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QUANTIFICATION OF SYSTEM-WIDE LIFE CYCLE BENEFITS OF RECYCLED MATERIALS IN HIGHWAYS

Final Report

by

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DISCLAIMER

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EXECUTIVE SUMMARY

Quantification of the system-wide benefits of recycled material use for the sustainable design and ranking of these sustainable systems is attractive to stakeholders. A study was conducted to evaluate the life-cycle cost benefits of a highway constructed with four different recycled materials. PaLATE, a popular software for life-cycle analysis of pavements, was used to conduct an environmental and economic analysis for highway projects from initial construction to end of the design phase. The analyses indicated that recycled materials replacing part of virgin materials in highway applications have lower life-cycle costs and are more environmentally friendly compared to using only virgin materials. Material production may have the greatest effect compared to transportation and process, consistent with the earlier studies. Some designs with recycled highways yielded comparably low scores due to high energy and/or water consumption, high green-house gas emission, or high hazardous contamination, which can help designers to choose the optimum type and content of materials.

1.0 LIFE CYCLE ANALYSIS FOR RECYCLED HIGHWAYS

1.1 EVALUATION OF RECYCLED MATERIALS IN HIGHWAY APPLICATION BY PALATE

1.1.1 Introduction

PaLATE is a popular pavement life-cycle assessment tool, which evaluates the economic and environmeantal effects of a highway project from initial construction to maintenance, and eventually to the design life (Horvath 2004). The economic module predicts the life-cycle cost of activities and materials (i.e., recycled materials) in a highway project. The environmental module estimates energy and water consumption, air emission (i.e., greenhouse gas) and fume pollution, as well as the discharge of metals (e.g., Hg and Pb) and organics (e.g., PAH). The primary objective of thisstudy was to investigate the benefits of using recycled mateials in highway applications and the influence of different content of recycled materials in pavement applications on cost and the environment. Pavements made with recycled materials are compared with conventional pavements containing only virgin materials. Results from PaLATE can assist on how to best utilize recycled materials and idenditfy the optimum substitution rate in highway applications

1.1.2 Project Description and Model Creation

1.1.2.1 Pavement Design

To model the life-cycle of pavements, dimensions (i.e., width, length, and depth of each layer) of the pavement structure should be defined at first. According to the literature, the minimum lane width is 12 feet (3.7 m) for most U.S. and state highways; thus, the width for two lanes (two directions) is assumed to be 24 feet. Shoulders cannot be included in the analysis because of their variability in width, thickness, and composition. Since the lengths of pavements are varied, 1 mile can be used to represent the bases for the analysis. In regards to layer thicknesses, concrete and asphalt pavements have different requirements due to the differences in pavement mechanics and load distribution behavior. . In pavement design, thickness of concrete, asphalt and base layers were fixed at 8 in., 4 in., and 4 in., respectively. Table 1 presents the design pavement inputs for the analysis. .

Following pavement design considerations, the volume of construction materials and their source (hauling distance), pertinent construction and maintenance activities can be defined. The density of materials is shown in Table 2. The project site was assumed to be 10 miles away from the RCA, RAP, and foundry sand suppliers, 30 miles away from the quarry of virgin aggregates, 5 miles away from bitumen plants, 10 miles from cement plants, and 30 miles away from disposal landfills. The transportation distance of in-place recycling is assumed to be 0.

The Asphalt Pavement Alliance recommends that the service life of pavements should be not less than 40 years, and to include at least one rehabilitation activity (APA 2010). FHWA recommends a minimum of 35 years analysis period. For this reasons, a service life of 40 years was selected for the analysis of this study.

Table 1 : Summary of dimensions design.

Design	**Material**	**Width (feet)**	**Length (mile)**	**Depth (inches)**	**Volume (yd^3)**
PCC layer	PCC with RCA	24	1	8	3129
	PCC with RAP	24	1	8	3129
	PCC with FS	24	1	8	3129
	Conventional PCC	24	1	8	3129
HMA layer	HMA with RAP	24	1	4	1564.5
	HMA with RCA	24	1	4	1564.5
	HMA with FS	24	1	4	1564.5
	Conventional HMA	24	1	4	1564.5
Base layer	GAB with RCA	24	1	4	1564.5
	GAB with RAP	24	1	4	1564.5
	FASB with RCA & RAP	24	1	1.4	547.6
	Base with FS	24	1	4	1564.5
	Conventional GAB	24	1	4	1564.5
Embankment	Embankment with FS	24	1	200	105382.7
	Conventional Embankment	24	1	200	105382.7

Note: The slope ratio for embankment is typically 2H : 1V (Ramanathan et al. 2015).

Table 2 : Density of materials suggested by PaLATE.

Material	**Density (tons/yd^3)**
RCA	1.88
RAP	1.85
Foundry Sand	1.50
Cement	1.27
Water	0.84
Bitumen	0.84
Virgin aggregate	1.25
FDR mixture	1.83

Note: Though studies provided different density value for these materials, the density listed here was used in the calculation. The "ton" is metric ton.

Treatment life is also a part of the economic assessment. Though in practice the time to first rehabilitation should be based on actual construction and pavement management data, timing may also be identified on experience. Information collected by APA (2010) from all 50 state highway agencies indicated that 20 years may be a reasonable period between initial construction and first rehabilitation, while the average interval was 15.7 years. FHWA (2000) also indicated that most asphalt overlays can last for over 15 years and many can work satisfactorily for more than 20 years. In this study, a 20-year interval was chosen between construction and the first rehabilitation for an asphalt pavement.

MDOT and MnDOT reported that concrete pavements normally have a life span of 27.5 years in average. In the report of Weland and Muench (2010), a span of 20 years was suggested for diamond grinding of PCC overlay. ACPA (1998) indicated that PCC overlay has a service life of 25 years or more. The rubblized PCC base with an asphalt overlay has an average service life of 22 years (ACPA 1998). In this study, a 20-year interval was chosen between construction and the first rehabilitation for concrete pavement.

The life span of base and embankment are generally assumed to be the same with the HMA overlay. In this case, a 20-year interval was assumed between construction and the first rehabilitation for base and embankments. The details of treatment life and activities are listed in Table 3 and Table 4.

Table 3: Summary of treatment life.

Types	Treatment Life (years)
Asphalt pavement	0, 20, 40
Concrete pavement	0, 20, 40
Base	0, 20, 40
Embankment	0, 20, 40

Table 4: Activities in construction and maintenance.

Pavement/Base	Initial Construction		Maintenance (Rehabilitation)	
	Conventional	**Recycled**	**Conventional**	**Recycled**
Concrete pavement	Install concrete pavement; Virgin material from quarry	Install concrete pavement; RCM from concrete plant; RAP from asphalt plant; FS from factory	Rubblization	Rubblization
Asphalt pavement	Install asphalt pavement; Virgin material from quarry	Install asphalt pavement; RCA from concrete plant; RAP from asphalt plant; FS from factory	From site to landfill; Virgin material from quarry; Install asphalt pavement	FDR; Install asphalt pavement

Base	Install subbase & embankment; Virgin material from quarry	Install subbase & embankment; RCM from concrete plant; RAP from asphalt plant; FS from factory	Install subbase & embankment; Virgin material from quarry	FDR; Install subbase & embankment
Embankment	Install subbase & embankment; Virgin material from quarry	Install subbase & embankment; FS from factory	Install subbase & embankment; Virgin material from quarry	FDR; Install subbase & embankment

1.1.2.2 Initial Construction and Maintenance

Activities of initial construction normally include installing pavement and hauling raw materials or processed materials to site. Activities of maintenance may be more complex to consider in the analysis, since they may include frequent repairs (i.e., patching, micro-surfacing, crack sealing, etc.). In this study, minor repairs are ignored, and thus only major rehabilitation is considered. Rehabilitation activities include handling of existing materials (i.e., landfill, recycling), hauling new pavement materials, and paving operations. Table 4 lists the specific activities during initial construction and maintenance. These activities are different in function of the pavement type and base used.

Rubblization is the process of breaking the existing Portland Cement Concrete slab into small fragments ranging from sand size particles to coarse aggregate particles that may be 100 mm (4 in.) to 200 mm (8 in.). . Studies indicated that rubblized roads with an asphalt overlay have an average service life of 22 years, and provide more than 60% cost savings compared to tear out and replace of concrete (ACPA 1998). Furthermore, replaced concrete base has a short useful life, which is only 20% of the rubblized concrete base (ACPA 1998). Thus, rubblization was selected in this study as the rehabilitation option with a service life of 20 years (ACPA 1998).

Concrete overlay can be rehabilitated by either constructing unbounded PCC overlay or removing and replacing the PCC slab (NAPA 2014). Weland and Muench (2010) proposed three methods to rehabilitate PCC pavements, including replacing with a new PCC pavement, replacing with a new asphalt pavement, and recycling the PCC pavement by CSOL (crack, seal, and overlay the existing PCC pavement with HMA) process. CSOL process is more environment-friendly compared to replacing with a new pavement, since the old pavement does not need to be removed and landfilled.

FHWA (2015) stated that full-depth reclamation (FDR) of asphalt road normally works well for 8-12 years with thin surface treatment, and 15-20 years or longer with a hot asphalt concrete pavement layer. FDR with emulsified asphalt perform e well for 7-10 years with thin surface treatment, and 15-20 years or longer with a hot asphalt concrete overlay. Considering the potential advantages of FDR over conventional pavement replacement with new materials, FDR was adopted in the rehabilitation stage for recycled pavements.

Maintenance costs are normally estimated based on procurement records. APA (2011) indicated that maintenance costs estimated in an LCCA procedure should follow the historical documentation of actual pavement activities and expenditures. In this study, life cycle cost only comprises of the expense in ininitial construction and first rehabilitation.The costs for small pavement repair (i.e., patching, crack sealant, etc.) were igonerd, since these costs are insignificant compared to construction. A summary of the construction costs are given in Table 5.

Table 5: Summary of construction costs.

Treatment	Unit	Unit Cost	Reference
Install 4-in. asphalt paving	$/yd^2	16.79	RS Means, 2015
Install 8-in. concrete paving	$/yd^2	34.44	NAPA, 2014
Rubblization	$/yd^2	1.5	
Install subbase & embankment	$/yd^2	16.50	RS Means, 2015
From site to landfill	$/ton	56.9	OC Waste & Recycling, 2015
FDR	$/ton	4.60	FHWA, 1998
FDR-emulsified asphalt	$/ton	5.45	FHWA, 1998

Environmental effects are estimated in PaLATE by summing up consumption and emission in each stage of pavement construction and maintenance. Energy use and air emissions are based on the productivity, fuel consumption rate, and the engine size of the construction equipment. HTP (human toxic potential) is a normalized risk factor reflecting the potential harm that a chemical can cause when released into the water or air (Hertwich et al. 2001). HTP and RCRA (Resource Conservation and Recovery Act) hazardous waste are measured based on the types of materials and activities. In this study, various construction equipment were chosen during the construction and maintenance process. Table 6 provides information on the type, productivity, and fuel consumption of this equipment.

Table 6: Summary of equipment characteristics.

Equipment	Engine capacity(hp)	Productivity (ton/h)	Fuel Consumption (l/h)	Fuel Type
Slipform Paver	106	564	19.7	Diesel
Texture curing machine	70	187	20.2	Diesel
Pneumatic roller	100	668	26.1	Diesel
Tandem roller	125	285	32.7	Diesel
Excavator	131	315	34.2	Diesel
Vibratory soil compactor	174	1832	27.6	Diesel
Multi head breaker	350	520	76.5	Diesel
Asphalt road reclamation	670	4800	120	Diesel
Excavator	131	225	34.2	Diesel
Wheel loader	135	225	35.3	Diesel
Dozer	285	225	71.4	Diesel
Generator	519	225	98.4	Diesel

1.1.2.3 Mix Design

The substitution rates of recycled materials were determined according to literature review. The schemes for mix design proposed by studies were listed in Table 7 for PCC (by weight) and Table 9 for HMA (percentage by weight). Since PaLATE's input for "initial construction" and "maintenance" requires the volume of each material, weight of materials should be transferred to volume. Table 8 and Tables 10-12 present the volume of materials used in PCC, HMA, base, and embankment, respectively.

Table 7: Suggested mix design for PCC.

Category	RCA (lb/yd^3)	RAP (lb/yd^3)	FS (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Cement (lb/yd^3)	Water (lb/yd^3)	Reference
PCC with RCA 50%[1]	845.9	-	-	979.1	1252.7	535	214	Volz et al. 2014
PCC with RCA 100%[1]	1650.5	-	-	-	1441.6	535	192.6	Volz et al. 2014
PCC with RAP 40%[2]	-	1150	-	1072	788	500	250	Hossiney 2012
PCC with RAP 100%[2]	-	2922	-	-	-	500	250	Hossiney 2012
PCC with FS 20%[3]	-	-	207	1941	726	677	298	Singh and Siddique 2012
Conventional PCC	-	-	-	1958.2	1252.7	535	214	Volz et al. 2014

Note: 1. RCA takes up the percentage of coarse aggregates by weight.

2. RAP takes up the percentage of both coarse and fine aggregates by weight.

3. FS takes up the percentage of fine aggregates by weight.

Table 8: Volumes of materials in PCC layer for PaLATE input.

Category	RCA (yd^3)	RAP (yd^3)	FS (yd^3)	Coarse Aggregate (yd^3)	Fine Aggregate (yd^3)	Cement (yd^3)	Water (yd^3)
PCC with RCA 50%	494.4	-	-	794.8	1098.3	463.1	278.5
PCC with RCA 100%	1023.2	-	-	-	1345.5	491.3	266.0
PCC with RAP 40%	-	710.3	-	907.4	719.7	450.6	341.1
PCC with RAP 100%	-	2177.8	-	-	-	541.3	409.9
PCC with FS 20%	-	-	140.8	1476.9	597.6	547.6	366.1
Conventional PCC	-	-	-	1451.9	1001.3	422.4	253.4

Note: 1. Total volume of PCC is 3129 yd^3, as shown in Table 1.1.

2. Air content is ignored in the calculation of volume.

3. Coarse aggregate and fine aggregate are merged as virgin aggregate in PaLATE input.

Table 9: Suggested mix design for HMA.

Category	RAP% by weight[2]	RCA% by weight[2]	FS% by weight[2]	Bitumen% by weight	Virgin aggregate% by weight	Reference
HMA with 25% RAP[1]	24.2%	-	-	4.4%	71.3%	Shirodkar et al. 2011
HMA with 35% RAP[1]	33.7%	-	-	4.4%	61.8%	Shirodkar et al. 2011
HMA with 45% RCA[1]	-	42.1%	-	6.5%	51.4%	Wong et al.2007
HMA with 10% FS[1]	-	-	9.5%	4.8%	85.7%	Bakis et al. 2006 and Braham 2002
Conventional HMA	-	-	-	5.3%	94.7%	Wong et al.2007

Note: 1. Recycled materials take up the percentage (i.e., 25%) of total aggregates by weight.

2. Recycled materials take up the percentage (i.e., 24.2%) of HMA mixture (bitumen is included) by weight.

Table 10: Volumes of materials in HMA layer for PaLATE input.

Category	RAP (yd^3)	RCA (yd^3)	FS (yd^3)	Bitumen (yd^3)	Virgin aggregate (yd^3)
HMA with 25% RAP	272.2	-	-	109.5	1184.3
HMA with 35% RAP	391.1	-	-	112.6	1060.7
HMA with 45% RCA	-	491.3	-	170.5	902.7
HMA with 10% FS	-	-	123.6	111.1	1329.8
Conventional HMA	-	-	-	120.5	1444.0

Note: 1. Total volume of HMA is 1564.5 yd^3, as shown in Table 1.

2. Air content is ignored in the calculation of volume.

Table 11: Volumes of materials in base layer for PaLATE input.

Category	RAP (yd^3)	RCA (yd^3)	FS (yd^3)	Emulsified Asphalt (yd^3)	Cement (yd^3)	Virgin aggregate (yd^3)	Reference
Conventional GAB[1]	-	-	-	-	-	1564.5	Aydilek et al. 2015
GAB with 100% RCA[1]	-	1564.5	-	-	-	-	
GAB with 100% RAP[1]	1564.5	-	-	-	-	-	Bennett and Maher 2005
Cement-stabilized FS base[2]	-	-	1383.0	-	181.5	-	Gedik 2008
FASB with 40% RAP & 60% RCA[3]	152.8	306.2	-	345.0	-	-	Schwartz and Khosravifar 2013

Note: 1. These GAB materials are made of only one material, which takes up total weight of GAB. Total volume of GAB is 1564.5 yd^3, as shown in Table 1.1.

2. Water usage is ignored in this calculation. The base material consists of 10% cement and 90% FS by weight. Total

volume of cement-stabilized FS base is 1564.5 yd^3, as shown in Table 1.

3. The optimum asphalt content is 3% by weight. RAP and RCA replace 40% and 60% of natural aggregates by weight, respectively. Total volume of FASB is 547.68 yd^3, as shown in Table 1.

Table 12: Volumes of materials in embankment for PaLATE input.

Category	FS (yd^3)	Virgin aggregate (yd^3)	Reference
Embankment with FS[1]	105382.7	-	Yazoghli-Marzouk et al. 2014
Conventional Embankment[2]	-	105382.7	-

Note: 1. The optimum moisture content of FS is about 12.5%. Water usage is ignored in this calculation. The optimal density of FS (1.34 ton/yd^3) is a little lower than the value listed in Table 2. In order to keep consistence, we use the density in Table 2. The total volume of designed embankment is 105382.7 yd^3.

2. Total volume of the designed embankment is 105382.7 yd^3.

PaLATE provides two different methods for performing life-cycle cost analysis. The first one includes a sum-up of the cost of each activity. The cost of each activity is calculated by multiplying unit cost of work (Table 5) with total amount of work. The second method, includes a sum-up of the cost of materials. The cost of each material (Table 10) is calculated by multiplying unit cost of material with total amount of materials. The second life-cycle cost analysis method was utilized in the current study, since the activities of constructing or maintaining pavements with recycled materials are the same for each application (i.e., PCC, HMA, etc.).

Table 13: Cost of labor, equipment, and materials.

Material	Unit	Unit Price
RAP	$/ton	6.18
RCA	$/ton	6.23
FS	$/ton	9.72
Virgin Aggregate	$/ton	30
Cement	$/ton	98.5
Bitumen	$/ton	534
Water	$/gal	6.7
Labor	$	16,000
Equipment	$	12,000
Overhead & Profit	$	11,000

1.1.2.4 Economic Parameters

Discount rate is used in calculating the present value and annual equivalent value of a project. Discount rate typically varies from 1% to 8%. The selection of a discount rate can significantly affect the final results. Adjusting discount rate can be a good solution in dealing with the uncertainty associated with future interest rates and inflation. Too high a discount rate would overemphasize the importance of the initial cost. According to a survey conducted by APA (2010), an average discount rate of 3.7% is used in the U.S. with a range between 2.3 and 6.0%. A total of 23 states used a discount rate of 4% when performing life-cycle cost analysis (APA 2011). In this study, discount rates of 3% and 6% were used.

1.1.3 Results and Discussion

1.1.3.1 Result of Economic Cost

PCC

Results of LCCA are shown in Figure 1-3 for PCC layer, HMA layer, and base, respectively. In this study, two discount rates were used (3% and 6%) in estimating net present value (NPV) and annual equavilent worth. Higer NPV or higher annual equivalent worth indicates higher cost. The range between NPV1 and NPV2 is the total cost with a devitation due to an uncertainty in inflation.

As seen in Figure 1, cost of PCC made with recycled materials are comparable to that of conventional PCC. PCC layer containing 20% foundry sand has the highest cost, due to high usage of cement and water as shown in Table 8. Cement has the highest unit price among all the components of PCC. The higher usage of cement will definitely raise the cost of PCC. Water has low unit price, but high water usage will elevate the cost significatly. Besides, foundry sand replaces only a small amount of fine aggregates (20%) in PCC. The small cost saving contributed by the low price of recycled foundry sand is offset by the high cost of cement and water. However, substitution rate greater than 20% is adverse to mechanical performance (Singh and Siddique 2012). The study of Bhat and Lovell (1997) indicated that if clean sand was replaced by FS which requires about 50% more cement, cost could still be reduced by 25% to $6.44/ton. The divergence may due to the higher price of FS and cement used in this study or the different mix design.

Cost of PCC made with RAP is 10% higher than that of conventional PCC. The higher cost is caused by the higher cement usage as shown in Table 8. Suprisingly, as RAP replacement rate increases from 40% to 100%, life-cycle cost increases a little. The cost saving contributed by the low price of RAP is offset by the increased usage of cement (increased by about 65 yd^3). Addition of RAP generally worsens the performance of concrete (Hossiney 2012), but RAP added at reasonable amounts (40% by weight) can meet the requirements of mechanical properties. As a result, 100% RAP replacement should not be used in producing PCC.

PCC incorporating RCA can reduce the life-cycle cost slightly at high RCA content (Figure 1). Even though PCC with 40% RCA replacement has higher cost than conventional PCC, 100% RCA replacement reduces the cost by about 6% ($27,000~$37,000 per mile). For a project of 150 mile-long pavement, $4.8 millon can be saved, consistent with NCHRP 435 which indicated that costs saved from recycling PCC are as high as $5 million on a single project. There should be a balance point when RCA replacing at a certain ratio, the cost saving contributed by low price of RCA compensates the increased cost in cement and water usage.

HMA

The life-cycle cost for HMA layer in asphalt pavement is presented in Figure 2. Aspahlt pavements were rehabilitated by FDR, except the conventional asphalt pavement. RAP addition significatly reduces the cost of HMA layer (cost reduced by about 40%) and cost reduction increases slightly with increasing RAP content. The reason for the cost reduction can be attributed to the lower unit price of RAP compared to virgin aggregates. Secondly, FDR technique greatly reduce the cost of maintenance activities, such as landfilling the waste asphalt concrete and transportation of new materials to the site. Thirdly, RAP requies less bitumen in producing HMA. As RAP content raises from 25% to 35%, cost reduces a little. Since higher bitumen requirement by higher RAP content offsets the savings due to low price of RAP aggregates.

