USE OF RECYCLED ASPHALT

by

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To my late grandparents, Mrs. Ellis 'maNyathi' Hlabano and Rev. Moses Hlabano, for raising me, loving me unconditionally, believing in me, teaching me the importance of God and education, praying over me, and now, angels watching over me. Thank you.

Zincane izibongo zami.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The term Reclaimed Asphalt Pavement (RAP) is used to designate a material obtained from the removal of pavement materials. RAP is used across the US in multiple applications, largely on asphalt pavement layers. RAP can be described as a uniform granular non-plastic material, with a very low percentage of fines. It is formed by aggregate coated with a thin layer of asphalt. It is often used mixed with other granular materials. The addition of RAP to aggregates decreases the maximum dry unit weight of the mixture and decreases the optimum water content. It also increases the Resilient Modulus of the blend, but decreases permeability. RAP can be used safely, as it does not pose any environmental concerns. The most important disadvantage of RAP is that it displays significant creep. It seems that this is caused by the presence of the asphaltic layer coating the aggregate. Creep increases with pressure and with temperature, and decreases with the degree of compaction. Creep can be mitigated by either blending RAP with aggregate or by stabilization with chemical compounds. Fly ash and cement have shown to decrease, albeit not eliminate, the amount of creep. Mechanical stabilizing agents such as geotextiles may also be used.

1. INTRODUCTION

1.1 Background and Problem Statement

The term Reclaimed Asphalt Pavement (RAP) is used to designate those materials that are obtained from the removal of and/or processed pavement materials. Asphalt pavement can be removed by milling, which usually excavates the top 2 inches of the pavement, or full removal of the entire pavement. The material is transported to a facility for processing, which typically consists of further crushing, screening and storing. If properly treated, RAP may consist of well-graded aggregates coated with a bituminous asphalt (FHWA, 97). In fact, the large part of RAP is made of mineral aggregate (93 to 97% by weight), and the rest of hardened asphalt cement (3 – 7%). The properties of reclaimed asphalt strongly depend on the type of aggregate and bitumen used for the pavement and on the reclamation, processing and storage operations.

There is interest and an opportunity to use more reclaimed asphalt in asphalt mixes and for a better process for finding methods to utilize the reclaimed asphalt in highway fill sections. One of the deterrents for the employment of RAP in the past was reaching a minimum comfort level with the compaction necessary for the use of reclaimed asphalt in construction fill sections. Before using RAP in pavement, other than in asphalt layers, fills and in confined areas, concerns regarding the granulometry of the reclaimed asphalt, compaction and long-term behavior and environmental impact (e.g., contamination and toxicity), if any, need to be addressed. Also, there could be advantages of using RAP mixed with other materials, e.g., gravel or crushed stone or chemically treated.

1.2 Objective and Scope

The goal of the thesis is to investigate the use of RAP in pavement layers (other than asphalt layers), fills and/or in confined areas. The scope of the work consisted of compiling and analyzing all information and experience available on the subject. The objectives of the research are as follows:

1. Improve understanding of the mechanical properties of RAP materials: There is a rich literature on the mechanical properties of RAP materials, but it is clear that the

properties are highly variable and strongly dependent not only on the parent material, but also on the operations conducted for excavation, transportation, processing and storage.

2. Determine performance of RAP materials: RAP materials have been heavily reused for cold- and hot-mix pavements, and to a lesser extent in pavement layers, e.g., base or subbase, and in fills. The focus of the research is on the material characteristics, means and methods to place RAP in fill and base or subbase layers, as well as the expected and actual performance of these materials. An important aspect is the leaching of some of the chemicals in the RAP to the environment, degradation and time-dependent chemo-mechanical processes.

The objectives are accomplished through a number of tasks that include a comprehensive literature review and review of best practices by neighboring DOTs, laboratory work, and analyses.

1.3 Organization of the Thesis

This thesis consists of 5 chapters showing the findings of an in-depth literature review, laboratory test results and results of a survey on practices of departments of transportation (DOT).

Chapter 1 introduces the subject of the research. Chapter 2 provides a detailed summary of the mechanical properties of RAP found in the literature. Chapter 3 summarizes the results of soil characterization and proctor tests. Chapter 4 highlights existing RAP practices within the USA. The standard specifications of 8 different DOTs were studied and in addition, a survey was conducted to gain further knowledge on how the states are making use of RAP in their applications. Chapter 5 concludes and discusses the advantages and disadvantages of RAP.

2. MECHANICAL PROPERTIES

2.1 Granulometry

The granulometry of recycled pavement materials, RAP (Reclaimed Asphalt Pavement) or RPM (Reclaimed Pavement Material), is generally determined using screening tests. Typical screening tests involve the use of sieve analysis according to ASTM standards C 117 and C 136, and AASHTO Standards T-27 and T-11. When compared to traditional aggregates used in base/subbase course layers, RAP generally has a higher content of fines primarily due to the milling process involved in the production of RAP. In case of RPM, the inclusion of subgrade materials contributes to the higher fines content present. The gradation of RAP provides crucial information pertaining to the expected mechanical properties of RAP. Gradation of RAP provides an indication for the permeability, freeze-thaw characteristics and, based on the nature and amount of fines content, the shear strength. Different agencies have different minimum standard specifications for aggregates used in base or subbase layers to ensure quality control standards, hence it is important to obtain knowledge of gradation of RAP before considering its use in unbound pavement layers.

Table 2.1 represents the particle size distribution for different sources of RAP taken from existing literature:

Table 2.1 Particle size distribution reported in existing literature (2000 – 2016)

Reference	Material	% Passing											
		#200	#100	#50	#30	#16	#8	#4	3/8"	1/2"	3/4"	1"	1.5"
Bennert et al. (2000)	RAP	1	2	3	5	10	20	39	68	76		98	
Saeed et al. (2008)	RAP-LS-MS	3	5	9	12	19	27	38	62	75	95	95	100
	RAP-GR-CO	1	2	5	12	18	25	39	63	75	92	97	100
Thakur et al. (2010)	RAP - K25	6	10	16	24	35	52	75	91	96			
	RAP - US 83	8	13	23	34	48	64	85	96	98			
Kazmee et al. (2016)	RAP	0		2		15	30	54	87	94	98	100	
Edil et al. (2012)	RAP - TX	0	3	6	9	15	23	44	64	78	84	85	92
	RAP - MN	2	4	8	22	40	56	73	86	94	98	100	
	RPM - MI	2	3	7	16	20	34	49	68	82	93	98	100
Camargo et al. (2012)	RPM	5	6	10	17	25	39	60	78	86	95	99	100

From the data obtained from the literature review, one can observe that RAP displays a somewhat large range of values. This can be attributed to the fact that the gradation of RAP depends on the material used in the original asphalt concrete and the process used for obtaining the RAP. Figure 2.1 plots the values in Table 2.1.

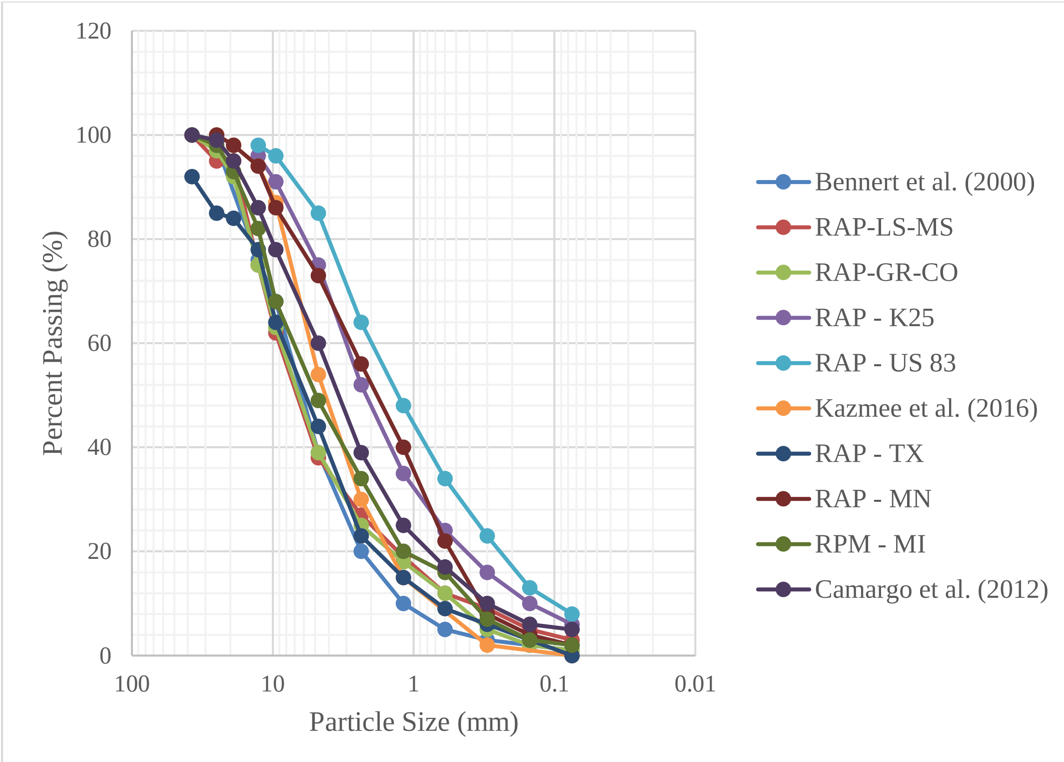

Figure 2.1 Gradation range of RAP

2.2 Compaction

The parameters of interest for compaction are the Optimum Moisture Content (OMC) and the Maximum Dry Density (MDD). The OMC and MDD values indicate the maximum relative density that can be achieved during field compaction. It is important to achieve a high relative density during compaction as it is significant for reducing the permanent deformation accumulated in the pavement layers. There is a clear trend in the literature about the presence of RAP leading to reductions in values of OMC and MDD. Wu et al. (2012) reported a decrease in OMC and MDD values as the percentage of RAP increased in blends of RAP and crushed basalt aggregates. Table 2.2 gives the values of OMC and MDD values for the different blends measured in Wu et al. (2012).

Table 2.2 OMC and MDD values reported in Wu et al. (2012)

RAP in aggregate blends	**OMC (%)**	**Max. Dry Unit Weight**	
		kN/m³	**lb/ft³**
0%	9.0	21.6	138.6
20%	8.8	21.0	135.0
40%	7.9	20.7	133.1
60%	7.5	21.0	135.0
80%	7.1	20.9	134.0

Bennert et al. (2000) also reported the OMC and MDD for blends consisting of different percentages of RAP and Dense Graded Aggregate Base Course (DGABC), as shown in Table 2.3.

Table 2.3 OMC and MDD values reported in Bennert et al. (2000**)**

Blended Material	**OMC (%)**	**Max. Dry Unit weight**	
		kN/m³	**lb/ft³**
100% DGABC	7.0	20.6	132.2
75% DGABC 25% RAP	7.0	20.2	129.5
50% DGABC 50% RAP	6.0	19.9	127.8
25% DGABC 75% RAP	5.5	19.2	123.2
100% RAP	5	18.4	118.0

It is clear from Table 2.3 that the OMC and MDD values decrease as the RAP percentage increases in the blend. The OMC and MDD values of pure RAP are also lower than the crushed aggregates. The lower values of MDD and OMC of RAP compared to those of crushed aggregates can be explained by the presence of asphalt coating of the RAP materials, which decreases the specific gravity and reduces the water absorption potential and inter-particle friction.

Most studies use Modified or Standard Proctor tests to determine compaction characteristics. In contrast, Kim et al. (2007) compared the results of a gyratory compaction test (GCT) versus those of proctor compaction test (PCT). Through comparisons with field measurements, it was determined that the OMC and MDD values obtained from GCT results had better correlation to field compaction results than PCT tests. The study also compared the values of OMC and MDD for different blends of RAP and MnDOT class 5 crushed aggregates for both GCT and PCT tests, as shown in Table 2.4.

Table 2.4 OMC and MDD values reported in Kim et al. (2007)

Blended Material	Proctor Compaction Test			Gyratory Compaction Test		
	OMC (%)	Maximum Dry Density		OMC (%)	Maximum Dry Density	
		kg/m^3	lb/ft^3		kg/m^3	lb/ft^3
100% Aggregate	10	2000	124.9	8.8	2032	126.9
75% Aggregate 25% RAP	10	2000	124.9	8.7	2032	126.9
75% Aggregate 50% RAP	9.5	1952	121.9	8.0	2032	126.9
25% Aggregate 75 RAP	8.5	1920	119.9	7.2	2032	126.9

From Table 2.4 one can infer that the OMC values decreased with the increase in RAP percentage for both types of compaction efforts as expected due to the presence of asphalt coating. The MDD values didn’t change as the RAP percentage increased in the GCT tests, but they decreased with increase in RAP percentage for the PCT tests.

The MDD and OMC values of pure RAP are generally lower than crushed aggregates used in base course layers. This has been systematically found in the literature (e.g., Edil et al. 2012, Saeed et al. 2008 and Kazmee et al 2016). Table 2.5 summarizes the OMC and MDD values of RAP and RPM obtained from the literature.

Table 2.5 Maximum Dry Density and Optimum Moisture Content of RAP and RPM

Material Used		Proctor Effort	Optimum Moisture Content (%)	Maximum Dry Unit Weight	
				(kN/m³)	(lb/ft³)
Bennert et al. (2000)	RAP	Standard	5	18.4	118.0
Saeed et al. (2008)	RAP (MS)[1]	Standard	6.3	19.5	125.3
	RAP (CO)	Standard	10.3	19.8	127.0
Thakur et al. (2010)	RAP - K25	Modified	3.8	17.5	112.2
	RAP - US 83	Modified	3.2	17.9	114.7
Kazmee et al. (2016)	RAP	Standard	6.2	18.9	121.4
Edil et al. (2012)	RAP (TX)	Modified	8	20.3	130.4
	RAP (MN)	Modified	6.7	20.8	133.6
	RPM (MI)	Modified	5.2	21.5	138.1
	RPM (NJ)	Modified	6.3	20.6	132.4
Camargo et al. (2012)	RPM	Modified	4.9	20.1	128.8

[1]*Values in parenthesis denote the State where the samples were collected*

OMC values for RAP range around 3.8 ~ 10.3 % and the MDD values range 1780 ~ 2121 kg/m^3. For RPM, the OMC values vary from 4.9 ~ 6.3 % and the MDD values range from 2,044 ~ 2,192 kg/m^3. The range of values is due to the method of compaction (Standard vs Modified Proctor) and to the different granulometry, as reported in the previous section. Figure 2.2 is a plot of the OMC and MDD values of RAP and RPM reported in the literature.

