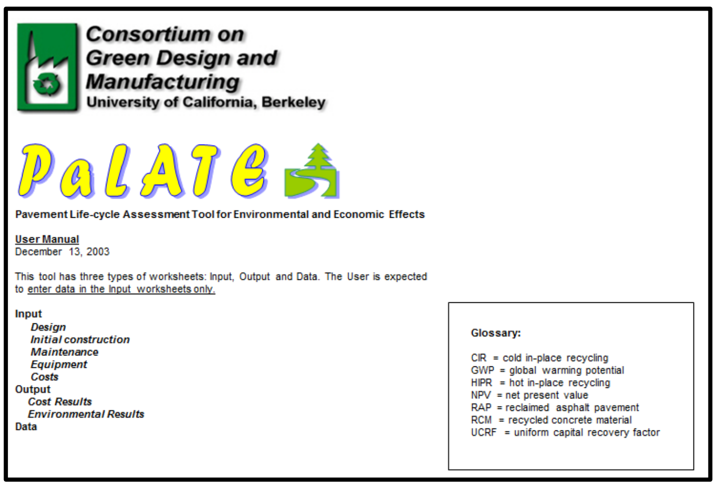

Figure 9 PaLATE

The PaLATE is Excel program which calculates the environmental effect of asphalt design and final cost of whole project. (figure.9) The input requires asphalt road design including volume, road distance, and binder price. With the provided density, cost and environmental data, PaLATE provides the environmental results as chemical emission amount and human toxicity calculated from chemicals. The further explanation of programs discussed in Appendix B

Scope of work

The main scope of the project is to improve road design by designing RAP. Asphalt is only pavement that construct in road, but it still requires few modifications to improve environmental effect and high performance with lower cost. The project researches the unique method to design RAP, which focuses benefits in cost, performance and environment.

The project aims road design to have as high proportion recycled material of RAP layer as possible. With the environmental and cost issues concerned, RAP is not always efficient to build as hundred percent of RAP. Using the specific designing tools, these issues will be analyzed and contribute to design of the road.

Methodology Review

The design of the RAP requires series of steps to be done exactly to construct long lasting recycled pavement with high proportion of recycled material. In previous chapter(), important factors that determine performance properties of recycled asphalt binder. But why are we using those standards? The first step is finding out the geometric features, climate, traffic density, and number of heavy vehicles of the location. These factors will allow to design the performance grade, which will be the target when construct the RAP. The location of the road which I designed RAP is general highway in New Jersey and the grade of PG binder use in this location is PG70-22. Since the location is near the ocean, the weather is expected to be cool and traffic is expected to be quite heavy due to heavy automobiles.

With the given data, the performance of design of pavement was analyzed with the RAP binder that was designed. Once the performance was analyzed, the energy consumption and environmental results were calculated and analyzed. The analysis was the most important part of the project because the project is not actually testing the created road designed; testing the actual performance requires building actual road and years of time to record performance.

Design and Analysis

The structural design and different rejuvenator types of RAP were tested through MEPDG and PaLATE to analyze physical properties, cost and environment. The rutting and fatigue cracking are analyzed and discussed its result. The cost concerns material production during initial construction and maintenance stages. The environmental result demonstrates the amount of chemical emissions during production and transportation during initial construction, and maintenance. The cost and environmental results are calculated at per kilometer length of road.

Asphalt Design

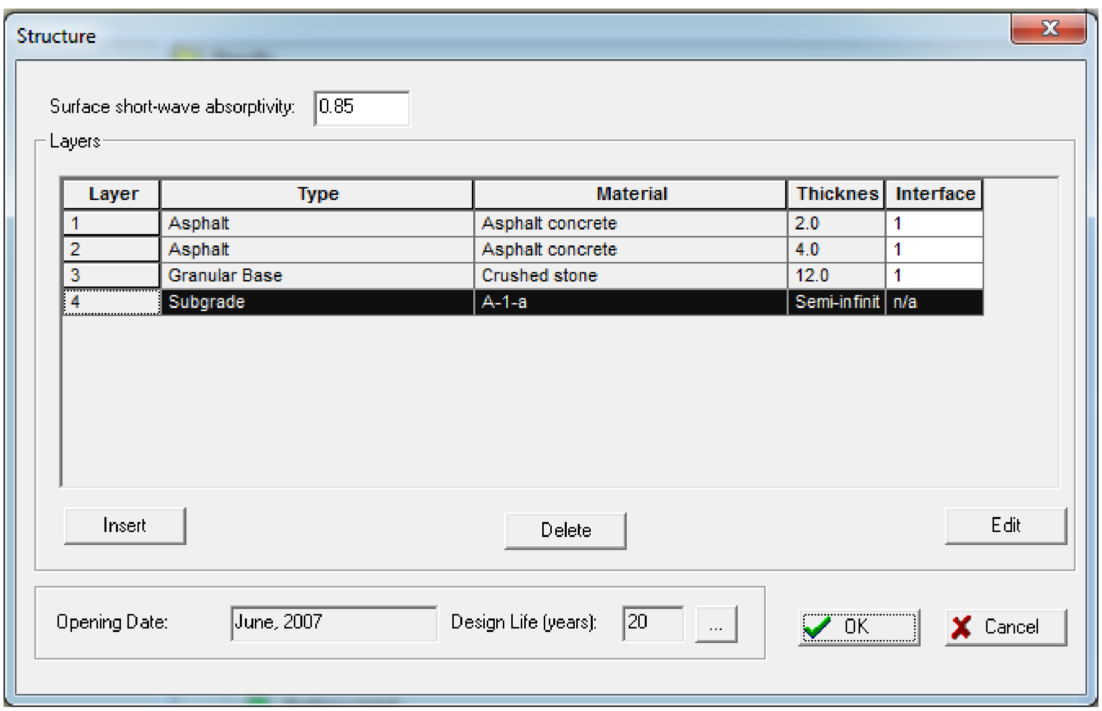

Figure 10 Structural design of asphalt mix road

The structural design of RAP asphalt road was created carefully by considering the climate information, RAP material property and traffic data. The program ME-PDG was very important tool which adjusted the structural design of asphalt road. The Figure 10 is an asphalt pavement design consists of three major layers; asphalt, base and subgrade.

When the rutting and fatigue cracking are tested, the asphalt and base layers have to be thick enough to prevent subgrade rut. The New Jersey high roads have 6inches of Asphalt layer thickness, which tells that there can be up to 6 inch-thick layer of RAP. The standard performance grade of New Jersey highway roads is PG70-22. The available RAP binder performance grades for the project are PG73.3-30.7, PG78.2-22.4, PG78.2-19.1, PG73.8-27.4, PG71.8-32.9 and PG71.9-28.6[12]. Since the RAP binders are slightly stiffer, it cannot have 100% RAP design: one or two inches are fixed with virgin asphalt layer. For the virgin asphalt layer, PG 64-22 binder was used; the stiffness of road may lower the quality road, because people prefer to drive on smoother road. Four inches thick RAP layer is stiff enough prevent subgrade rutting. Also, the RAP binders can perform much below -22 degrees Celsius that thermal crack is prevented highly. In ME-PDG, the performance grades of both asphalt layers were input as PG70-22 to test general performance. Although the aggregate data and air void ratio are automatically determined by standard road system in ME-PDG, they were changed to actual design in order to adjust the performance and to have accurate RAP design.

The type of base layer was determined by geographic feature. The base of the road contains mostly crushed stones because New Jersey directly contacts Atlantic Ocean. The thickness of base is tested though ME-PDG and resulted as 12 inches thick, which is viable. The total thickness of asphalt and base are 18 inches thick and these layers can perform at least 20 years. Although 10 inches thick also can perform for 20 years without rutting and cracking failure, the design was overestimated since there are roads with even thicker base. If there are roads with thicker base layer such as 15inches thick or 20inches thick, it is great opportunity to improve performance of the design as long as within the average thickness.

General Classification	Granular Materials 35 percent or less of total sample passing No. 200 (75 µm)								Silt-Clay Materials More than 35 percent of total sample passing No. 200 (75 µm)						
Group Classification	A-1		A-3 [1]		A-2				A-4		A-5	A-6		A-7	
	A-1-a	A-1-b	A-3	A-3a	A-2-4	A-2-5	A-2-6	A-2-7	A-4a	A-4b		A-6a	A-6b	A-7-5	A-7-6
Sieve analysis, percent passing:						*				**	*			*	
No. 10 (2 mm)	50 max														
No. 40 (425 µm)	30 max	50 max	51 min	[2]					[3]	[4]					
No. 200 (75 µm)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	35 max	36 min	50 min	36 min	36 min		36 min	
Characteristics of fraction passing No. 40															
Liquid limit	—	—	Non-	—	40 max	41 min	40 max	41 min	40 max		41 min	40 max		41 min	
Plasticity index	6 max	6 max	Plastic	6 max	10 max	10 max	11 min	11 min	10 max		10 max	11 – 15	16 min	≤LL-30	>LL-30
Group Index	0						4 max		8 max		12 max	10 max	16 max	20 max	
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine sand	Sand	Silty or clayey gravel and sand				Silty soils			Clayey soils			
General rating as subgrade	Excellent to good								Good to fair						

Notes

With the test data available, the classification of a soil is found by proceeding from left to right on the chart. The first classification that the test data fits is the correct classification.

* A-2-5 is not allowed under 703.16.B. A-5 and A-7-5 is not allowed under 703.16.A. See "Natural Soil and Natural Granular Soils" (203.02.H) in this manual

** A-4b is not allowed in the top 3 feet (1.0 m) of the embankment under 203.03.A.

[1] The placing of A-3 before A-2 is necessary in the "left to right" process, and does not indicate superiority of A-3 over A-2.

[2] A-3a must contain a minimum 50 percent combined coarse and find sand sizes (passing No. 10 but retained on No. 200, between 2 mm and 75 µm).

[3] A-4a must contain less than 50 percent silt size material (between 75 µm and 5 µm).

[4] A-4b must contain 50 percent or more silt size material (between 75 µm and 5 µm).

Table 1 AASSHTO Soil Classification

The table 1 demonstrates the standard specification of soils generated by AASHTO, American Association of State Highway and Transportation Officials. As determined previously, the New Jersey highway will have granular type of ground. The subgrade, A-1-a, is one of the soils with high performance and composes of granular materials.

Rutting Analysis

After the structure of asphalt was designed, the completed RAP road design was analyzed its rutting and fatigue cracking performance through ME-PDG with actual performance grades of asphalt layers. The PG grade of top virgin asphalt layer was fixed to PG64-22 and the PG grade of four-inch asphalt layer used all the available RAP binders: PG73.3-30.7, PG78.2-22.4, PG78.2-19.1, PG73.8-27.4, PG71.8-32.9 and PG71.9-28.6

The figures below are the analysis of rutting result.