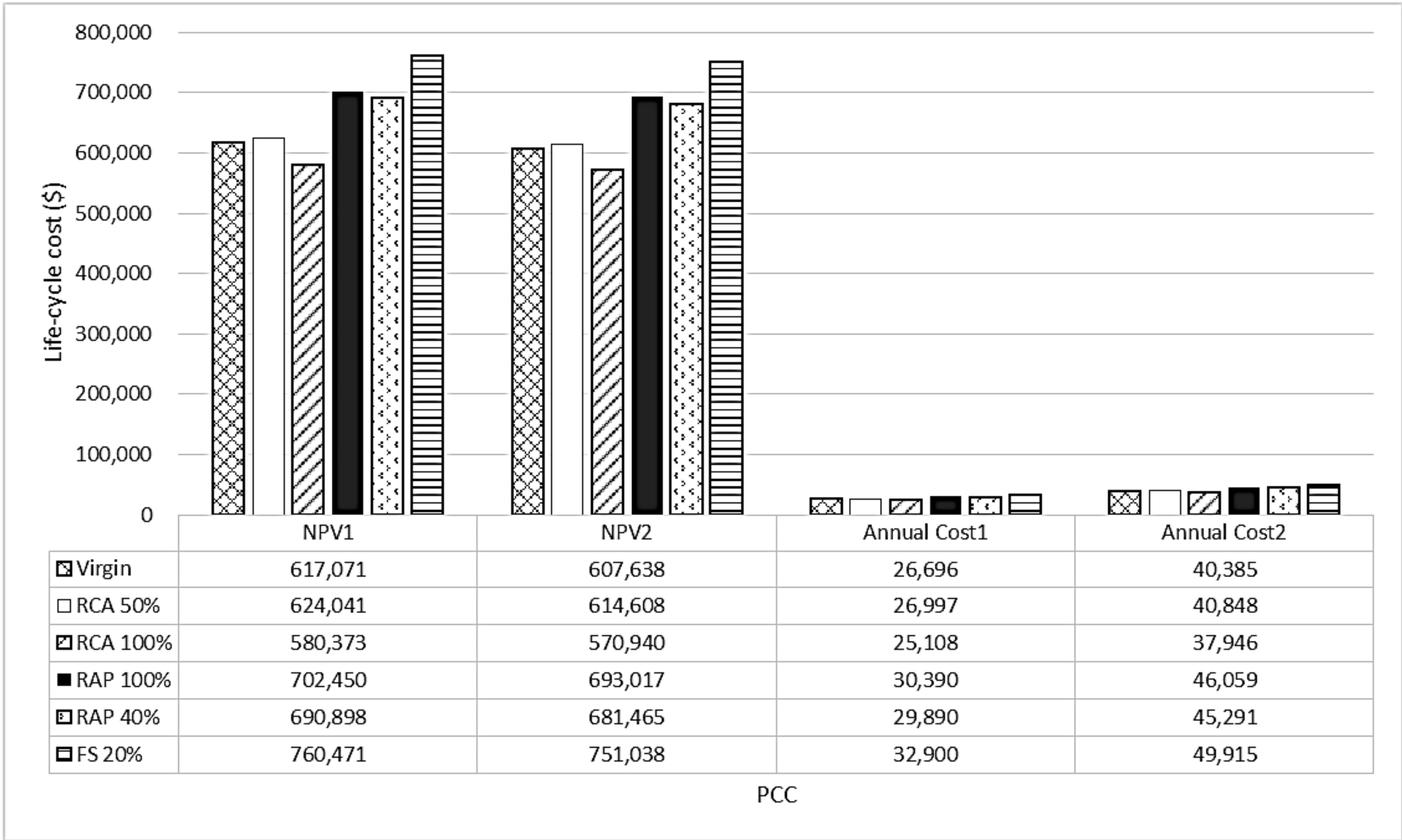
In Figure 2, HMA made with RCA anf FS have lower cost compared to conventional HMA (cost reduced by about 23%), largely due to the FDR technique used in rehabilitation stage. FIRST (2003) also indicated that 10% gray iron FS used in HMA showed $50,000 savings when using 4,000 tons of FS. HMA with 45% RCA replacement has similar cost as 10% FS replacement (cost reduced by about 23%). Higher percentage of RCA replacement does not reduce more cost, since RCA requires large amount of bitumen in producing HMA (Table 10). FS has little influence on the cost due to the much small replacement ratio of 10%, though 10% is the optimum replacement ratio in respect of mechanical poperties (Bakis et al. 2006 and Braham 2002).

Base

The life-cycle cost for base layer in asphalt pavement is presented in Figure 3. Bases were rehabilitated by full-depth reclamation, except the conventional GAB base. Recycled GAB base either with 100% RCA or 100% RAP show the lowest cost (cost reduced by about 50%) due to the lower price of recycled materials. Similarly, TFHRC (2010) indicated that incorporating 20%~50% RAP into base mixtures can save the cost by 14~34% per tonnage. For stabilized base, cement usage elevates the total cost significatly; however, the cost for cement-stabilized base with FS is still lower than conventional GAB (cost reduced by about 30%). FASB also shows great cost saving(cost reduced by about 47%), though emulsified asphalt costs much.

Embankment

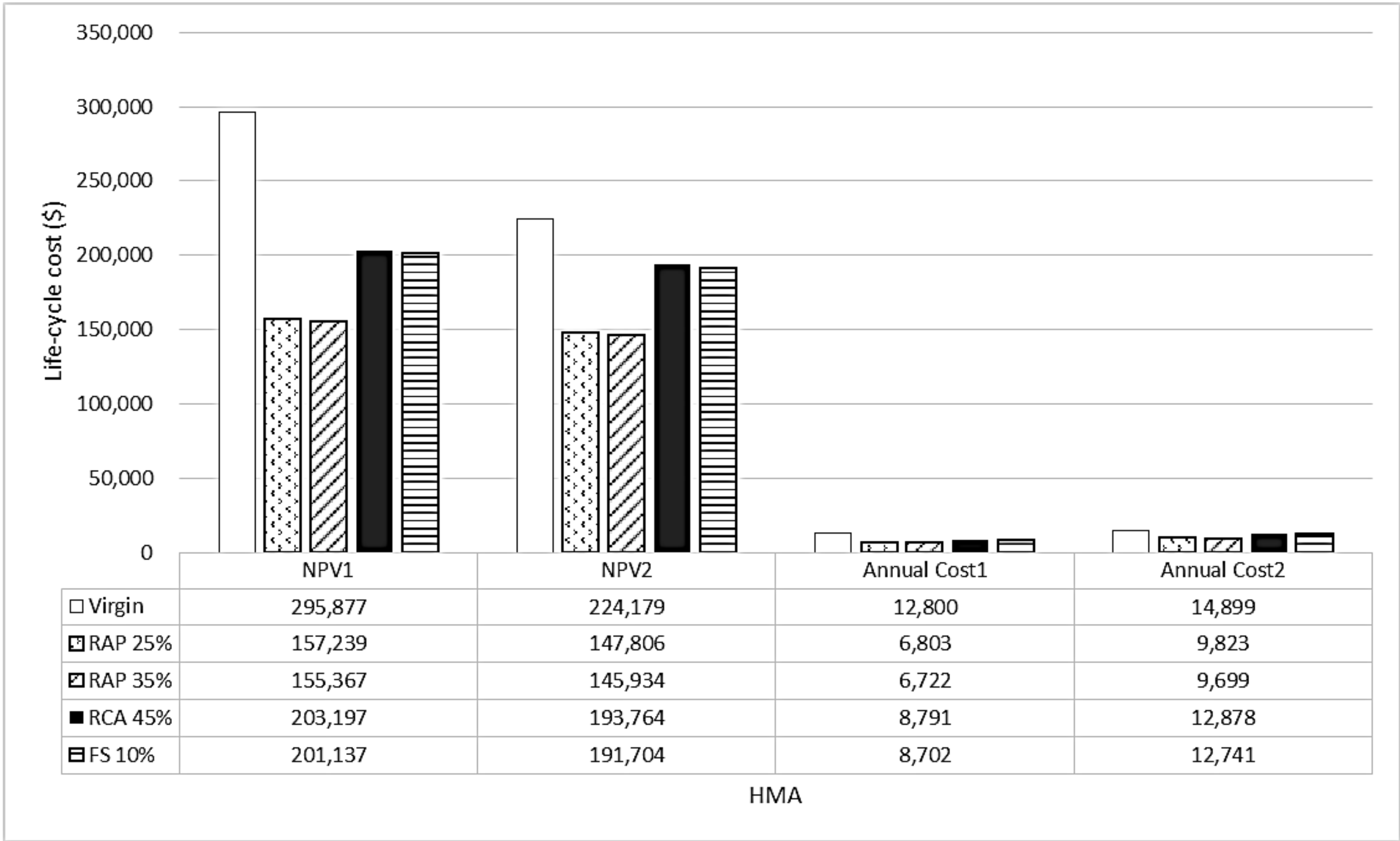
Table 14 lists the life-cycle cost of an embankment constructed with two different geomaterials. Embankment with 100% foundry sand exhibits great cost saving compared to conventional embankment (cost reduced by about 60%), owing to the lower price of FS.



	NPV1	NPV2	Annual Cost1	Annual Cost2
Virgin	617,071	607,638	26,696	40,385
RCA 50%	624,041	614,608	26,997	40,848
RCA 100%	580,373	570,940	25,108	37,946
RAP 100%	702,450	693,017	30,390	46,059
RAP 40%	690,898	681,465	29,890	45,291
FS 20%	760,471	751,038	32,900	49,915

Figure 1: Life-cycle cost for PCC layer made with recycled materials.

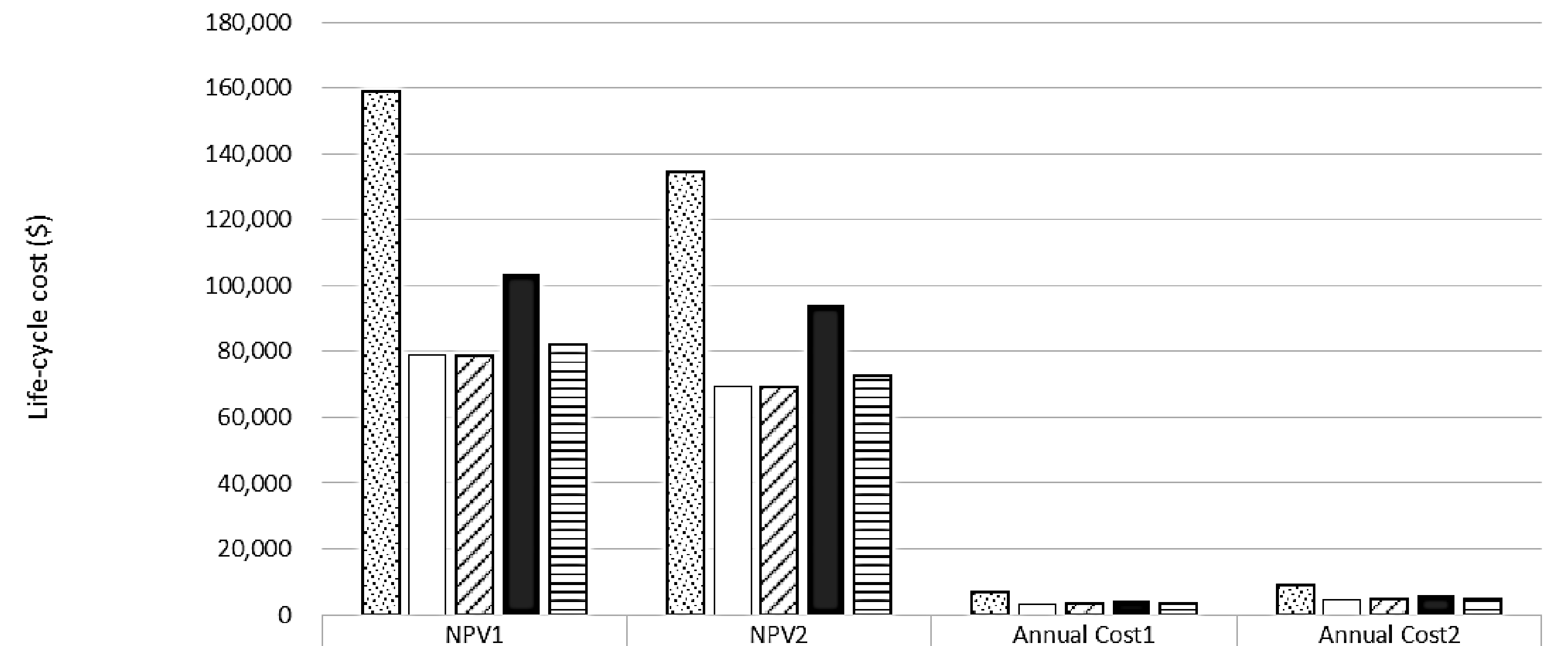
Note: NPV=net present value; Annual cost=annual equivalent worth. NPV 1 and Annual cost 1 are calculated at discount rate of 3%. NPV 2 and Annual cost 2 are calculated at discount rate of 6%.



	NPV1	NPV2	Annual Cost1	Annual Cost2
Virgin	295,877	224,179	12,800	14,899
RAP 25%	157,239	147,806	6,803	9,823
RAP 35%	155,367	145,934	6,722	9,699
RCA 45%	203,197	193,764	8,791	12,878
FS 10%	201,137	191,704	8,702	12,741

Figure 2: Life-cycle cost for HMA layer made with recycled materials.

Note: NPV=net present value; Annual cost=annual equivalent worth.NPV 1 and Annual cost 1 are calculated at discount rate of 3%. NPV 2 and Annual cost 2 are calculated at discount rate of 6%.



	NPV1	NPV2	Annual Cost1	Annual Cost2
Virgin GAB	159,034	134,276	6,880	8,924
100%RCA|GAB	78,917	69,484	3,414	4,618
100%RAP|GAB	78,480	69,047	3,395	4,589
90%FS|Base	103,459	94,026	4,476	6,249
40%RAP,60%RCA|FASB	82,024	72,591	3,549	4,825

Base

Figure 3: Life-cycle cost for base layer made with recycled materials.

Note: NPV=net present value; Annual cost=annual equivalent worth.NPV 1 and Annual cost 1 are calculated at discount rate of 3%. NPV 2 and Annual cost 2 are calculated at discount rate of 6%.

Table 14: Life-cycle cost for embankment made with recycled materials.

Materials	Virgin Embankment	100%FS|Embankment
NPV1	6,200,489	2,447,785
NPV2	5,235,218	2,066,722
Annual Cost 1	268,248	105,897
Annual Cost 2	347,941	137,358

Note: NPV=net present value; Annual cost=annual equivalent worth. NPV 1 and Annual cost 1 are calculated at discount rate of 3%. NPV 2 and Annual cost 2 are calculated at discount rate of 6%.

1.1.3.2 Results of Environmental Effect

PCC

In concrete pavements, the environmental loads of conventional PCC and PCC layers made with recycled materials can be seen in Table 15. Most energy is consumed in material production; part of energy is consumed in transportation; and process consumes the least energy. Gases emission and hazardous waste generation have the same trend. Materials production involves large amount of chemical reactivities and physical activities like milling, cruching, heating, etc. Environmental loads of transportation is associated with the distance of hauling. Process is related to the construction of pavement.

RAP replacement reduce life-cycle energy consumption of PCC slightly, while RCA replacement have comparable energy consumption (deviation with in 1%), and FS replacements increase energy consumption (Figure 4). Though producing and transporting virgin aggregates is more energy-consuming compared to recycled materials, high cement content required in recycled PCC lead to higher energy consumtion. Producing cement needs much energy, even more than producing virgin aggregates. PCC with 100% RAP has the lowest energy consumption (reduced by 6%) among the six scenarios. Increasing the content of RAP can reduce more energy consumption. PCC made with 20% FS has the highest energy consumption (increased by 7%), which can be attributed to the higher cement content. Besides, FS replaces only a small amount of fine aggregates in PCC; thus, energy saved by producing FS cannot offset the increased energy needed by cement.

Water consumption is higher for recycled PCC than conventional PCC (Figure 5), especially PCC with 100% RAP replacement and PCC with 20% FS replacement. Water consumption is determined by the mix design and distance of transportation in PaLATE. In this case, higher water consumption can be attributed to the higher water and cement content in mix design of recycled PCC (Table 8). Producing cement is water-consuming, which needs about the same amount of water to produce PCC. Increasing RCA content hardly affects water consumption, while increasing RAP content significantly raises water consumption.

Greenhouse gas emission has the same trend to energy consumption (Figure 6 and Figure 9). The only difference is the gas emission increases linearly with increasing RCA content, though it is contradicted with the findings of Evangelista and Brito (2007) that greenhouse gas emission reduces by 6.8% to 20.4% as RCA content increases from 30% to 50%. The reason for the divergence may be that Evangelista and Brito (2007) used fine RCA in PCC. Fine RCA can work as a filler in PCC, reducing cement content. NOx emission is comparable between conventional PCC and recycled PCC (Figure 7). PCC with 100% RAP has higher SO_2 emission than PCC with RCA replacement and conventional PCC (Figure 8). PCC with 20% FS has the highest amount of SO_2 emission due to high amount of cement used in producing PCC. SO_2 emission increases as RAP and RCA content increases. CO emission is comparable between conventional PCC and recycled PCC (Figure 9), except 20% FS. Recycled PCCs have lower fume emission of PM10 than conventional PCC (Figure 10), since fume emission is related to the production of virgin aggregates. Cement is an inferior source of the fume emission. Thus, PM10 emission decreases as replacement ratios of recycled materials rise.

Hazardous discharge for PCC made with recycled materials is lower than that of conventional PCC (Figures 11-13). Virgin aggregate and cement is the main source of hazardous. PCCs made with recycled materials generally have higher cement content; thus, recycled PCCs produce the comparable amount of RCRA hazardous waste as conventional PCC (Figure 11). PCC with 100% RAP shows the lowest hazardous waste generation. Human toxic potential (non-cancer) is reduced by 14% to 27% as the content of RCA increases from 50% to 100% (Figure 13), consistent with the finding of Evangelista and Brito (2007) that human toxixity decreases by 6.8% to 20.7% as RCA content increases from 30% to 50%. Human toxic potential also falls as RAP content increases (Figures 12 and 13). PCC with 100% RAP shows the lowest human toxic potential.

HMA

In asphalt pavement, HMA layers made with recycled materials have less environmental loads compared to conventional HMA (Table 16). The less environmental loads can be attributed to the FDR technology used in recycled HMA. Most energy is consumed in material production; part of energy is consumed in transportation; and process consumes the least energy. Gas emission and hazardous waste generation have the same trend.

HMA made with 25% RAP shows the lowest life-cycle energy consumption (reduced by 42%), comparable to the energy consumption by HMA with 35% RAP (Figure 14). HMA with 45% RCA has higher energy consumption (reduced by 16%), higher water consumption (comparable to conventional HMA), and higher greenhouse gas, NO_x and CO emissions than other recycled HMA due to higher bitumen content (Figures 15-17 and Figure 20). Similarly, CIPEC (2005) indicated that using 50% RAP in HMA applications can reduce energy consumption by 33%. HMA with 10% FS has higher fume emission of PM10 than other recycled HMA due to high content of virgin aggregate (Figure 18). SO_2 emission are comparable for the recycled HMAs, reduced by 50% compare to virgin HMA (Figure 19), though source of SO_2 is different with different recycled materials in use.

HMA made with 45% RCA generates the highest amount of RCRA hazardous waste among the five scenarios of HMA due to the high content of bitumen (Figure 21). Besides, RCA demolition and crushing all produce much hazardous waste. HMA made with 45% RCA and 10% FS may have higher human toxic potential (Figure 22 and Figure 23), which are related to the bitumen content and virgin aggregate content. Since the old asphalt pavement typically exposed to natural environment and human activities, they absorbed much detrimental matter in their serving period. When the old asphalt pavement is processed to reuse, some chemicals may stay in the recycled materials. With an increase of RAP content from 25% to 35%, the hazardous discharge increases by about 3% (Table 16)

Base

For base layer, recycled GAB generally has less environmental loads than conventional GAB (Table 17), since virgin aggregate has longer transportation distance (one-way distance of 30 miles compared to 10 miles of recycled materials). Besides, virgin aggregates (i.e., limestone) has higher potential to generate hazardous waste and toxic chemicals. Most energy is consumed in material production, transportation inferiors, and process consumes the least energy. Hazardous waste generation has the same trend. Gases emission may be higher in transportation than materials production (i.e., NO_x).

Cement-stabilized base with 90% FS has the highest energy consumption (Figure 24), water consumption (Figure 25), gas emission (Figure 26, 27,.30), which can be attributed to the present of cement. However, cement-stabilized base with 90% FS has the lowest hazardous discharge among the five scenarios (Figure 31-33), since FS and cement have low hazardous discharge compared to other materials. FASB with 40% RAP and 60% RCA has medium energy consumption, water consumption, gas emission, but the highest SO_2 emission (Figure 29) and hazardous discharge, due to the present of emulsified asphalt. Recycled aggregate can reduce fume (PM10) emission by 50% or more (Figure 28), since hualing distance is reduced (from 30 mile to 10 mile based on assumption). Besides, producing virgin materials (i.e., milling) can release considerable fume into environment.

Embankment

As seen in Table 17, embankment made of 100% FS has 12% higher energy consumption and 6% higher greenhouse gas emission than conventional embankment. Water comsumption is comparable for recycled embankment and conventional embankment. Other gases emission and hazardous discharges are lower for recycled embankment than convenional embankment. Particularly, recycled embankment can reduce RCRA hazardous waste generation by up to 58% and NO_x emission by 47%.

Table 15: Recycled materials used in PCC.

Environment	Materials	Virgin	RCA 50%	RCA 100%	RAP 100%	RAP 40%	FS 20%
Energy consumption/MJ	Materials Production	6,273,521	6,319,040	6,308,454	6,020,774	6,131,476	6,776,293
	Materials Transportation	185,520	155,049	126,059	50,881	139,574	161,598
	Processes (Equipment)	34,778	34,778	34,762	34,778	34,779	34,778
	Total	6,493,820	6,508,868	6,469,275	6,106,433	6,305,829	6,972,669
CO_2 Emission/Mg	Materials Production	437	449	458	423	429	473
	Materials Transportation	14	12	9	4	10	12
	Processes (Equipment)	3	3	3	3	3	3
	Total	454	464	470	430	442	487
NOx Emission/kg	Materials Production	5,330	5,543	5,707	5,736	5,419	5,823
	Materials Transportation	742	621	506	207	559	648
	Processes (Equipment)	58	58	58	58	58	58
	Total	6,130	6,222	6,270	6,001	6,036	6,528
Water Consumption /kg	Materials Production	2,391	2,479	2,510	2,675	2,485	2,760
	Materials Transportation	32	26	21	9	24	28
	Processes (Equipment)	3	3	3	3	3	3
	Total	2,426	2,509	2,534	2,687	2,512	2,791
RCRA Hazardous Waste Generated/kg	Materials Production	7,777	7,948	8,114	7,192	7,554	7,924
	Materials Transportation	1,337	1,117	908	367	1,006	1,164
	Processes (Equipment)	115	115	115	115	115	115
	Total	9,229	9,181	9,137	7,674	8,675	9,204

Table 15: Recycled materials used in PCC (continued).