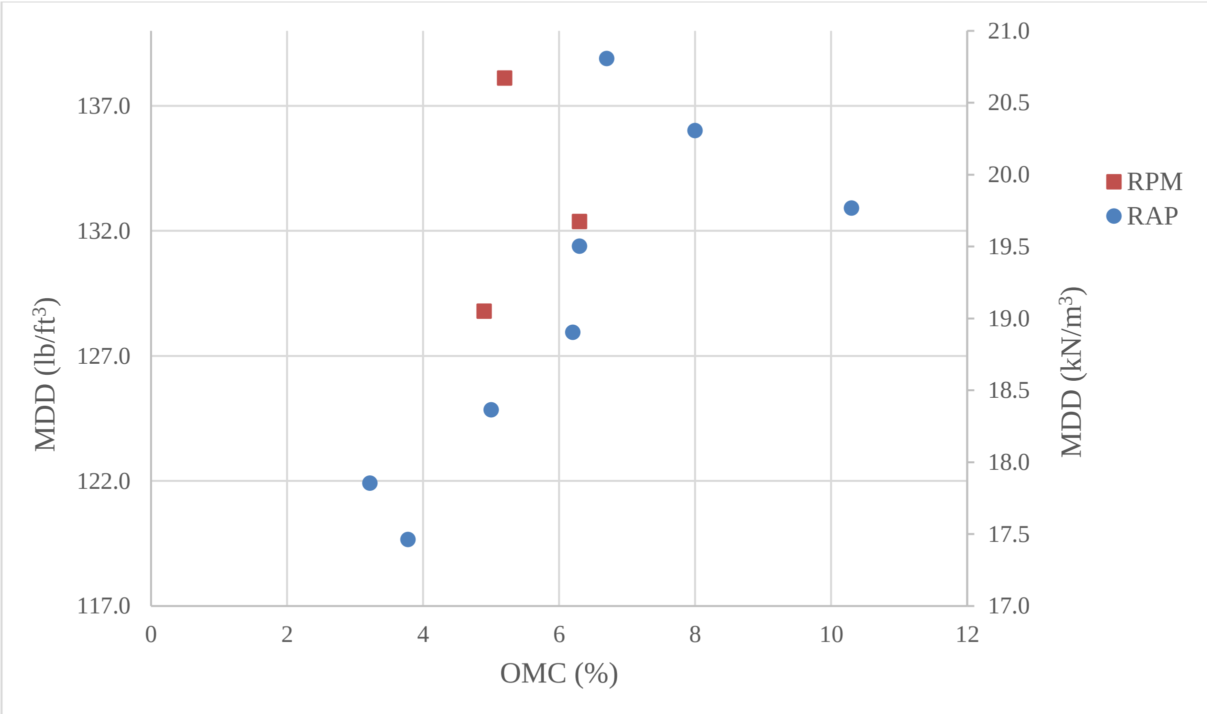

Figure 2.2 OMC and MDD values of RAP and RPM reported in the literature

2.3 Resilient Modulus

The resilient modulus, M_R, is a fundamental material property used to characterize the stiffness of unbound pavement materials. It is a linear-elastic modulus obtained from dynamic loading, defined as the ratio of the cyclic deviator stress to the resilient (recoverable) strain. It is a basic property that represents the stiffness of the material. The resilient modulus of recycled pavement materials RAP (Reclaimed Asphalt Pavement) or RPM (Reclaimed Pavement Material) is determined using tests. Typical tests may be done in accordance with the NCHRP protocol or following AASHTO specifications. A number of factors affect the M_R, some of which are moisture content, density, stress history, aggregate type, gradation, temperature, percent fines, and degree of saturation.

The literature shows that adding RAP to unbound base courses generally leads to an increase of the M_R of the material. Wu et al. (2012) reported an increase in M_R values as the percentage of RAP increased in blends of RAP and crushed basalt aggregates at both low and high cyclic stress. Figure 2.3 is a plot of the MR values of RAP reported in Wu et al. (2012), measured at a confining pressure of 103.5 kPa.

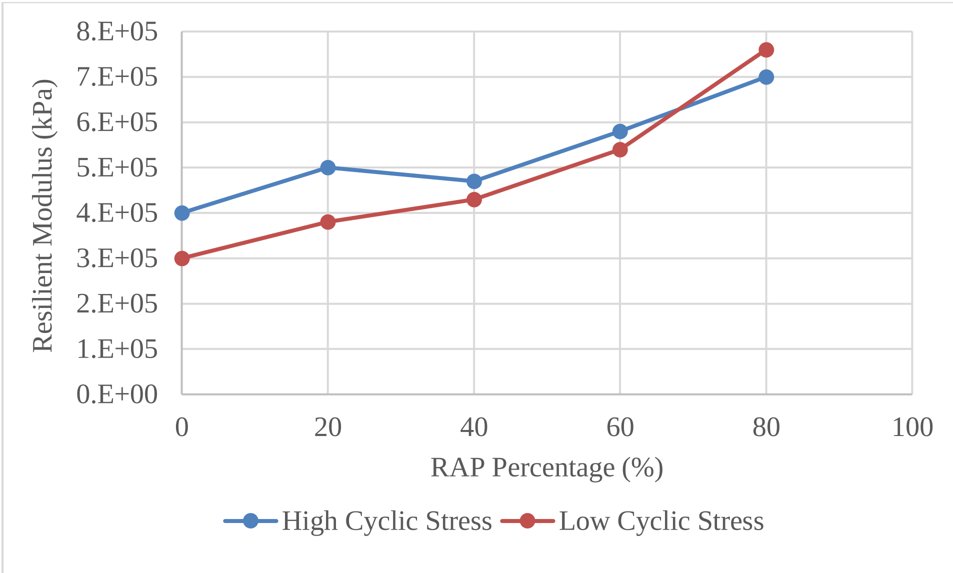

Figure 2.3 Resilient Modulus values of RAP reported in Wu et al. (2012)

Bennert et al. (2000) also reported the M_R for blends consisting of different percentages of RAP and Dense Graded Aggregate Base Course (DGABC). The DGABC has a maximum dry density of 2,098 kg/m^3, 7.6 % fines and a 7 % moisture content. The test results are shown in Table 2.6:

Table 2.6 Resilient Modulus of blended materials reported in Bennert et al. (2000)

Blended Material	M_R @ Bulk Stress of 144.7 kPa		M_R @ Bulk Stress of 344.7 kPa	
	MPa	psi	MPa	psi
100% DGABC, 0% RAP	116.1	16,838	179.5	26,034
75% DGABC, 25% RAP	159.1	23,076	234.2	33,968
50% DGABC, 50% RAP	178.1	25,831	279.5	40,538
25% DGABC, 75% RAP	188.9	27,398	280.9	40,741
100% RAP, 0% DGABC	263.2	38,174	360.9	52,344

Camargo et al. (2012) evaluated the mechanical properties of a full-depth Reclaimed Pavement Material (RPM) and RPM stabilized with high carbon/high calcium fly ash, (SRPM). The fly ash has a carbon content of 16.35 % and a calcium oxide content of 22.37 %. The RPM, stabilized and un-stabilized, was compared with properties of a conventional crushed aggregate

(Class 6 crushed aggregate). Class 6 crushed aggregate is classified as well-graded gravel (GW) in accordance with the Unified Soil Classification System (USCS). It has a maximum grain size of 25 mm and 2 % fines. The characteristics of the material are shown in Table 2.7:

Table 2.7 Classification of material tested reported in Camargo et al. (2012)

Material	Fly Ash Content (%)	Optimum Water Content (%)	Max. Dry Density	
			(kg/m^3)	(lb/ft^3)
Class 6 aggregate	0	5.2	2,220	138.6
RPM	0	4.9	2,044	127.6
SRPM	14	6.5	2,111	131.8

Three replicates of each test were done. The tests were done in accordance to NCHRP-A. The results from the laboratory tests are shown in Table 2.8:

Table 2.8 Laboratory test results reported in Camargo et al. (2012)

Material	Curing Time (days)	Resilient Modulus	
		MPa	psi
Class 6 aggregate	0	220	31,908
RPM	0	257	37,275
SRPM	7	2,984	432,793
SRPM	28	4,334	628,594

From Table 2.8, it was found that adding fly ash to RPM significantly increased the M_R from 257 MPa to 2,984 MPa and to 4,334 MPa (nearly 17 times higher than un-stabilized RPM) after 7 and 28 day of curing, respectively.

Bozyurt et al. (2012) investigated the stiffness of Recycled Concrete Aggregate (RCA) and RAP sources used as unbound base without treatment. The power function and NCHRP models were used to estimate the values of M_R. A gravel base course meeting Class 5 aggregate specifications in Minnesota, per the Minnesota Department of Transportation (MnDOT), was used as reference. Samples of 100% RCA, 100% RAP, and 100% class 5 aggregate and a blend of 50% RCA + 50% aggregate by mass were tested for M_R. The results follow the trend in the literature review in that the RAP samples exhibit higher M_R values than natural aggregates.

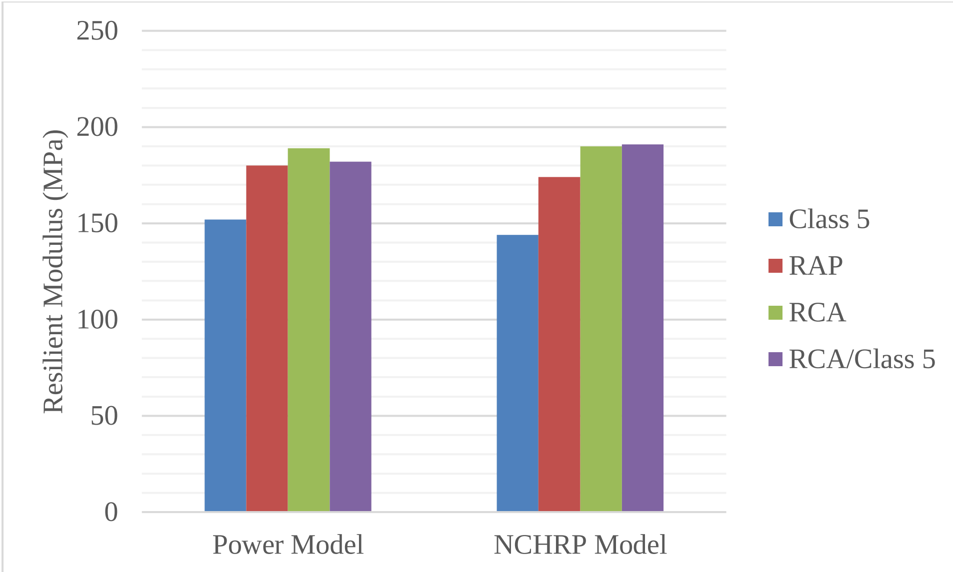

Figure 2.4 Resilient Modulus of the tested material reported in Bozyurt et al. (2012)

2.4 Plastic Strain

Plastic strain or permanent deformation is an important parameter because it is associated with fatigue cracking and rutting of pavements. Tensile and compressive strains lead to both fatigue cracking and rutting which affect pavement life. Cyclic loading tests or extended loading analysis may be used to predict plastic strain. Camargo et al. (2012) evaluated the effect of adding fly ash to Reclaimed Pavement Material, or RPM. The characteristics of the material tested are shown in Table 7 and the results of the laboratory tests are plotted in Figure 2.5. From the plot, it is clear that the addition of the fly ash significantly reduced the plastic strain of RPM.

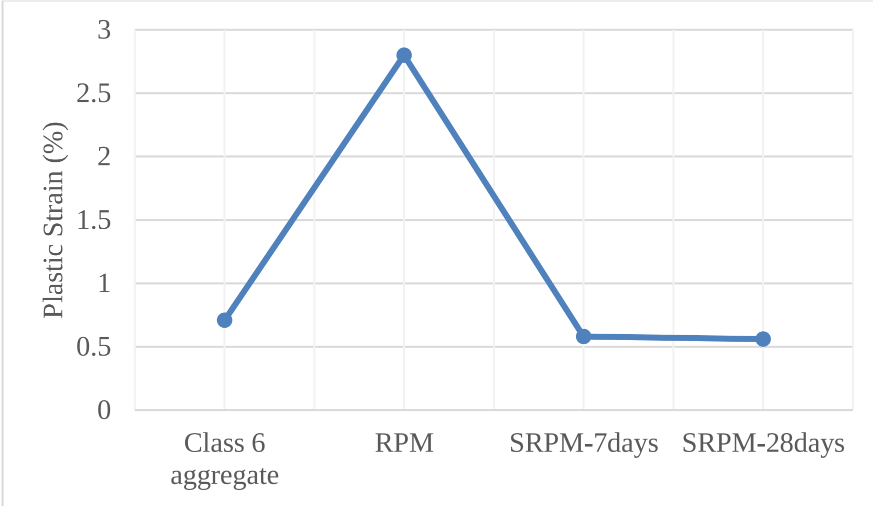

Figure 2.5 Plastic Strain of the tested material reported in Camargo et al (2012)

Bennert et al. (2000) also reported the plastic strain for blends consisting of different percentages of RAP and Dense Graded Aggregate Base Course (DGABC). Tests were conducted on cylindrical samples according to AASHTO TP46-94 for Type I soils. The DGABC had a maximum dry density of 2,098 kg/m^3, 7.6 % fines and a 7 % moisture content. The test results are shown in Figure 2.6. The figure shows that plastic strain is directly proportional to the amount of RAP in the blend. That is, the more RAP, the larger the plastic strain.