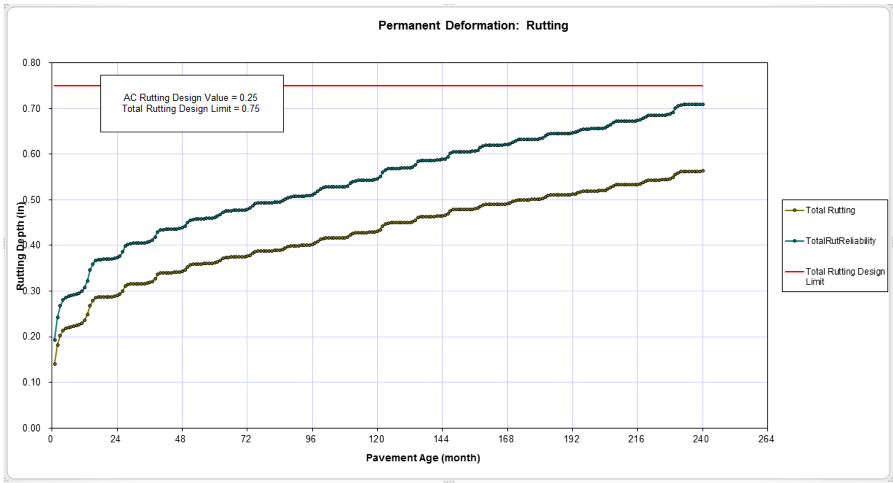

Figure 11 Rutting Result of PG70-28

Since the performance grade has six degree interval, PG73.3-30.7 binder and PG73.8-27.4 binder are rounded to PG70-28. The red line in the line graph represents the total rutting design limit, which means if the total rutting depth exceeds the limit, rutting failure will occur. The brown line is the expected total rutting and blue line is the total rut reliability, which is overestimation of rutting result. Throughout the rutting and fatigue cracking analysis, reliability result was used to prevent underestimation. The PG70-28 binder has total rutting depth of .71inch at 20 years, which does not exceed limit of .75inch as illustrated in the Figure 11.

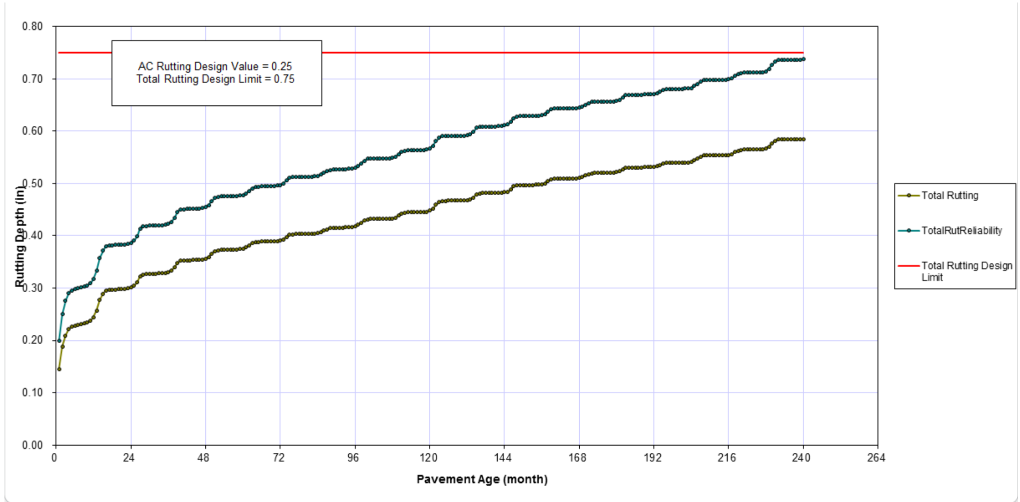

Figure 12 Rutting Result of PG70-34

When the PG70-34 binder used, total rutting reliability depth was .74 inch at 20 years which does not exceed total rutting design limit of .75 inch. It is very important not to exceed the design limit because the RAP asphalt road design will not fail for at least 20 years even without maintenance.

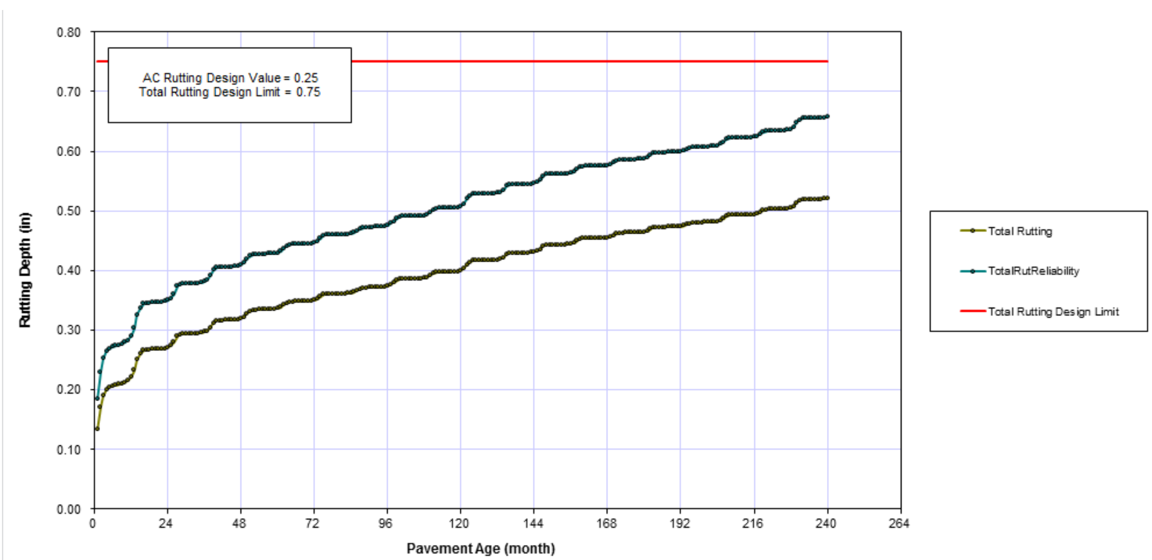

Figure 13 Rutting Result of PG76-22

When the PG76-22 binder used, total rutting reliability depths was .65inch at 20 years which is much below the total rutting design limit of .75 inch. This RAP is stiff enough to use for intersection or roads with large traffic. .

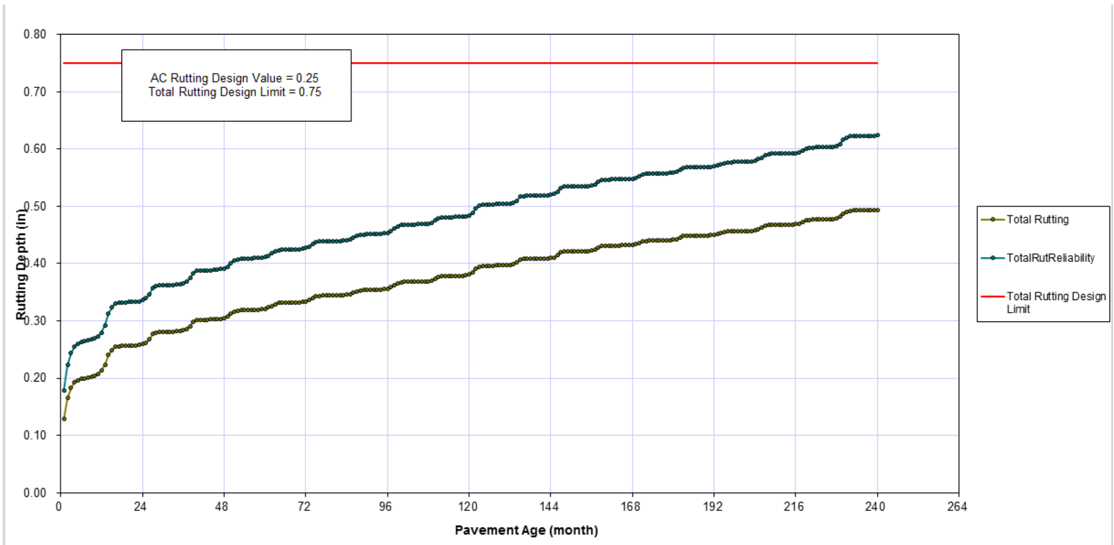

Figure 14 Rutting Result of PG82-10 (no rejuvenator)

When the PG82-10 binder used, total rutting reliability depths was .63inch at 20 years which is much below the total rutting design limit of .75 inch. This RAP is also stiff enough to use for intersection or roads with large traffic.

The Rutting Results of all the RAP binders can perform with the created structural design. These results that the created RAP design viable to use for actual road design. However, the fatigue cracking and thermal cracking also have to be evaluated to determine whether the RAP binders have endurance or not.

Fatigue Cracking Analysis

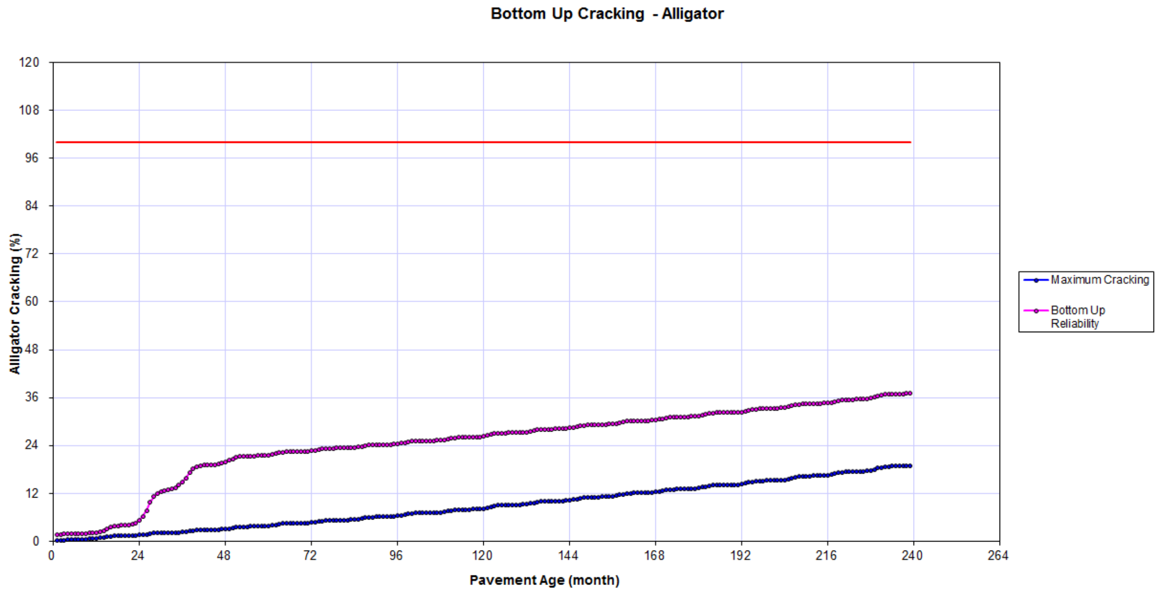

Figure 15 Fatigue Cracking Result of PG70-28

The blue line in the graph represents the maximum fatigue cracking of PG70-28 RAP binder. The purple line represents the bottom up reliability, or the fatigue cracking reliability. Unfortunately, the fatigue cracking graph of program ME-PDG does not have maximum cracking limit, which is about 50%, or the thermal cracking result. Therefore, the thermal cracking results can be estimated with the performance grade. New Jersey performance grade for highways have -22 degrees Celsius. Since the low temperature of this binder is -28 degrees Celsius, thermal cracking will not affect the fatigue cracking result. Same manner as rutting result, the bottom up reliability overestimates and determine the cracking result. The bottom up reliability is resulted as 37.1% cracking which is below the limit.