Environment	Materials	Virgin	RCA 50%	RCA 100%	RAP 100%	RAP 40%	FS 20%
SO_2 Emission/kg	Materials Production	3,891	4,046	4,149	4,312	3,986	4,386
	Materials Transportation	45	37	30	12	34	39
	Processes (Equipment)	4	4	4	4	4	4
	Total	3,940	4,087	4,183	4,329	4,023	4,429
CO Emission/kg	Materials Production	2,824	2,878	2,913	2,926	2,841	2,995
	Materials Transportation	62	52	42	17	47	54
	Processes (Equipment)	12	12	12	12	12	12
	Total	2,899	2,942	2,968	2,956	2,901	3,061
Human Toxic Potential (cancer)	Materials Production	181,451	177,540	174,658	162,661	174,285	171,597
	Materials Transportation	164	137	111	45	123	143
	Processes (Equipment)	0	0	0	0	0	0
	Total	181,615	177,677	174,769	162,706	174,408	171,740
PM_{10} Emission/kg	Materials Production	2,269	2,110	1,945	1,507	2,003	2,265
	Materials Transportation	145	121	99	40	109	126
	Processes (Equipment)	4	4	4	4	4	4
	Total	2,418	2,235	2,048	1,551	2,117	2,396
Human Toxic Potential (non-cancer)	Materials Production	1,201,715,412	1,033,902,538	874,919,844	300,899,790	896,902,931	1,051,114,892
	Materials Transportation	7,003	5,853	4,759	1,921	5,269	6,100
	Processes (Equipment)	0	0	0	0	0	0
	Total	1,201,722,416	1,033,908,391	874,924,603	300,901,711	896,908,199	1,051,120,993

Table 16: Recycled materials used in HMA.

Environment	Materials	Virgin	RAP 25%	RAP 35%	RCA 45%	FS 10%
Energy Consumption/ MJ	Materials Production	4,198,677	2,485,873	2,513,975	3,619,547	2,765,550
	Materials Transportation	218,453	54,885	52,221	77,325	100,340
	Processes (Equipment)	21,769	14,440	14,430	14,431	14,431
	Total	4,438,899	2,555,198	2,580,626	3,711,303	2,880,322
CO_2 Emission/ Mg	Materials Production	205	124	126	198	143
	Materials Transportation	16	4	4	6	8
	Processes (Equipment)	2	1	1	1	1
	Total	223	130	131	205	152
NOx Emission/ kg	Materials Production	1,655	964	977	1,362	1,001
	Materials Transportation	870	219	208	308	400
	Processes (Equipment)	38	26	26	26	26
	Total	2,563	1,209	1,211	1,696	1,427
Water Consumption / kg	Materials Production	1,235	795	813	1,231	841
	Materials Transportation	37	9	9	13	17
	Processes (Equipment)	2	1	1	1	1
	Total	1,274	805	823	1,246	860
RCRA Hazardous Waste Generated/kg	Materials Production	49,567	32,575	33,469	50,938	33,309
	Materials Transportation	1,574	395	376	557	723
	Processes (Equipment)	70	70	70	70	70
	Total	51,212	33,041	33,916	51,565	34,102

Table 16: Recycled materials used in HMA(continued).

Environment	Materials	Virgin	RAP 25%	RAP 35%	RCA 45%	FS 10%
SO_2 Emission/ kg	Materials Production	65,475	32,860	32,873	33,160	32,885
	Materials Transportation	52	13	12	18	24
	Processes (Equipment)	3	2	2	2	2
	Total	65,530	32,875	32,888	33,180	32,911
CO Emission/ kg	Materials Production	714	459	469	721	487
	Materials Transportation	73	18	17	26	33
	Processes (Equipment)	8	6	6	6	6
	Total	795	483	492	752	526
Human Toxic Potential (cancer)	Materials Production	818,312	532,189	544,213	821,419	550,555
	Materials Transportation	193	49	46	68	89
	Processes (Equipment)	0	0	0	0	0
	Total	818,505	532,238	544,259	821,488	550,644
PM_{10} Emission/ kg	Materials Production	727	330	308	472	592
	Materials Transportation	171	42	40	60	78
	Processes (Equipment)	12	11	11	11	11
	Total	910	383	359	542	680
Human Toxic Potential (non-cancer)	Materials Production	696,981,483	292,480,939	263,953,963	432,919,401	548,194,476
	Materials Transportation	8,247	2,072	1,971	2,919	3,788
	Processes (Equipment)	0	0	0	0	0
	Total	696,989,730	292,483,011	263,955,934	432,922,320	548,198,264

Table 17: Recycled materials used in base and embankment.

Environ mental effect	Materials	Virgin GAB	100%RCA|GAB	100%RAP|GAB	90%FS|Base	40%RAP,60% RCA|FASB	Virgin Embank-ment	100%FS|Embank-ment
Energy consumption/MJ	Materials Production	651,445	112,092	110,303	1,189,913	618,688	40,631,507	48,757,808
	Materials Transportation	139,361	32,345	31,829	22,814	10,551	4,346,067	1,738,427
	Processes (Equipment)	18,720	13,035	12,827	10,215	4,467	1,167,599	1,401,119
	Total	809,526	157,472	154,960	1,222,942	633,706	46,145,173	51,897,355
CO_2 Emission/Mg	Materials Production	46	8	8	84	35	2,878	3,453
	Materials Transportation	10	2	2	2	1	650	260
	Processes (Equipment)	1	1	1	1	0	88	105
	Total	58	12	12	86	36	3,615	3,818
NOx Emission/kg	Materials Production	93	197	194	780	253	5,798	6,958
	Materials Transportation	555	129	127	91	42	34,620	13,848
	Processes (Equipment)	30	21	21	17	7	1,108	1,329
	Total	678	347	341	887	302	41,526	22,135

Table 17: Recycled materials used in base and embankment (continued).

Environmental effect	Materials	Virgin GAB	100%RCA|GAB	100%RAP|GAB	90%FS|Base	40%RAP,60%RCA|FASB	Virgin Embank-ment	100%FS|Embank-ment
Water Consumption /kg	Materials Production	91	0	0	476	240	5,659	6,791
	Materials Transportation	12	6	5	4	2	1,480	592
	Processes (Equipment)	2	1	1	1	0	114	136
	Total	104	7	7	481	243	7,253	7,519
RCRA Hazardous Waste Generated/kg	Materials Production	757	808	795	749	10,433	28,331	28,331
	Materials Transportation	502	233	229	164	76	62,632	25,053
	Processes (Equipment)	67	94	92	74	32	4,207	5,048
	Total	1,327	1,135	1,117	987	10,541	95,170	58,432
SO_2 Emission/kg	Materials Production	45	13	13	799	881	2,825	3,390
	Materials Transportation	33	8	8	5	3	2,077	831
	Processes (Equipment)	2	1	1	1	0	125	150
	Total	81	22	22	806	884	5,027	4,371

Table 17: Recycled materials used in base and embankment (continued).

Environmental effect	Materials	Virgin GAB	100%RCA|GAB	100%RAP|GAB	90%FS|Base	40%RAP,60% RCA|FASB	Virgin Embank-ment	100%FS|Embank-ment
CO Emission/kg	Materials Production	61	42	42	291	151	3,789	4,546
	Materials Transportation	46	11	11	8	4	2,885	1,154
	Processes (Equipment)	7	5	4	4	2	267	320
	Total	114	58	57	302	156	6,940	6,021
HTP (cancer)	Materials Production	61,797	43,025	42,377	4,645	171,519	193,376	193,376
	Materials Transportation	123	29	28	20	9	7,683	3,073
	Processes (Equipment)	0	0	0	0	0	0	0
	Total	61,920	43,053	42,405	4,665	171,529	201,059	196,449

Table 17: Recycled materials used in base and embankment (continued).

Environmental effect	Materials	Virgin GAB	100%RCA|GAB	100%RAP|GAB	90%FS|Base	40%RAP,60%RCA|FASB	Virgin Embank-ment	100%FS|Embank-ment
PM_{10} Emission/kg	Materials Production	661	14	14	462	35	41,234	49,481
	Materials Transportation	108	25	25	18	8	6,748	2,699
	Processes (Equipment)	4	2	1	1	1	134	161
	Total	773	41	40	481	44	48,117	52,341
HTP (non-cancer)	Materials Production	780,139,774	194,263,305	75,455,492	6,388,100	48,081,982	162,062,470	970,627,316
	Materials Transportation	5,261	1,221	1,202	861	398	328,126	131,250
	Processes (Equipment)	0	0	0	0	0	0	0
	Total	780,145,035	194,264,526	75,456,694	6,388,962	48,082,380	162,390,596	970,758,566

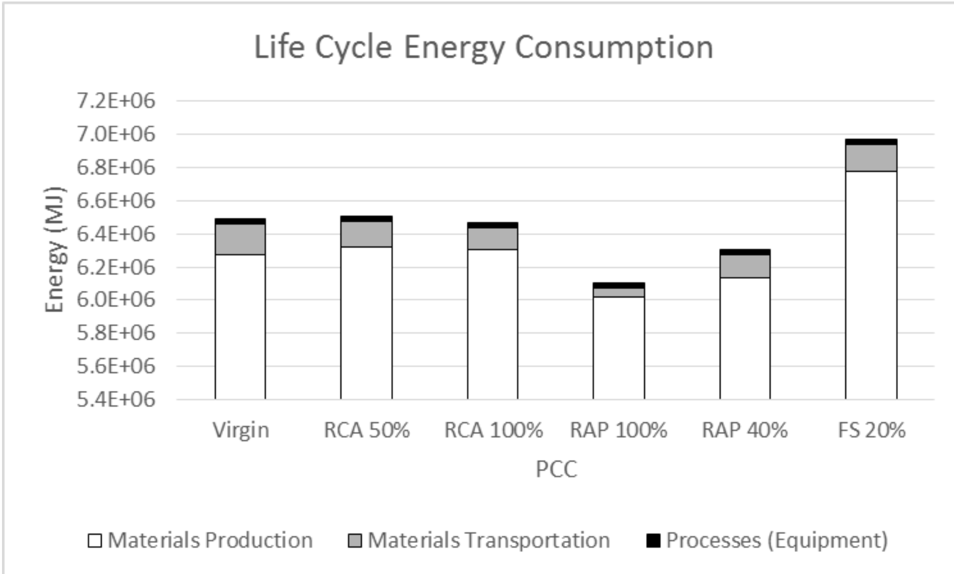


Figure 4: Life-cycle energy consumption for PCC made with recycled materials.

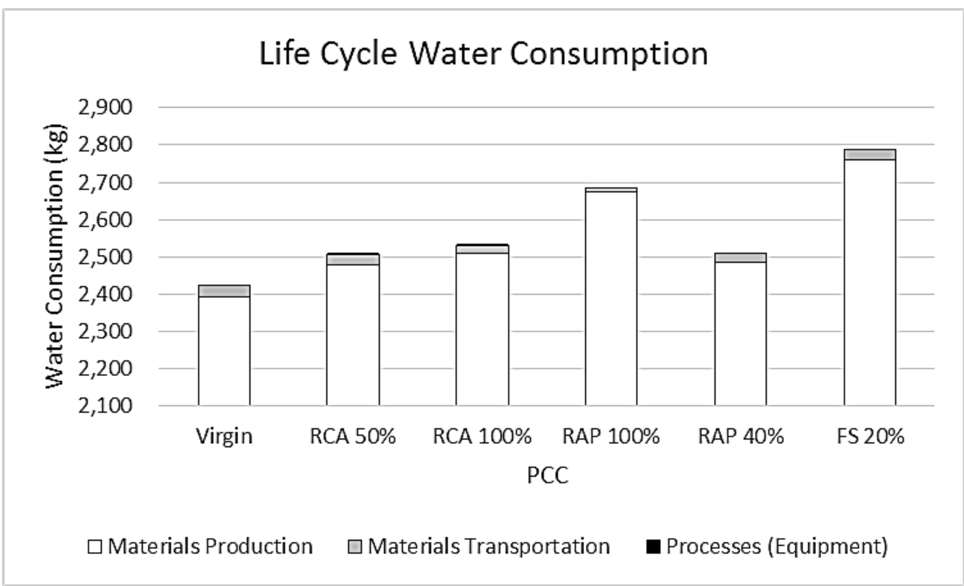


Figure 5: Life-cycle water consumption for PCC made with recycled materials.

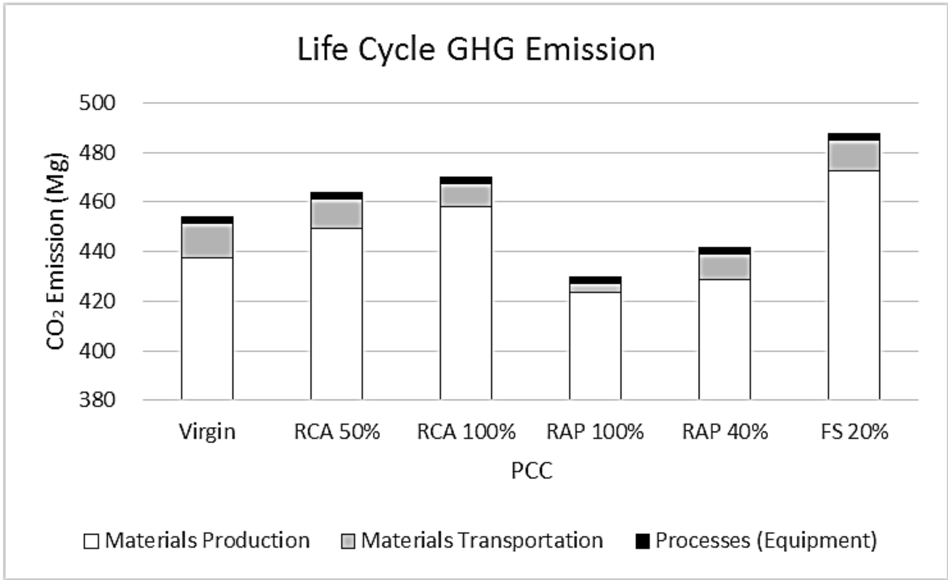


Figure 6: Life-cycle greenhouse gas emission for PCC made with recycled materials.

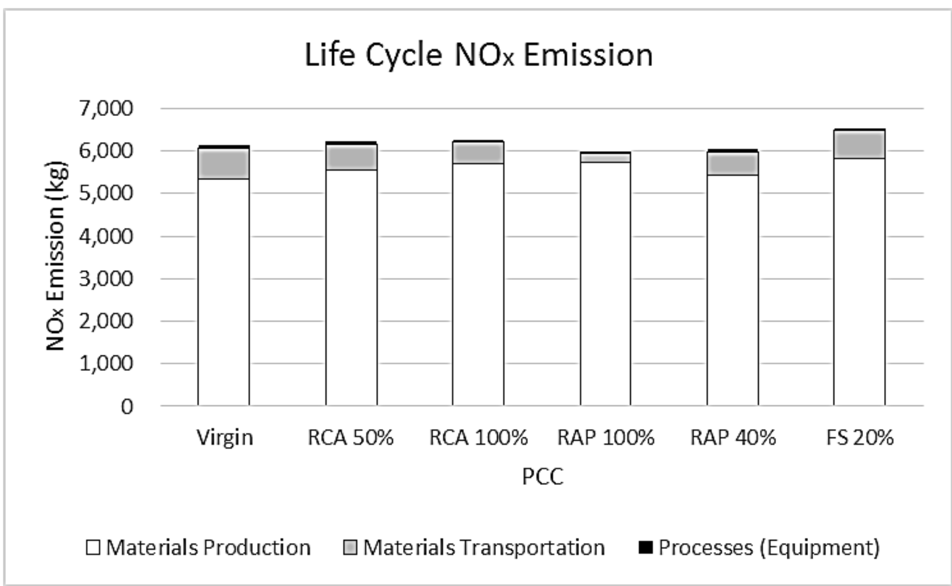


Figure 7: Life-cycle NO_x emission for PCC made with recycled materials.

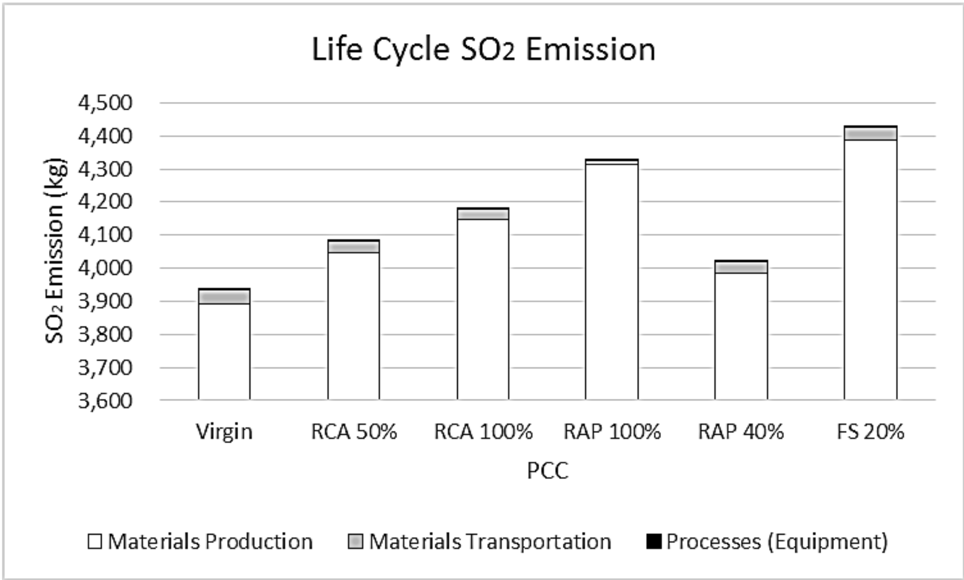


Figure 8: Life-cycle SO_2 emission for PCC made with recycled materials.

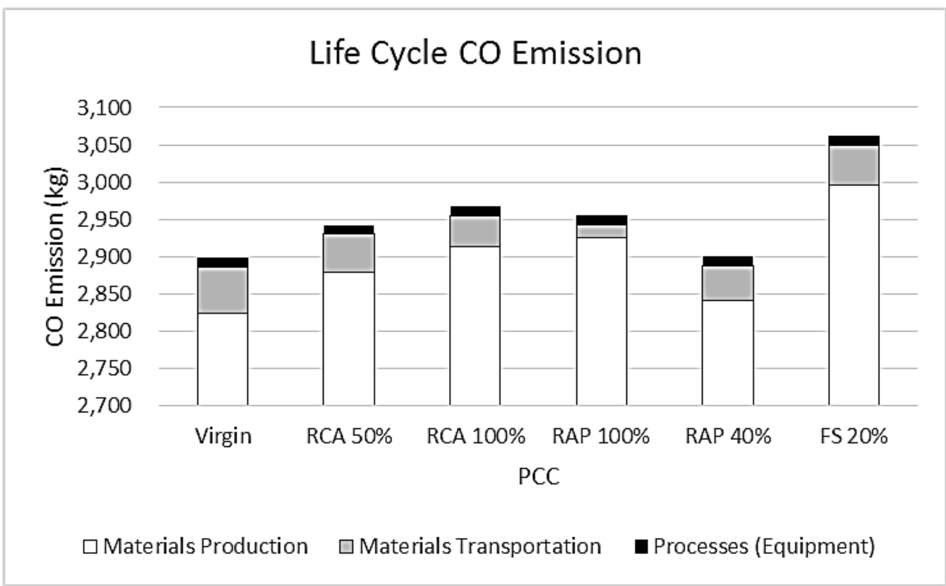


Figure 9: Life-cycle CO emission for PCC made with recycled materials.

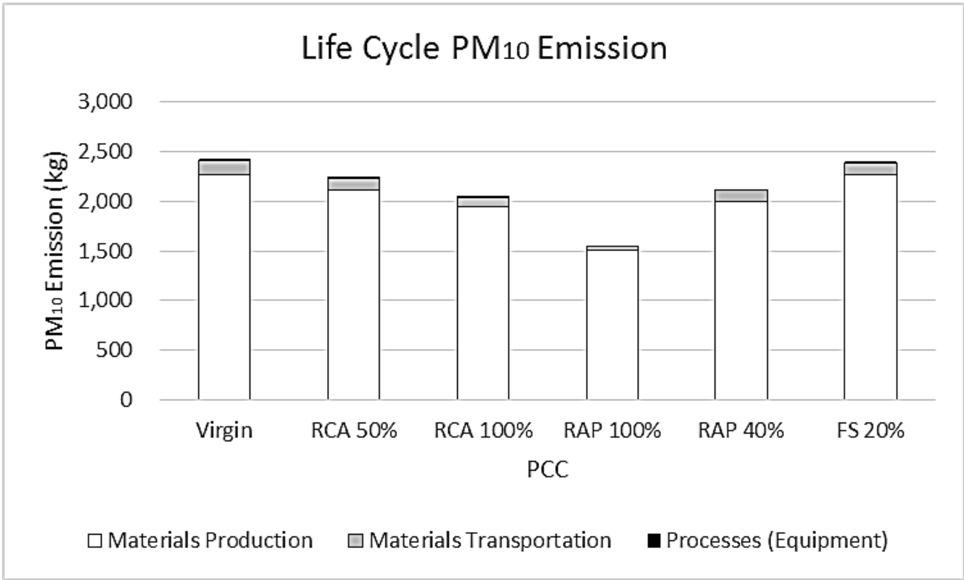


Figure 10: Life-cycle PM_{10} emission for PCC made with recycled materials.

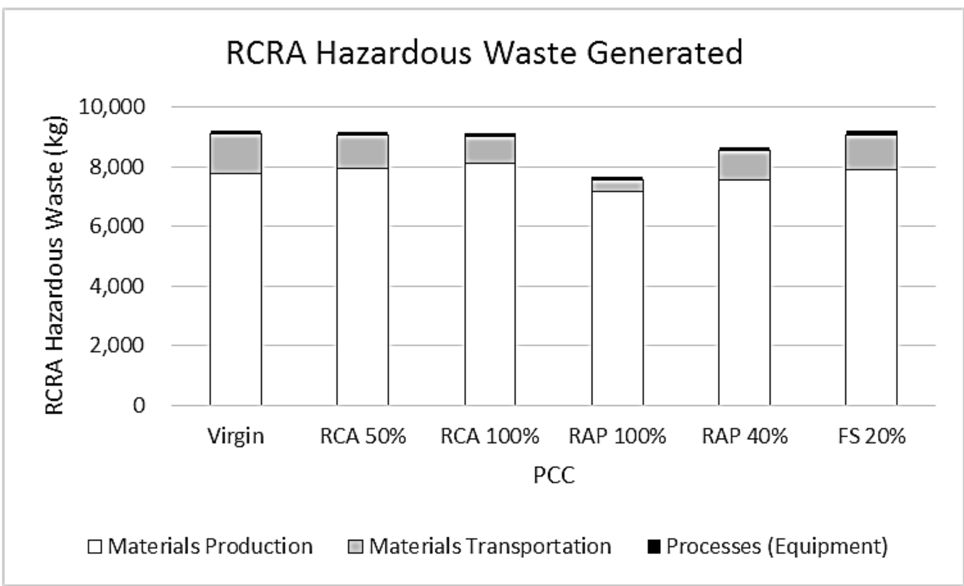


Figure 11: Life-cycle RCRA hazardous waste generated for PCC made with recycled materials.