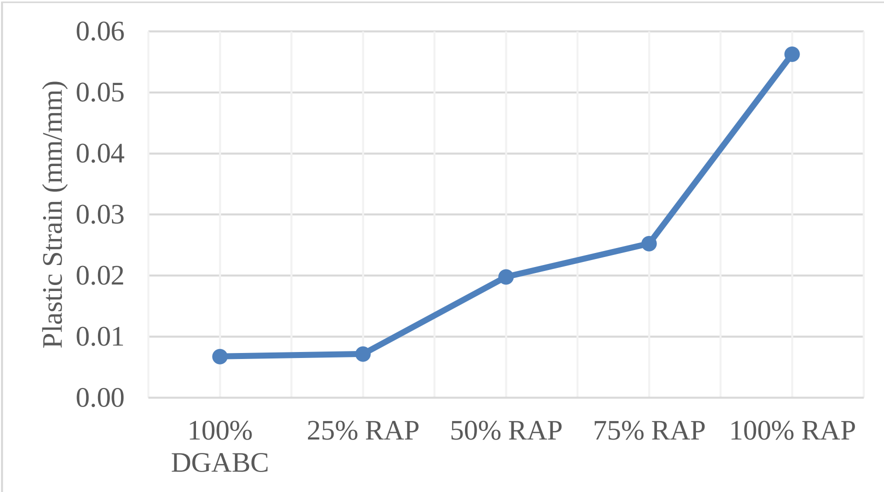

Figure 2.6 Plastic Strain of the tested material reported in Bennert et al. (2000)

Waldenmaier et al. (2013) studied the strain response of RAP blends under extended loading testing, where the number of cycles for the M_R test was increased while the confining pressure and deviator stress remained constant. The material tested is shown in Table 2.9. Six different samples were tested at different moisture and fines content. The fines used are Class 5 particles that pass the #200 (0.075 mm) sieve and the Class 5 aggregate is composed of well-graded aggregate particles.

Table 2.9 Tested material reported in Waldenmaier et al. (2013)

Material	**Description of material**	**Moisture Content**	**Fines content**
T	50% RAP + 50% Class 5 aggregate	Optimum	6%
T		Optimum +2%	
AR2	50% RAP + 50% Class 5 aggregate	Optimum	10%
AR2		Optimum +2%	
C	100% Class 5 aggregate	Optimum	6%
C		Optimum +2%	

When tested for plastic strain, the material with 10% fines content and a moisture content 2% above optimum had the largest strains. The results also follow the trend of increased plastic strain with the addition of RAP. The effect of the number of cycles was also assessed and those results are shown in Figure 2.7.

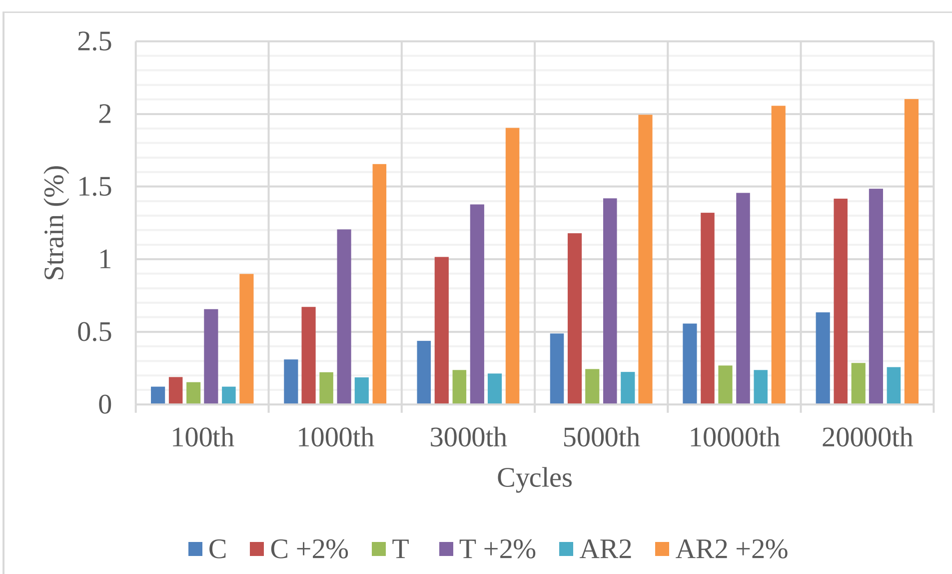

Figure 2.7 Plastic Strain of the tested material reported in Waldenmaier et al. (2013)

2.5 Permeability

Permeability has an effect on pavement life. If the subbase material gets saturated, the pavement degrades faster. Wu et al. (2012) used constant head testing to test for permeability in blends of RAP and crushed basalt aggregates following AASHTO T215. From their results, they concluded that adding RAP led to a reduction in porosity and permeability. The lower permeability also increases moisture retention time in the subbase/base layers. This may weaken the layer particularly under cycles of freezing and thawing, and thus decrease pavement life. The test results are shown in Figure 2.8 and it is clear that permeability decreases as RAP percentage increases.

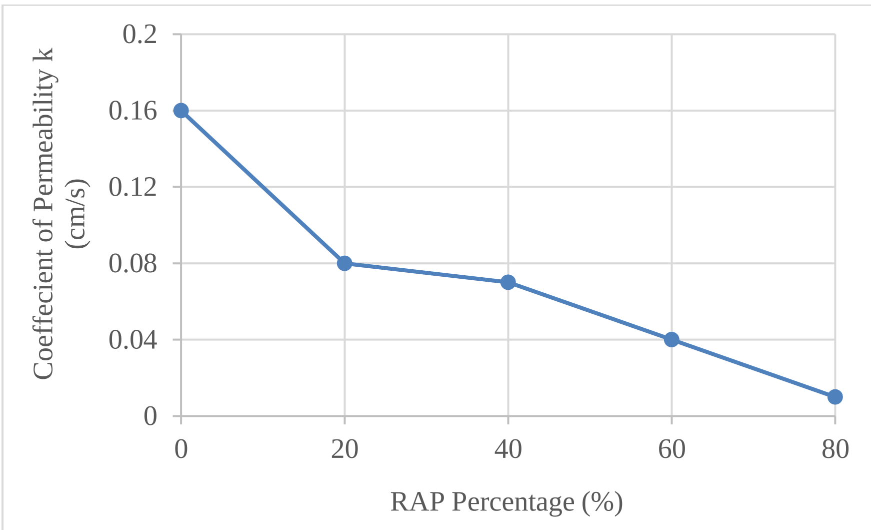

Figure 2.8 Permeability of the tested material reported in Wu et al. (2012)

Seferoglu et al. (2018) investigated the effect of RAP on the permeability of a base layer. Samples of RAP plus virgin aggregate blends and 100% RAP treated with cement were tested. The constant head permeability test following ASTM D 2434 was used. The results follow the trend in the literature, where permeability decreases as RAP percentage in the blends increases. The results of the tests on the blends are shown in Figure 2.9. The lowered permeability could be attributed to lowered porosity as well as bonds forming between particles due to the asphalt coating.

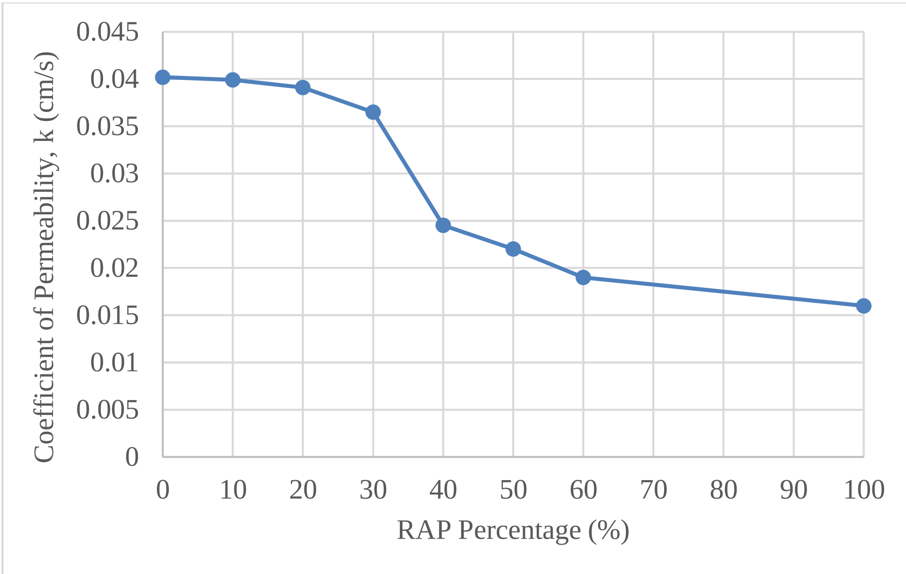

Figure 2.9 Permeability of the RAP blends material reported in Seferoglu et al. (2018)

The permeability of cement treated 100% RAP was also tested to evaluate the effect of adding cement. The results are shown in Figure 2.10.

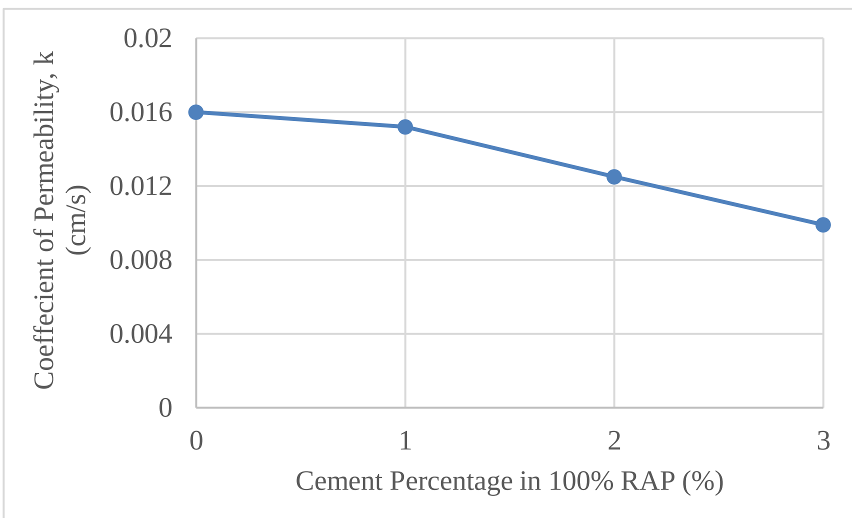

Figure 2.10 Permeability of cement treated RAP reported in Seferoglu et al. (2018)

2.6 Life Cycle Assessment

The environmental effect of using RAP should not be overlooked even as RAP is favored over more expensive natural aggregates. With the increase in usage of RAP, there is a need to ensure that this material is environmentally neutral. Aurangzeb and Al-Qadi (2014) used the Life

Cycle Assessment (LCA) tool and the Life Cycle Cost Analysis (LCCA) to assess the environmental effect of using up to 50% RAP in asphalt mixtures.

LCCA is a tool used by pavement designers to find cost effective construction, maintenance and rehabilitation procedures. A 1-mile asphalt pavement section was selected for the study and a 45-year analysis period was used. Maintenance cost was the same for all mixtures because the analysis assumed that all the RAP mixtures had the same performance level as virgin mixtures. Results from this analysis showed a clear drop in the cost of construction, as shown in Figure 2.11.

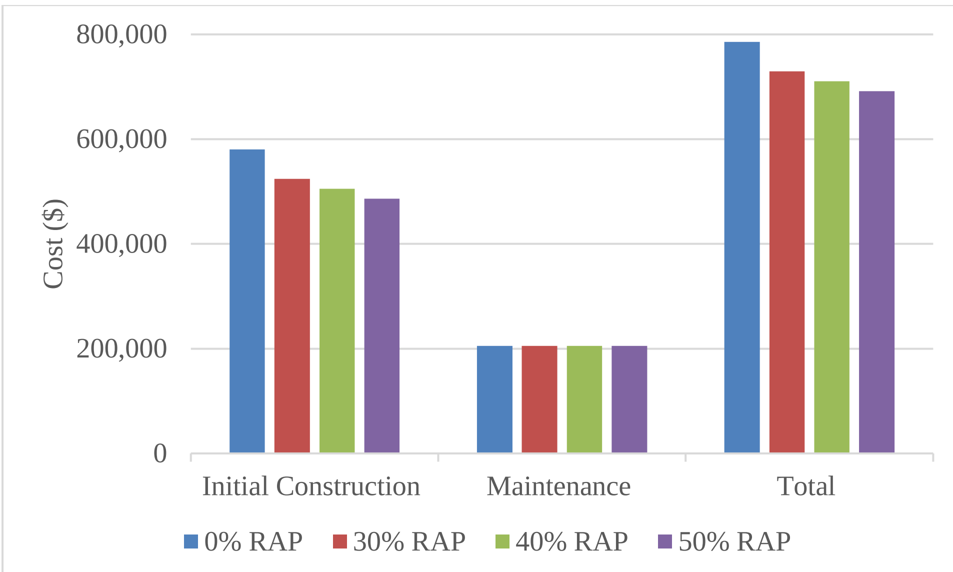

Figure 2.11 LCCA Results reported in Aurangzeb and Al-Qadi (2014)

The LCA analysis was used to investigate energy consumption and greenhouse gas emissions**.** The analysis showed that as the amount of RAP in the asphalt mixtures increased, the energy consumption and greenhouse gas emissions reduced. Two life cycle phases were assessed: construction and material. Table 2.10 reports the results of adding the contributions of the two phases. It is important to note that the construction phase had the same environmental effect for all mixtures with and without RAP. This is because the same construction procedures were used for all mixtures. The reductions obtained in all parameters is attributed to the material phase only.

Table 2.10 LCA Results reported in Aurangzeb and Al-Qadi (2014)

Parameter	**Life Cycle Phase**	**0% RAP**	**30% RAP**	**40% RAP**	**50% RAP**
Energy (Btu millions)	Total	10,897	10,100	9,834	9,569
CO_2 (lb CO_2e)	Total	1,528,780	1,416,499	1,379,072	1,341,645
CH_4 (lb CO_2e)	Total	272,749	251,459	244,362	237,265
N_2O (lb CO_2e)	Total	11,324	10,418	10,115	9,813
GHG (lb CO_2e)	Total	1,821,700	1,686,510	1,641,446	1,596,383

Note: CO_2e = CO_2 equivalent, Btu = 1,055 J

The results from both the LCA and LCCA analysis show that including RAP in asphalt mixtures is both less costly and more environmentally friendly than the control mixture that contains no RAP. It is however noteworthy that the analysis and results from this study were based on the assumption that RAP mixtures and virgin mixtures had similar performance levels.

Hong and Prozzi (2017) evaluated the use of RAP in pavement rehabilitation by using both the LCA and LCCA tools, focusing on energy consumed and emissions during production, transportation and placement of the recycled materials. Eight 500ft long sections constructed in 1991 were tested, four of the sections had 0% RAP and the other four contained 35% RAP by weight. At the time of this study, the pavement performance data analyzed ranged from the year 1991 to 2007. A 40-year analysis was used to evaluate construction, rehabilitation and operation of the pavement sections. The LCCA results are shown in Figure 2.12. The graph shows that the cost is lower for thinner overlays with RAP and higher for thicker overlays with RAP. Therefore, using RAP in thin overlays according to the LCCA analysis is more economical than using virgin material.