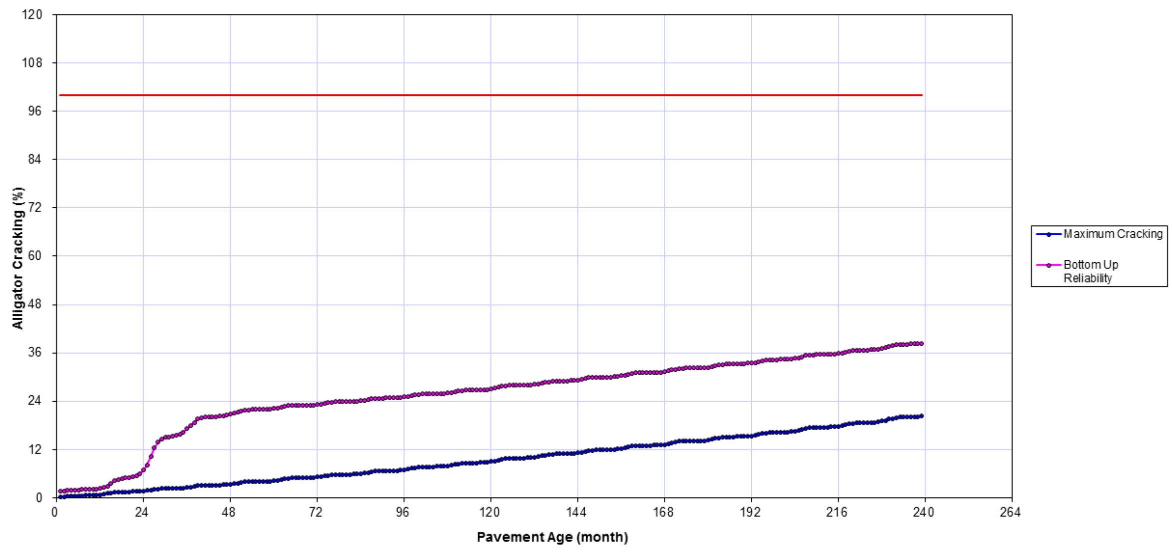

Figure 16 Fatigue Cracking Result of PG70-34

PG70-34 RAP binder has great performance in preventing thermal cracking. When PG70-34 RAP binder was used, the bottom up reliability was 37.1% at 20 years which is much below 50%. This RAP binder is durable enough to perform at least 20 years.

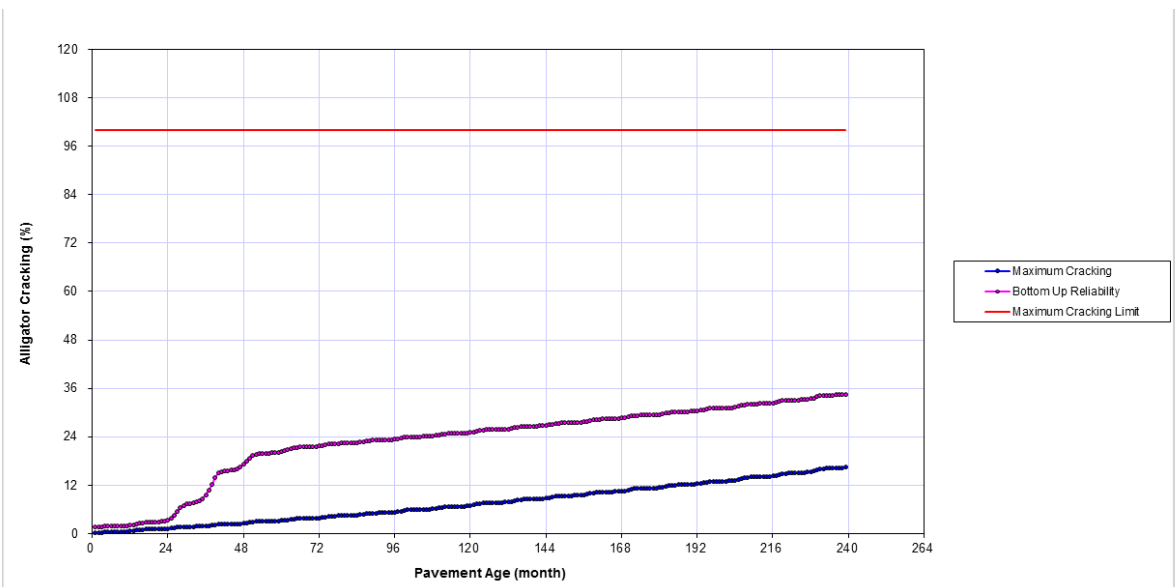

Figure 17 Fatigue Cracking Result of PG76-22

PG76-22 RAP binder has good performance in preventing thermal cracking. When PG76-22 RAP binder was used, the bottom up reliability was 34.4% at 20 years which is much below 50%. This RAP binder is durable enough to perform at least 20 years.

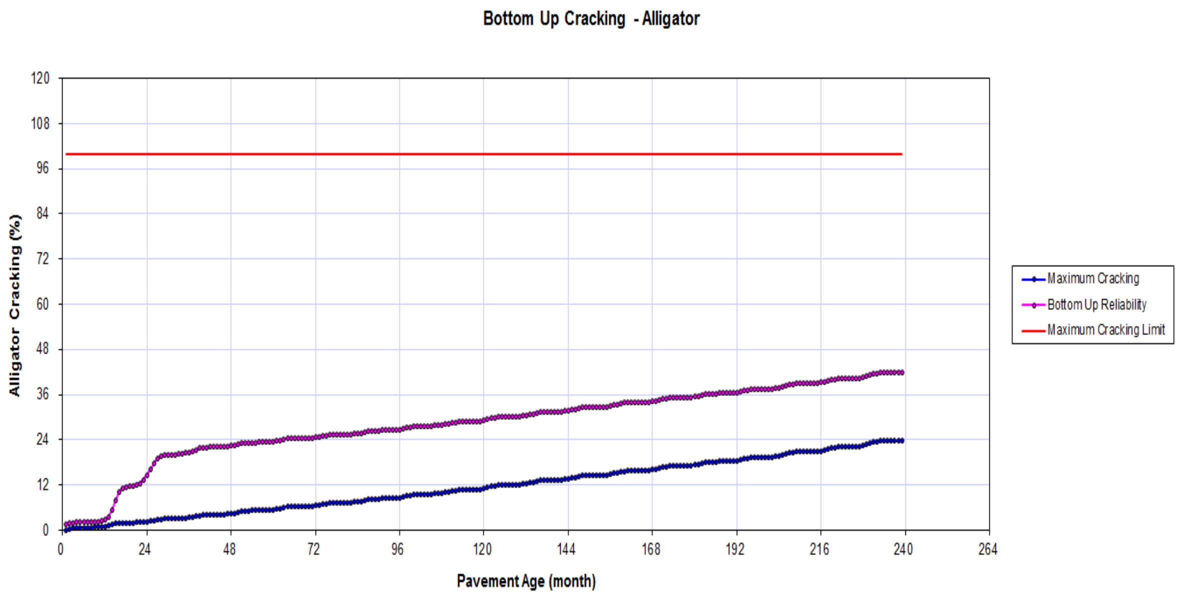

Figure18 Fatigue Cracking Result of PG82-10 (no rejuvenator)

The figure 17 explains the importance of rejuvenator. PG82-10 RAP binder will not prevent thermal cracking because the lowest temperature binder can stand is -10 degrees Celsius; average lowest temperature of highway is -22 degrees Celsius to -26 degrees Celsius. Although the bottom up reliability of PG82-10 calculated as below 50% of cracking, overly high stiffness and thermal crack will affect the fatigue cracking result. This RAP binder is not durable enough to perform at least 20 years.

Table2 Rutting and Fatigue Result Comparison

PG	Rutting at 20yrs (in)	Cracking at 20years(%)
70-28	0.71	37.1
70-34	0.74	38.3
76-22	0.65	34.4
82-10	0.62	42.1
	Choose 76-22	

The table 2 is the comparisons of rutting and fatigue cracking results for each RAP binders with different rejuvenators. The table definitely demonstrates that RAP binder of PG76-22 has least rutting depth. Also fatigue cracking is very low that thermal cracking will not crack over 50% cracking. The rutting and fatigue cracking analysis shows that the created RAP asphalt road design works best with RAP binder of PG76-22.

The performance grade of RAP binder that is going to be used for the design is determined, the next question is, is the 4inch RAP layer is economically and environmentally efficient? In order to understand these factors, I replaced portions of RAP layer to virgin material and calculated the total construction cost and environmental result to figure out if there should be more proportion of RAP required or not.

Cost Analysis

The total cost analysis contains two major stages, the initial construction of asphalt layers and maintenance costs. The spread sheet, PaLATE contains all the cost data and materials densities information. Starting from 4inches of RAP asphalt mix, each analysis replace 1inch of RAP asphalt mix with virgin asphalt layer; so compared among 4inch RAP asphalt layer, 3inch RAP asphalt layer plus 1inch new asphalt layer, 2inch RAP asphalt layer plus 2 inch new asphalt layer, 1inch RAP plus 3 inch new asphalt layer, and pure virgin asphalt.

Table3 New material cost per Km during initial construction

	binder volume (yd^3)	binder mass (tons)	binder price (fixed, $/ton)	binder cost ($)	Aggregate Volume (yd^3	Aggregate Mass (tons)	Aggregate price ($/ton)	Aggregate cost ($)
0in RAP	58.7	49.3	532.5	26252.25	1114.4	2485.1	9.33	23185.98
1in RAP	48.925	41.1	532.5	21885.75	928.7	2071	9.33	19322.43
2in RAP	39.2	32.9	532.5	17519.25	743	1656.9	9.33	15458.88
3in RAP	29.4	24.7	532.5	13150.62	557.3	1242.8	9.33	11595.13
4in RAP	19.6	16.5	532.5	8767.08	371.5	828.4	9.33	7729.39

Table4 RAP cost per Km during initial construction

	Rap binder volume	binder mass	Rap production cost	(40~60% less than reconstruction)		RAP cost ($)
0in RAP	0	0	266.25	(-50%)		0.00
1in RAP	9.8	18.13	266.25	(-50%)		4827.11
2in RAP	19.6	36.26	266.25	(-50%)		9654.23
3in RAP	29.32	54.242	266.25	(-50%)		14441.93
4in RAP	39.1	72.335	266.25	(-50%)		19259.19

Table 3 and 4 represent the inputs of required materials, average price of materials output of initial construction cost. The two key factors, material mass and material costs, are the mainly concerned to compare the efficiency.

The 0inch RAP contains 6inche-thick layer of virgin asphalt binder and aggregates and virgin materials consist most of production cost. The densities of materials and binder price are provided in given data from PaLATE[13]. The masses of required asphalt were 49.3-tons of binder and 2,485.1 tons of aggregates, which resulted to have 26,252.25 US dollars of binder cost and 23,185.98 dollars of aggregate cost. Since there was no asphalt reused for this design, the result should be the most expensive.

The 1inch RAP contains 5inch-thick layer of new asphalt and 1inch-thick layer of asphalt mix with RAP. The mass of required new asphalt were 41.1 tons of binder and

2,071 tons of aggregates. The construction of asphalt binder cost was 21,885.75 dollars and aggregate cost was 19,322.43 dollars. The mass of RAP binder was 18.13 tons, which costs 4,827.11 dollars. Also, producing RAP saved 18.13tons of asphalt binder and 414.1 tons of new aggregates.

The 2inch RAP contains 4inch-thick layer of new asphalt and 2inch-thick layer of RAP. The mass of required materials were 32.9 tons of new asphalt binder and 1,656.9 tons of new aggregates. The construction of asphalt binder cost was 17,519.25 dollars and aggregate cost was 15,458.88 dollars. The mass of RAP binder was 36.26 tons, which resulted 9,654.23 dollars of RAP cost. Producing RAP saved 36.26 tons of asphalt binder and 828.2 tons of new aggregates which are twice of the saved masses of 1inch RAP.