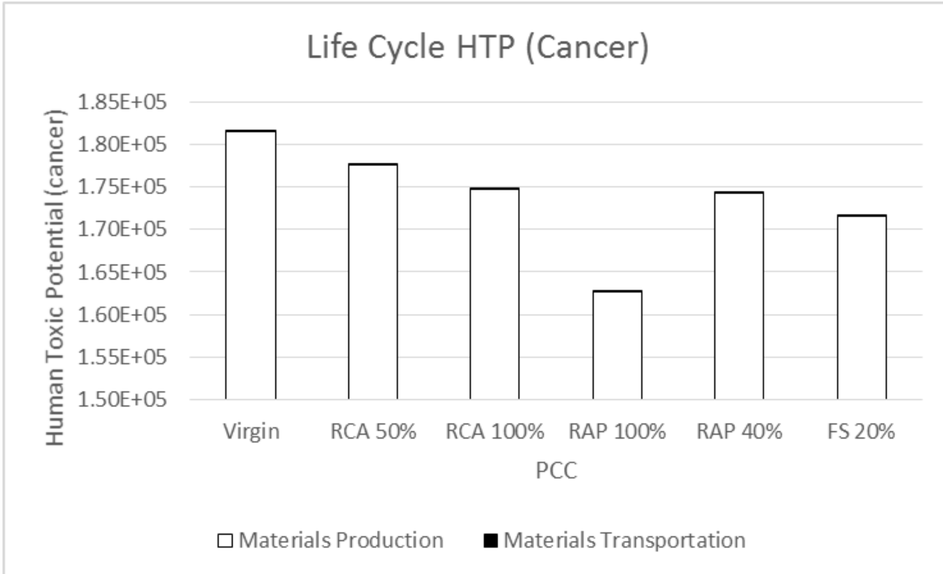


Figure 12: Life-cycle human toxicity potential (cancer) for PCC made with recycled materials.

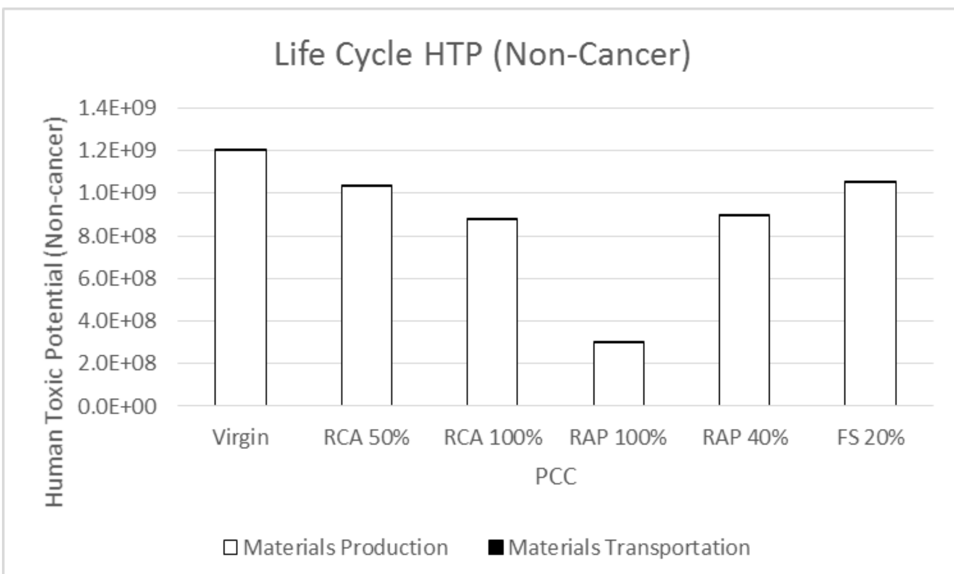


Figure 13: Life-cycle human toxicity potential (non-cancer) for PCC made with recycled materials.

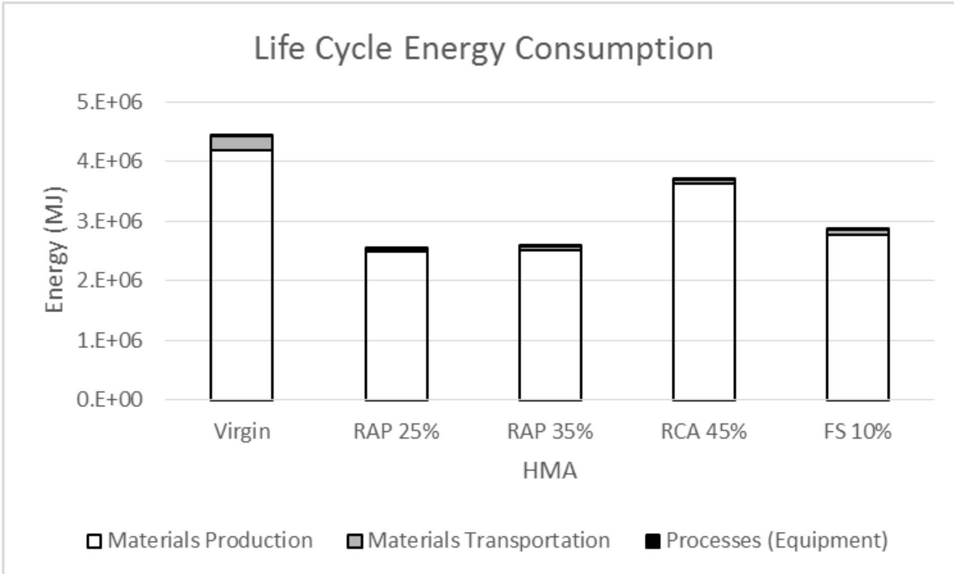


Figure 14: Life-cycle energy consumption for HMA made with recycled materials.

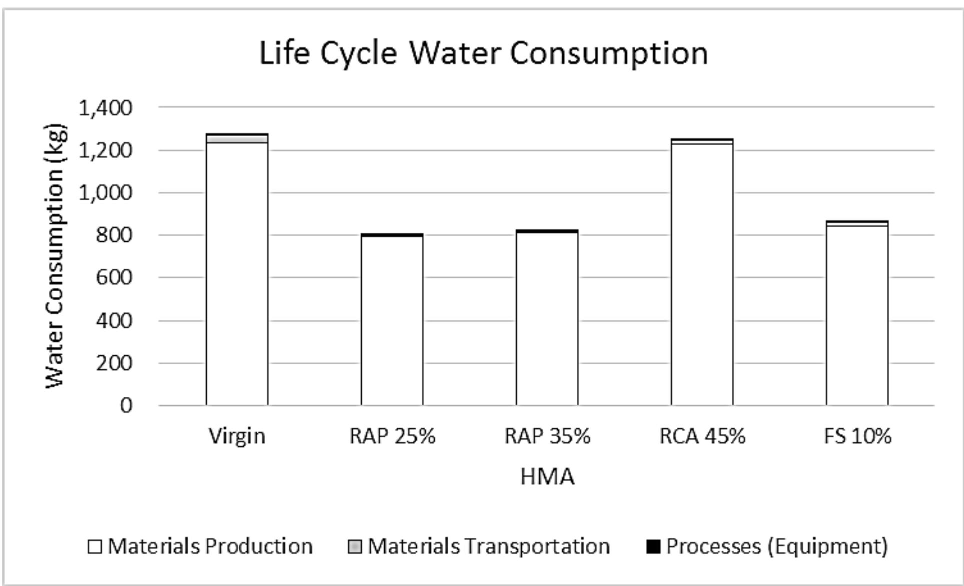


Figure 15: Life-cycle water consumption for HMA made with recycled materials.

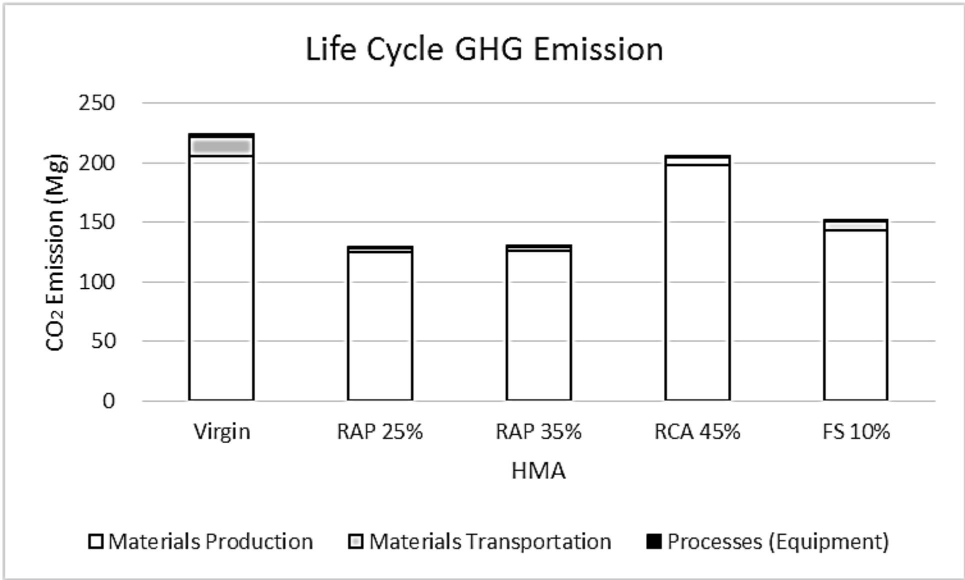


Figure 16: Life-cycle greenhouse gas emission for HMA made with recycled materials.

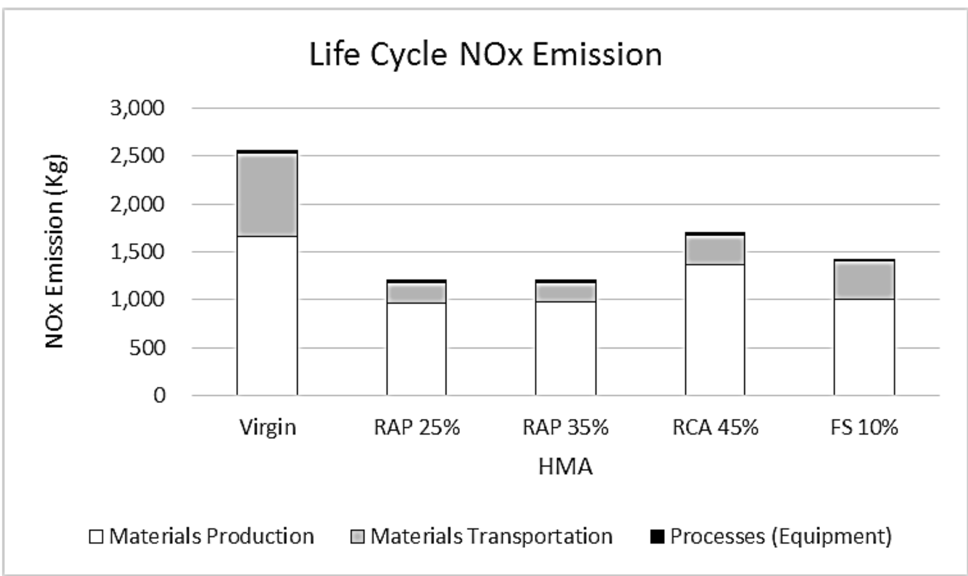


Figure 17: Life-cycle NO_x emission for HMA made with recycled materials.

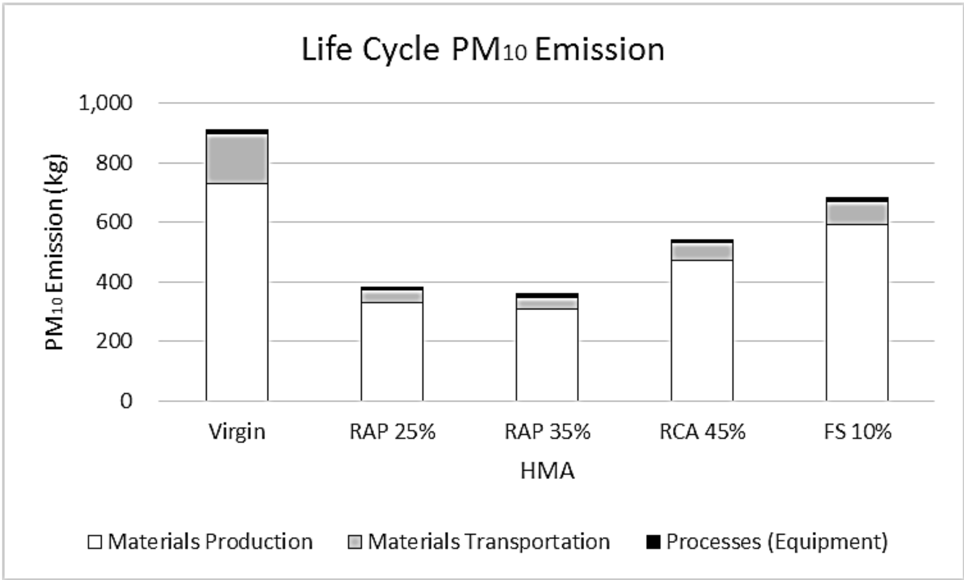


Figure 18: Life-cycle PM_{10} emission for HMA made with recycled materials.

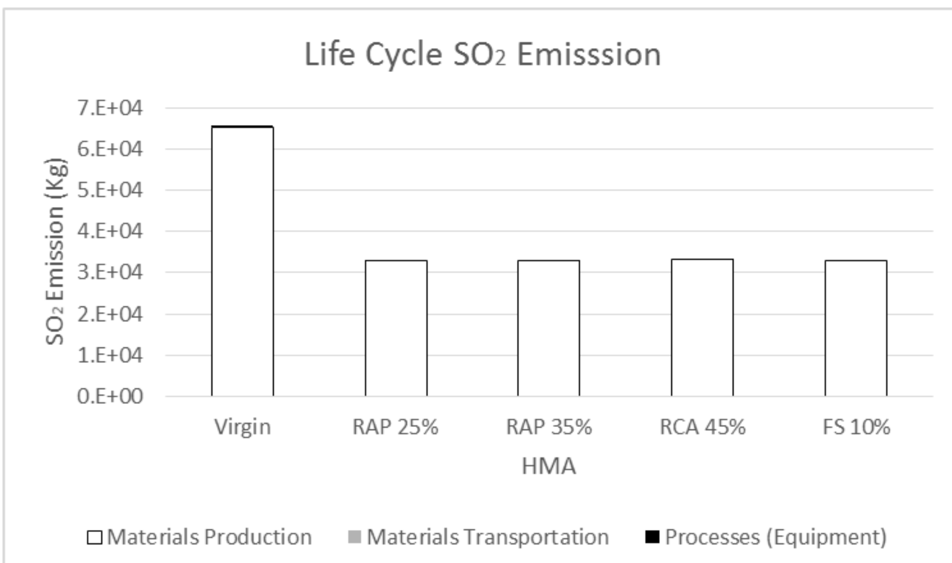


Figure 19: Life-cycle SO_2 emission for HMA made with recycled materials.

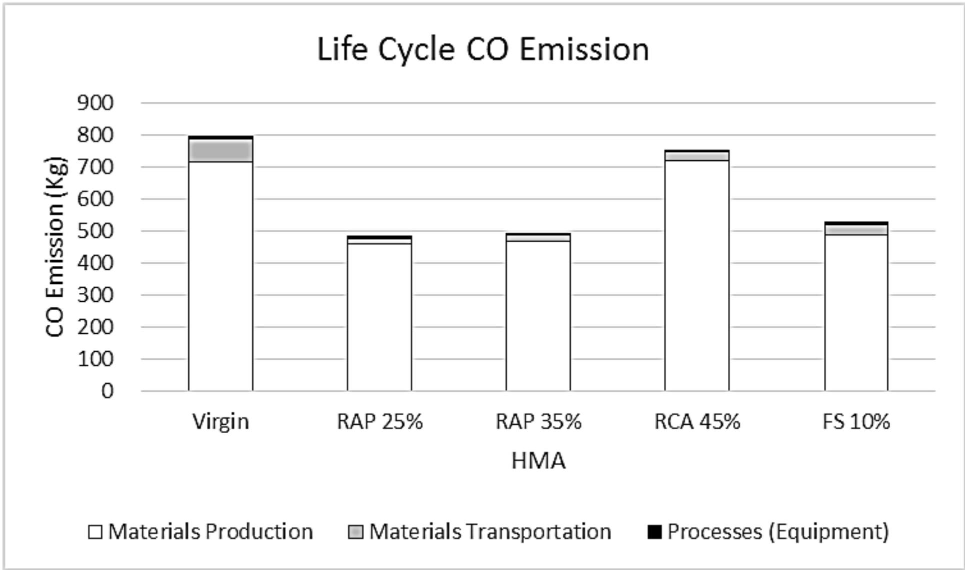


Figure 20: Life-cycle CO emission for HMA made with recycled materials.

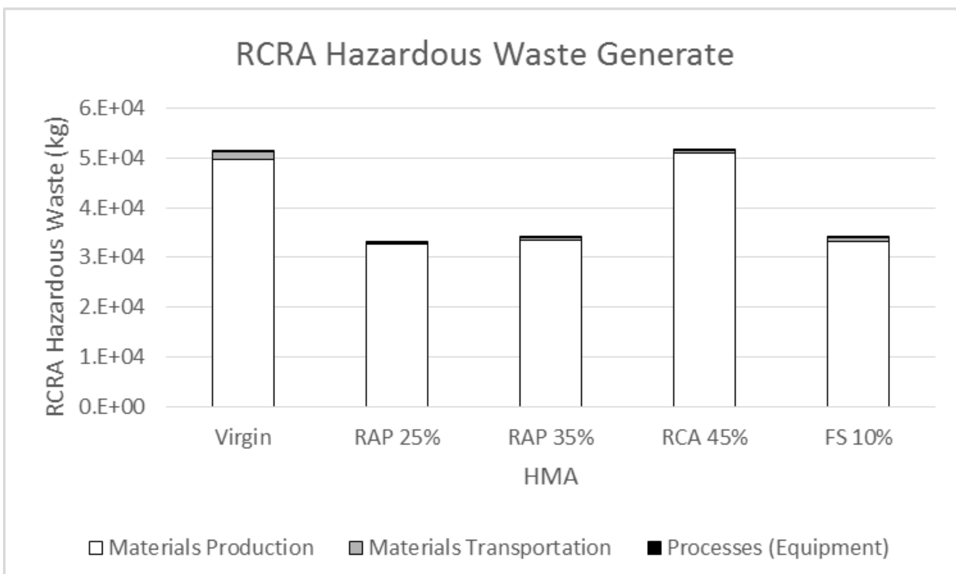


Figure 21: Life-cycle RCRA hazardous waste generated for HMA made with recycled materials.

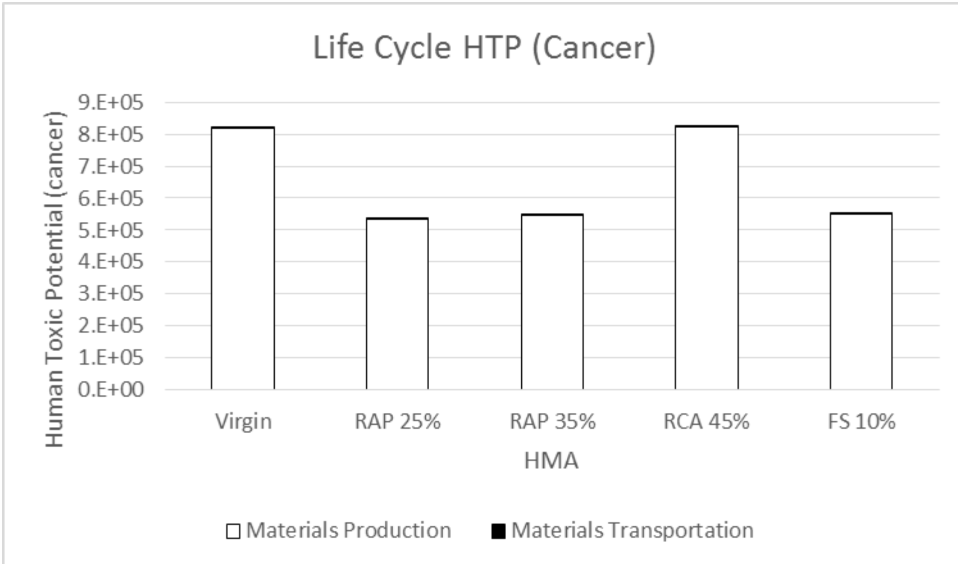


Figure 22: Life-cycle human toxicity potential (cancer) for HMA made with recycled materials.

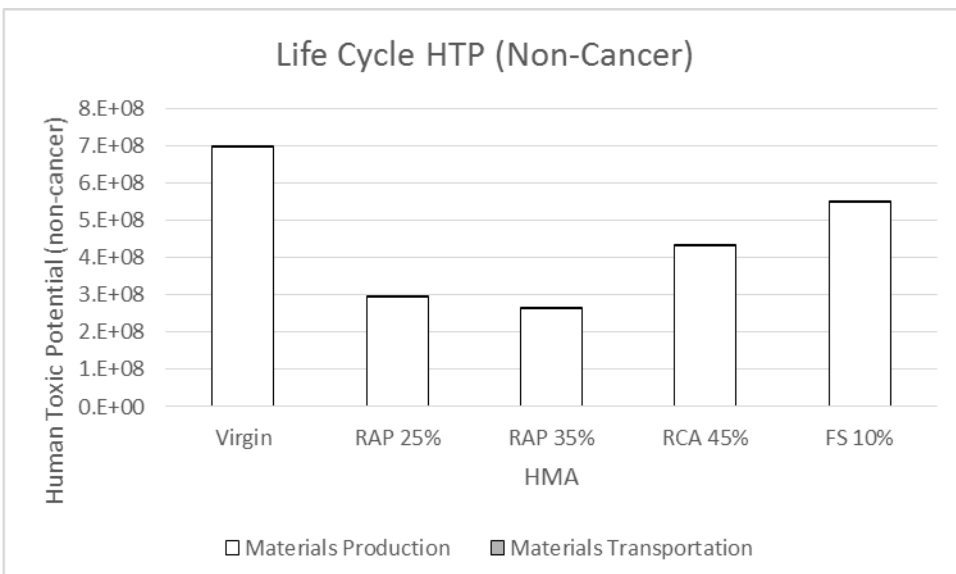


Figure 23: Life-cycle human toxicity potential (non-cancer) for HMA made with recycled materials.