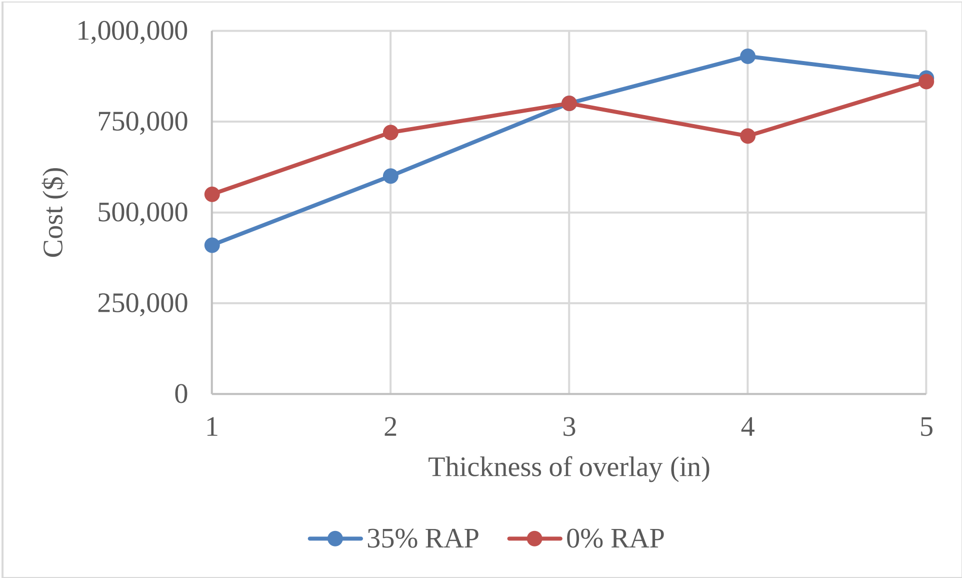

Figure 2.12 LCCA Results reported in Hong and Prozzi (2017)

The study also looked at rehabilitation of the pavements as well as the timing of the rehabilitation. To determine the timing, a failure criterion based on cracking and rutting was developed. For the study, the failure criterion was set at 100ft. (33.3 m) per section for transverse crack length and, 0.4in. (10mm) for rutting. The pavement life, i.e., the number of years it takes before the pavement section reaches the set failure criterion thresholds, was determined for various overlay thicknesses for both virgin and recycled materials. The results are shown in Figure 2.13. From the graph, it is clear that RAP resulted in shorter pavement life as the thickness of the overlay was larger. A longer pavement life means less rehabilitation work and this results in lower cost and lower energy consumption.

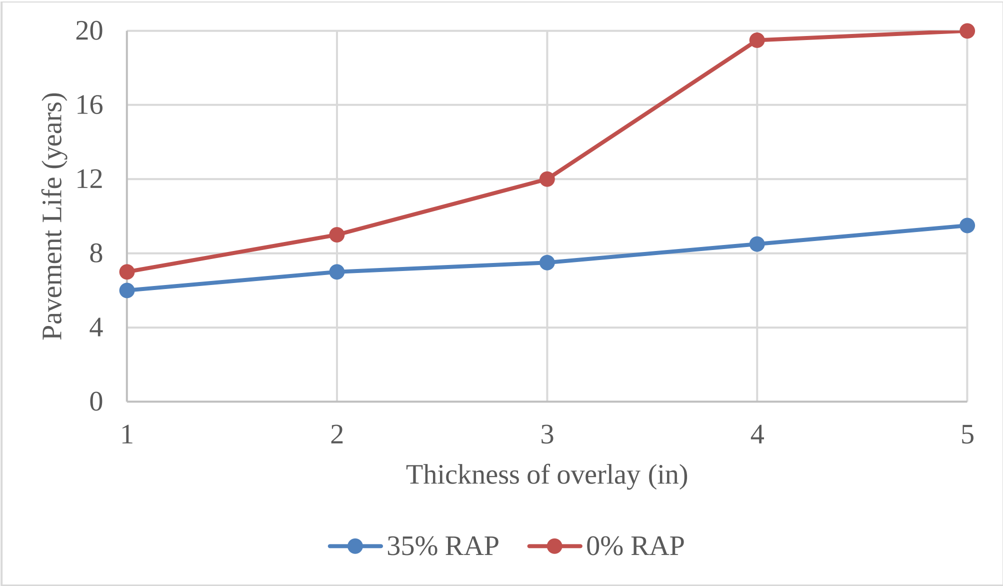

Figure 2.13 Pavement Overlay Life Results reported in Hong and Prozzi (2017)

Similarly, the LCA analysis (the software Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) was used) favored the use of RAP in thinner overlays. Energy consumption, Carbon Monoxide (CO), Carbon Dioxide (CO_2) and Particulate Matter 10 (PM10) emissions were evaluated and the results are shown in Figures 2.14 to 2.17

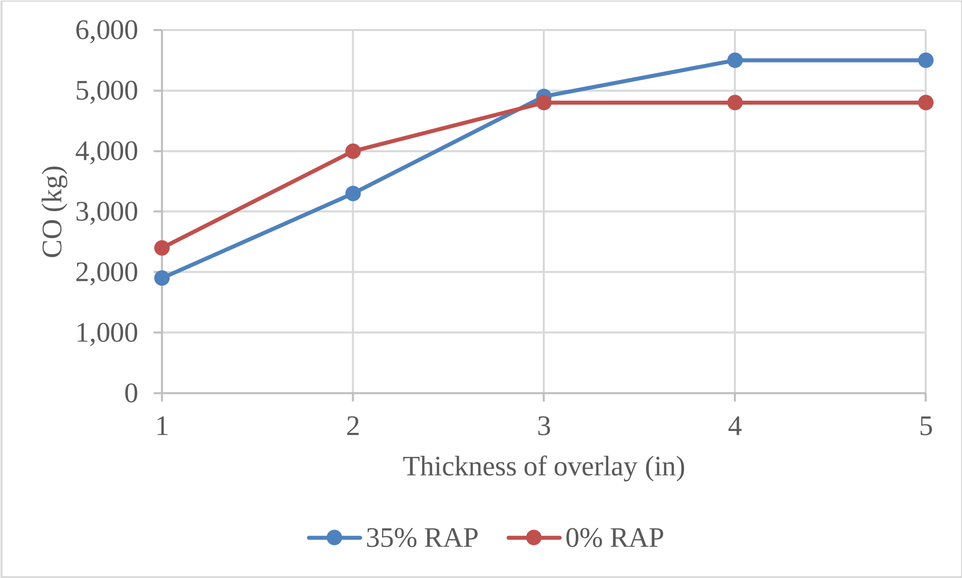

Figure 2.14 CO emission comparison between RAP and virgin mixes, after in Hong and Prozzi (2017)

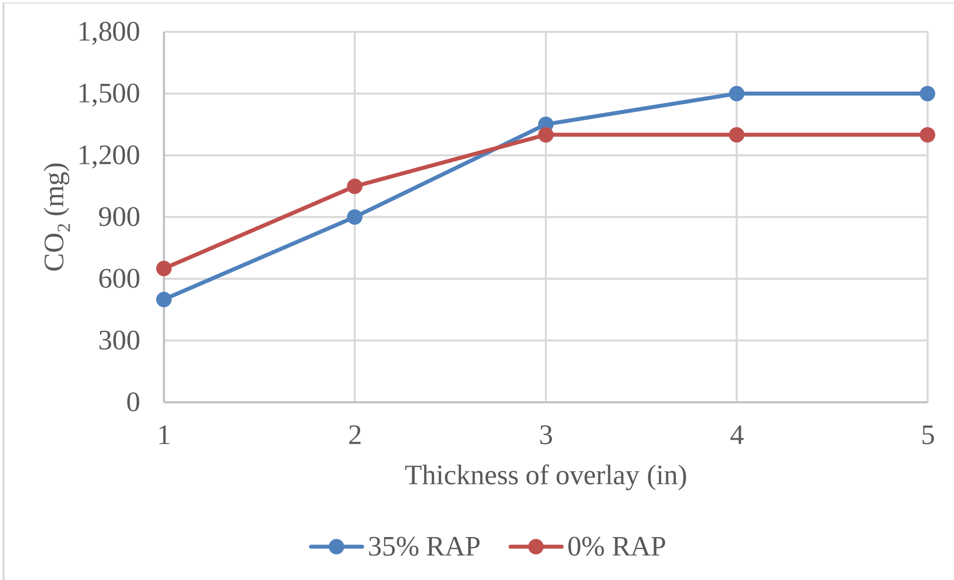

Figure 2.15 CO_2 emission comparison between RAP and virgin mixes, after Hong and Prozzi (2017)

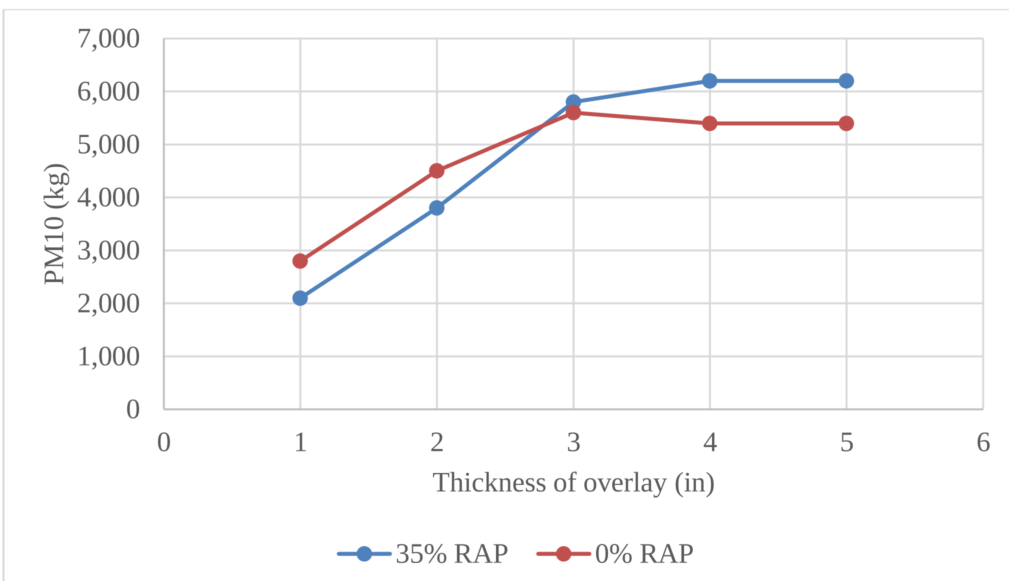

Figure 2.16 PM10 emission comparison between RAP and virgin mixes, after Hong and Prozzi (2017)

As the overlay becomes thicker, the energy consumed increases, as shown in Figure 2.17. This is because thicker overlays involve the use of more material, which translates into increased transportation and placement energy. The increase in energy is to be expected. The same trend is noted for the emissions. It is important to note that RAP use favors thinner overlays; however, thinner overlays require more rehabilitation as they have a shorter pavement life, as one can see in Figure 2.13. The more frequent the rehabilitations, the higher the cost, energy consumption and greenhouse gas emissions.

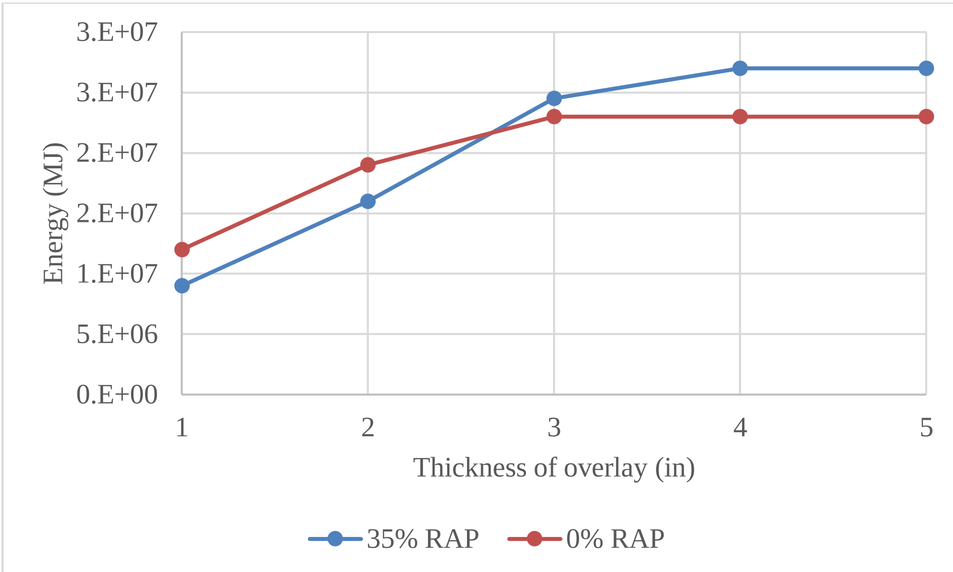

Figure 2.17 Energy consumption comparison between RAP and virgin mixes, after Hong and Prozzi (2017)

Faysal et al. (2017) investigated the environmental impact of RAP and Recycled Crushed Concrete Aggregate (RCCA) blends treated with cement. Tests were done on blends of 50% RAP plus 50% RCCA treated with varying percentages of cement ranging from 2% to 6%.

The results of permeability and leachate tests showed that the hydraulic conductivity decreased as the cement content increased. This is because cement acted as a bonding material resulting in decreased voids. The pH values for the recycled materials, in general, were lower than those of natural aggregates. The presence of asphalt in RAP causes a reduction in pH, the addition of cement to the blend, however, had a negligible effect on the pH. Turbidity decreased as cement content increased, as well as the chemical oxygen demand and total suspended solids. The total dissolved solids was the only result that increased as cement content increased. The results are shown in Figures 2.18 to 2.20.