The 3inch RAP contains 3inch-thick layer of new asphalt and 3inch-thick layer of RAP. The mass of required new asphalt were 32.9 tons of binder and 1,242.8 tons of aggregates. The construction costs were 13,150.62 dollars of new binder and 11,595.13 dollars of new aggregates. The mass of RAP binder was 29.32 tons, which costs 14,441.93 dollars. These results are very important, because this design contains 3 inches of RAP and 3 inches of virgin material. The construction of virgin materials costs total of 24,745.75 dollars while RAP construction costs only 14,441.93 dollars; RAP construction is much economical than the new asphalt construction. Producing RAP saved 54.242 tons of asphalt binder and 1,242.3 tons of new aggregates.

Finally, the 4inch RAP contains 2inch-thick layer of new asphalt and 6inch-thick layer of RAP. The mass of required materials were 16.5 tons of new asphalt binder and 828.4 tons of new aggregates. The construction of asphalt binder cost was 8,767.08 dollars and aggregate cost was 7,729.39 dollars. The mass of RAP binder was 72.34 tons, which costs

19,259.19 dollars. The result is significant that the cost of RAP construction exceeds the cost of virgin asphalt construction. Producing RAP saved 72.34 tons of asphalt binder and 1656.7 tons of new aggregates.

The two tables, 5 and 6, show the significant change of materials and costs. When the more RAP is used for asphalt mix, the result seems better because higher content RAP asphalt road design saves more resources and money. Higher content of RAP has less new material cost but higher RAP construction cost.

Table5 Maintenance for Rutting cost per Km

Rutting Thickness (inch)	Volume (yd^3	Binder mass (tons)	Aggregate mass (tons)	Binder cost ($)	Aggregate Cost ($)	Overlay Cost ($)
1.5	293	12.3	620.7	6552.945	5791.322265	512.75

Table 6 Maintenance for Cracking cost per Km

	At 4 year Fatigue	At 8 year Fatigue	At 12 year Fatigue	At 16 year Fatigue	at 20 year Fatigue
Cracking result	20%	23%	27%	31%	34%
Cracking volume (yd^3)	234.6	269.79	316.71	363.63	398.82

Crack Sealing	At 4 yrs	At 8 yrs	At 12 yrs	At 16 yrs	At 20 yrs
Sealing Cost ($)	117.3	134.895	158.355	181.815	199.41

Tables 5 and 6 demonstrate the total maintenance cost which requires road maintenance. Table 5 shows the required amount of materials required for overlay to prevent excessive rutting. There will be two maintenance frequency required for rutting prevention at eighth year and 16th year. The expected rutting depth of asphalt design is estimated from rutting result of PG76-22 analysis[14]. Table 6 illustrates the expected costs of crack sealing every four years. The result explains that major cracking happens in first four years and the cracking volume increases linear over time.

The main expense during maintenance is rutting prevention. Generally, there are four maintenances required for twenty years. The rutting is prevented through new HMA overlay, which pave new thin layer of new asphalt mix. The thickness of required new asphalt was found in rutting result of PG76-22. The total thickness of overlay asphalt is 1.5 inch, volume of 293 cubic yard, 12.3 tons of virgin binder, and 620.7 tons of virgin aggregates. Using the same densities and price of materials from initial construction, the binder was cost 6552.95 dollars, thin hot mix overlay procedure was cost 512.75 dollars and virgin aggregate was cost 5791.32 dollars.

The maintenance result supports the idea of using higher content of RAP binder. Since the high content of RAP asphalt mix designs has two maintenance frequencies, the material cost, which consists of majority maintenance cost, is much less than the high content of new asphalt designs.

Environmental Results Analysis

The Environmental Results include consumptions of energy in mega-Jules and water in kilo-gram. Also, the table summarizes the production of chemicals such as carbon dioxide (CO_2) in kilo-gram, mono-nitrogen oxide (NO_x) in gram, sulfur dioxide (SO_2) in gram, and carbon oxide (CO) in gram. The environmental results are summarized into tables to compare how much energy was consumed or chemical was released during construction and maintenance. These data contributed in finding final design of hot asphalt mix of RAP. The targeting designed RAP content in the asphalt mix is less chemical emission and less energy consumption. The asphalt mix was tested for 1km length of the road.

Table 7 Chemical Emission per Km for 0 inch RAP Asphalt Mix Layer

Chemical Emission for 0 inch RAP layer				
	CO_2 (Kg)	Nox (g)	SO2(g)	CO(g)
Initial Production	82,405	362,039	305,138	269,062
Initial Transportation	2,966	158,000	9,480	13,167
Maintenance	52,750	369,385	187,568	171,819
Total	138,121	889,424	502,186	454,048

Table 8 Energy & Water Consumption per Km for 0 inch RAP Asphalt Mix Layer

0inch RAP		
	Energy (MJ)	Water Consume (Kg)
initial construction	706374	469
Maintenance	226071	183
Total	932445	652

The Table 7 and 8 demonstrate the environmental results of new asphalt design conducted from PaLATE; the chemical emission and energy and water consumption respectively. The hot asphalt mix design with new materials consumes about 700,000 mega-Jules of energy and 469 kilo-grams of water during the construction. To the environment, new asphalt design emits about 85,000 kilo-grams of carbon dioxide, 500,000 grams of mono-nitrogen oxide, 314,000 grams of sulfur dioxide, and 282,000 grams of carbon oxide.

During the maintenance, new asphalt design also consumes 226,071 mega-Jules of energy and 183 kilo-grams of water. The maintenance process will emit 52,750 kilo-grams of carbon dioxide, 369,385 grams of mino-nitrogen oxide, 187,568 grams of sulfur dioxide and 171,819 grams of carbon oxide.

The total environmental data is expected result data at 20 years if the design is constructed. Total environmental data includes both initial construction and maintenance environmental data. For the designed model, new hot asphalt mix design consumes total of 932,445 mega-Jules of energy, 652 kilo-grams of water. The asphalt emits total of 138,121 kilo-grams of carbon dioxide, 889,424 grams of mono-nitrogen oxide, 502,186 grams of sulfur dioxide and 454,048grams of carbon oxide.

Table 9 Chemical Emission per Km for 1 inch RAP Asphalt Mix Layer

Chemical Emission for 1 inch RAP layer				
	CO_2 (Kg)	Nox (g)	SO2(g)	CO(g)
Initial Production	69,450	306,788	254,617	225,314
Initial Transportation	3,954	210,665	12,640	17,555
Maintenance	52,750	369,385	187,568	171,819
Total	126,154	886,837	454,825	414,688

Table 10 Energy & Water Consumption per Km for 1 inch RAP Asphalt Mix Layer

1inch RAP		
	Energy (MJ)	Water Consume (Kg)
initial construction	626369	396
Maintenance	226071	183
Total	852440	579

The table 9 and 10 demonstrate the environmental results of 1 inch RAP asphalt mix design. The data includes data in the same manner as 0 inch RAP asphalt mix road data (new asphalt). The maintenance environmental results are exactly the same as new asphalt, because they require same maintenance procedures. In total, the 1 inch RAP design will consume 852,440 mega-Jules of energy and 579 kilo-grams of water during the construction. The design will emit 126,154 kilo-grams of carbon dioxide, 886,837 grams of mono-nitrogen oxide, 454,825 grams of sulfur dioxide and 414,688 grams of carbon oxide. The results show the energy consumption and chemical emission reduced over all.

Table 11 Chemical Emission per Km for 2 inch RAP Asphalt Mix Layer

Chemical Emission for 2 inch RAP layer				
	CO_2 (Kg)	Nox (g)	SO2(g)	CO(g)
Initial Production	56,496	251,541	204,099	181,569
Initial Transportation	4,943	263,329	15,800	21,944
Maintenance	52,750	369,385	187,568	171,819
Total	114,189	884,255	407,467	375,332

Table 12 Energy & Water Consumption per Km for 2 inch RAP Asphalt Mix Layer

2inch RAP		
	Energy (MJ)	Water Consume (Kg)
initial construction	546,364	319
Maintenance	226071	183
Total	772,435	502

The table 11 and 12 summarizes the environmental result of 2 inch RAP design. The environmental results of maintenance are equal to new asphalt and 1 inch RAP designs. The total cost of energy consumption is 772,435 mega-Jules of energy and water consumption of 502 kilo-grams. This asphalt design emits total of 114,189 kilo-grams of carbon dioxide, 884,255 grams of mono-nitrogen oxide, 407467 grams of sulfur dioxide and 375,332 grams of carbon oxide. The energy consumption and chemical emission are also reduced as the RAP content increased.

Table 13 Chemical Emission per Km for 3 inch RAP Asphalt Mix Layer

Chemical Emission for 3 inch RAP layer				
	CO_2 (Kg)	Nox (g)	SO2(g)	CO(g)
Initial Production	43,544	196,295	153,581	137,825
Initial Transportation	5,835	310,856	18,651	25,905
Maintenance	52,750	369,385	187,568	171,819
Total	102,129	876,536	359,800	335,548

Table 14 Energy & Water Consumption per Km for 3 inch RAP Asphalt Mix Layer

3inch RAP		
	Energy (MJ)	Water Consume (Kg)
initial construction	466,348	242
Maintenance	226071	137
Total	692,419	380

The table 13 and 14 are tables of the environmental result of 3 inch RAP asphalt mix design. The environmental results during maintenance were improved by having less energy and water consumption and less gas emission, because of new maintenance method. During the construction, 3 inch RAP design consumes total of 692,419 mega-Jules of energy and 380 kilo-grams of water. The asphalt emits total of 102,129 kilo-grams of carbon dioxide, 876,536 grams of mono-nitrogen oxide, 359,800 grams of sulfur dioxide and 335,548grams of carbon oxide. The environmental result of 3inch RAP asphalt mix design is improved from 2inch RAP asphalt mix design.

Table 15 Chemical Emission per Km for 4 inch RAP Asphalt Mix Layer

Chemical Emission for 4 inch RAP layer				
	CO_2 (Kg)	Nox (g)	SO_2(g)	CO(g)
Initial Production	30,587	141,042	103,060	94,076
Initial Transportation	6,727	358,382	21,503	29,865
Maintenance	52,750	369,385	187,568	171,819
Total	90,065	868,809	312,131	295,760

Table 16 Energy & Water Consumption per Km for 4 inch RAP Asphalt Mix Layer

4inch RAP		
	Energy (MJ)	Water Consume (Kg)
initial construction	386,244	169
Maintenance	226071	137
Total	612,315	307

The table 15 and 16 are the environmental results of 4inch RAP design. During the construction, 4 inch RAP design consumes total of 612,315 mega-Jules of energy and 307 kilo-grams of water. The 4inch RAP asphalt mix design emits total of 90,065 kilo-grams of carbon dioxide, 868,809 grams of mono-nitrogen oxide, 312,131 grams of sulfur dioxide and 295,760 grams of carbon oxide.

The tables 6 through 10 discover that energy requirement and water consumption are linearly decreasing, which explains more use of reclaimed asphalt pavement saves energy significantly. The chemical emission results also seem to have linear relationship. The major chemical emission is during the production of hot asphalt mix. Although the transportation has less amount of chemical emission compare to production, the results explain how more distance travel effects environment negatively.