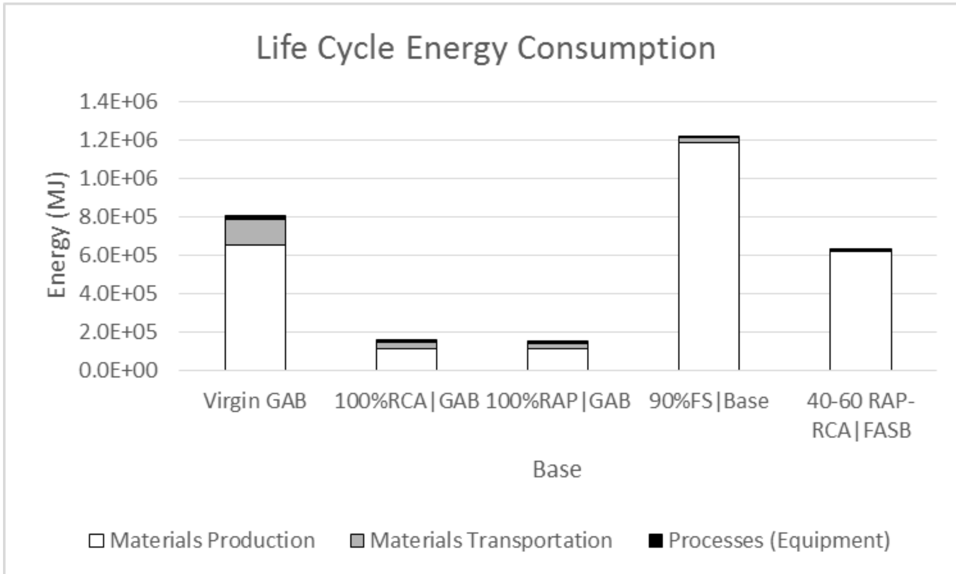


Figure 24: Life-cycle energy consumption for base made with recycled materials.

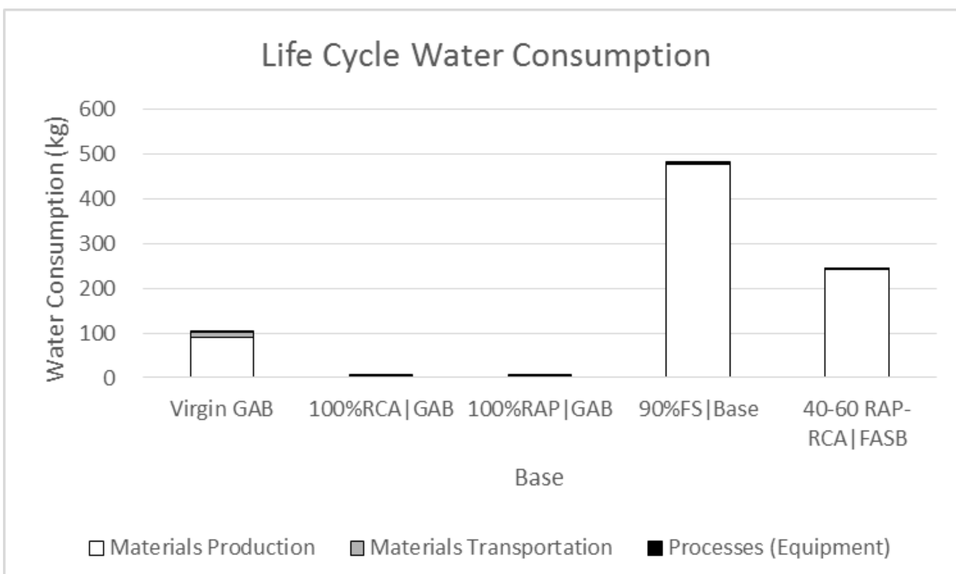


Figure 25: Life-cycle water consumption for base made with recycled materials.

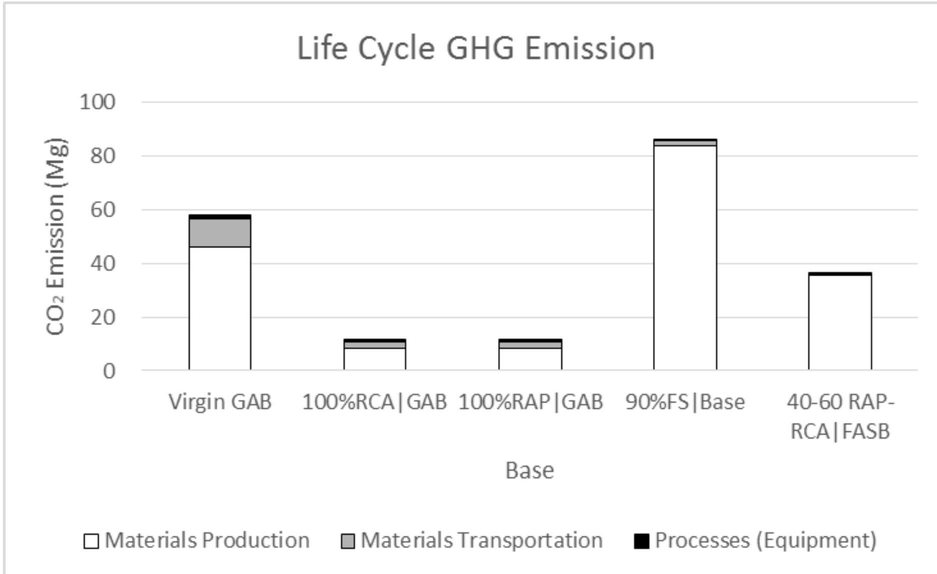


Figure 26: Life-cycle greenhouse gas emission for base made with recycled materials.

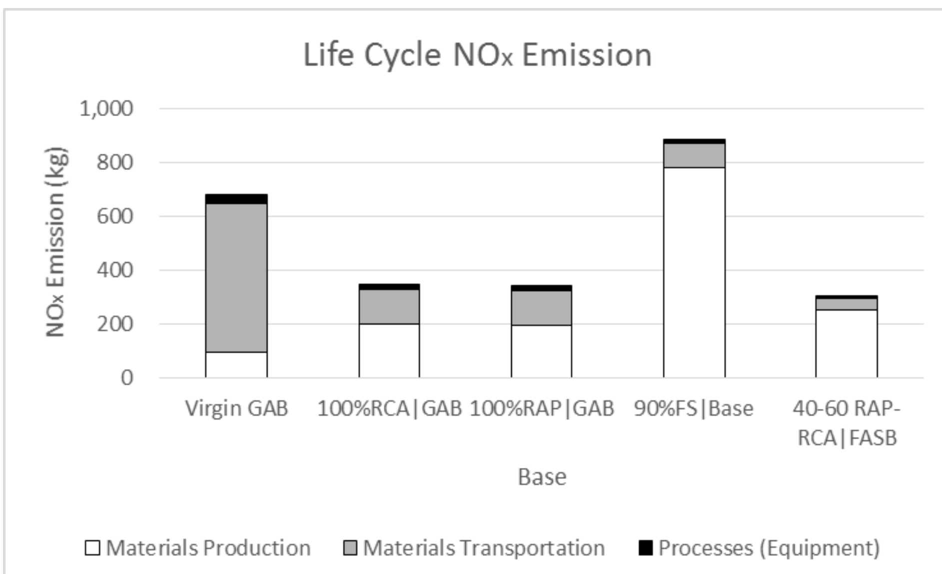


Figure 27: Life-cycle NOx emission for base made with recycled materials.

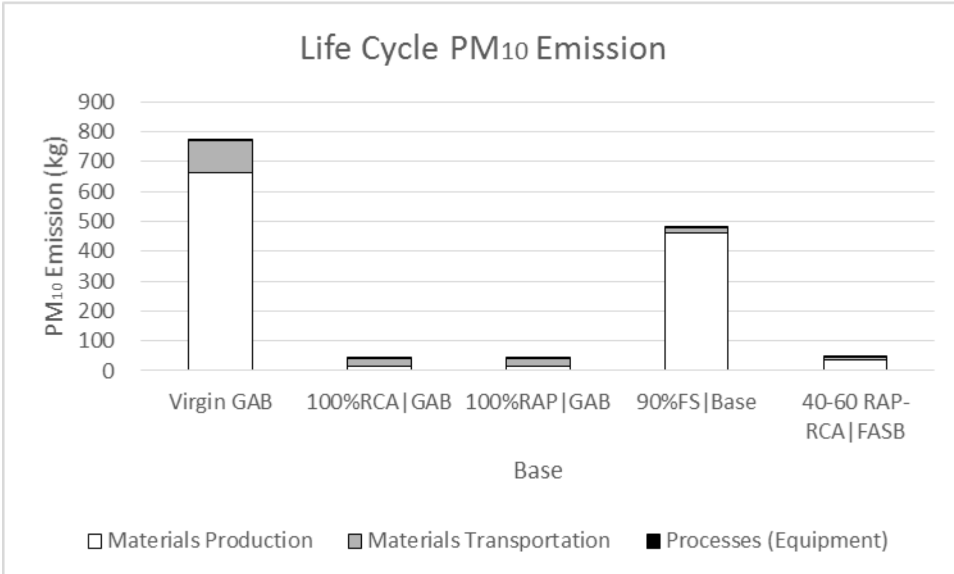


Figure 28: Life-cycle PM_{10} emission for base made with recycled materials.

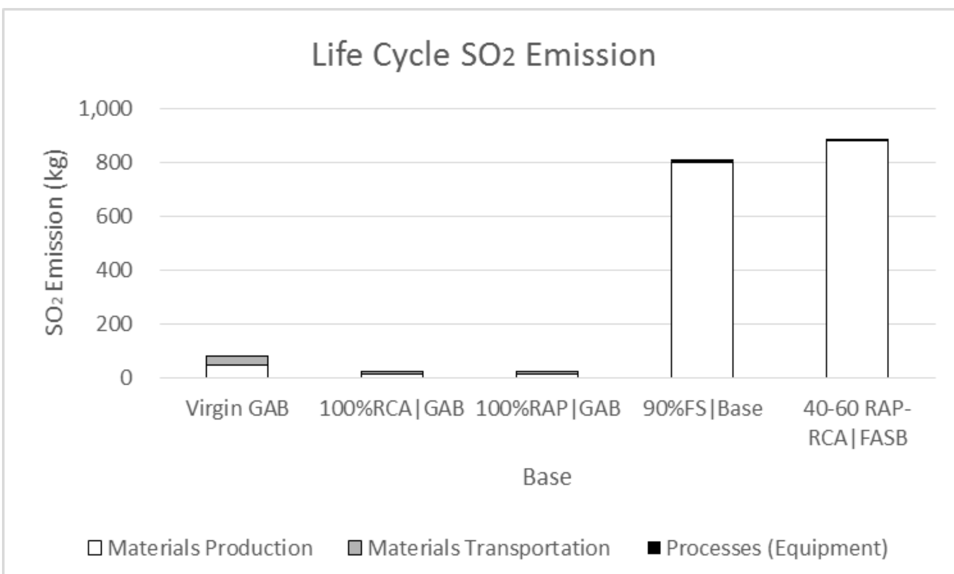


Figure 29: Life-cycle SO_2 emission for base made with recycled materials.

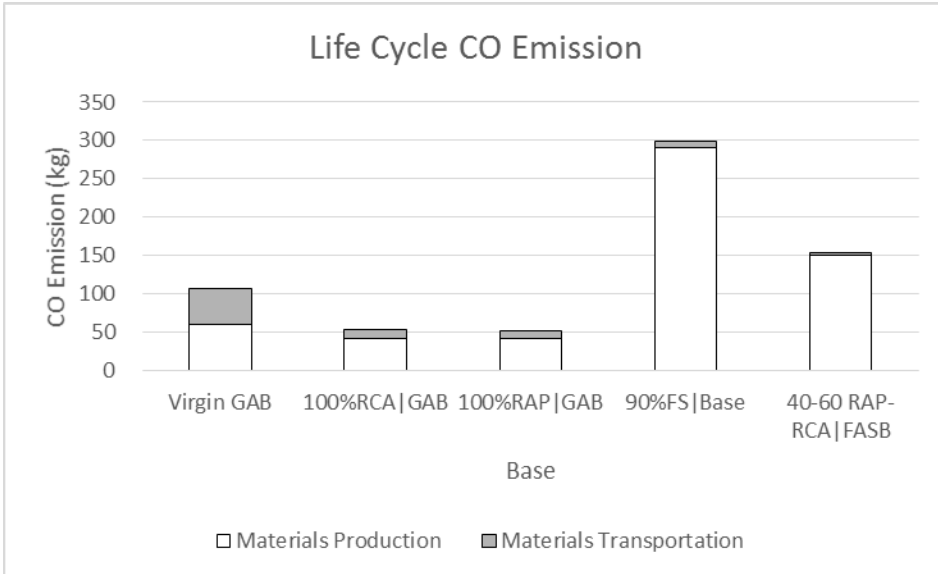


Figure 30: Life-cycle CO emission for base made with recycled materials.

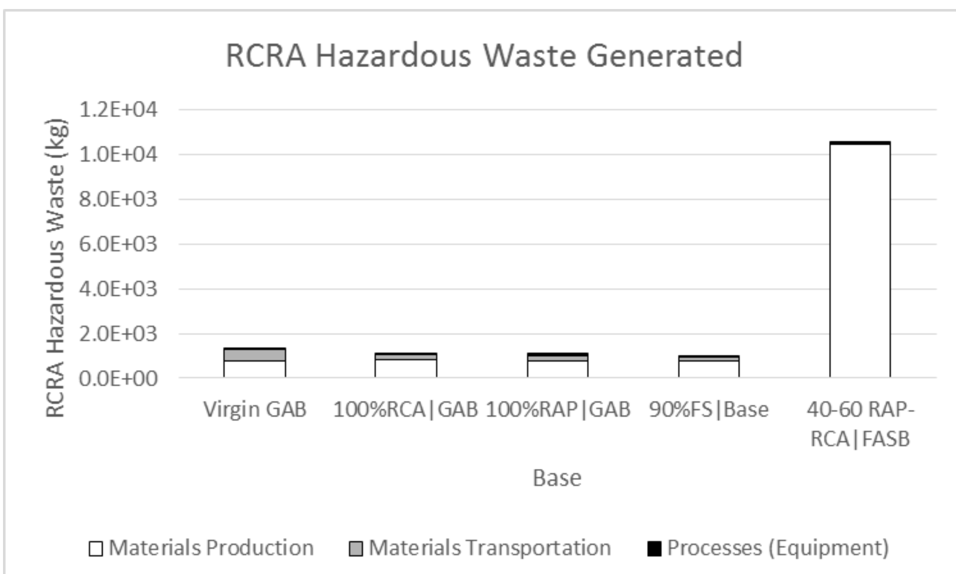


Figure 31: Life-cycle RCRA hazardous waste generated for base made with recycled materials.

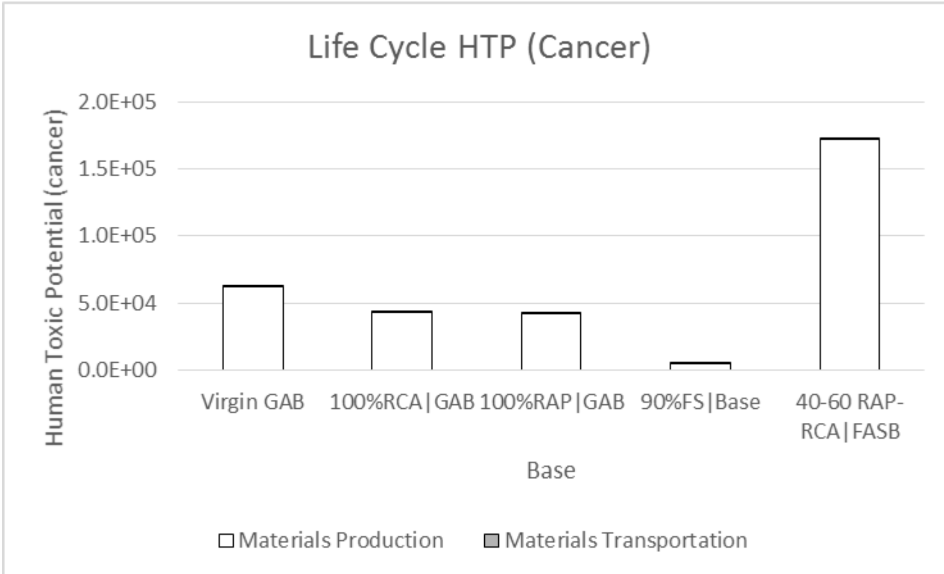


Figure 32: Life-cycle human toxicity potential (cancer) for HMA made with recycled materials.

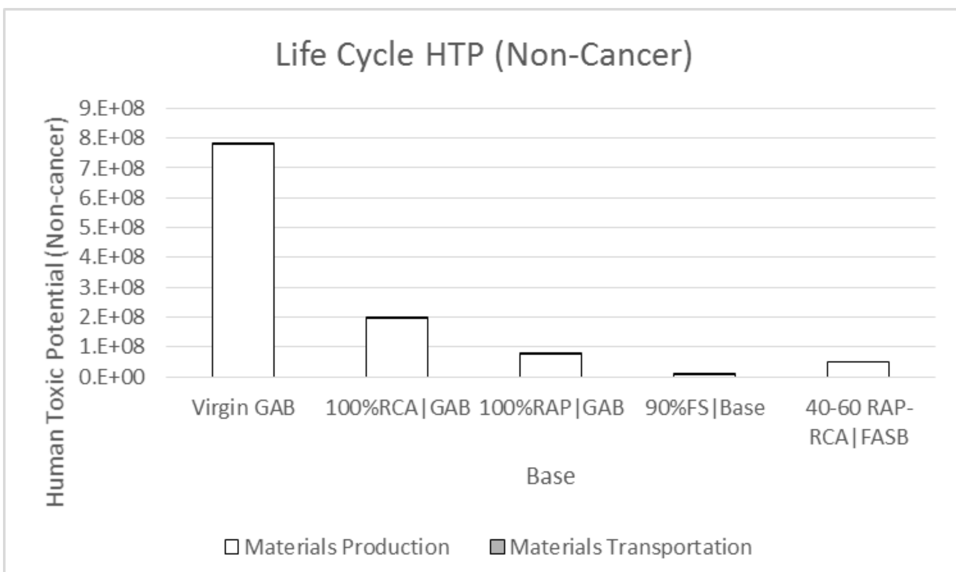


Figure 33: Life-cycle human toxicity potential (non-cancer) for base made with recycled materials.

1.1.3.3 Data Deficency and Uncertainty

LCCA may be affected by various factors. First, the unit price of materials used in LCCA are collected from different sources and in different years. Prices vary signifcantly year by year, and are different from one contractor to another. Perhaps unit prices for some materials are overestimated or underestimated. Second, the expense for construction activities (i.e., milling, crushing, demolition, rubblization, transportation, etc.) should be included in the unit price of materials for material-based LCCA. However, the data may cover only materials production, processing, and transportation. Thirdly, the discount rate (1%-8%) used to measure the future interest rate and inflation increases the uncertainty in LCCA. For example, in asphalt pavements, HMA produced with 25% RAP has a cost reduced by 47%-34% as discount rate ranges between 3% and 6%.

LCA may also be affected by several factors. First, equipement chosen (i.e., engine capacity, productivity, fuel consumption, etc.) in the initial construction and maintenance can affect the environmental effects. Second, the activities in initial construction and maintenance are simplified. Mroueh et al. (2001) indicated that it is difficult to determine the most common working methods and implementation methods of the work stages for recyceld materials. As a result, experience-based or measurement-based data on the working stages and their environmental loadings are hardly available.

1.1.4 Conclusions

Use of recycled materials highway applications may yield cost savings and considerable environmental benefits compared to highway applications with only virgin materials. In LCCA, PCCs made with recycled materials have comparable or higher cost (-6%~23%) than conventional PCC as a result of higher amount of cement and water required in producing recycled PCC. HMAs made with recycled materials significatly reduce cost by 14%~47% due to the FDR technique used in recycled HMA. Bases made with recycled materials also reduce cost greatly (30%~50%) than conventional GAB base contributed by the low price of recycled materias. Embankment also shows reduced cost with FS in use (60%). In LCA, material production generally have the highest environmental loads, transportation inferiors, and process has the least effect, which is consistent with the study of Apyal (2008). In respect of the materials that has the most environmental loads, cement and asphalt bitumen has the highest energy consumption, water consumption, and gas emission; cement, asphalt bitumen and virgin aggregates has the highest hazardous waste generation and toxic chemicals discharge; cement and FS has the highest fume emission (PM_{10}); and recycled materials generally have the least environmental loads. Though there are many uncertainties within the life-cycle analysis, the reuslts from PaLATE can be helpful for decision makers to identify the optimum scheme of pavements.

1.2 EVALUATION OF RECYCLED MATERIALS IN HIGHWAY APPLICATION BY BE2ST-IN-HIGHWAYS^{TM}

1.2.1 Introduction

The BE^{2}ST-in-Highways^{TM}, based on MS Excel, is a highway rating system that utilizes life-cycle analysis of pavements constructed with various materials. BE^{2}ST-in-Highways^{TM} consists of five subprograms: M-EPDG for service life design, RealCost for life-cycle cost analysis, PaLATE for environmental analysis, and the other two for noise and storm-water evaluation. The environmental effect accessed in BE^{2}ST-in-Highways^{TM} includes energy consumption, greenhouse gas emission, social carbon cost, water consumption, in-situ recycling, ex-situ recycling, traffic noise, and hazardous waste. Since noise and storm-water involve the design for surroundings and facilities, not only the pavement itself, the default values were used in this study.

The structure of BE^{2}ST-in-Highways^{TM} system is presented in Figure 34 (RMRC 2010). Judgement layer is dependent on the mandatory screening layer which is dependent on regulations of local, state, and national organizations, as well as the specific requirements from the project. Eventually, there are three classes (gold, silver, and bronze) for rating the overall performance of pavements.

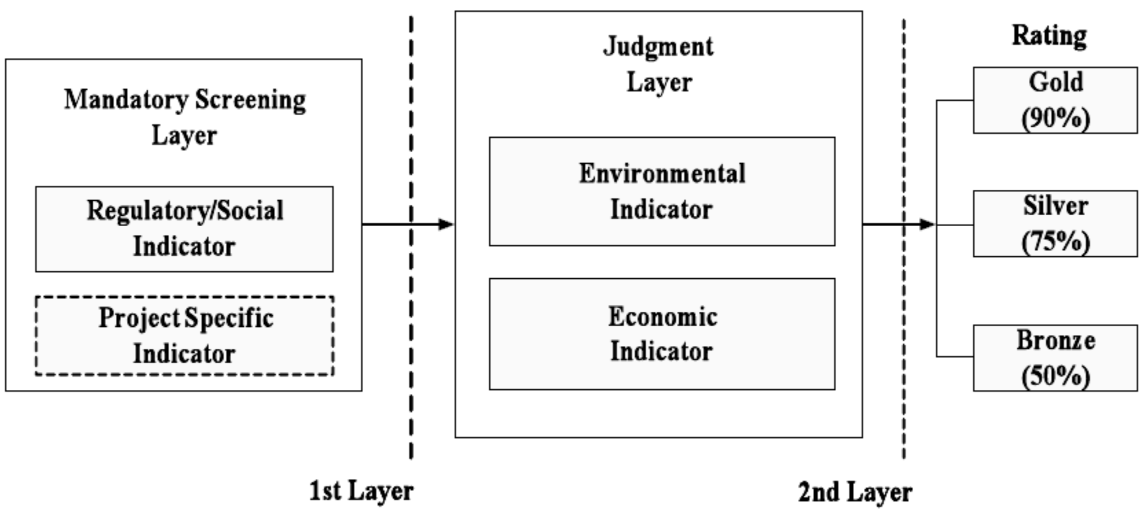


Figure 34: Structure of the BE2ST-in-HighwaysTM system (RMRC 2010).