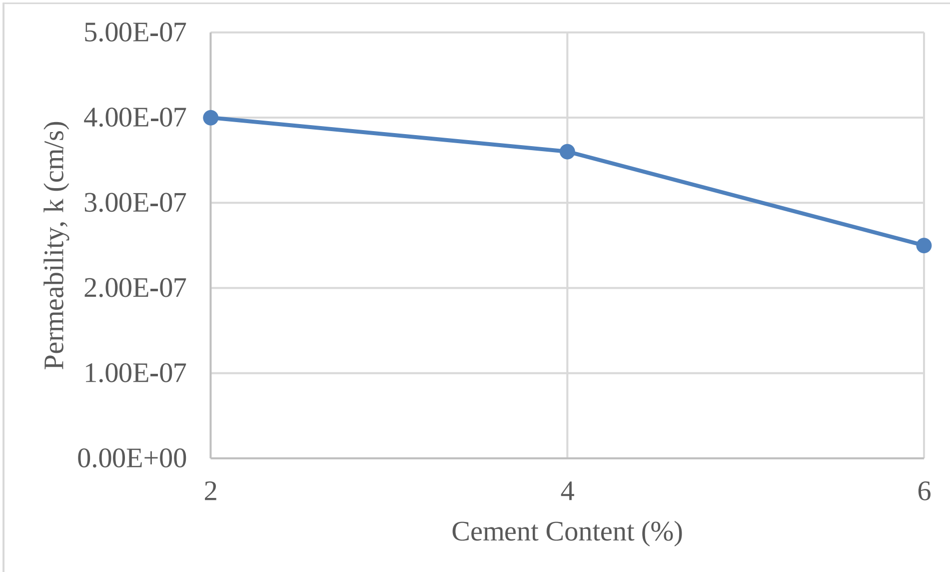

Figure 2.18 Permeability Test Results recorded in Faysal et al. (2017)

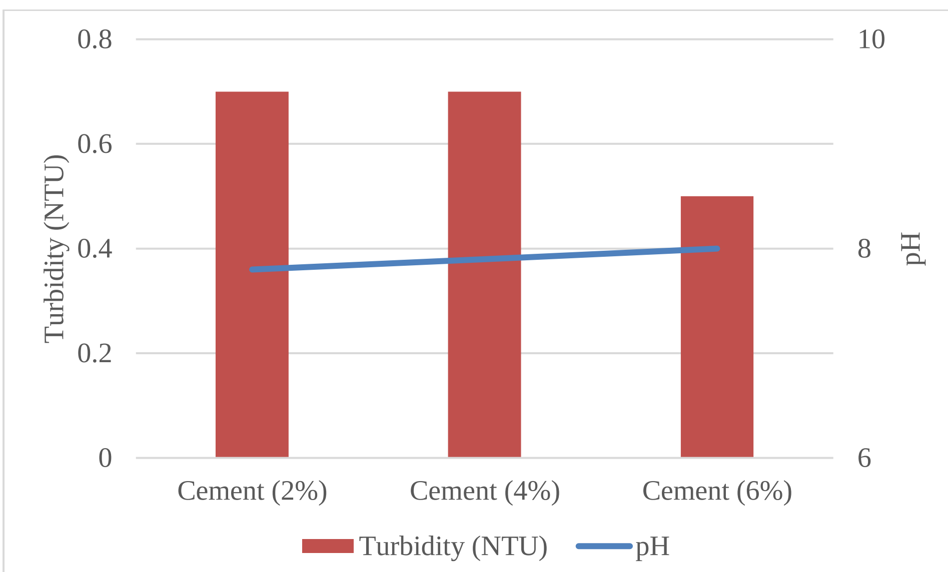

Figure 2.19 Turbidity and pH Test Results recorded in Faysal et al. (2017)

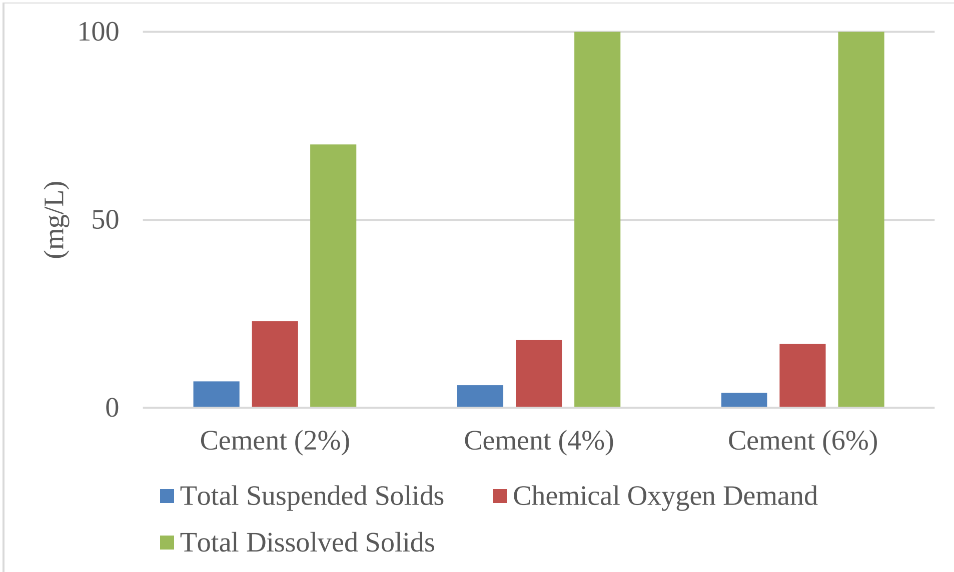

Figure 2.20 Leachate Test Results recorded in Faysal et al. (2017)

The results of this study were compared with the Environmental Protection Agency (EPA) guidelines. pH values fell within the recommended range of 6 to 9 and turbidity values were all under the recommended 5 NTU. For Total Dissolved Solids, EPA recommends readings under 500mg/L and for Chemical Oxygen Demand, under 120mg/L. All the results adhered to the EPA guidelines showing that using recycled base materials is a viable, more environmentally friendly option than using virgin aggregates.

2.7 Creep

Mitchell and Soga (2005) stated that creep is the accumulation of time-dependent shear strain under a sustained shear stress that is controlled by the viscosity of the soil structure. It is important to evaluate creep of RAP materials because the asphalt coating the aggregate may increase the compressibility and creep of RAP materials.

Yin et al. (2016) used tri-axial compression tests at sustained deviator stresses to investigate the creep characteristics of compacted RAP with temperature. Three samples of RAP were compacted and consolidated at three different temperatures, i.e., 22°C, 35°C and 50°C. Such a study is important because the asphalt binder in RAP is sensitive to temperature. Table 2.11 shows the results obtained.

Table 2.11 Test results reported in Yin et al. (2016)

Compaction & Consolidation Temp. (°C)	Test Temperature (°C)	Void Ratio (e)	Void Ratio Percentage Reduction (%)	Time to Creep Rupture, t_r (min)	Axial Strain after 30 min (%)
22	22	0.26	-	24	30
35	22	0.20	23	850	9
50	22	0.14	46	4630	3

From the table, it is clear that compaction and consolidation at higher temperatures led to a reduced void ratio, which in turn led to increased stiffness and shear strength due to an increase in inter-particle contact and friction. This ultimately led to decreased creep strain. In addition, the time to rupture significantly increased for the samples prepared at higher temperatures. To this end, any construction involving RAP should be done during the summer when temperatures are elevated, to minimize creep.

In a separate study, Thakur et al. (2014) looked at ways to stabilize RAP used in pavement construction to decrease its susceptibility to excessive creep, and thus to increase the pavement life. They proposed the use of geocells, a three-dimensional geosynthetic product. Static and cyclic plate loading tests were used to test the effect of the geocells on creep and deformation of RAP. Unstabilized, single geocell-stabilized and multi geocell-stabilized RAP bases were tested. Upon testing, the stiffness values of both single and multi-geocell stabilized RAP base specimens increased by 1.2 and 1.6 times, respectively, compared to the unstabilized specimen. Results of the creep strain and creep rate measured at a vertical stress of 276kPa are shown in Figures 2.21 and 2.22.

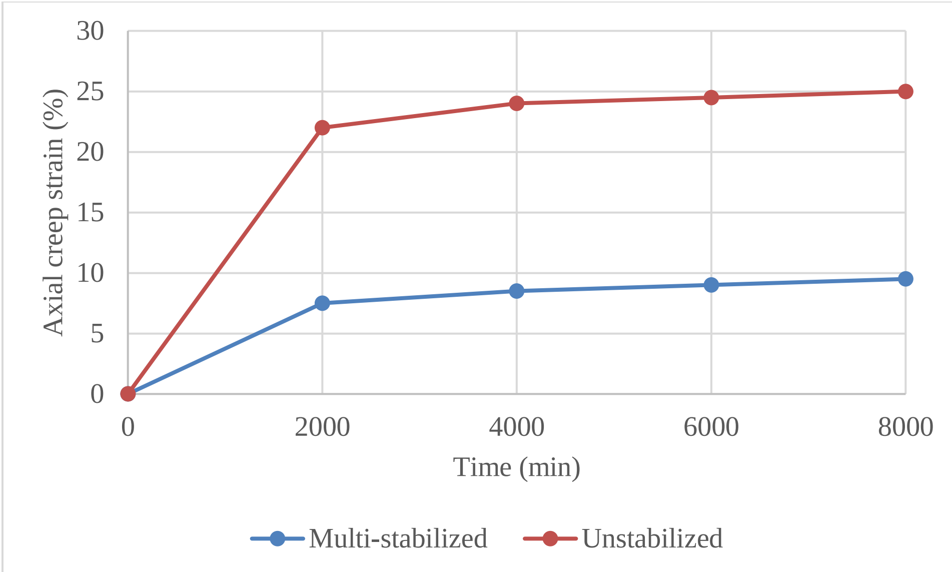

Figure 2.21 Creep Strain vs Time reported in Thakur et al. (2014)

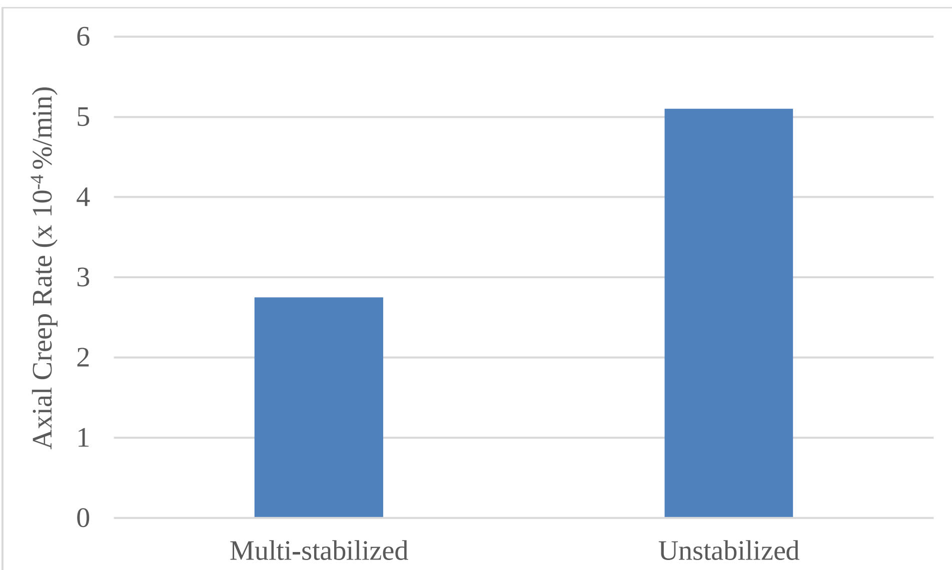

Figure 2.22 Creep rate reported in Thakur et al. (2014)

From this study, it is noted the inclusion of geocells effectively reduced creep, creep rate and deformation. It also increased resilient deformation and stiffness of the RAP bases.

2.8 Stabilization of RAP

RAP, due to the asphalt coating, has a high propensity to permanent deformation and creep. Despite RAP being favorable for the environment and cost-wise, as well as providing an increased resilient modulus, it is advisable to use it with some form of stabilizing agent to reduce deformation and creep. This can lead to a longer pavement life which is ultimately the goal.

Bleakly and Cosentino (2013) sought to develop methods to improve blends of RAP and crushed limestone aggregates using chemical stabilization. Available chemical stabilizing agents include polymers, fly ash, enzymatic stabilizers, cement or lime. In this study, cationic asphalt emulsion (CSS-1H) and Portland cement (PC) were used. Tests for strength and creep were done on 100% RAP, 100% crushed limestone and on blends of both materials with and without the chemical stabilizing agent. The strength test used was the Limerock Bearing Ratio (LBR) which is a variation of the California Bearing Ratio (CBR). The minimum acceptable LBR was 100.

Unsoaked LBR testing was done on specimens containing 100% RAP, 75% RAP, 50% RAP, 25% RAP and 100% limestone without chemical stabilization. Test results showed that the LBR increased as limestone increased in the blend. The 50:50 blend had an LBR reading of 142 which doubled to 284 in the 25:75 RAP to limestone blend. Unsoaked LBR testing was done on specimens containing 50% RAP and 25% RAP with 0 to 3% chemical stabilization. Specimens were allowed to cure prior to testing. The results are shown in Figure 2.23.

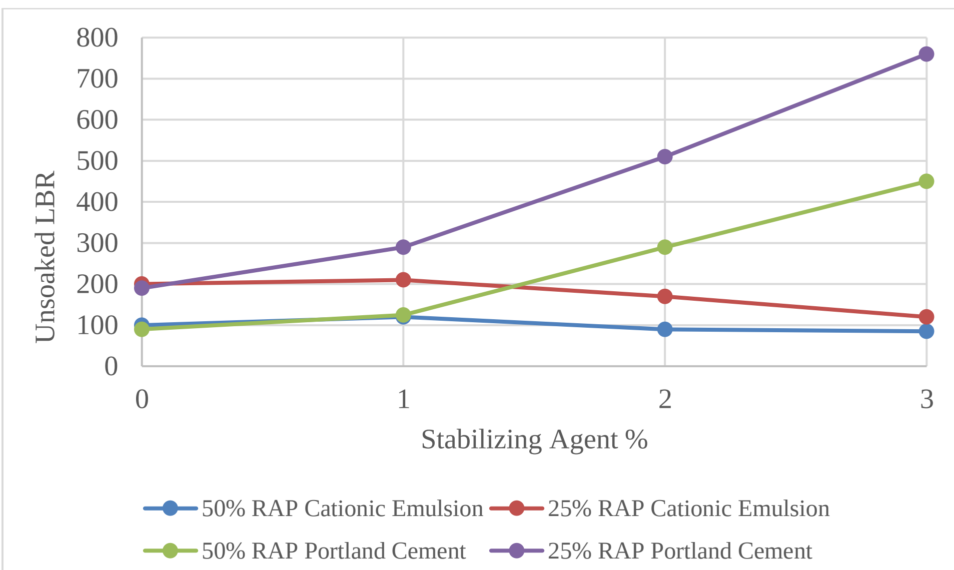

Figure 2.23 Unsoaked LBR results reported in Bleakly and Cosentino (2013)

After curing and soaking, soaked LBR testing was done on specimens containing 100% limestone and a blend of 25:75 RAP to limestone without any chemical stabilizing, as well as on stabilized 50:50 blends. The results are shown in Figure 2.24.