Results

The programs, ME-PDG, produced the rutting and fatigue data to design 100% RAP road design, which gave positive result that it is technically possible to construct 100% RAP road and can last for 20 years. However, the design had to be modified for a smoother design and higher quality.

Table17 Total Cost per Km

Total Cost	Total Cost ($/Km)
0 inch RAP	62,295.25
1 inch RAP	58,892.31
2 inch RAP	55,489.37
3 inch RAP	52,044.70
4 inch RAP	48,612.68

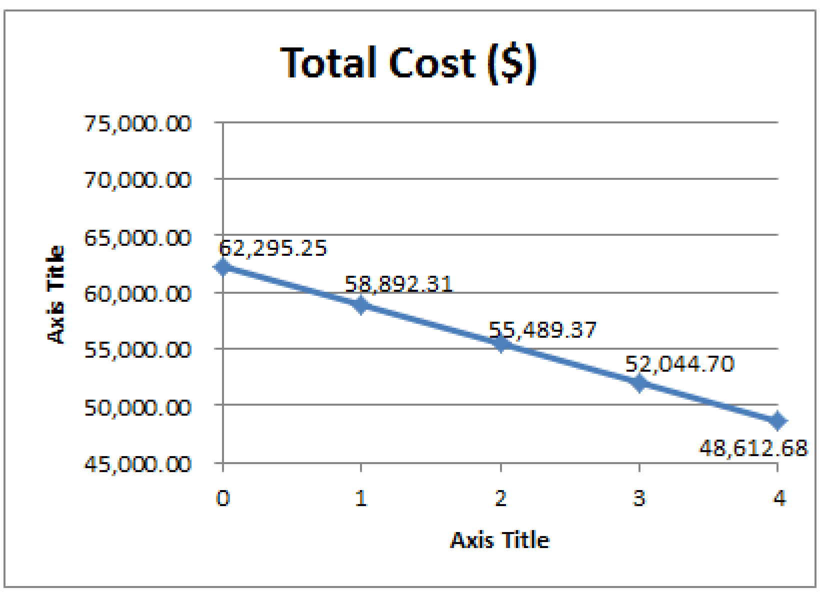

Figure 19 Total cost result plot

The analysis of initial construction and maintenance costs explains that producing hot asphalt mix higher RAP reduces the cost by a lot. The cost is directly related to amount new material required. Therefore, 4 in RAP asphalt mix design is most cost efficient among other RAP asphalt mix designs. The table 17 concludes the total amount of spending during construction and maintenances. Due to high price of new material, new asphalt road design, or 0 inch RAP design, has cost of 62,295 dollars in total which is the most among. When 1inch of new asphalt replaced with RAP, 1inch RAP asphalt mix design, the total cost required 58,892 dollars. When 2inch of new asphalt mix materials replaced with RAP, the total cost was 55,489 dollars. About 52,044 dollars is expected spent for 3 inch RAP asphalt mix design. And for the most amount of RAP, 4 inch RAP asphalt mix design requires about 48,612 dollars. The graph in figure 19 illustrates the total result in scatter plot. The cost is reducing at linear way with slope of about 3400 dollars.

Table 18 Total Resource Consumptions per Km

Total Resource Consumption per Km	Aggregate (tons)	Binder (tons)	Energy (MJ)	Water (Kg)
0 inch RAP	3,438	68	932,445	652
1 inch RAP	3,024	60	852,440	579
2 inch RAP	2,610	52	772,435	502
3 inch RAP	1,967	39	692,419	380
4 inch RAP	1,553	31	612,315	307

The table 18 includes major consuming resources for each RAP designs. The 0 inch RAP design, or new asphalt design, consumes 3,438 tons of aggregates, 68 tons of binder, 932,445 mega Jules of energy and 652 kilo-grams of water in total. The 1 inch RAP design consumes 3,024 tons of aggregates, 60 tons of binder, 852,440 mega-Jules of energy and 579 kilo-grams of water. The 2 inch RAP design consumes 2,610 tons of aggregate, 52 tons of binder, 772,435 mega-Jules of energy and 502 kilo-grams of water. The 3 inch RAP design consumes 1,967 tons of aggregates, 39 tons of binder, 692,419 mega- Jules of energy and 380 kilo-grams of water. The 4 inch RAP design has 1,553 tons of aggregates, 31 tons of binder, 612,315 mega-Jules of energy and 307 kilo-grams of water consumptions in total.

This table finalizes the higher content of RAP asphalt mix saves more than half of resources than pure virgin asphalt. Furthermore, over thirty percent of energy was saved by using 4 in of asphalt with RAP.

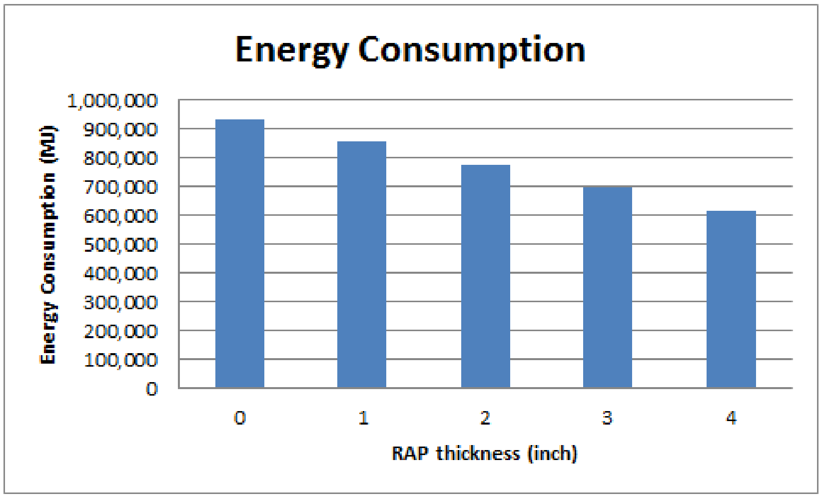

Figure 20 Energy Consumption vs RAP thickness

The figure 20 is bar graph of energy consumption of each RAP asphalt mix design: 0 inch through 4 inch. The graph illustrates the linear relationship between energy consumption and RAP content.

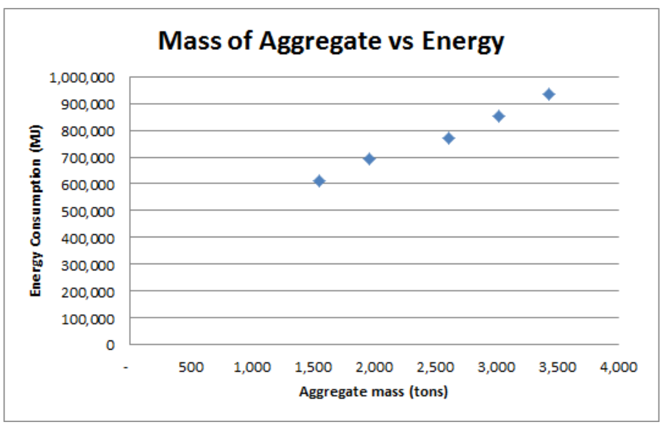

Figure 21 Energy Consumption vs Aggregate mass

Since both Energy consumption and aggregate mass same relationship with RAP content, they were compared in scatter plot in Figure 21. As expected, the scatter plot of mass of aggregate versus energy had positive linear relationship. The slope is about 164.7 mega-Jules required for each ton of aggregate.

Table 19 Total Chemical Emission per Km Result

Total Chemical Emission per Km	CO_2 (Kg)	NOx (g)	SO_2(g)	CO(g)
0 inch RAP	138,121	889,424	502,186	454,048
1 inch RAP	126,154	886,837	454,825	414,688
2 inch RAP	114,189	884,255	407,467	375,332
3 inch RAP	102,129	876,536	359,800	335,548
4 inch RAP	90,065	868,809	312,131	295,760

Table 19 represents the total chemical release amout results. The results for certain designs are very similar. The main reason of having such relationship is constant amount of chemical production during transportation (appendix #). The new asphalt design and 3 inch RAP design have less than 6,000 kilo-grams of carbon dioxide production, around 300,000 grams of mono-nitrogen oxide production, around 20,000 grams of sulfur dioxide and 25,000grams of carbon oxide productions. On the other hand, the 1 inch RAP design, 2 inch RAP design and 4 inch RAP designs have higher chemical productions; less than 30% (Appendix#). These designs produced about 7,600 kilo-grams of carbon dioxide, 400,000 grams of mono-nitrogen oxide, 24,500 grams of sulfer dioxide and 34,000grams of carbon oxide. The 4 inch RAP had the most chemical emission in all and new asphalt had least among all designs.

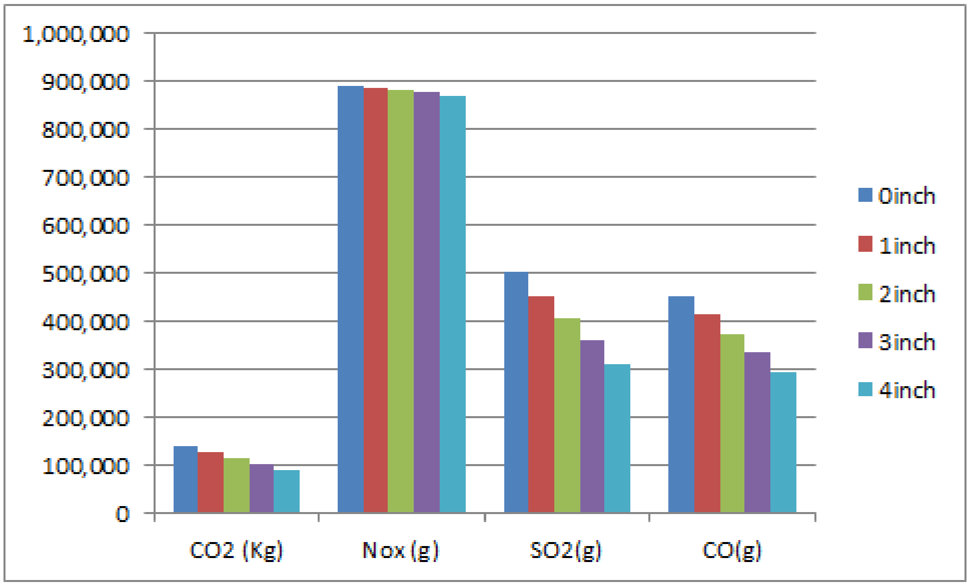

Figure 22 Total Chemical Emission Bar Graph for each design

The figure 22 is a bar graph of chemicals each design produce, which the data conducted from table 19. The graph shows as more RAP is replaced by new material, less chemicals are produced. Each graph has linear reduction of chemical emission. The reason the chemical emission is reduced linearly that major emission is produced during the new asphalt mix production. Since higher RAP content of asphalt mix requires less, these relationships illustrated on graph directly.

The results concludes that 4 inch RAP design has best result in cost and resource saving but most energy consumption and chemical production. Although, the pollution amount is less than 30% compare to new asphalt design, the environmental result is not so efficient for 4 inch RAP. The 3 inch RAP binder has efficient results for every factors, cost, material and pollution. The final design of the project is 3 inch RAP of 4 inch thick main asphalt design.

Conclusion

Result conclusion

Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	12	1	2	391
Wearing Course 2	12	1	4	782
Wearing Course 3				0
Subbase 1	12	1	12	2,347
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			18	3,520

Embankment and Shoulder Volume [yd^3]:	
Period of Analysis [yrs] (40 yrs or less)	20

Figure 23 Final Design

The expected result for the project was to show that the asphalt design of 4 inch RAP, 100% RAP, can perform best in every aspect. The result had best efficient cost, energy consumption and resource consumption of 4 inch RAP asphalt mix as well.