1.2.2 Project Description and Model Creation

A two-lane roadway that is 1mile long and 24 feet wide is assumed. The thickness of base layer is designed in accordance with AASHTO (1993). Service life is designed to be 20 years for each case, implying that after 20 years performance of pavement degrades to the degree that is unable to meet normal usage. The design period is 40 years, which covers initial construction and one rehabilitation in the 20 years. The equivalent single axle load (ESAL) calculations for low-volume traffic road is listed in Table 18.

Table 18: ESAL Calculations per AASHTO (1993).

Vehicle Description	Traffic Volume			Analysis Period (years)	Axle Load/Type			Gross Weight (pounds)	Equivalency Factors			ESAL's
	Quantity in the Design Lane	Days per Week	Weeks per Year		Axle 1 (kips)	Axle 2 (kips)	Axle 3 (kips)		Axle 1	Axle 2	Axle 3	
Passenger car	400	7	52	20	2/S	2/S	-	4,000	0.0002	0.0002	0	1,160
School bus	50	7	52	20	2	4	-	6,000	0.0002	0.0002	0	800
Package delivery truck	10	7	52	20	4	14	-	18,000	0.002	0.354	0	25,920
Beverage delivery truck	10	7	52	20	6	12	12/S	30,000	0.011	0.189	0.189	28,320
Garbage/dumpster truck	5	7	52	20	20	35/T		55,000	1.56	1.23	0	101,560
Semi-tractor trailer	25	7	52	20	12	34/T	34/T	80,000	0.189	1.08	1.08	427,520
Total	-	-	-	-	-	-	-	-	-	-	-	585,280

Note: S=single axle; T=tandem axle.

Parameters for structural design of flexible pavement and rigid pavement are presented in Table 19 and Table 21, respectively. The schematic of flexible pavement designs and rigid pavement designs are listed in Table 20 and Table 22, respectively. Replacement ratio of recycled materials keeps consistence with the previous work in PaLATE. Thickness of surface and base of pavements is determined by structural requirements, different from the previous work in PaLATE. The details for thickness design is explained in the later sections.

Table 19: Flexible/Asphalt Pavement Design

Total AASHTO ESALs	585,280
Suggested mixture class	ESAL 2
Suggested binder grade	PG 64-22
Initial serviceability	4.5
Terminal serviceability	2.0
ΔPSI	2.5
Zr	-1.28
Combined Standard Deviation (Sd)	0.45
Reliability	90%
Resilient modulus of subgrade	10,389 psi
Required SN	2.700

Table 20: Schematic of Seven Alternative Flexible/Asphalt Pavement Designs

Design#	Surface type	Material in surface	Thickness of surface (in.)	Base type	Material in base	Thickness of base (in.)
1	HMA	Virgin materials	3	GAB	Virgin aggregate	4
2		35% RAP	3		100% RCA	3
3		35% RAP	3		100% RAP	3
4		45% RCA	3		100% RCA	3
5		45% RCA	3		100% RAP	3
6		10% FS	3.5	Cement-stabilized Base	90% FS + 10% cement	4
7		35% RAP	3	FASB	40% RAP + 60% RCA	1.4

Note: All the subgrade are made of virgin material, and the thickness of subgrade is 12 in.

Table 21: Rigid/Concrete Pavement Design

Roadway Classification	Local
Total Design ESALs	585,280
Suggested Mixture Class	ESAL 2
Terminal Serviceability	2.0
Combined Standard Error S_d	0.4
Change in Serviceability ΔPSI	2.5
Reliability Level	90%
Z_R	-1.282
Efficient modulus of subgrade reaction (k)	250 psi/in.
Joint Spacing	170 in.
Load Transfer Coefficient	3
Edge Support	1
Slab/Base Friction Coefficient	1.1
Drainage coefficient of base	1.2

Table 22: Schematic of Six Alternative Rigid/Concrete Pavement Designs

Design#	Surface type	Material in surface	Thickness of surface (in.)	Base type	Materials in base	Thickness of base (in.)
1	PCC	Virgin materials	8.5	GAB	Aggregate	7
2		50% RCA	8		100% RCA	7
3		100% RCA	8.5		100% RCA	7
4		40% RAP	8		100% RAP	7
5		100% RAP	6.5		100% RAP	7
6		20% FS	8.5		100% RCA	7

1.2.3 Assessment results

1.2.3.1 Flexible/Asphalt Pavement

<u>Structural design</u>

In conventional pavements, both the initial construction and the first rehabilitation use the new virgin materials. The old materials from conventional pavement are landfilled in rehabilitation stage, while old materials in recycled pavements are full-depth reclaimed in the rehabilitation stage. In this study, subbase and subgrade properties are kept the same in each case. The variables in life cycle analysis are HMA surface and base layer. The structural design for conventional asphalt pavement is summarized in Table 23. Total structural number (SN) is 2.72, greater than the minimum requirement of 2.700. The conventional pavement is considered as the reference strategy for comparison purposes.

Table 23: Conventional asphalt pavement with virgin HMA & virgin GAB

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface	N+N	3	0.44	1	1.32
GAB	N+N	4	0.12	1	0.48
Subgrade	-	12	0.08	1	0.96
Total	-	19	-	-	2.76

Strategy 1 is a recycled pavement, in which HMA surface consists of 35% RAP by weight (Shirodkar et al. 2011) and GAB base consists of 100% RCA (Aydilek et al. 2015). The structural design is summarized in Table 24. The total structural number (SN) is 2.738, greater than the minimum requirement of 2.700.

Table 24: Recycled asphalt pavement with 35% RAP in HMA & 100% RAP in GAB

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface with 35% RAP	N+E	3	0.44	1	1.32
GAB with 100% RCA	N+E	3	0.166	1	0.498
Subgrade	-	12	0.08	1	0.96
Total	-	18	-	-	2.778

Note: HMA produced with RAP generally has higher stiffness and strength; thus, layer coefficient of 0.44 is also applied to HMA made with RAP.

Strategy 2 is a recycled pavement, in which HMA surface consists of 35% RAP by weight (Shirodkar et al. 2011) and GAB base consists of 100% RAP (Bennett and Maher 2005). The structural design is summarized in Table 25. The total structural number (SN) is 2.735, greater than the minimum requirement of 2.700.

Table 25: Recycled asphalt pavement with 35% RAP in HMA & 100% RAP in GAB

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface with 35% RAP	N+E	3	0.44	1	1.32
GAB with 100% RAP	N+E	3	0.165	1	0.495
Subgrade	-	12	0.08	1	0.96
Total	-	18	-	-	2.775

Strategy 3 is a recycled pavement, in which HMA surface consists of 45% RCA by weight (Wong et al. 2007) and GAB base consists of 100% RCA (Aydilek et al. 2015). The structural design is summarized in Table 26. The total structural number (SN) is 2.735, greater than the minimum requirement of 2.700.

Table 26: Recycled asphalt pavement with 45% RCA in HMA & 100% RCA in GAB

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface with 45% RCA	N+E	3	0.435	1	1.305
GAB with 100% RCA	N+E	3	0.166	1	0.498
Subgrade	-	12	0.08	1	0.96
Total	-	18	-	-	2.763

Strategy 4 is a recycled pavement, in which HMA surface consists of 45% RCA by weight (Wong et al. 2007) and GAB base consists of 100% RAP (Bennett and Maher 2005). The structural design is summarized in Table 27. The total structural number (SN) is 2.720, greater than the minimum requirement of 2.700.

Table 27: Recycled asphalt pavement with 45% RCA in HMA & 100% RAP in GAB

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface with 45% RCA	N+E	3	0.435	1	1.305
GAB with 100% RAP	N+E	3	0.165	1	0.495
Subgrade	-	12	0.08	1	0.96
Total	-	18	-	-	2.760

Strategy 5 is a recycled pavement, in which HMA surface consists of 10% FS by weight (Bakis et al. 2006 and Braham 2002) and base is made of 90% FS and 10% cement additive (Gedik 2008). The structural design is summarized in Table 28. The total structural number (SN) is 2.716, greater than the minimum requirement of 2.700.

Table 28: Recycled asphalt pavement with 10% FS in HMA & 90% FS in Base

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface with 10% FS	N+E	3.5	0.435	1	1.54
Base with 90% FS	N+E	4	0.064	1	0.256
Subgrade	-	12	0.08	1	0.96
Total	-	19.5	-	-	2.756

Strategy 6 is a recycled pavement, in which HMA surface consists of 35% RAP by weight (Shirodkar et al. 2011) and FASB consists of 40% RAP plus 60% RCA (Schwartz and Khosravifar 2013). The structural design is summarized in Table 29. The total structural number (SN) is 2.730, greater than the minimum requirement of 2.700.

Table 29: Recycled asphalt pavement with 30% RAP in HMA & 40% RAP + 60% RCA in FASB

Layer	New/Existing	Thickness (in)	Layer coefficient	Drainage coefficient	SN
HMA surface with 35% RAP	N+E	3	0.44	1	1.32
FASB with 40% RAP + 60% RCA	N+E	1.4	0.35	1	0.490
Subgrade	-	12	0.08	1	0.96
Total	-	16.4	-	-	2.770

Weighting system for BE^{2}ST-in-Highways^{TM}

Weighting system of BE^{2}ST-in-Highways^{TM} comprises of eight environmental indicators and one economic indicator. The weights (level of importance) of these indicators are dependent on the requirement of specific projects. In this study, storm water design and noise reduction method are assumed to be the same for each case, but different pavement materials resulting in different level of traffic noise. For example, the default score of asphalt pavement is 1, while the default score of concrete pavement is 0. As a result, cost for storm water management has not been included in the total cost. Traffic noise is granted a light weight (2%) in the weighting system. Other indicators take up 10%~15% of the total weight, respectively, which are nearly equal. The weighting system is listed in Table 30.

Table 30: Weighting System

Indicators	Weighting (%)	Weight
Energy	10.00	0.10
Global Warming	10.00	0.10
In situ Recycle	15.00	0.15
Ex situ Recycle	15.00	0.15
Water Consumption	10.00	0.10
LCC	15.00	0.15
SCC	10.00	0.10
Traffic Noise	2.00	0.02
Hazardous Waste	13.00	0.13
Total	100.00	1.00

Note: LCC = life cycle cost; SCC = social cost of carbon.

Results and discussions

Tables 31~36 compare the performance of recycled pavements with conventional pavements. In these tables, life cycle analyses (life-cycle cost and life-cycle environmental effect) were conducted by using PaLATE. Social cost of carbon (SCC) is the cost to reduce global warming potential, often used by agency (e.g., a state DOT) to enforce sustainable construction. Average SCC are $5, $21, and $35 per Mg estimated in 2010 (in 2007 dollars) at the 5, 3, and 2.5 percent discount rates, respectively (RMRC 2010). RMRC (2010) suggested to use $65 per Mg in calculating the SCC, so as to consider the worst situation that may occur. The default targets were used in this study, which can be modified with the requirements of a specific project.

Accomplished scores and awarded labels are listed in Table 37. Accomplished score is the sum of scores gained by indicators times their weight. Label is granted “gold” for score between 100 and 90, “silver” for score between 90 and 75, “bronze” for score between 75 and 50. Accomplished score less than 50 implies the recycled pavements is not as “green” as the conventional pavements. The results may vary with varied weighting system and/or varied targets.

As shown in Table 37, recycled asphalt pavements award either “gold” or “silver” labels, implying excellent performance of these recycled pavements. The excellent performance should be attributed to the FDR technology, by which in situ recycling can be achieved. The conventional asphalt pavement requires landfilling the old materials and hauling the new materials to site in the rehabilitation stage, resulting in higher consumption in resources, higher gas emission, and higher generation in hazardous waste.

Strategy 1 has high recycled rate of 75.6%, and shows a 57% reduction in CO_2, a 55% reduction in energy, a reduction of 54% in life cycle cost, and a $9750 saving per mile in SCC (Table 31). Strategy 2 is similar to Strategy 1, which exhibits a 56% reduction in CO_2, a 57% reduction in energy, a reduction of 54% in life cycle cost, and a $9880 saving per mile in SCC (Table 32). These results are consistent with the study of Lee et al. (2011). Lee et al. (2011) indicated that asphalt pavement in which HCA surface containing 15% RAP and base made of recycled pavement materials showed a 43% reduction in CO_2, a 43% reduction in energy consumption, a 54% reduction in life cycle cost, and a $16,967 saving per km in SCC. The divergence in savings of SCC is due to different dimension of pavement and distance of transportation assumed.

Strategy 5 (10% FS in HMA & 90% FS in Base) awards “silver” due to high greenhouse gas emission and high water consumption (Table 35). Strategy 6 (35% RAP in HMA & 40% RAP+60% RCA in FASB) also gets “silver” due to low ex-situ recycling rate (Table 36). FASB base has high ex-situ recycling rate, in which aggregates are made of RCA and RAP. However, the volume of FASB (1.4 in. thickness) is far less than that of HMA layer (3 in. thickness), and hence the HMA layer controls the awarded label (Tables 20 and 29).

Comparing Strategies 1 and 2 or Strategies 3 (45% RCA in HMA & 100% RCA in GAB) and 4 (45% RCA in HMA & 100% RAP in GAB), GAB made with 100% RAP and 100% RCA have nearly the same accomplished score (Table 37), though the score for single indicator is different (Tables 31-34). Comparing Strategies 1 and 6, recycled GAB shows higher accomplished score than recycled FASB (Table 37), though FASB is much thinner than GAB. Strategy 5 has two variables, different overlay and different base. Since the thickness of cement-stabilized base is greater than that of other bases (Table 28), we can infer that the cement-stabilized base should be not as “green” as other bases.

Figures 35~40 present the AMOEBA graphs for different strategies. The AMOEBA graphs allow a quantitative comparison between the target score (2 scores) and the score gained in the project. Using these graphs, the pros and cons of each strategy can be identified easily, which can help designers advance their design schemes and achieve the goals for a green highway design. For examples, Strategies1~5 all have a deficiency in SCC (Figure 35~40), implying that the cost reduced in managing carbon dioxide is not satisfactory. SCC is related to the emission of greenhouse gas, cost to prevent global warming, as well as the yearly salary of one job (the base of the target set). Decision makers can choose other schemes or think of a good way to reduce the greenhouse emission. It can be seen in Figure 39 that Strategy 5 (10% FS in HMA & 90% FS in Base) has a deficiency in greenhouse gas reduction and water saving, and in Figure 40 that Strategy 6 (35% RAP in HMA & 40% RAP+60% RCA in FASB) has a deficiency in ex-situ recycling rate.

Table 31: Results of BE²ST-in-Highway for Strategy 1 (asphalt pavement).

Criteria	Unit	Target	Reference	Strategy 1	Perfor-mance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 ptss)**	4,708,671	2,113,977	55.10%	2.00
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 ptss)**	263	113	57.03%	2.00
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 ptss)**	0.00	0.500	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 ptss)**	0.00	0.256	25.60%	2.00
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 ptss)**	1,230	617	49.84%	2.00
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 ptss)**	347,975	161,152	53.69%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 ptss)**	$17,095.00	$7,345.00	$9,750	0.49
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 ptss)**	1	1	1	1.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 ptss)**	45,539	25,541	43.91%	2.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

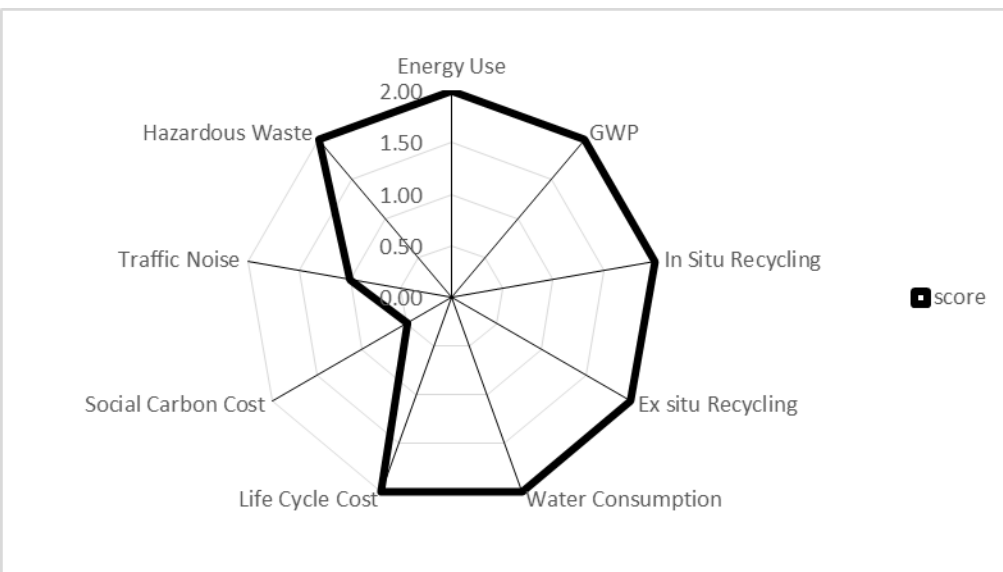


Figure 35: AMOEBA graph for recycled asphalt pavement of Strategy 1.

Table 32: Results of BE²ST-in-Highway for Strategy 2 (asphalt pavement).

Criteria	Unit	Target	Reference	Strategy 2	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)**	4,708,671	2,032,270	56.84%	2.00
		>= 20% Reduction (2 pts)				
GWP	**Mg**	**>= 10% Reduction (1 pt)**	263	111	57.79%	2.00
		>= 20% Reduction (2 pts)				
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)**	0.00	0.500	50.00%	2.00
		>= 20% Recycling Rate (2 pts)				
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)**	0.00	0.256	25.60%	2.00
		>= 20% Recycled Content (2 pts)				
Water Consumption	**kg**	**>= 5% Reduction (1 pt)**	1,230	616	49.92%	2.00
		>= 10% Reduction (2 pts)				
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)**	347,975	157,927	54.62%	2.00
		>=20% Reduction (2 pts)				
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)**	$17,095.00	$7,215.00	$9,880	0.50
		>= $39,500/mi Saving (2 pts)				
Traffic Noise	**no unit**	**HMA (1 pt)**	1	1	1	1.00
		SMA or OGFC (2 pts)				
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)**	45,539	25,462	44.09%	2.00
		>=10% Reduction (2 pts)				

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

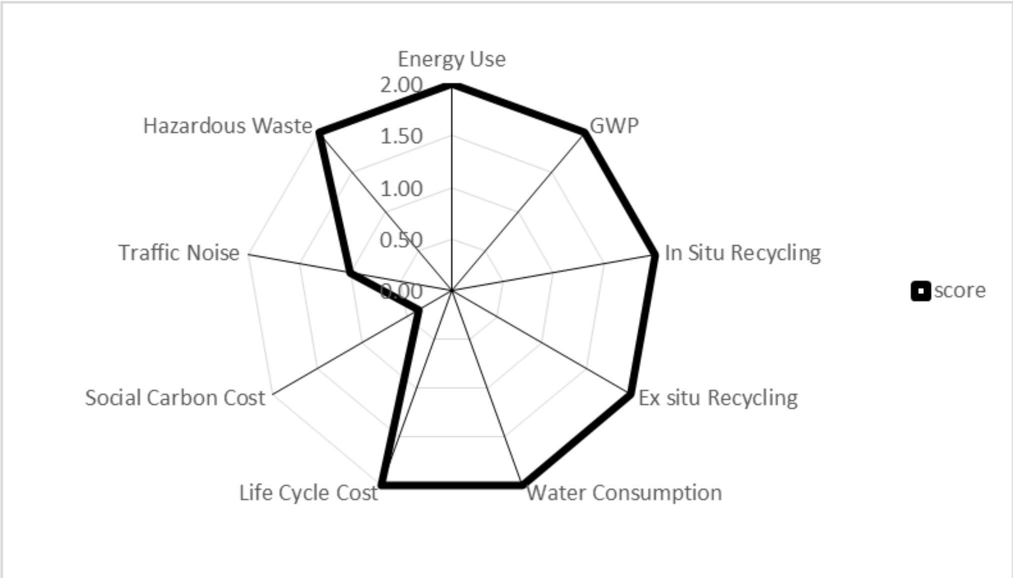


Figure 36: AMOEBA graph for recycled asphalt pavement of Strategy 2.

Table 33: Results of BE²ST-in-Highway for Strategy 3 (asphalt pavement).

Criteria	Unit	Target	Reference	Strategy 3	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	4,708,671	2,901,582	38.38%	2.00
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	263	163	38.02%	2.00
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 pts)**	0.00	0.500	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 pts)**	0.00	0.3285	32.85%	2.00
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 pts)**	1,230	939	23.66%	2.00
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 pts)**	347,975	177,494	48.99%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 pts)**	$17,095.00	$10,595.00	$6,500	0.33
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 pts)**	1	1	1	1.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 pts)**	45,539	39,525	13.21%	2.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

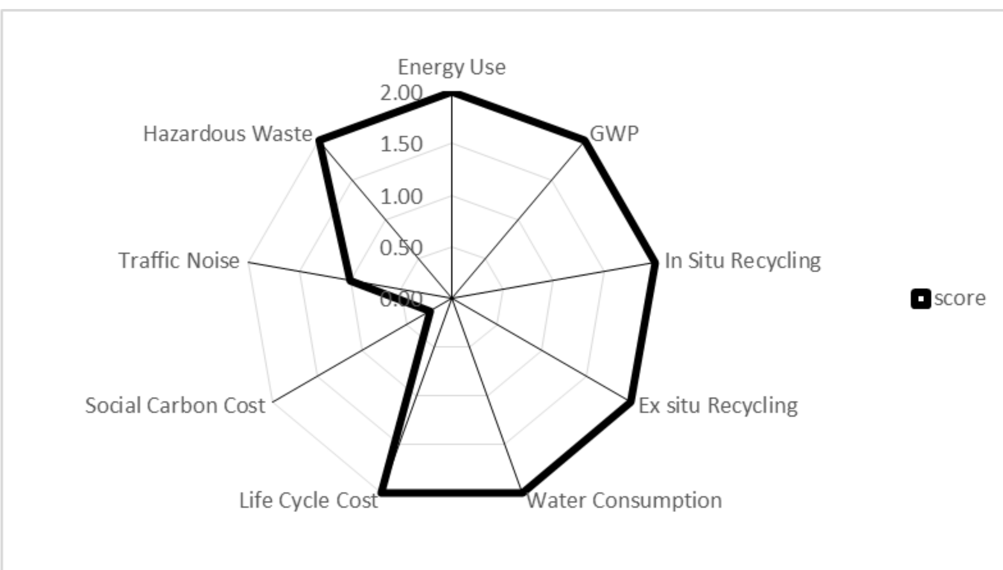


Figure 37: AMOEBA graph for recycled asphalt pavement of Strategy 3.