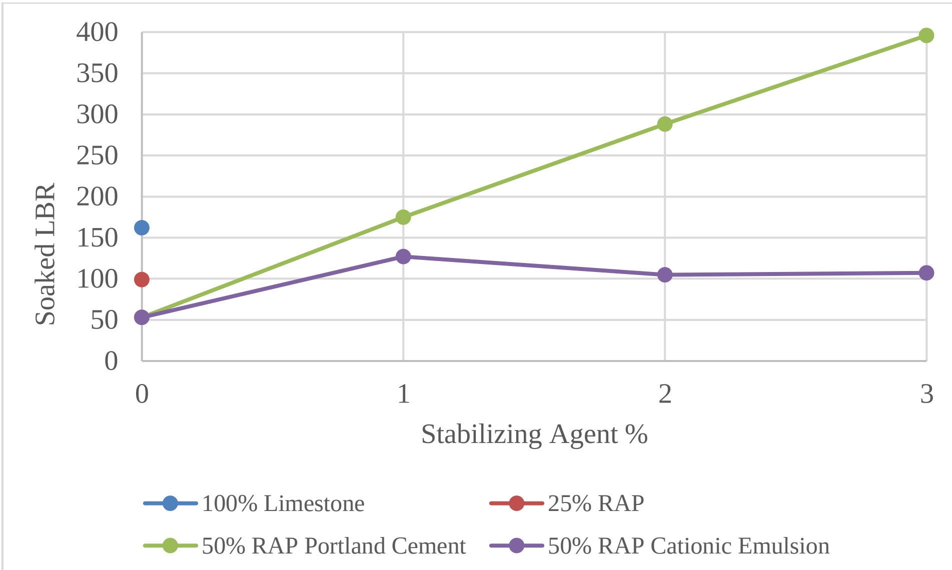

Figure 2.24 Soaked LBR results reported in Bleakly and Cosentino (2013)

It is clear that Portland cement drastically increased the strength of the blends. It should be noted, however, that the samples were only cured for 14 days, so it is possible that hydration of cement over a longer period of time may further increase the strength. With the cationic emulsion, the strength peaked at 1% and decreased thereafter with increase in emulsion.

Bleakly and Cosentino (2013) also conducted creep tests on specimens stabilized with cationic asphalt emulsion (CSS-1H) and Portland Cement (PC). Blends of 75:25 RAP to limestone had creep strain rates (CSR) similar to those of 100% RAP. The inclusion of PC had a much greater effect than CSS-IH in reducing the creep strain rate. The results are shown in Figures 2.25 and 2.26.

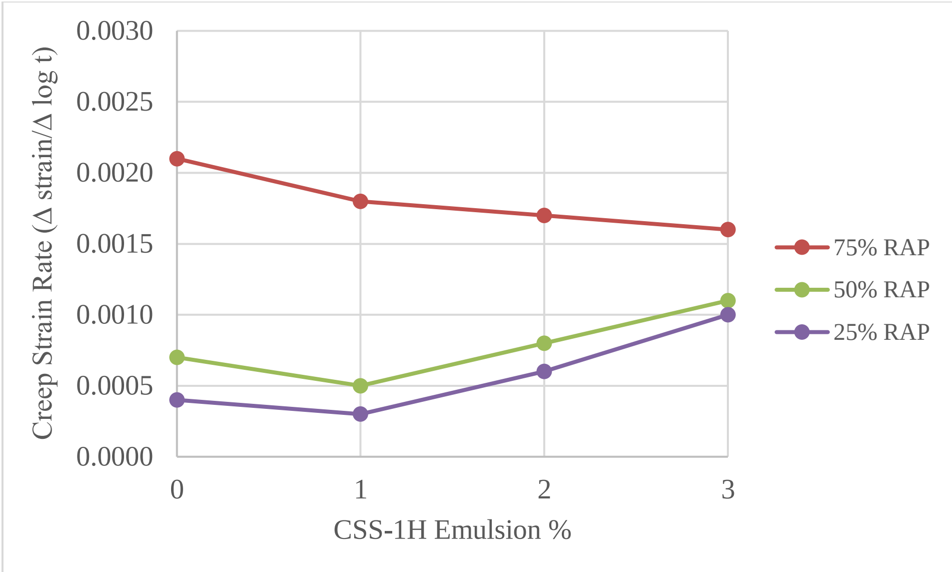

Figure 2.25 CSR of CSS-1H stabilized blends reported in Bleakly and Cosentino (2013)

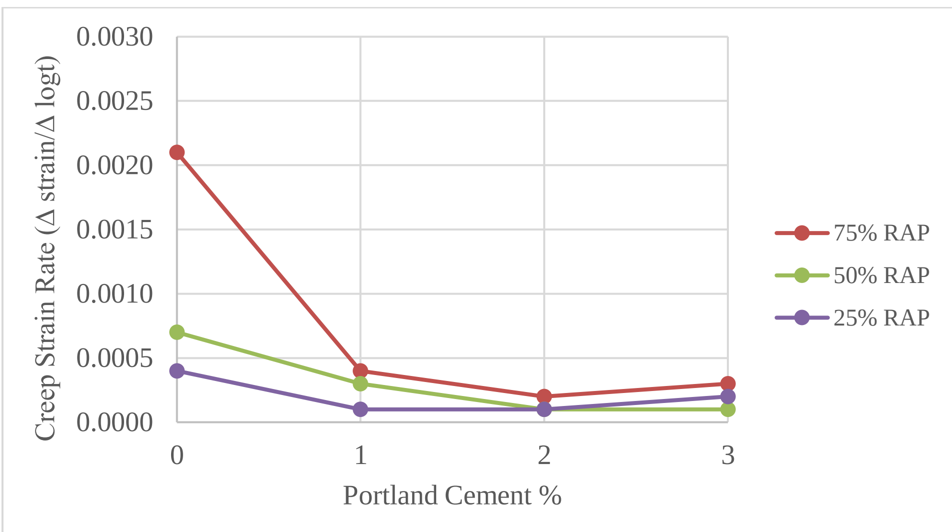

Figure 2.26 CSR of PC stabilized blends reported in Bleakly and Cosentino (2013)

In regards to the emulsion, it should be noted that formulas of emulsions are proprietary, so definite conclusions about their effectiveness cannot be drawn. Inclusion of PC led to drastic increases in LBR. However, the authors recommend limiting PC to 1% to reduce the risk of cracking.

Soares et al. (2013) modeled the in-situ performance of cement-stabilized granular base layers for urban roads. They found that stabilizing RAP base layers with 2% cement resulted in a

25% decrease in maximum shear strains compared to unstabilized granular base layers. Cement stabilization has also been found to improve the durability of granular materials and this is of particular interest to areas that experience freezing and thawing. A three-dimensional computational model, PSIPave3D model, was used to determine the deflection response and strain behavior of the pavement structure. PSIPave3D is a nonlinear orthotropic road model used to calculate mechanistic responses across diverse road materials, structures, and field conditions for both road structural analysis and design, Soares et al. (2013).

Gyratory compaction was used to prepare the samples to determine the dynamic modulus. Cement treated, well graded, RAP was compared with a granular base material sourced from a sandy pit. The results are shown in table 2.12. As one can see, the stiffness modulus of RAP was larger than that of the granular base, and the stiffness largely increased with the cement-treated RAP.

Table 2.12 Modulus test results reported in Soares et al. (2013)

	Cement %	**Dynamic Modulus**
Granular Base	0	198
RAP	0	564
RAP	2	1130

To predict surface deflections, PSIPave3D model simulations were used on pavement structures with cement treated base layers, as well as on untreated. The pavement structure with an untreated RAP base had peak surface deflections 30% lower than those with the granular base. The treatment with cement had deflections 41% smaller. The results are shown in Figure 2.27.

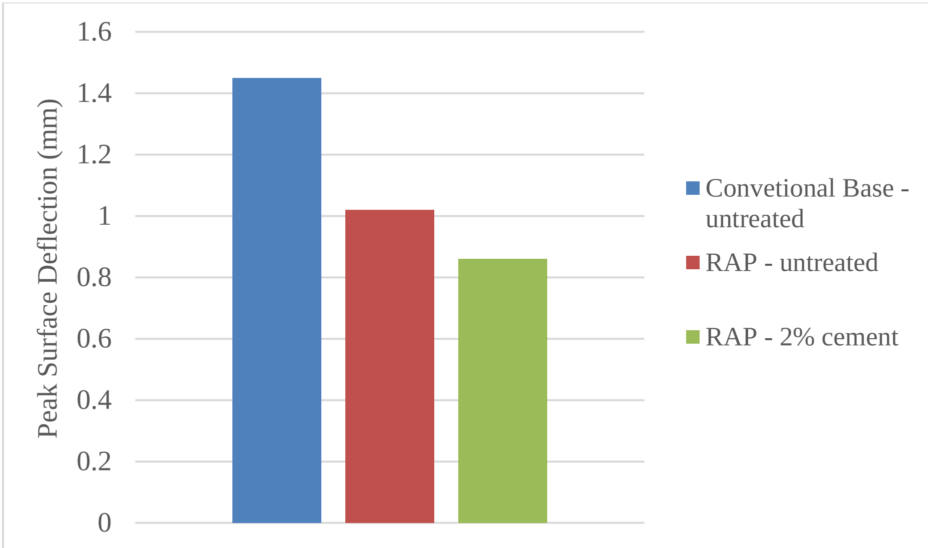

Figure 2.27 Model predictions of peak surface deflections reported in Soares et al. (2013)

Strain at the base and at the subgrade interface was also model-predicted. Those are important for thin pavements, as the structural integrity of the thin pavement becomes more dependent on the subgrade. Stabilizing the RAP base layer with 2% cement resulted in reducing the strain by as much as 60%, compared with the granular base layer. This is important because lower shear strains at the base and subgrade interface can prevent failure of the pavement structure. The results for the shear strains from the model are shown in Figure 2.28.

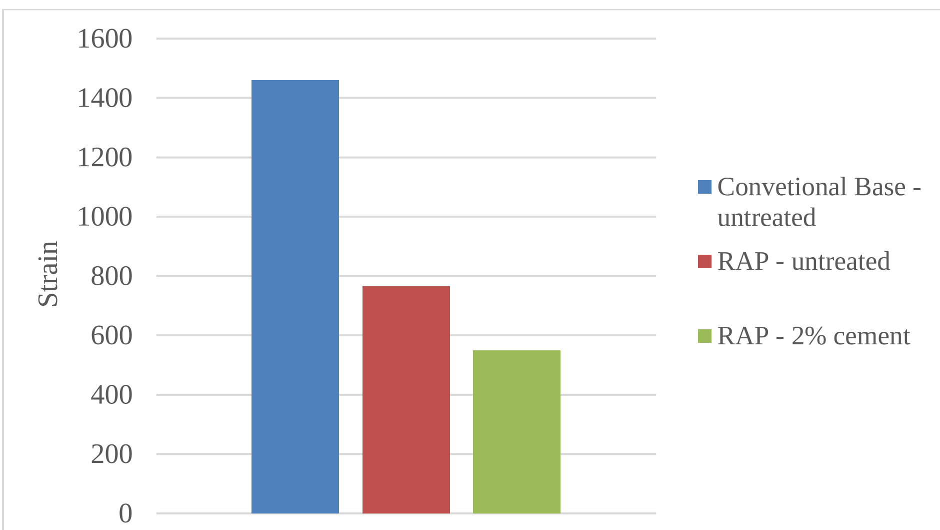

Figure 2.28 Model predictions of strain at base and subgrade interface reported in Soares et al. (2013)

Adhikari et al. (2018) studied the mechanical characteristics of Soil-RAP-Geopolymer mixtures for road base and subbase layers. Geopolymer binder was found to produce fewer greenhouse gases than Portland cement, when used to stabilize bases or subbases. A fly-ash based geopolymer was used in this study. Fly-ash (FA), which is an industrial by-product, can be used alongside alkali which works as an activator to produce geopolymer binders. Sodium Hydroxide (NaOH) and Sodium Silicate (Na2SiO3) were used as the alkali activator. Two different soil types were used in this study. The characteristics of the soils are shown in Table 2.13.

Table 2.13 Physical characteristics of the soil reported in Adhikari et al. (2018)

No.	LL	PL	PI	Description	OMC (%)	MDD	
						kg/m^3	lb/ft^3
Soil 1	49.3	33.3	16	Lean clay	13.9	1841	114.9
Soil 2	98.5	39.5	59	Elastic silt	13.8	1655	103.3

Unconfined compressive strength (UCS) tests were done according to the ASTM D2166 procedure. The compressive strength of the Soil-RAP-Geopolymer mixture increased with increase in FA. This is because FA accelerated the geo-polymerization process. UCS increased by approximately 7 times with respect to the untreated soil. The addition of RAP to the soil also resulted in increased UCS. The characteristics of the samples tested, to explore the effects of FA, are shown in Table 2.14 and the results are displayed in Figure 2.29.