The final design of RAP highway contains 4 layers, 2 inch thick new asphalt layer, 4 inch RAP layer, 12 inch of subbase and the subgrade. The design's life expectancy is at least 20 years without rutting or fatigue cracking failure. The expected construction and maintainenace cost is 54,195 dollars. It consumes almost same energy and produce less chemicals. However, the design saves a lot of materials and perform long period.

Possible Improvements

There are many possible improvements that engineers have been made in RAP production: such as HERA system and SMART Pave. These improvements are made to counter the historical failure in RAP road design and can change the environmental and cost result.

HERA system is improvement in asphalt binder production and recycling. “This is something we can be very proud of,” says Chairman of VolkerWessels’ Management Board, Gerard van de Aast. “The HERA System showcases our innovative strength and helps create a cleaner environment.” The asphalt is normally produced by directly heating the raw material, which cause high chemical emission and worsen of quality.[15] HERA system is indirect heating system which heats the layer that covers asphalt. This method significantly reduces the chemical emission and produces the better quality asphalt binder.

SMART Pave is the portable asphalt recycler, which produces RAP on site in environmentally friendly way.[16] The analysis and result of the project demonstrated how RAP production emits too much chemical. Such technology encourages pavement engineers to design 100% RAP design road.

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Appendix A – RAP Binders

There are 6 types of rejuvenators used to rejuvenate RAP binders: organic oil, aromatic extract, wasted engine oil, tall oil, wasted vegetable oil and grease. The RAP binders are provided by Martin S. Zaumanis[17], Graduate Students of WPI.

The figure 24 is the material property of the asphalt mix. The figure shows there are 5% of binder content and 95% of aggregates. Once the old asphalt is milled and binder and aggregates are segregated, the aggregates are directly reused without any treatment. The proportion of size of aggregates follows the standard. About 95% of aggregates passing 9.5 millimeters diameter sieve size, 67% of aggregates passing 4.75 millimeters diameter sieve size, and less than 10% passing .08 millimeter diameter sieve size. The aggregates are relatively fine because there is no aggregate larger than 12.5 millimeters diameter.

The advantage in using fine aggregate is the asphalt mix becomes malleable, which gives cracking resistance to asphalt mix. The only disadvantage is producing finer aggregates require energy to crush them; fortunately, RAP does not require to produce aggregate.

		Material:			Re-graded RAP	
		Test date:			01.08.2013	
sample before washing, g					2355.3	
f sample after washing, g					2168.5	
Sieve Size			Size, mm	.45 Power	Retained on sieve, g	Passing, %
coarse aggregate	50mm	2"	50	5.815		
coarse aggregate	37.5mm	1 1/2"	37.5	5.109		
coarse aggregate	25.0mm	1"	25.00	4.257		
coarse aggregate	19.0mm	3/4"	19.00	3.762		100.00
coarse aggregate	12.5mm	1/2"	12.50	3.116		100.00
coarse aggregate	9.5mm	3/8"	9.50	2.754	55.2	97.66
coarse aggregate	5.6mm		5.60	2.171		
fine aggregate	4.75mm	#4	4.75	2.016	715.3	67.29
fine aggregate	2.36mm	#8	2.36	1.472	632.3	40.44
fine aggregate	1.18mm	#16	1.18	1.077	210.9	31.49
fine aggregate	600μm	#30	0.60	0.795	130.6	25.94
fine aggregate	300μm	#50	0.30	0.582	199.8	17.46
fine aggregate	150μm	#100	0.15	0.426	202	8.88
fine aggregate	75μm	#200	0.08	0.312	23	7.91
	Dust content				7.93%	
precision (total mass), %					100.03	
Binder content					5.22%	
ective binder content Pbe						
efore rejuvenator addition					1.52	
Rejuvenator content						
after rejuvenator addition					5.22%	
after rejuvenator addition					1.52	

Figure 24 Material Property of Asphalt mix with RAP

The Table 20 is the reference for PG grade of virgin binder, pure RAP binder and RAP binders with different types of rejuvenators. Compare to virgin binder, pure RAP binder perform better in high temperature but worse in low temperature. In other word, RAP binder is very stiff. After the pure RAP binder's performance grade was tested, about 5% volume of binder of rejuvenators were added to RAP binder; which is about .25% of total volume.

Table 20 PG grades of tested binders

Test sample	Virgin PG64-22	RAP binder	Organic Oil	Aromatic Extract	WEO	Tall oil	WV Oil	WV Grease
Continuous PG Grade	67.4 - 25.6	94.0 - 12.3	73.3 - 30.7	78.2 - 22.4	78.2 - 19.1	73.8 - 27.4	71.8 - 32.9	71.9 - 28.6
Rotational Visc, 135C, cps	812.5	4325	1000	1638	1225	1050	962.5	1163

Appendix B – Programs

This section of the report illustrates the procedure for using program input with images. As explained in Program[18] section, both MEPDG and PaLATE requires the asphalt road design as input, but MEPDG provides retting and fatigue cracking result and PaLATE provides cost and environmental result.

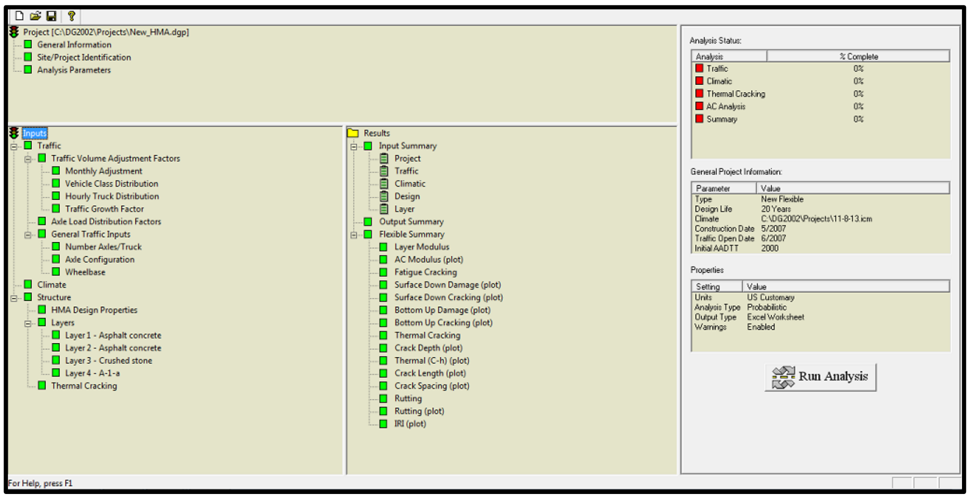

Figure 25 M-E PDG main page

MEPDG calculates many types of road design. Other than hot mix asphalt design, it also manages continuously reinforced concrete pavement (CRCP), jointed plain concrete pavement (JPCP) and RAP. The special characteristic of this program is that it contains the traffic, geometric feature and climate data for different locations, which were provided by American Association of State and Highway Transportation Officials (AASHTO). The data includes up to 2002 year data, which is accurate enough to calculate road performance for next twenty years.

The Figure 25 is the main page of program, MEPDG. The input can be done by double clicking the text under “inputs”. When there is required input that is not completed, the green box next to the input will turn red box. As the figure represents, the main inputs are traffic, climate and structural design.

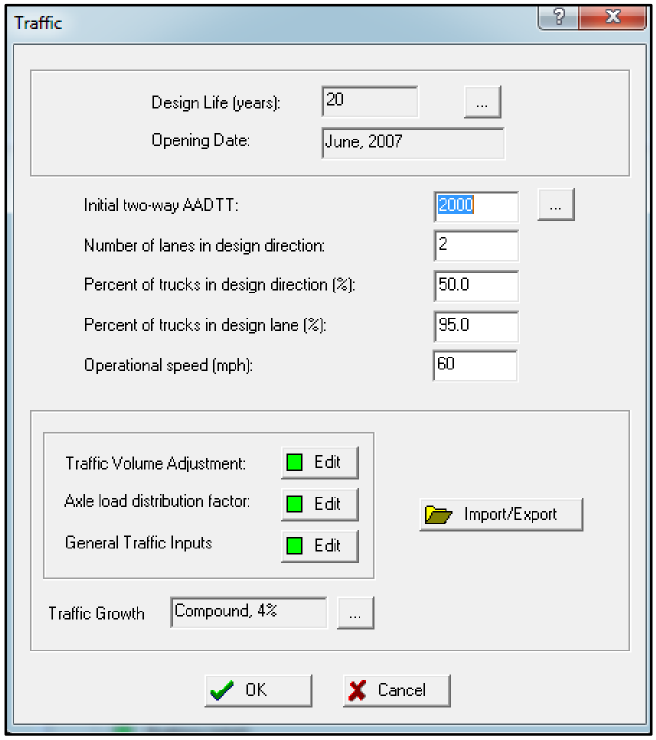

Figure 26 M-E PDG Traffic Input

Since traffic and climate data are already programmed in MEPDG, there is no need to change the input for traffic unless the location has specific characteristics which needs to be changed. The Figure 26 demonstrates the required inputs. The project is looking for twenty years of design life for general highway road. The design life was fixed to twenty years and rest inputs are unchanged as average traffic roads. However, average annual daily truck traffic (AADTT), number of lanes, speed limit and road size can be changed.

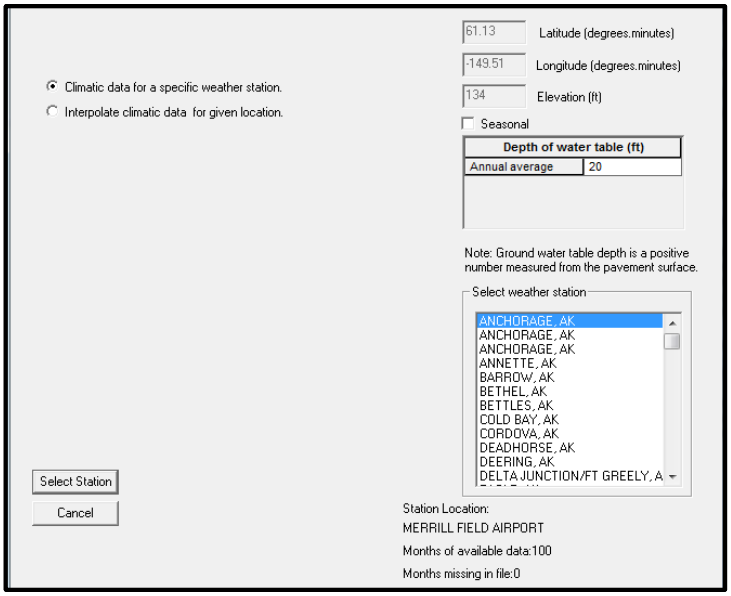

Figure 27 M-E PDG Climate Input

The figure 27 is the climate input for MEPDG. As the figure shows, the input contains latitude, longitude, elevation and water depth as geometric feature. The locations are listed under the Select weather station.