Table 34: Results of BE²ST-in-Highway for Strategy 4 (asphalt pavement).

Criteria	Unit	Target	Reference	Strategy 4	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	4,708,671	2,899,697	38.42%	2.00
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	263	163	38.02%	2.00
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 pts)**	0.00	0.500	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 pts)**	0.00	0.3285	32.85%	2.00
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 pts)**	1,230	939	23.66%	2.00
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 pts)**	347,975	177,167	49.09%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 pts)**	$17,095.00	$10,595.00	$6,500	0.33
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 pts)**	1	1	1	1.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 pts)**	45,539	39,511	13.24%	2.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

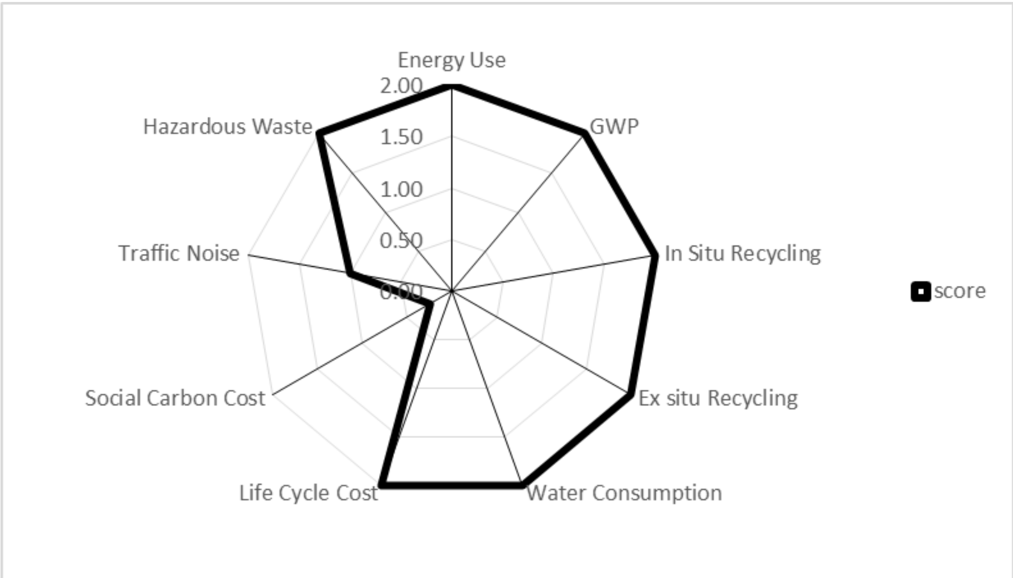


Figure 38: AMOEBA graph for recycled asphalt pavement of Strategy 4.

Table 35: Results of BE^{2}ST-in-Highway for Strategy 5 (asphalt pavement).

Criteria	Unit	Target	Reference	Strategy 5	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	4,708,671	3,718,206	21.03%	2.00
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	263	217	17.49%	1.75
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 pts)**	0.00	0.5000	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 pts)**	0.00	0.2540	25.40%	2.00
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 pts)**	1,230	1,229	0.08%	0.02
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 pts)**	347,975	178,198	48.79%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 pts)**	$17,095.00	$14,105.00	$2,990	0.15
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 pts)**	1	1	1	1.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 pts)**	45,539	30,797	32.37%	2.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

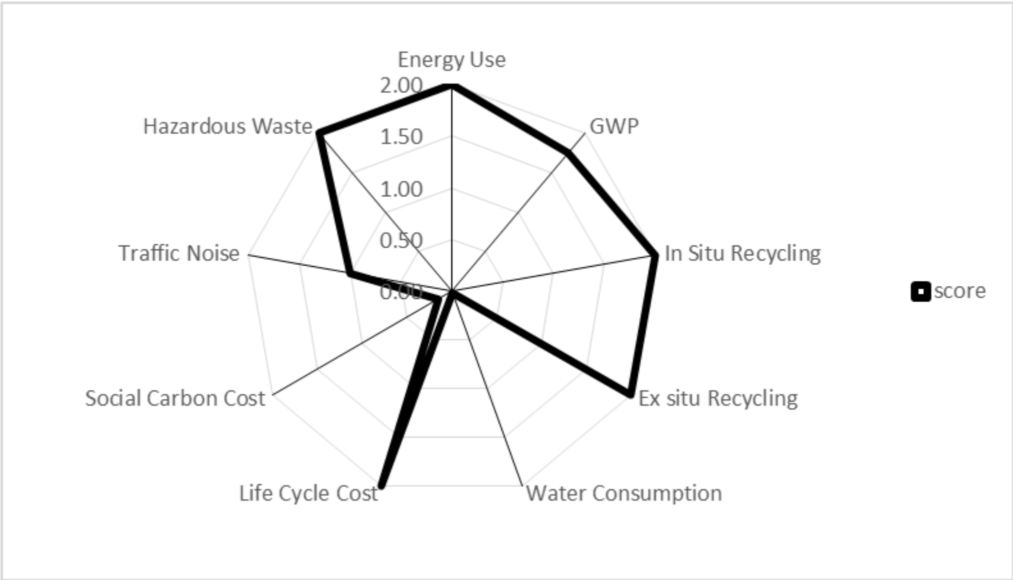


Figure 39: AMOEBA graph for recycled asphalt pavement of Strategy 5.

Table 36: Results of BE^{2}ST-in-Highway for Strategy 6 (asphalt pavement).

Criteria	Unit	Target	Reference	Strategy 6	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	4,708,671	2,013,328	57.24%	2.00
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	263	114	56.65%	2.00
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 pts)**	0.00	0.5000	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 pts)**	0.00	0.1575	15.75%	1.58
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 pts)**	1,230	807	34.39%	2.00
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 pts)**	347,975	114,868	66.99%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 pts)**	$17,095.00	$7,410.00	$9,685	0.49
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 pts)**	1	1	1	1.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 pts)**	45,539	34,422	24.41%	2.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

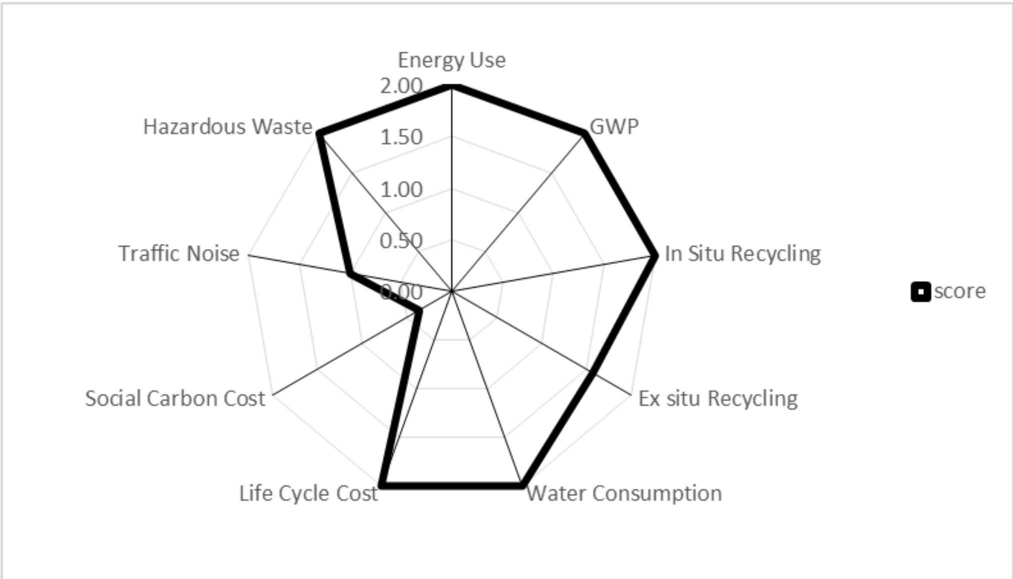


Figure 40: AMOEBA graph for recycled asphalt pavement of Strategy 6.

Table 37: Rating of BE^2ST-in-Highway for asphalt pavement.

Strategy #	Scenarios	Accomplished Score	Awarded Label
1	35% RAP in HMA & 100% RCA in GAB	91.47%	Gold
2	35% RAP in HMA & 100% RAP in GAB	91.50%	Gold
3	45% RCA in HMA & 100% RCA in GAB	90.65%	Gold
4	45% RCA in HMA & 100% RAP in GAB	90.65%	Gold
5	10% FS in HMA & 90% FS in Base	78.58%	Silver
6	35% RAP in HMA & 40% RAP+60% RCA in FASB	88.26%	Silver

1.2.3.2 Rigid/Concrete Pavement

Structural design

In conventional pavements, virgin materials are used during both the initial construction and the first rehabilitation stage new. The old materials from conventional pavement are landfilled in rehabilitation stage. In recycled pavements, PCC surface is reclaimed and used in GAB base, and GAB base is recycled and used in PCC surface. In this study, subgrade properties are kept the same in each case. The variables in life cycle analysis are PCC surface and base layer. The structural design for conventional concrete pavement is summarized in Table 38. The conventional pavement is considered as the reference strategy for comparison purpose.

Table 38: Conventional concrete pavement with virgin PCC & virgin GAB

Layer	Thickness (in)	Elastic Modulus (ksi)	Modulus of Rupture (psi)	Poisson's Ratio
Conventional PCC Layer	8.5	4091	590	0.2
Aggregate Base	7	15,000	-	-
Subgrade	-	-	-	-

Note: Poisson's ratio is between 0.15 and 0.2 for PCC layer.

Strategy 1 is a recycled pavement, in which PCC surface consists of 50% RCA (Volz et al. 2014) and GAB base consists of 100% RCA (Aydilek et al. 2015). The structural design is summarized in Table 39.

Table 39: Recycled concrete pavement with 50% RCA in PCC &100% RCA in GAB.

Layer	Thickness (in)	Elastic Modulus (ksi)	Modulus of Rupture (psi)	Poisson's Ratio
PCC Layer with 50% RCA	8	3811	610	0.2
GAB with 100% RCA	7	20,000	-	-
Subgrade	-	-	-	-

Note: Poisson's ratio is between 0.15 and 0.2 for PCC layer.

Strategy 2 is a recycled pavement, in which PCC surface consists of 100% RCA (Volz et al. 2014) and GAB base consists of 100% RCA (Aydilek et al. 2015). The structural design is summarized in Table 40.

Table 40: Recycled concrete pavement with 100% RCA in PCC & 100% RCA in GAB.

Layer	Thickness (in)	Elastic Modulus (ksi)	Modulus of Rupture (psi)	Poisson's Ratio
PCC Layer with 100% RCA	8.5	4,243	605	0.2
GAB with 100% RCA	7	20,000	-	-
Subgrade	-	-	-	-

Note: Poisson's ratio is between 0.15 and 0.2 for PCC layer.

Strategy 3 is a recycled pavement, in which PCC surface consists of 40% RAP (Hossiney 2012) and GAB base consists of 100% RAP (Bennett and Maher 2005). The structural design is summarized in Table 41.

Table 41: Recycled concrete pavement with 40% RAP in PCC & 100% RAP in GAB.

Layer	Thickness (in)	Elastic Modulus (ksi)	Modulus of Rupture (psi)	Poisson's Ratio
PCC Layer with 40% RAP	8	2,800	517	0.2
GAB with 100% RAP	7	20,000	-	-
Subgrade	-	-	-	-

Note: Poisson's ratio is between 0.15 and 0.2 for PCC layer.

Strategy 4 is a recycled pavement, in whichPCC surface consists of 100% RAP (Hossiney 2012) and GAB base consists of 100% RAP (Bennett and Maher 2005). The structural design is summarized in Table 42.

Table 42: Recycled concrete pavement with 100% RAP in PCC & 100% RAP in GAB.

Layer	Thickness (in)	Elastic Modulus (ksi)	Modulus of Rupture (psi)	Poisson's Ratio
PCC Layer with 100% RAP	6.5	1,250	370	0.2
GAB with 100% RAP	7	20,000	-	-
Subgrade	-	-	-	-

Note: Poisson's ratio is between 0.15 and 0.2 for PCC layer.

Strategy 5 is a recycled pavement, in which PCC surface consists of 20% RAP (Singh and Siddique 2012, Siddique et al. 2009) and GAB base consists of 100% RCA (Bennett and Maher 2005). The structural design is summarized in Table 43.

Table 43: Recycled concrete pavement with 20% FS in PCC & 100% RCA in GAB.

Layer	Thickness (in)	Elastic Modulus (ksi)	Modulus of Rupture (psi)	Poisson's Ratio
PCC Layer with 20% FS	8.5	4,525	594	0.2
GAB with 100% RCA	7	20,000	-	-
Subgrade	-	-	-	-

Note: Poisson's ratio is between 0.15 and 0.2 for PCC layer.

Results and discussions

Life cycle cost and environmental analysis were conducted by using PaLATE. Tables 44~48 compare the performance of recycled pavements with conventional pavements. Accomplished scores and awarded labels are listed in Table 49. The results may be different in different weighting system. Figures 41~45 present the AMOEBA graphs for different strategies. Using these graphs, the pros and cons of each strategy can be identified easily, which can help decision maker to identify the optimum scheme or designers to reverse their design scheme to achieve the goal of green highway.

Comparing Strategies 1 and 2, when RCA content increases from 50% to 100% in PCC surface, accomplished score falls by about 20% (Table 49). The reason is that incorporating RCA leads to higher energy consumption, higher water usage, higher greenhouse gas emission, and higher hazardous waste produced (Tables 44 and 45). PCC made with 100% RCA is 0.5 in. thicker than PCC made with 50% RCA (Table 22), which is a reason for the increment in consumption and emission. The thickness of layer is a structural requirement. RCA improves elastic modulus and reduces modulus of rupture of PCC (Tables 39 and 40); thus, PCC with 100% RCA should become thicker to meet required stiffness.

Strategy 2 (100% RCA in PCC, 100% RCA in GAB) received the lowest score approximated to 50% (Table 49), indicating the recycled pavement is as "green" as conventional pavement. Score of 50% is the threshold whether recycled pavement is more "green" than conventional pavement or not. As seen in Table 45, Strategy 2 has high recycling rate (50%+31.55%) and cost savings (41.6%), while water consumption and hazardous waste generation are higher than conventional concrete pavement. Based on the result from One can conclude that the concrete pavements with 100% RCA in GAB and RCA replacement of coarse aggregates at any percentage in PCC should be more "green" than conventional concrete pavements. The accomplished score increases with increasing RCA replacement ratio until the optimum replacement ratio (between 35% and 100%), after which score will decrease to 50%.

Comparing Strategies 3 and 4, when RAP content increases from 40% to 100% in PCC layer, accomplished score rises by 20% and label upgrades from "silver" to "gold" (Table 49). The reason is that RAP replacing virgin aggregates reduces energy consumption, water usage, greenhouse gas emission, and hazardous waste produced (Table 46 and Table 47). Table 22 shows that PCC with 100% RAP is 1.5 in. thinner than PCC with 40% RAP, which is a reason for the reduction in consumption and emission. The reduced thickness is due to the reduced elastic modulus when RAP incorporated into PCC (Table 41 and Table 42), though the modulus of rupture of PCC made with RAP reduces as well.

Strategy 4 (100% RAP in PCC, 100% RAP in GAB) is labeled "gold", implying excellent performance of the recycled pavement (Table 49). Besides, PCC made with 100% RAP has the lowest thickness (Table 22), which is a reason that Strategy 4 has the most reduction in consumption and emission. Through the above analysis, one can conclude that RAP replacement of both coarse and fine aggregates at any percentage in PCC should improve the performance (accomplished score) of a recycled highway, and the score increases as replacement ratio increases.

Strategy 5 (20% FS in PCC, 100% RCA in GAB) is labeled “bronze” for its higher energy consumption, higher water usage, and higher greenhouse gas emission (Table 48). However, the reduction in hazardous waste is higher than the other strategies (Table 48). PCC with 20% FS has a higher thickness compared to other recycled PCC (Tables 22 and 43), which is a reason for the higher consumption and emission. Since the score for single indicator cannot be negative, too higher water consumption and greenhouse gas emission cannot be reflected in the rating system. Otherwise, the total score of Strategy 5 may be reduced a little. However, this does not mean that FS replacement of fine aggregates in PCC is not recommended, since additives can be used to modify their properties.

Table 44: Results of BE²ST-in-Highway for Strategy 1 (concrete pavement).

Criteria	Unit	Target	Reference	Strategy 1	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)**	15,213,544	13,382,180	12.04%	1.20
		>= 20% Reduction (2 pts)				
GWP	**Mg**	**>= 10% Reduction (1 pt)**	1,066	961	9.85%	0.98
		>= 20% Reduction (2 pts)				
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)**	0.00	0.5000	50.00%	2.00
		>= 20% Recycling Rate (2 pts)				
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)**	0.00	0.2754	27.54%	2.00
		>= 20% Recycled Content (2 pts)				
Water Consumption	**kg**	**>= 5% Reduction (1 pt)**	5,381	5,076	5.67%	1.13
		>= 10% Reduction (2 pts)				
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)**	1,097,804	652,312	40.58%	2.00
		>=20% Reduction (2 pts)				
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)**	$69,290.00	$62,465.00	$6,825	0.35
		>= $39,500/mi Saving (2 pts)				
Traffic Noise	**no unit**	**HMA (1 pt)**	0	0	0	0.00
		SMA or OGFC (2 pts)				
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)**	21,811	20,682	5.18%	1.04
		>=10% Reduction (2 pts)				

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

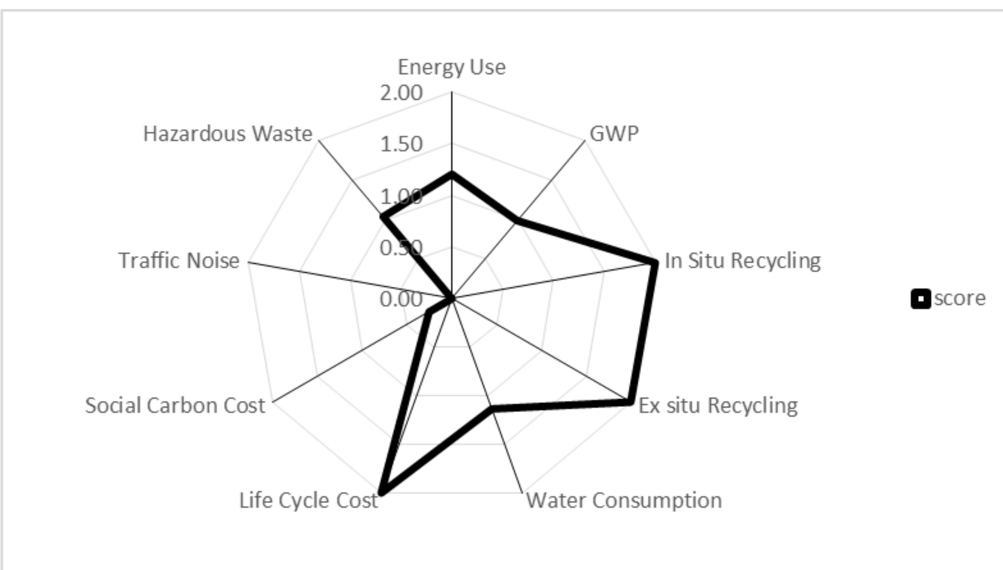


Figure 41: AMOEBA graph for recycled concrete pavement of Strategy 1.

Table 45: Results of BE²ST-in-Highway for Strategy 2 (concrete pavement).

Criteria	Unit	Target	Reference	Strategy 2	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	15,213,544	14,279,082	6.14%	0.61
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	1,066	1,035	2.91%	0.29
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 pts)**	0.00	0.5000	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 pts)**	0.00	0.3155	31.55%	2.00
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 pts)**	5,381	5,446	-1.21%	0.00
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 pts)**	1,097,804	641,130	41.60%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 pts)**	$69,290.00	$67,275.00	$2,015	0.10
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 pts)**	0	0	0	0.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 pts)**	21,811	22,573	-3.49%	0.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

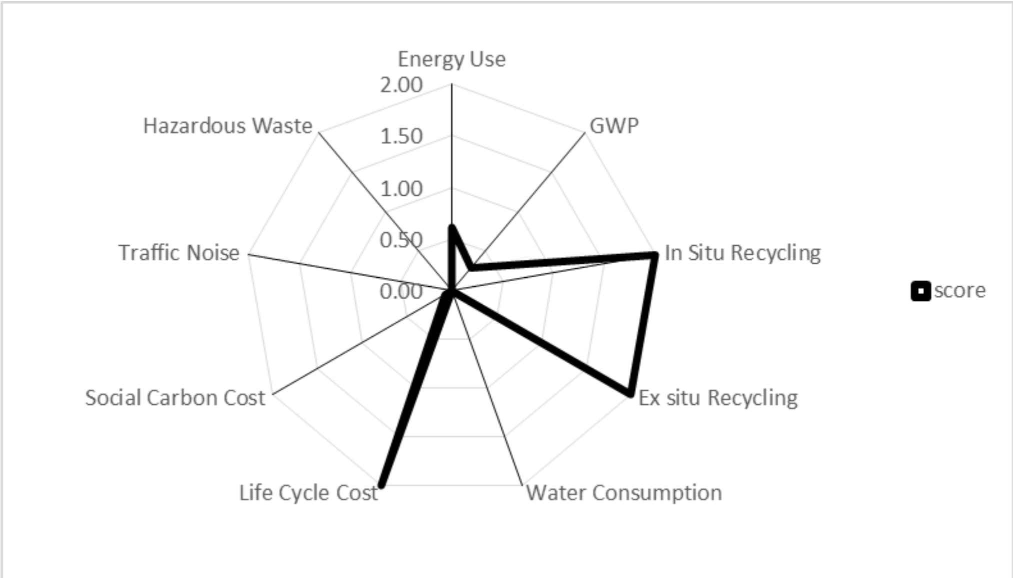


Figure 42: AMOEBA graph for recycled concrete pavement of Strategy 2.

Table 46: Results of BE^{2}ST-in-Highway for Strategy 3 (concrete pavement).