Table 2.14 Samples tested for the effect of Fly-Ash (FA) on UCS in Adhikari et al. (2018)

Soil 1				
	Soil (%)	**RAP (%)**	**FA (%)**	**Alkali ratio**[2]
Control[1]	100	0	0	0
1	90	10	0	0.2
2	75	10	15	0.2
3	65	10	25	0.2
Soil 2				
	Soil (%)	**RAP (%)**	**FA (%)**	**Alkali ratio**
Control	100	0	0	0
1	85	15	0	0.2
2	70	15	15	0.2
3	20	25	25	0.2

[1] *The control soil was compacted at optimum moisture content with no RAP, FA or alkali activator.*
[2] *The ratio of: Na2SiO3/NaOH*

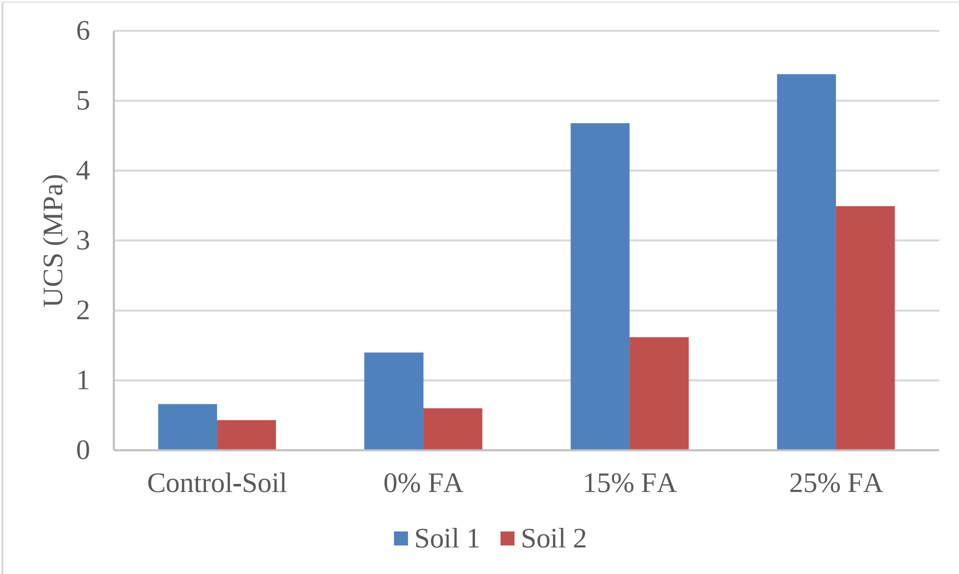

Figure 2.29 Effect of fly-ash (FA) on compressive strength reported in Adhikari et al. (2018)

The characteristics of the samples tested for the effect of RAP are shown in Table 2.15, and the results are plotted in Figure 2.30.

Table 2.15 Samples tested for the effect of RAP and Fly-Ash (FA) on UCS in Adhikari et al. (2018)

Soil 1				
	Soil (%)	**RAP (%)**	**FA (%)**	**Alkali ratio[2]**
Control[1]	100	0	0	0
1	85	0	15	0.2
2	70	15	15	0.2
3	60	25	15	0.2
Soil 2				
	Soil (%)	**RAP (%)**	**FA (%)**	**Alkali ratio[2]**
Control[1]	100	0	0	0
1	85	0	15	0.2
2	70	15	15	0.2
3	60	25	15	0.2

[1] *The control soil was compacted at optimum moisture content with no RAP, FA or alkali activator.*
[2] *The ratio of: Na2SiO3/NaOH*

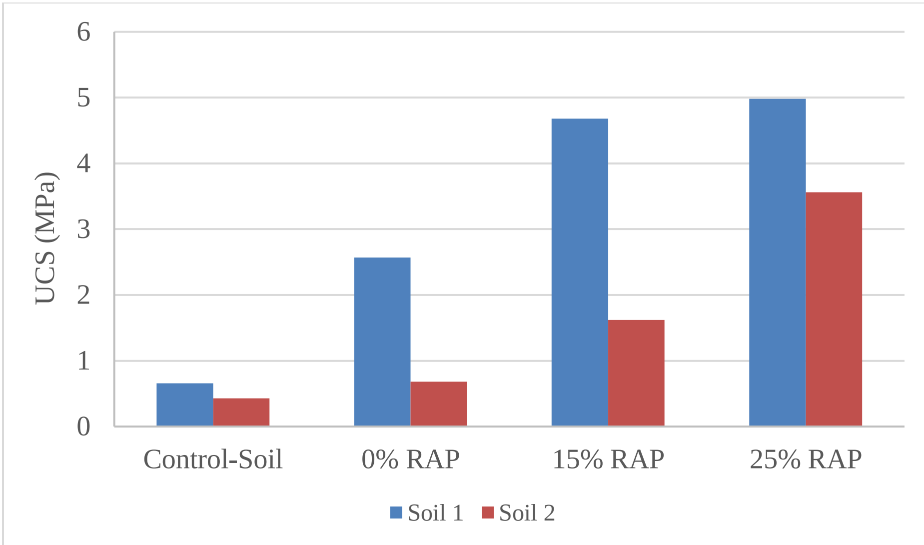

Figure 2.30 Effect of RAP on compressive strength reported in Adhikari et al. (2018)

Figure 2.31 is a plot of the elastic modulus of the soil mixtures. The modulus increased as the FA increased, while the RAP remained constant. For Soil-1, the elastic modulus ranged from 183 to 658 MPa, while for Soil-2, it was much lower, from 8 to 96 MPa. From the figure, it is clear that Soil-1 had a much higher elastic modulus than Soil-2. This can be attributed to the different properties of the soils. Soil-2 was an elastic silt with a liquid limit twice as large as that of Soil-1, which was a lean clay.

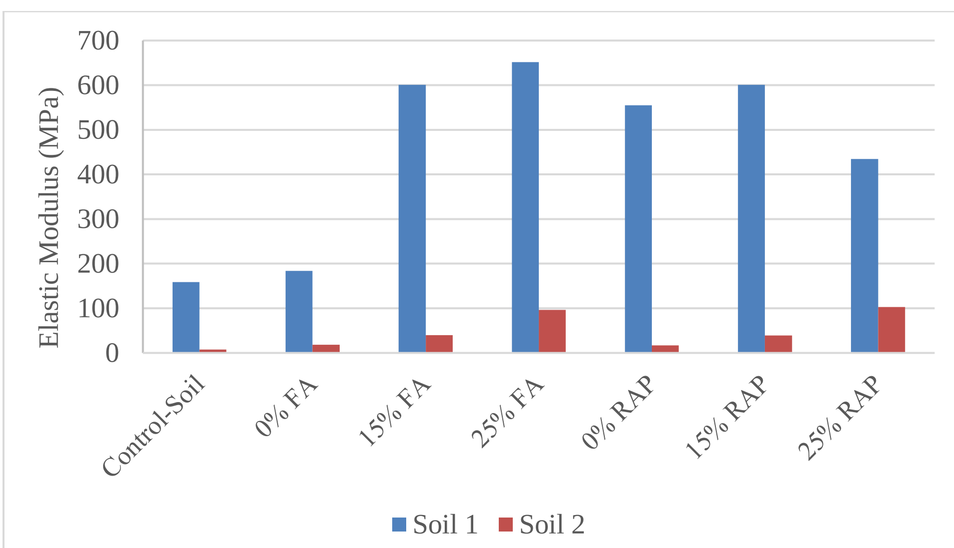

Figure 2.31 Effect of RAP and FA on elastic modulus reported in Adhikari et al. (2018)

3. LABORATORY TESTS

Sieve and proctor tests were done to characterize RAP in the state of Indiana. RAP samples were collected from 4 different plants in the cities of Lafayette, Kokomo and Logansport: Rieth-Riley (RR), E and B Paving (EBP), Central Paving (CP) and Milestone (MS).

3.1 Soil Characterization

The RAP collected from RR was processed and designated as 1/2" dense graded RAP. The samples collected from MS and CP were both 3/8" fractionated RAP. The sample collected from EBP was a 3/4" RAP. All RAP samples were non plastic, coarse grained and relatively poorly graded. A sieve analysis test was conducted to assess the particle size distribution. Two separate, replicate tests were done for each sample. The sample from EBP had the highest percentage of coarse material and the least percentage of fines, while the MS sample had the highest percentage of fines. The results of the gradation test are shown in Figure 4.1.

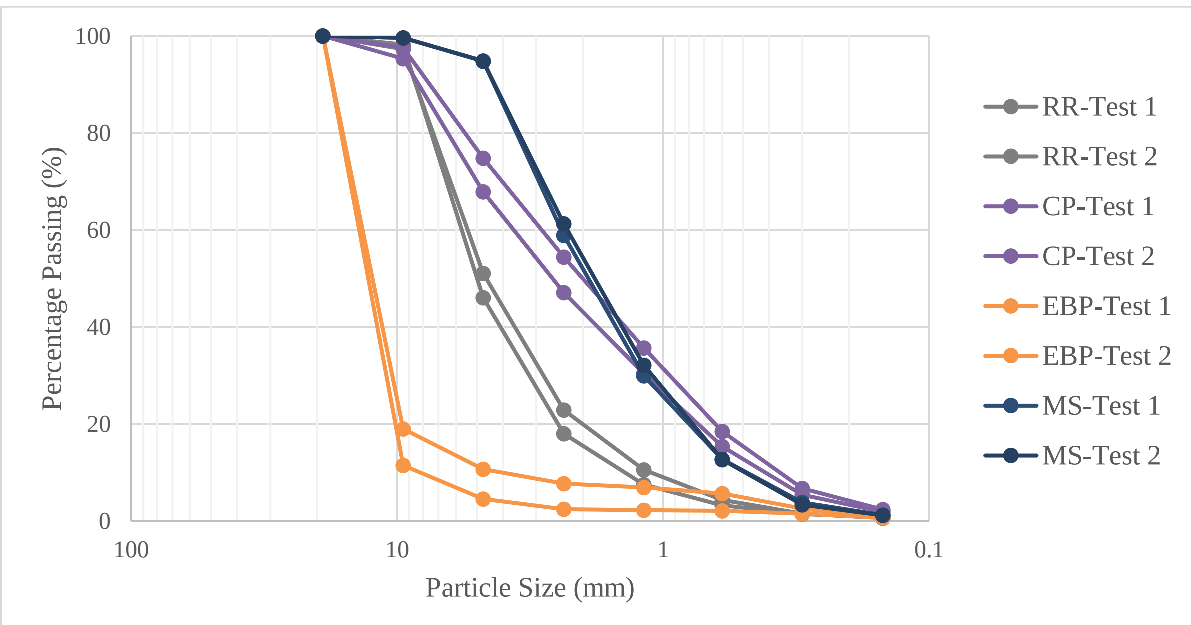

Figure 3.1 Particle size distribution of Indiana RAP

3.2 Proctor Tests

A standard proctor compaction test was performed on three of the RAP samples. The EBP sample was excluded for this test as the grains were too coarse. The results were as expected and showed that the flat curves, in Figure 4.2, are independent of water content because the material is rather uniform.

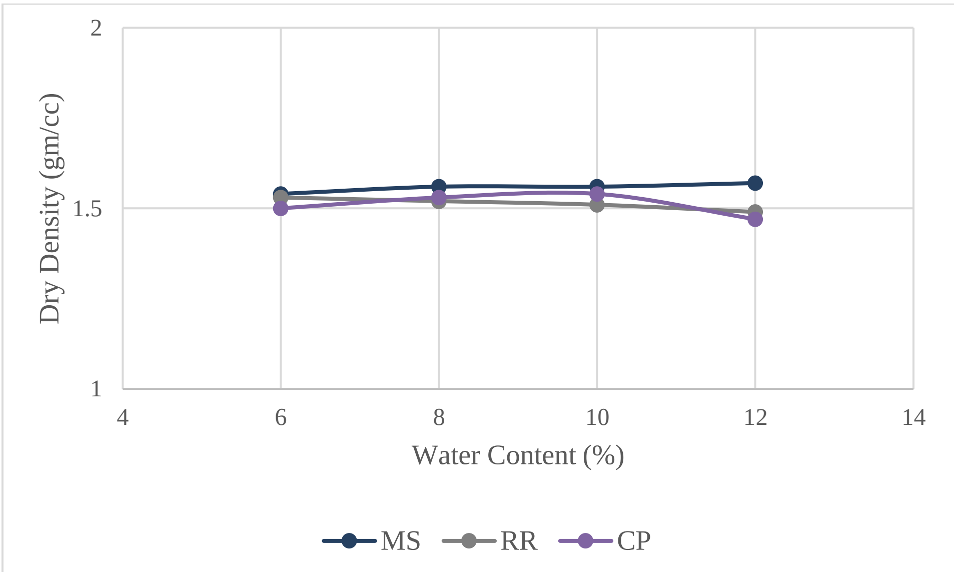

Figure 3.2 Proctor test results of Indiana RAP

4. DOTS PRACTICES

The following is a review of the practices of various Departments Of Transportation (DOT) in the USA. The States selected, in addition to Indiana, are California, Colorado, Florida, Illinois, Minnesota, Texas and Wisconsin. These states were selected because they are large states, and so they tend to engage in larger projects and in more research on the topic. Table 4.1 lists all the DOTs studied. It also includes RAP applications other than on pavements. These applications include RAP used as granular fills, structural backfills (e.g., for mechanically stabilized earth walls or retaining structures) and for embankments.

In addition, a survey was prepared and disseminated through AASHTO to learn about the experience of the DOTs on the use of RAP for pavement and other applications.

Table 4.1 DOT Survey

State	RAP use in HMA	Embankment /Fill	Structural Fill	Pavement Applications: Non-traffic bearing only			
				RAP use in subgrade	Max % RAP allowed	RAP use in base /subbase	Max % RAP allowed
California	✓	-	-	-	-	✓	40%
Colorado	✓	✓	-	✓(*)	-	✓(*)	-
Florida	✓	✓	-	✓	-	✓	-
Illinois	✓	✓	-	✓	40%	✓	50%
Minnesota	✓	-	-	-	-	✓	25%
Texas	✓	✓	✓	-	-	✓	20%
Wisconsin	✓	-	-	-	-	✓	-

* *Colorado state does not specify that RAP is applied in non-traffic bearing roadways*

4.1 California

The California Department of Transportation (Caltrans) considers RAP to be removed or reprocessed pavement materials containing asphalt and aggregates. This material is created when existing asphalt pavements are removed for the purposes of resurfacing or reconstruction. RAP is obtained by milling using a milling machine or full depth removal using pavement breakers. As of July 2016, Caltrans increased allowable RAP usage to 40%, by aggregate weight for subsurface courses, i.e., the base and subbase of the shoulder. The 2018 Caltrans Standard Specifications state that RAP can be used in the construction of shoulder backings adjacent to the edges of pavement. RAP may be used in combination with broken stone, crushed gravel, sand or concrete. When used alone in the shoulder backing, 100% RAP must conform to the requirements listed in Table 4.2. The Caltrans construction guidelines for RAP pavement aggregates states that grading equipment must be a motor grader, spreading equipment must uniformly distribute the aggregate and must be equipped with a measuring device to control the spread rate.