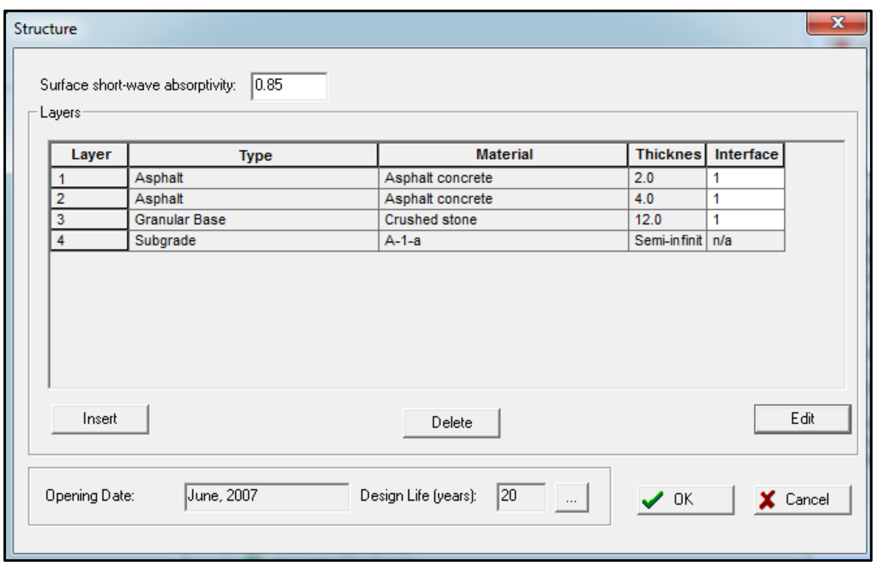

Figure 10 Structural design of asphalt mix road

The Figure 10 is input screen of structural design. The layers can be designed anyways user want to be, but the result can be design failure. The program uses the terms from AASHTO, so the program is very easy to make input. Each layer requires the material property as input as shown in Figure 28.

The Figure 28 is input for asphalt material properties. Under the asphalt mix tab, the RAP material property was input as shown in Figure 22[19]. Under Asphalt Binder tab, the performance grade of asphalt binder is input as the figure below shows. The Asphalt General property requires general properties such as effective binder content, air void ratio, unit weight and Poisson's ratio.

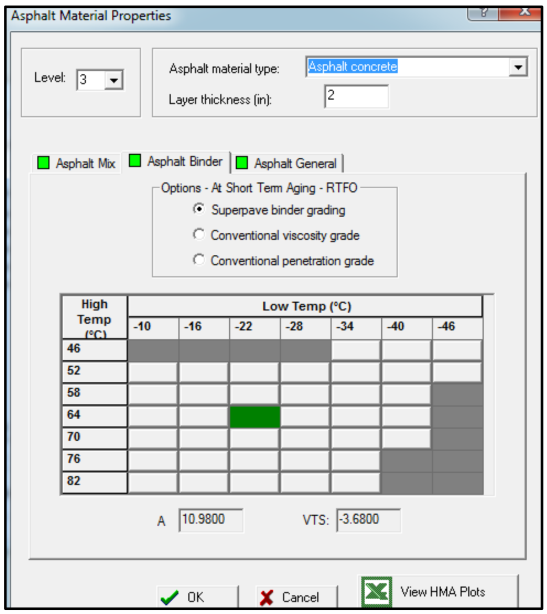

Figure 28 M-E PDG asphalt material properties

Once three inputs, traffic, climate and structure, are made, the program produces the performance result of design in Microsoft Excel spread sheet. As shown in Figure 24, the result includes layer modulus, fatigue cracking[20] and damages, Surface down damage and cracking, thermal cracking, and rutting. For fatigue cracking and rutting, even the scatter plot is also produced to visually represent the result.

The spread sheet PaLATE is a tool which has equations and reference data to calculate cost and environmental results in Microsoft Excel. The spread sheet requires concrete or asphalt pavement design, initial construction information, maintenance information, equipment and costs as inputs.

Only fill in the appropriate cells

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]:	
Period of Analysis [yrs] (40 yrs or less)	**40**

Figure 29 PaLATE design input

The design has input on the width, length and depth of the different layers of the pavement. The Volumes for each layer are calculated and used as reference for volume inputs on other worksheets, such as initial construction and maintenance. Furthermore, the volume of embankment can be input and shoulder material if the project requires. The period of analysis is the input for the design life of the pavement design. Densities for materials are listed under the inputs to help users to use as reference. The graphic of the assumed roadway design is color-coded to guide the user throughout the analysis.

Initial Construction has input for each layer of the road design. For each layer, volume, transportation distance and transportation mode are required to be entered or selected. Using the total volume of each layer from design part, the 5% volume of binder and 95% volume of aggregates were input for initial construction for this project. Transportation distance is the input of distance measurements between hot asphalt mix plant and site, and between site and landfill. The transportation distance determines the chemical emission during transportation. The expected distances were less than 25 miles long, but for overestimation, the both distances, plant to site and landfill to site, were assumed to be 25 miles. If the road requires 4 inch of RAP material, the distance between site and landfill becomes 0. If RAP is reused on-site, enter 0 for transport distance. For a particular material for each layer, if multiple transportation methods are used, user should select the most dominant one.

Maintenance contains same input as initial construction, because same procedures in initial construction are repeated but only 1 layer of asphalt pavement requires. Since only new asphalt mix will be pave over damaged road, the distance from site to landfill is 0.

The equipment part provides the default equipment types for each process. The user can modify equipment model choice as needed, or disable equipment type by process by selecting "none". The properties of equipment are summarized next to the input to help user determine which equipment should be used. Some equipment might be outdated or consumes more energy than newer equipment. Therefore, the result is expected to be overestimated.

The costs of total project can be calculated through the spread sheet once the material costs are known. There are two tables for the cost input, green table and orange table. The green table is used for entering the total installed costs of the ready-mix materials, such as materials, equipment, labor, and overhead and profit, by year over the period of analysis. The orange requires entering the cost of each material that comprises the ready-mix materials by year over the period of analysis. In addition to the material cost, the cost of labor, equipment, and overhead and profit can be entered for each year for further investigation.

If the data for certain input are unknown, the provided data in data parts of worksheets can be used. There might be price change over time, but the provided data are import from actual data.

Appendix C – Human Toxicity

The human toxicity potential is total chemical produce during the construction and maintenance which harm to human body. The potential is cumulative measurement of every chemicals produced in grams. The Figures 30 through 34 are human toxicity which PaLATE calculated. This section of the report explains further environmental result which related to human body.

- The data are taken from 1Kilo-meter length of the road

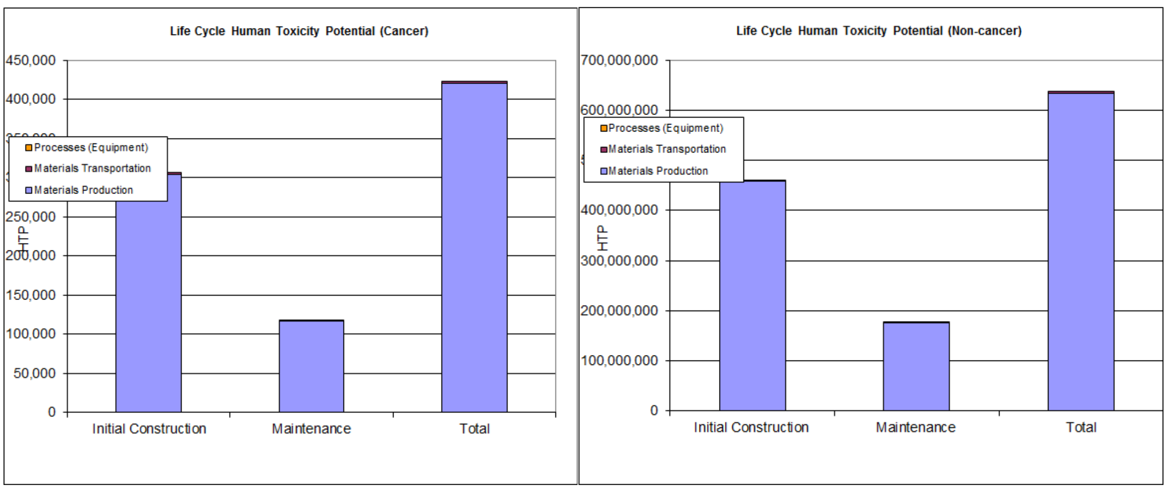

Figure 30 Human toxicity potential (Cancer & Non-cancer) for 0 inch RAP asphalt mix design

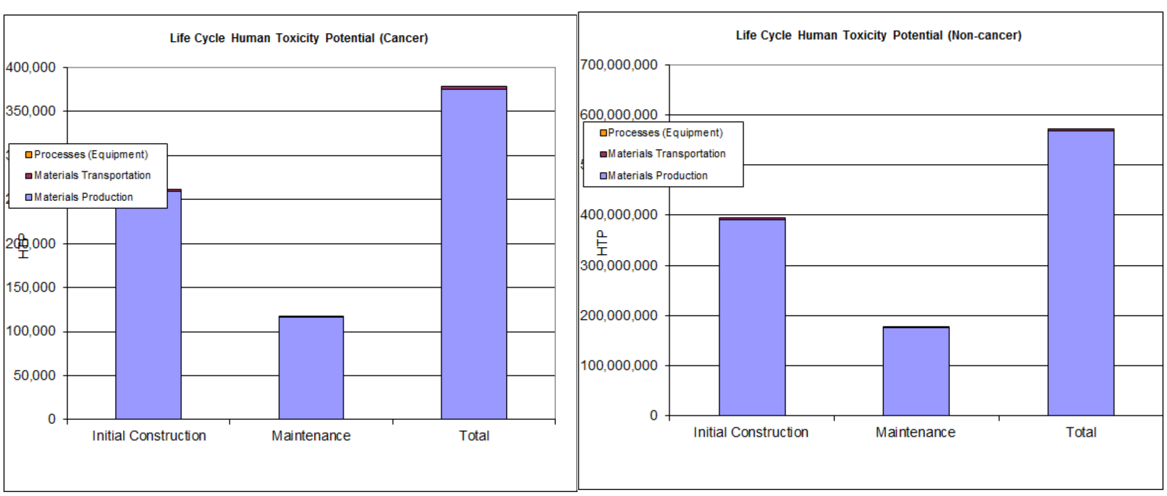

Figure 31 Human toxicity potential (Cancer & Non-cancer) for 1 inch RAP asphalt mix design

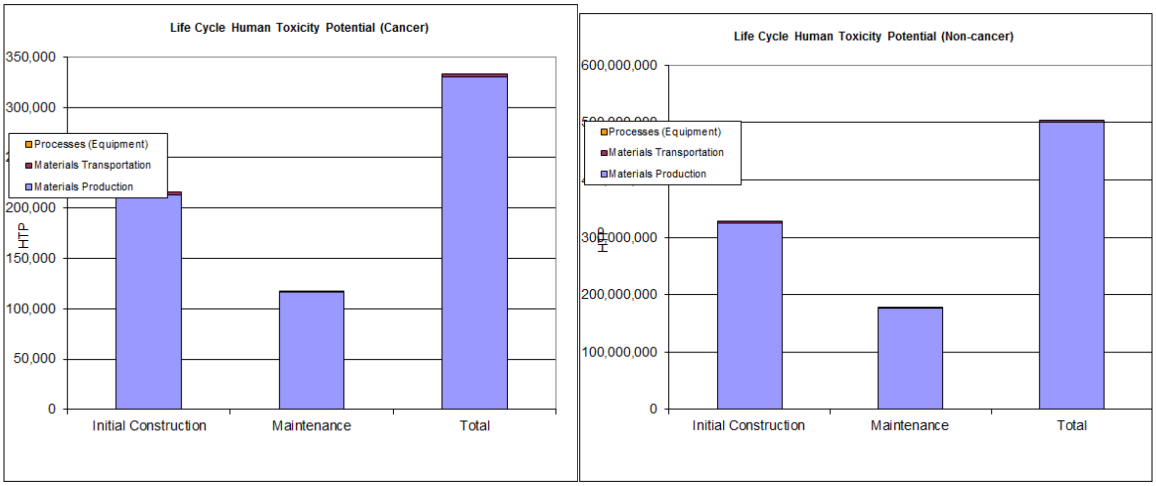

Figure 32 Human toxicity potential (Cancer & Non-cancer) for 2 inch RAP asphalt mix design

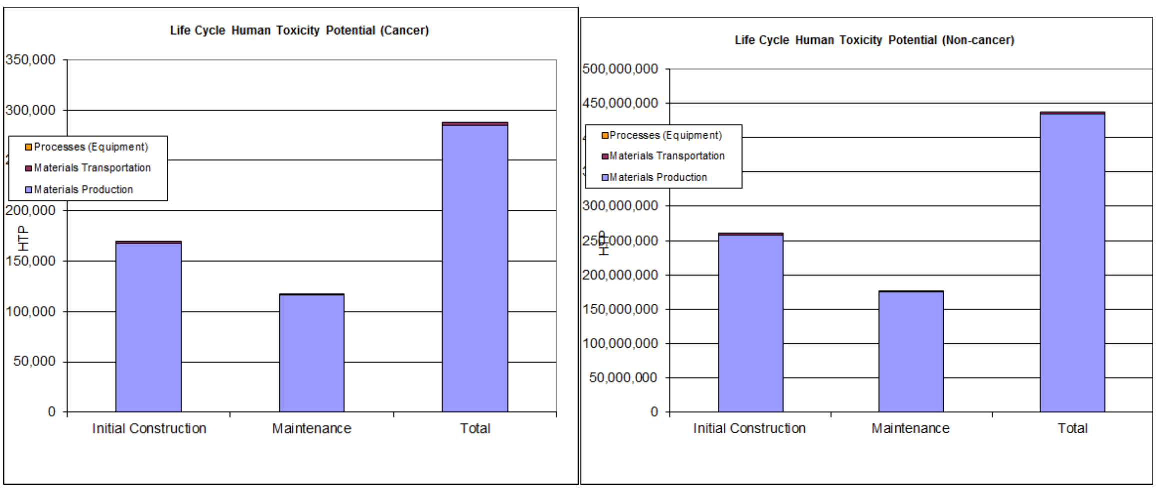

Figure 33 Human toxicity potential (Cancer & Non-cancer) for 3 inch RAP asphalt mix design

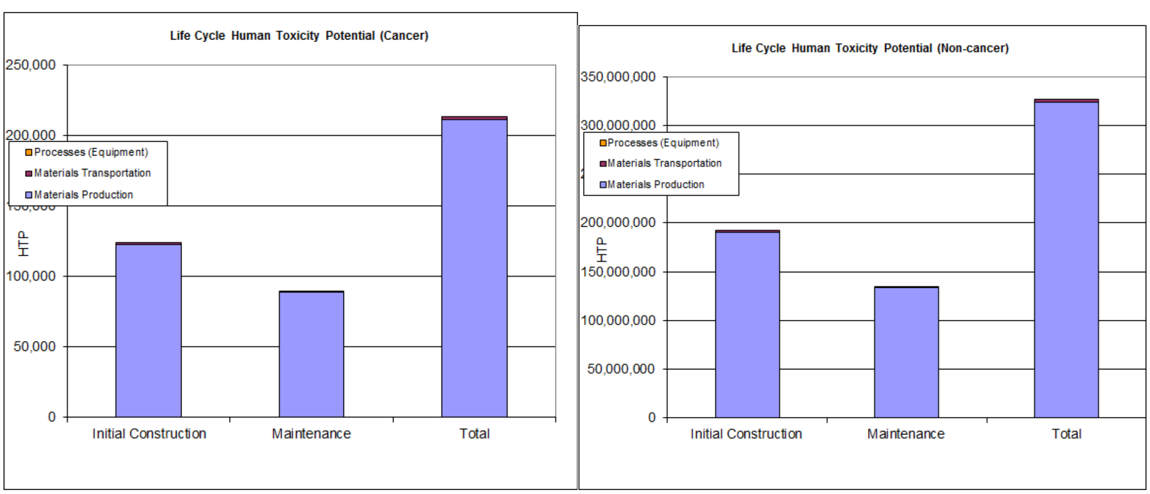

Figure 34 Human toxicity potential (Cancer & Non-cancer) for 4 inch RAP asphalt mix design

For analysis, 0 inch RAP asphalt mix design resulted about 420,000 grams of cancer potential and over 600,000 Kilo-grams of non-cancer toxicity. For 1 inch RAP asphalt mix design, there were over 350,000 grams of cancer potential and about 580,000 Kilo-grams of non-cancer toxicity. 2 inch RAP asphalt mix design resulted over 300,000 grams of cancer potential and about 500,000 Kilo-grams of non-cancer toxicity. The 3 inch RAP asphalt mix design had near 290,000 grams of cancer potential and about 440,000 Kilo-grams of non-cancer toxicity. The 4 in RAP asphalt mix design resulted about 210,000 grams of cancer potential and over 300,000 Kilo-grams of non-cancer toxicity

As summarized in Table 21, the chemicals that are harmful to human body are produced from 4 in RAP asphalt mix is almost half of the toxicity from new asphalt mix. The spread sheet did not specify the least or most amount chemical should be produced, but definitely explains the effect of RAP use decrease human toxicity.

Table 21 Human toxicity result

Total toxicity per Km	Cancer potential (g)	Non-Cancer potential (Kg)
0 inch RAP	425,000	630,000
1 inch RAP	375,000	580,000
2 inch RAP	330,000	500,000
3 inch RAP	290,000	440,000
4 inch RAP	210,000	330,000

Appendix D – Calculation

Cost: This is the calculation to find the total cost of RAP asphalt mix design and new material design. There are material production during initial stage and maintenance. The costs are calculated from the volume of materials are used by converting units to dollars. The density and price per mass are data found from PaLATE data tables[21].

Equation

Total Cost (C_T) = Binder cost during initial construction (C_{B-I}) + Aggregate cost during initial construction (C_{A-I}) + RAP production cost during initial construction (C_{RAP}) +maintenance cost (M)

M=Constant, because every design will experience same maintenance

Initial construction stage

$$C_{B-I} = Volume\ (yd^3) * Density\ \left(\frac{tons}{yd^3}\right) * New\ Binder\ price\ (\frac{\$}{ton})$$

$$C_{A-I} = Volume\ (yd^3) * Density\ \left(\frac{tons}{yd^3}\right) * New\ Aggregate\ price\ (\frac{\$}{ton})$$

$$C_{RAP} = Volume\ (yd^3) * Density\ \left(\frac{tons}{yd^3}\right) * RAP\ binder\ production\ price\ (\frac{\$}{ton})$$

binder cost ($/ton)	Binder Density (tons/yd^3)
532.5	0.84

Aggregate Cost	Aggregate Density(tons/yd^3)
9.33	2.23

RAP density (tons/yd^3)	RAP production cost ($/tons)
1.85	266.25

Maintenance

$$M = Binder\ cost + Aggregate\ Cost + Overlay\ Cost$$

$$Binder\ cost = Volume\ (yd^3) * Density\ \left(\frac{tons}{yd^3}\right) * New\ Binder\ price\ (\frac{\$}{ton})$$

$$Aggregate\ Cost = Volume\ (yd^3) * Density\ \left(\frac{tons}{yd^3}\right) * New\ Aggregate\ price\ (\frac{\$}{ton})$$

$$Overlay = Volume\ (yd^3) * Overlay\ price\ (\frac{\$}{yd^3})$$

Overlay Price ($/yd^3)
1.75

binder cost ($/ton)	Binder Density (tons/yd^3)
532.5	0.84

(RAP)

Aggregate Cost	Aggregate Density(tons/yd^3)
9.33	2.23

The equations above are equations used to calculate total cost. The volume of binder, aggregate and RAP binder depend on the RAP content for each design. Here is an example of cost calculation with 2 inch RAP asphalt mix design.

2inch RAP asphalt mix design cost example

- Initial production

$$C_{B-I} = 39.2\ (yd^3) * 0.84\ \left(\frac{tons}{yd^3}\right) * 532.5\ \left(\frac{\$}{ton}\right) = 17519.25$$

$$C_{A-I} = 743(yd^3) * 2.23\ \left(\frac{tons}{yd^3}\right) * 9.33\ \left(\frac{\$}{ton}\right) = 15458.88$$

$$C_{RAP} = 19.6(yd^3) * 1.85\ \left(\frac{tons}{yd^3}\right) * 266.25\left(\frac{\$}{ton}\right) = 9654.23$$

- Maintenance

$$Binder\ cost = 14.7(yd^3) * .84\ \left(\frac{tons}{yd^3}\right) * 532.5\left(\frac{\$}{ton}\right) = 6552.95$$

$$Aggregate\ Cost = 278.4\ (yd^3) * 2.23\ \left(\frac{tons}{yd^3}\right) * 9.33\ \left(\frac{\$}{ton}\right) = 5791.3$$

$$Overlay = 293\ (yd^3) * 1.75\ \left(\frac{\$}{yd^3}\right) = 512.75$$

$$C_T = 17{,}519.25 + 15{,}458.88 + 9{,}654.23 + 6{,}552.95 + 5{,}791.3 + 512.75$$

$$\boldsymbol{C_T = 55{,}489.37}\text{ dollars}$$

Notes

[1] Nam H. Tran, Adam Taylor, Richard Willis, *Effect Of Rejuvenator On Performance Properties Of Hma Mixtures With High RAP And RAS Contents*, http://www.eng.auburn.edu/research/centers/ncat/files/reports/2012/rep12-05.pdf

[2] Robert E. Boyer, *Asphalt Rejuvenators "Fact, or Fable"* (Asphalt Institutes, 2000) http://www.totalasphalt.com/docs/products/Asphalt-Rejuvenators_Fact-or-Fable.pdf

[3] Robert E. Boyer, *Asphalt Rejuvenators "Fact, or Fable"* (Asphalt Institutes, 2000) http://www.totalasphalt.com/docs/products/Asphalt-Rejuvenators_Fact-or-Fable.pdf

[4] Rajib B. Mallick & Tahar El-Korchi, *Pavement Engineering Principle and Practice* (CRC press Taylor & Francis group, 2009)

[5] Rajib B. Mallick & Tahar El-Korchi, *Pavement Engineering Principle and Practice* (CRC press Taylor & Francis group, 2009)

[6] http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/PDF/pgb_faq.pdf

[7] http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/PDF/pgb_faq.pdf

[8] Asphalt Institute, *Superpave Series 1* (Asphalt Institute, 1997)

[9] Table 17

[10] Page 48
[11] Appeidix B

[13] AppendixB
[14] Page 28
[15] https://sites.google.com/site/martinszaumanis/100-rap#TOC-RAP-Technologies

[16] https://sites.google.com/site/martinszaumanis/100-rap#TOC-RAP-Technologies

[17] https://sites.google.com/site/martinszaumanis/100-rap#TOC-RAP-Technologies

[18] Page 17

[19] Page 47

[20] Also called Bottom Up cracking
[21] Appendix B