Table 4.2 Classification of 100% RAP shoulder backing (Caltrans, 2018)

Sieve Size		**RAP Mass % passing**
1.5 in	38 mm	100
0.75 in	19 mm	70 - 100
No. 4	4.75 mm	30 - 80

4.2 Colorado

Colorado Department of Transportation (CDOT) defines RAP as material that is generated during cold milling of existing hot mix asphalt pavement. The 2019 standard specifications of CDOT states that the Aggregate Base Course (RAP) shall be 100% crushed recycled asphalt pavement material conforming to the requirements of Table 4.3. Colorado permits the incorporation of RAP into embankment material and into the subgrade and base/subbase layers. For the construction of the base course, each lift must be placed and compacted continually until a density of 95% has been achieved in accordance with AASHTO T 180 using proof rolling with pneumatic equipment. CDOT does not specify any limits on specific gravity, absorption, permeability or resilient modulus.

Table 4.3 Classification of RAP aggregate base course (CDOT, 2019**)**

Sieve Size		**Mass % passing RAP**
2 in	50 mm	100
1 in	25 mm	85 - 100
0.75 in	19 mm	75 - 100
0.5 in	12.5 mm	55 - 90
0.375 in	9.5 mm	45 - 80
No. 4	4.75 mm	25 - 55
No. 16	1.18 mm	5 - 25
No. 200	0.07 mm	0 - 5

4.3 Florida

The Florida Department of Transportation (FDOT) defines RAP as a material obtained by either milling or crushing an existing asphalt pavement. The 2020 FDOT standard specifications allow the use of RAP material as a base course only on non-limited access paved shoulders, shared use paths, or other non-traffic bearing applications. The RAP may be obtained by either milling or crushing an existing asphalt pavement and must be used such that at least 97% (by weight) pass a 3.5 in sieve and is graded uniformly down to dust. When placing the RAP, it must be spread with a blade or a device that will strike off the material uniformly to produce evenly distributed RAP. When the compacted thickness of the base is greater than 6 inches, the base must be built in two layers. Compaction may be performed with vibratory compactors, trench rollers, or other special equipment to a density of not less than 95% of maximum determined by the standard proctor.

Florida also allows for RAP to be used as a local stabilizing material for the subgrade. In order for RAP to be applied, it has to be blended, have a maximum plasticity index of 10, a maximum liquid limit of 40 and have 97% passing the 3.5 in sieve.

4.4 Illinois

The Illinois Department of Transportation (IDOT) defines RAP as a bituminous concrete material removed and/or reprocessed from pavements undergoing reconstruction or resurfacing. Reclaiming RAP involves cold milling a portion of the existing bituminous concrete pavement or full depth removal and crushing.

IDOT allows the use of crushed RAP obtained from either method of reclamation. The RAP must be blended with natural aggregate with gradations CS 01 and CS 02 (defined in Table 4.4), to be used as aggregate subgrade. IDOT allows up to a maximum of 40% of RAP of the total material in the subgrade due to stability concerns. Well graded RAP having 100% passing the 37.5 mm (1.5 in) sieve may be used as capping aggregate in the top 75 mm (3 in) of the subgrade. Compaction of the subgrade may be done with a steel wheel or pneumatic-tired roller.

Table 4.4 Coarse aggregate subgrade gradations (IDOT, 2016)

	Sieve Size and % passing				
	8 in (200 mm)	**6 in (150 mm)**	**4 in (100 mm)**	**2 in (50 mm)**	**No. 4 (4.75cmm)**
CS 01	100	97 ± 3	90 ± 10	45 ± 25	20 ± 20
CS 02		100	80 ± 10	25 ± 15	

IDOT also allows RAP to be used in place of aggregate or soil for non-structural backfill. RAP may also be used in the shoulder as base/subbase material, but must be blended with aggregate with a maximum of 50% RAP by weight. For the construction of the base/subbase layers, steel wheel rollers or pneumatic-tired rollers may be used to compact the material. The subbase may not be constructed in lifts greater than 4 inches (100 mm) thickness and each lift must be compacted to at least 95% according to AASHTO T 224.

4.5 Indiana

Indiana Department of Transportation (InDOT) describes RAP to be the product resulting from the cold milling or crushing of an existing HMA pavement. Before entering the plant, RAP shall be processed so that 100% will pass the 2 in. (50 mm) sieve. InDOT permits the incorporation of RAP in the construction of reclaimed base courses (RBC). This work consists of pulverizing and stabilizing an existing asphalt pavement along with existing base and subgrade materials to construct the RBC. RBC consists of a homogenous blend of RAP, base and subgrade materials that are combined with cement, water and, when required, recycling additives such as corrective aggregate. The cement may be dry powder or slurry.

4.6 Minnesota

The Minnesota Department of Transportation (MnDOT) describes RAP as a material produced through milling operations involving the grinding and collection of existing hot mix asphalt (HMA). MnDOT allows the use of less than 25% RAP in aggregate mixtures meant for the base and subbase courses. MnDOT allows up to 3.5% bitumen content in granular bases and up to 3% in subbases. Placement and compaction of aggregate base courses including RAP should meet the requirements shown in Table 4.5.

Table 4.5 Roller requirements for compaction (MnDOT, 2016)

Base Lift Thickness	**Bitumen Content**	**Required Rollers**
≤ 3 in (75 mm)	Any Bitumen	Pneumatic Rollers only
> 3 in (75 mm) to ≤ 6 in (150 mm)	≤ 2.5%	Vibratory and Pneumatic Rollers
> 3 in (75 mm) to ≤ 6 in (150 mm)	> 2.5%	Vibratory Pad Foot roller weighing at least 25,000 lb. (11,300 kg) and Pneumatic Roller 25 ton (22.7 tons)

Gradation requirements for base and subbase courses containing less than 25% of RAP are shown in Table 4.6, where all classes may have a maximum bitumen content of 3.5%.

Table 4.6 Gradation requirements for base and subbase aggregates (MnDOT, 2016)

Sieve Size		**Class 3 (subbase)**	**Class 4 (subbase)**	**Class 5 (base)**	**Class 5Q (base)**	**Class 6 (base)**
2 in	50.8 mm	100	100	-	100	-
1 ½ in	38.1 mm	-	-	-	-	-
1 in	25.4 mm	-	-	100	65 – 95	100
¾ in	19.1 mm	-	-	90 – 100	45 – 85	90 – 100
3/8 in	9.5 mm	-	-	50 – 90	35 – 70	50 – 85
No. 4	4.75 mm	35 – 100	35 – 100	35 – 80	15 – 45	35 – 70
No. 10	2.0 mm	20 – 100	20 – 100	20 – 65	10 – 30	20 – 55
No. 40	0.42 mm	5 – 50	5 – 35	10 – 35	5 – 25	10 – 30
No. 200	0.07 mm	5 – 10	4 – 10	3 – 10	3 – 10	3 – 7

4.7 Texas

The Texas Department of Transportation (TxDOT) defines RAP as salvaged, milled, pulverized, broken or crushed asphalt pavement. TxDOT allows the use of RAP in flexible bases. These are base courses in pavement structures that are composed of flex base material. This material is used to supply foundational support and capacity to the pavement structure while minimizing flexural tensile stresses in the surface layers and dissipating stresses caused by traffic loading to subbases and subgrades. In Texas, RAP has been used in paved driveways, country road approaches, pavement edges, sidewalks and construction entrances. Where RAP is allowed, it should not exceed 20% by weight of the total base material, unless otherwise specified. The aggregate including RAP used in the flexible bases must meet the requirements shown in Table 4.7.

In addition, recycled materials must be free from reinforcing steel and other objectionable material and have, at most, 1.5% deleterious material such as clay lumps, shale or laminated particles. Compaction may be performed with rollers at a speed between 2 and 6 mph and should achieve at least 100% of maximum density determined by Tex-113-E. Texas also allows use of RAP as backfill for mechanically stabilized walls.

Table 4.7 Classification of RAP for aggregate base course (TxDOT, 2019)

Sieve Size		**Mass % passing RAP**
2.5 in	63.5 mm	-
1.75 in	44.5 mm	0
7/8 in	22.2 mm	10 - 35
3/8 in	9.5 mm	30 - 50
No. 4	4.75 mm	45 - 65
No. 40	0.42 mm	70 - 85

4.8 Wisconsin

According to the Wisconsin Department of Transportation (WisDOT), RAP is the material resulting from cold milling or crushing of existing asphaltic pavement or surfacing. Wisconsin permits incorporation of RAP in dense graded bases and in the construction of pavement shoulders. Compaction of the bases may be done using pneumatic rollers or vibratory rollers. The base must be compacted until there is no displacement laterally or longitudinally under the compaction equipment. Each layer must be compacted to 95% of maximum density according to AASHTO T99. WisDOT does not allow RAP applications in backfills.

4.9 Survey

A survey was prepared with a number of questions to assess how RAP is used by different DOTs and what experience was gained. The survey was posted to AASHTO late in November 2020 and closed in early February of 2021. The questions were as follows:

1. Does your state allow RAP as material for the base course, subgrade, and fill/structural fill or drainage layers? If yes, please proceed to the next question.
2. What is the maximum percentage of RAP (by weight) allowed for each application?
3. What type of quality assurance (QA) testing is required for the use of RAP in these applications?
4. What is your state's experience with the use of RAP other than HMA mixes? Please include challenges, issues, advantages, and disadvantages related to handling, compaction, constructability, and QC/QA. Tell us also a success story (if any).
5. What are your preferred storage practices of RAP for purposes other than HMA mixes?
6. If we can contact you, please type your name, email and phone number below.

Various state representatives including Nevada, Montana, Missouri, Maine, Wyoming, Ohio, Kansas, New Jersey, North Carolina, Arkansas, Iowa, Georgia and Hawaii responded. The following provides a summary of the responses provided.

Question 1: 23 responses were received and 15 of them were positive

Question 2: responses ranged from 15% to 50%, and 100%, for the maximum RAP allowed, and it was used exclusively for shoulder applications.

Question 3: most responses cited gradation, compaction and binder content for QA.

Question 4: problems cited with RAP use included difficulty with field compaction tests, stockpile management, contamination of stockpiles and RAP's tendency to creep. Some of the advantages mentioned were that RAP works best in shoulder applications, in roads that are in rural areas and as dust control. Other responses mentioned RAP's lower cost per mix ton and less stress on sources such as binder and aggregates.

Question 5: there was no distinction between RAP storage for base or for HMA applications.

Other comments included the need for good compaction of RAP when used in any application, that stockpiles should be well managed and that RAP use should be limited in high traffic applications because of creep. Most DOTs advocated for the use of RAP to decrease cost.

4.10 Discussion

The information from all the DOTs surveyed showed that RAP is widely used across the country for HMA. Many states use RAP in the base/subbase layers and fewer states use RAP in the subgrade, as seen in Table 4.1. Most importantly, RAP applications are normally confined to non-traffic bearing pavements. A recurring trend among the studied DOTs was the level to which the RAP was compacted. Regardless of the different compaction methods, most DOTs require that the subbase/base or subgrade be compacted at 95% of maximum Proctor density. This is in line with literature findings that state that maximum compaction can significantly reduce creep.

Generally, RAP is used jointly with other virgin materials in blends of various percentages. This is to counter creep deformations due to plastic strain effects of RAP, which would eventually affect the service life of whatever application that RAP is used for. Because of the need to stabilize RAP, RAP pavement applications are limited to non-critical pavements such as side-walks, driveways or temporary roadways. That is, pavements that do not experience large traffic loads. RAP use in embankments or in structural backfill is very limited.

The National Asphalt Pavement Association (NAPA) states that RAP must not be considered a hazardous waste and can be used as a clean fill. This recommendation is consistent with literature findings that show that RAP poses no threat to the environment and can be used safely.

5. CONCLUSIONS

5.1 Introduction

This study addressed the use of Reclaimed Asphalt Pavement (RAP). A comprehensive review of existing literature was done to compile and analyze all information and experience on the subject so as to improve understanding of the mechanical properties of RAP, as well as to determine the performance of RAP materials. The work was carried out with the goal of listing the range of mechanical properties expected with a focus on the application of RAP to fill and base/subbase layers in pavements, as well as to document the current RAP practices by state DOTs.

This section summarizes the main conclusions drawn from the study.

5.2 Conclusions

RAP (Reclaimed Asphalt Pavement) is a material obtained from the removal of asphalt pavements or from processed asphalt pavement materials. RAP is used across the US in multiple applications, largely in asphalt pavement layers. The literature is rich with reports describing the use of RAP. Indeed, an in-depth review of the technical specifications of eight States, including Indiana, shows that RAP can be potentially used in fills, in pavement layers and even in structural fills. The following provides a summary of the most important advantages and disadvantages of using RAP.

Advantages: RAP can be described as a rather uniform non-plastic granular material, with a low percentage of fines. It is formed by aggregate coated with a thin layer of asphalt. It is often used mixed with other granular materials. The addition of RAP to other aggregates decreases the maximum dry unit weight of the mixture and decreases the optimum water content. Those effects increase as the percentage of RAP in the mixture increases. RAP also increases the Resilient Modulus of the blended aggregate, but decreases permeability. RAP can be used safely, as it does not pose any environmental concerns. RAP use falls in line with EPA recommendations and limitations. Economically, the use of RAP is advantageous as it can replace natural aggregate and is a more sustainable practice than using virgin aggregate.

Disadvantages: The most important disadvantage of RAP is that it displays significant creep. It seems that this is caused by the presence of the asphaltic layer coating the aggregate. Creep increases with pressure and with temperature, and decreases with the degree of compaction. Creep can be mitigated by either blending the RAP with aggregate or by stabilization with chemical compounds. Fly ash and cement have shown to decrease, albeit not eliminate, the amount of creep. Mechanical stabilizing agents such as geotextiles may also be used. While there is a financial benefit upfront in using RAP over the more expensive virgin materials, the savings can be easily offset by the need of frequent rehabilitation of the pavement due to its faster deterioration because of the creep deformations induced by RAP. Such rehabilitation work will incur additional costs to the users, because of the impact on traffic by the rehabilitation work. In addition to milling, RAP requires proper transport and storage to prevent segregation and excessive moisture during storage.

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