Criteria	Unit	Target	Reference	Strategy 3	Performance	Score
Energy Use	MJ	>= 10% Reduction (1 pt) >= 20% Reduction (2 pts)	15,213,544	13,151,670	13.55%	1.36
GWP	Mg	>= 10% Reduction (1 pt) >= 20% Reduction (2 pts)	1,066	924	13.32%	1.33
In Situ Recycling	CY	>= 10% Recycling Rate (1 pt) >= 20% Recycling Rate (2 pts)	0.00	0.5000	50.00%	2.00
Ex situ Recycling	CY	>= 10% Recycled Content (1 pt) >= 20% Recycled Content (2 pts)	0.00	0.2938	29.38%	2.00
Water Consumption	kg	>= 5% Reduction (1 pt) >= 10% Reduction (2 pts)	5,381	5,093	5.35%	1.07
Life Cycle Cost	$	>= 10% Reduction (1 pt) >=20% Reduction (2 pts)	1,097,804	718,405	34.56%	2.00
Social Carbon Cost	$	>= $19,750/mi Saving (1 pt) >= $39,500/mi Saving (2 pts)	$69,290.00	$60,060.00	9,230	0.47
Traffic Noise	no unit	HMA (1 pt) SMA or OGFC (2 pts)	0	0	0	0.00
Hazardous Waste	kg	>=5% Reduction (1 pt) >=10% Reduction (2 pts)	21,811	20,580	5.64%	1.13

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

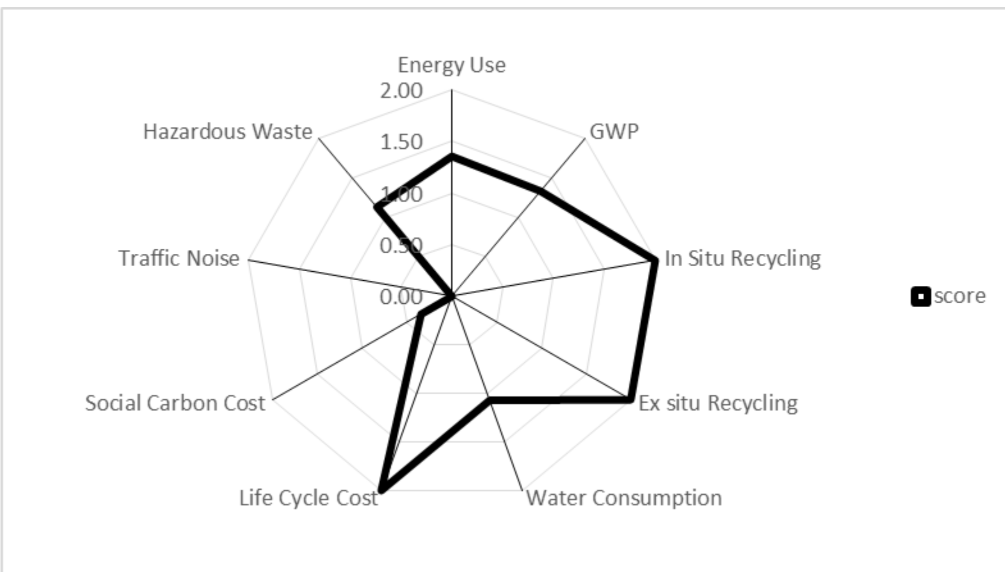


Figure 43: AMOEBA graph for recycled concrete pavement of Strategy 3.

Table 47: Results of BE²ST-in-Highway for Strategy 4 (concrete pavement).

Criteria	Unit	Target	Reference	Strategy 4	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	15,213,544	10,463,405	31.22%	2.00
GWP	**Mg**	**>= 10% Reduction (1 pt)** **>= 20% Reduction (2 pts)**	1,066	739	30.68%	2.00
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)** **>= 20% Recycling Rate (2 pts)**	0.00	0.5000	50.00%	2.00
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)** **>= 20% Recycled Content (2 pts)**	0.00	0.4268	42.68%	2.00
Water Consumption	**kg**	**>= 5% Reduction (1 pt)** **>= 10% Reduction (2 pts)**	5,381	4,434	17.60%	2.00
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)** **>=20% Reduction (2 pts)**	1,097,804	609,609	44.47%	2.00
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)** **>= $39,500/mi Saving (2 pts)**	$69,290.00	$48,035.00	$21,255	1.08
Traffic Noise	**no unit**	**HMA (1 pt)** **SMA or OGFC (2 pts)**	0	0	0	0.00
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)** **>=10% Reduction (2 pts)**	21,811	15,722	27.92%	2.00

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

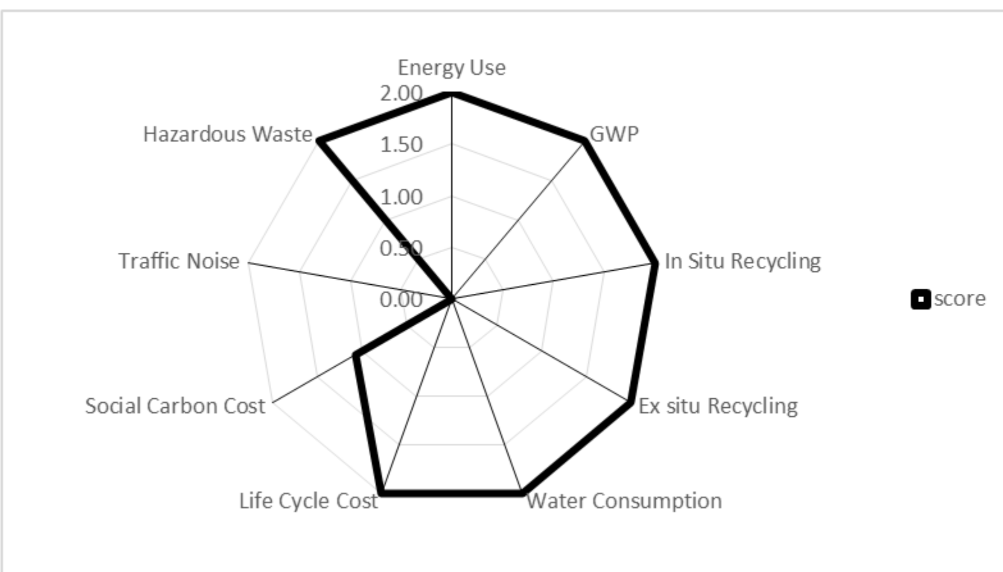


Figure 44: AMOEBA graph for recycled concrete pavement of Strategy 4.

Table 48: Results of BE^{2}ST-in-Highway for Strategy 5 (concrete pavement).

Criteria	Unit	Target	Reference	Strategy 5	Performance	Score
Energy Use	**MJ**	**>= 10% Reduction (1 pt)**	15,213,544	15,199,630	0.09%	0.01
		>= 20% Reduction (2 pts)				
GWP	**Mg**	**>= 10% Reduction (1 pt)**	1,066	1,067	-0.09%	0.00
		>= 20% Reduction (2 pts)				
In Situ Recycling	**CY**	**>= 10% Recycling Rate (1 pt)**	0.00	0.5000	50.00%	2.00
		>= 20% Recycling Rate (2 pts)				
Ex situ Recycling	**CY**	**>= 10% Recycled Content (1 pt)**	0.00	0.2382	23.82%	2.00
		>= 20% Recycled Content (2 pts)				
Water Consumption	**kg**	**>= 5% Reduction (1 pt)**	5,381	5,997	-11.45%	0.00
		>= 10% Reduction (2 pts)				
Life Cycle Cost	**$**	**>= 10% Reduction (1 pt)**	1,097,804	830,304	24.37%	2.00
		>=20% Reduction (2 pts)				
Social Carbon Cost	**$**	**>= $19,750/mi Saving (1 pt)**	$51,061.31	$51,109.21	$-65	0.00
		>= $39,500/mi Saving (2 pts)				
Traffic Noise	**no unit**	**HMA (1 pt)**	0	0	0	0.00
		SMA or OGFC (2 pts)				
Hazardous Waste	**kg**	**>=5% Reduction (1 pt)**	21,811	15,722	27.92%	2.00
		>=10% Reduction (2 pts)				

Note: The discount rate is 4%. Performance is the degree of achievement in reducing the consumption of resources, reducing the generation of gas and hazardous waste, cutting down the costs, and increasing recycling rate. Positive performance means more environmental benefits gained, negative performance means more environmental loads caused.

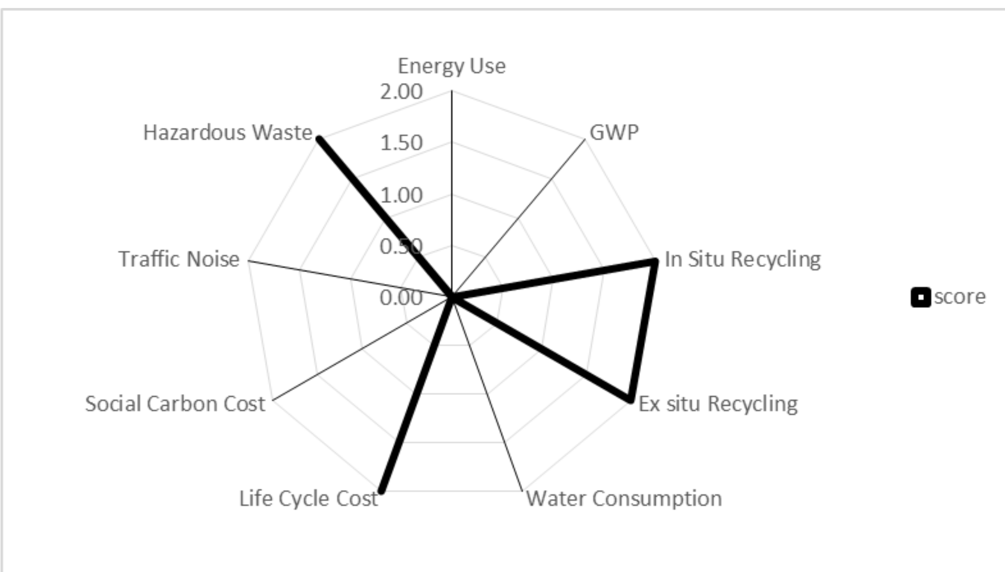


Figure 45: AMOEBA graph for recycled concrete pavement of Strategy 5.

Table 49: Rating of BE^{2}ST-in-Highway for rigid/concrete pavement.

Strategy #	Scenarios	Accomplished Score	Awarded Label
1	50% RCA in PCC, 100% RCA in GAB	70.07%	Bronze
2	100% RCA in PCC, 100% RCA in GAB	50.04%	Bronze
3	40% RAP in PCC, 100% RAP in GAB	73.46%	Bronze
4	100% RAP in PCC, 100% RAP in GAB	93.38%	Gold
5	20% FS in PCC, 100% RCA in GAB	58.05%	Bronze

1.2.4 Conclusions

BE^{2}ST-in-Highway^{TM} provides a unique ranking system for recycled pavements' life-cycle analysis. BE^{2}ST-in-Highway^{TM} starts with the structure design of pavements to ensure the pavement has desirable bearing capacity and durability in service. The system takes advantages of PaLATE to conduct life cycle economic and environmental analysis, as well as other components to estimate service life and assessing traffic noise and storm water management. BE^{2}ST-in-Highway^{TM} also quantifies the performance of pavements with a score and label, which helps decision makers to easily identify the optimum strategies. From this study, the following conclusions can be drawn:

1. Recycled materials replacing part of virgin materials in highway applications generally reduce life-cycle cost and contribute to sustainable development of pavements compared to using only virgin materials.

2. Recycled asphalt pavements generally meet the requirement of "green highway", while recycled concrete pavements may have difficulties in obtaining the "gold" label of "green highway." FDR used in recycled asphalt pavements is a main reason for the significant reduced in cost, consumption, and emission.

3. Though some strategies for recycled concrete pavement (i.e., 100% RCA in PCC and 100% RCA in GAB) received low scores, these strategies can be advanced by using additives (i.e., fly ash) or using new technologies (i.e., CSOL).

4. GAB with 100% RAP and 100% RCA have nearly the same performance. Recycled GAB may be more "green" than FASB and cement-stabilized base, since cement, asphalt, or emulsified asphalt are not required in the production of GAB materials.

5. Since there is no negative point to reflect the worse performance of recycled pavements compared to conventional pavements, extra attention should be paid to avoid or modify the disadvantages of using recycled pavements.

2.0 SURVEY ON THE STATE OF PRACTICE OF RECYCLED MATERIALS IN HIGHWAY APPLICATIONS

In order to receive feedback from various Department of Transportation (DOTs on the use of recycled materials in highway applications, the research team developed a survey, included in the appendix, which was distributed through the AASHTO subcommittee on recycled materials to all 50 states with the help of Maryland State Highway Administration. The summary findings are presented herein. The survey indicated the usage level of the four recycled materials by state and identified the details of their source and uses in highway applications. The following 16 state DOTs responded to the survey: Alaska, Alabama, Colorado, Connecticut, Delaware, Florida, Georgia, Montana, North Dakota, Ohio, South Dakota, Texas, Virginia, Washington D.C., Wisconsin and Wyoming. The questionnaire is attached in the appendix. The responses are summarized in Tables 50 through 53.

2.1 RESULTS

As seen in the results, RAP and RCA have been widely used, while DM and FS have been used less in highway applications. Many states have reported using RAP primarily in HMA and foamed asphalt. RCA has been mainly used in GAB, drainage/fill, and PCC. No record on the use of DM was reported. FS has been used in flowable fill/SCC materials.

Table 54 lists the potential sources of the recycled materials. Bridge and highway structures are the main sources. A few states reuse these materials from demolished buildings or pavement. Only Delaware accepts recycled materials from out of state plants or contractors. One potential reason for preventing some states from using recycled materials may be concerns of environmental suitability (Table 55). However, only a few states indicated that using recycled materials may elevate concentrations of metal/organic contaminants and cause high/low pH levels. In addition, the generation of HMA plant fumes is a concern in Alaska and may hinder RAP use.

Table 56 presents the technical challenges documented when recycled materials were used in highway applications. The major challenge for using RAP is related to the lack of consistent mechanical properties. Such inconsistent properties can negatively affect the durability, low temperature performance and fatigue resistance in pavements. Other challenges, such as the difficulty of finding the optimum binder replacement and testing the equivalent binder grade, also exist in using RAP, as indicated by Montana and Utah DOTs, respectively. Delaware DOT also indicated that the high permeability of RAP may be a problem in GAB application.

The major challenge surrounding the use of RCA is related to alkali-silica reaction (ASR), which may cause clogging in drains. According to Ohio DOT, RCA is gradually being recognized in GAB application, since ASR problems have primarily been solved. The problem of RCA gradation may be solved by further processing, as suggested by Delaware DOT. For FS, a concern from Alaska DOT is that FS may carry some toxic ingredients during the production progress. Thus, a stockpile requires approval by state engineers before using FS in construction. For DM, Ohio DOT also indicated that permission for using DM is possible depending on the source.

Technical reports from several full-depth reclamation (FDR) projects were provided from the Maine DOT, where the existing asphalt pavement, as well as part of the underlying unbound base, were recycled in-place to produce a stabilized base course (Table 57). In these projects, the objective was to solve cracking and rutting problems. Some techniques and recommendations for FDR are mentioned, including how to compact each layer in FDR, determine bulk specific gravity, and select additives and optimum binder contents. Suitable testing procedures and better methods for mix design are also suggested. Increasing structural numbers for surface layers were proposed.

Similar reports from Virginia DOT were provided in projects where RAP was used for in-place recycling for the base and/or sub-base. In the I-81 rehabilitation project, three in-place recycling techniques (FDR, cold-in place recycling (CIR), and cold-central plant recycling (CCPR)) were implemented and the field performance has shown the acceptability of all three methods with RAP. Because of concerns related to lower shear strength and excessive permanent deformation, resulting from large strains as RAP content increases, it was suggested using up to 50% RAP content by weight in virgin aggregate base and subbase layers.

The specifications provided by DOTs are listed in Table 58. Though the details of requirements differ in various states, the concerns in requirements are similar. The concerns involve the source, processing, mix design, tests, plants and construction. Furthermore, the recycled material content, gradation, mechanical properties, leaching properties, stockpile management and plant equipment, as well as quality control during construction are all considered. The requirements differ by application, weather conditions and traffic volume (i.e., high versus low volume roadways).

RAP is widely used in HMA and bituminous concrete. Granular base and shoulders are also considered. Most states have a limit on the percentage of RAP, however an increase in RAP is allowed if approved by DOT engineers. For instance, Alaska DOT restricts the use of RAP to 15% in wearing course and 25% in lower course for HMA construction. South Dakota DOT has a restriction of 20% maximum in mainline HMA mix and 40% maximum in shoulders. Wyoming limits usage of RAP to 20% or less. For applications of bituminous concrete, Connecticut sets up a maximum of 10% RAP used with no binder grade modification; however, a contractor is allowed to increase the RAP percentage in 5% increments up to a maximum of 30%, provided the engineer approves a new JMF (job mix formula). States adjust the requirements in different cases. Georgia limits the usage of RAP to 5% of the total mix for interstate projects, 0 to 40% for remaining roadways, 40% for continuous drum plants and 25% for batch plants. In Ohio, the maximum usage of RAP is determined according to the traffic load and layer. In heavy traffic, where a polymer modified surface mixture is used, the maximum percentage of RAP is 10% by dry weight of mix. Wisconsin has a regulation that, in shoulder applications or surfacing, 45% to 55% RAP (by weight) can be included in reprocessed or blended material.

RCA is often used in granular base. Some states (e.g. Ohio) allow only the use of coarse aggregates since fine aggregates may produce undesirable properties. In South Dakota, the requirements for using RCA in subbase, gravel cushion, aggregate base course, gravel surfacing, pit run and granular bridge end backfill are different. The requirements are mainly related to the percent passing, liquid limit, plasticity and LA abrasion loss. Ohio has requirements in water absorption as well.

FS has been used in granular base, drainage, flowable fill, embankment and other applications. The requirements of FS primarily relate to the gradation and proportioning. Ohio adopted a set of standards to ensure that FS is non-toxic before it is used in highway applications. The leached concentrations of selenium, phenol, cyanide and fluoride are required in Ohio. In addition, it is required that the solution of FS be tested for acidity, alkalinity, pH, sulfates, as well several metals. Table 9 provides some of these requirements and recommendations.

No information on the use of DM in highway applications was provided in the surveys. DM from maintaining navigable waterways routes are not used as a recycled material, since the grain size tend to be very fine-grained, uniform in size and generally cannot be processed to meet gradation requirements for typical highway applications. DM from mining operations of waterways is used, since these locations may provide larger size materials, which generally meet the requirements within construction specifications.

Mix design is a necessary step in achieving desired properties of recycled materials. It is often thoroughly tested in a laboratory in order to gain optimum performance and sometimes a balance of desired properties. Mitigating ASR is an important issue related to the use of RCA. For example, Ohio requires blending RCA with 20% type F fly ash, 30% granulated blast-furnace slag or a combination of both materials, up to 50%. Moreover, a new mix design for recycled materials is encouraged by several states, but the new design needs to be checked by DOTs before implementation.

Table 50: Use of RCA in Highway Applications

Applications / Byproducts	GAB	Foam Asphalt	Drainage/Fill	HMA	PCC
RCA	AL,CO,D.C., DE,GA,ME, ND,OH,SD,UT,VA,WI,WY,	-	AL,DE,OH,WI	-	AL,CO,OH, VA

Note: GAB= Granular Aggregate Base; PCC= Portland Cement Concrete; HMA= Hot Mix Asphalt.

Table 51: Use of RAP in Highway Applications

Applications / Byproducts	GAB	Foam Asphalt	Drainage/ Fill	HMA
HMA, Plant	AK	AK,ME, VA,WI	-	AK,AL,CO,CT,D.C., DE,GA,ME, MT, ND,OH, SD, UT,VA,WI,WY

Table 52: Use of Foundry Sand in Highway Applications

Applications / Byproducts	Crack Sealant	Base	Drainage/ Embankment	Flowable Fill/ SCC	HMA	PCC
Sand Foundry	-	-	-	WI,OH,AL	-	-

Note. SCC = Self Consolidated Concrete.

Table 53: Use of Dredged Materials in Highway Applications

Applications / Byproducts	Fill Materials
Clay/Silty Sediments	-

Table 54: Source of Recycled Materials.

Source	State
Bridge/ highway structures	CT,D.C.,GA,ME,UT,WI,WY,OH,CO,AL,ND,MT,DE,VA
Buildings/other structures	D.C.,GA,DE,VA
Recycling plants within state	AK,D.C.,GA,WI,OH,AL,DE
Out-of-state recycling plants	DE
Pavements	SD,WI
Contractors	DE

Table 55: Environmental Concerns

Environmental concerns	State
Metal/Organic contaminants	UT,CO,AL
High/low pH levels	OH,AL,VA
HMA plant fumes	AK

Table 56: Technical Challenges

State	Responses
AL	FS FS chemical reactions during processing of iron and steel are of concern. Thus, a stockpile must be approved by the Materials and Testing Engineer before it may be used.
AL, CT, DE, ME, MT, UT	RAP RAP is too permeable to work as a base material in GAB, though spec allows it. Additional virgin asphalt is needed for RAP to avoid dry and stiff mixtures. Poor performance of RAP results in more frequent resurfacing. Inconsistent RAP properties results in decreased pavement durability. Variable quality of RAP. The optimum binder replacement is difficult to find. RAP quality affects cold temperature and fatigue behavior of the pavement.
DE, OH	RCA RCA gradation variability is of concern. RCA associated in past with clogged drains and tufa formation.
OH	DM No ban for using DM, so there is currently a source for using these materials.

Table 57: Study Findings

State	Recycled Materials & Application	Study Results
ME	RAP in HMA & Base	*Peabody, 2009. "Full Depth Reclamation with Cement."* ❖ Roadway failure is mainly due to insufficient support for the HMA surface. ❖ Transverse and longitudinal cracking in the soil cement section is a concern. ❖ Four percent cement may be too much to make the pavement section flexible in the harsh environment.
		Marquis et. al., 2004. "Potential Benefits of Adding Emulsion to FDR Material." ❖ Use of emulsion has improved the overall pavement performance, reduced the occurrence of load cracks and rutting of the surface layer, and increased the structural capacity of the pavement. ❖ Preliminary investigation of the existing roadway materials is necessary to select the best alternative for base stabilization and avoid problems during construction.
		Marquis et. al., 2004. "Using Foamed Asphalt as a Stabilizing Agent in FDR of Route 8 in Belgrade, Maine" ❖ Sections with FDR had the lowest structural numbers compared to sections with asphalt stabilized base. ❖ Sections treated with FDR material and either granular base, asphalt stabilized base or HMA base had similar costs.
		Mallick et al., 2002."Development of a Rational and Practical Mix Design System for FDR Mixes" ❖ Use of a slotted mold (i.e., a sample extrusion device to remove emulsified asphalt from compactor immediately after compaction) is suggested to squeeze out of water during compaction of FDR mixes. ❖ Use samples in sealed bags to determine bulk specific gravity in the laboratory. ❖ Use density and resilient modulus versus total additive content (i.e., water and asphalt emulsion) criteria to select optimum additive content. ❖ Mix design for FDR samples (RAP and unbound base material) should be compacted to 50 gyrations. Control strip in the field should meet at least 95% density of in-place loose mixes, and be compacted to 50 gyrations. ❖ Increase structural numbers for FDR layers to design binder and surface layers. Use a suitable test procedure, such as the soaked, conditioned strength, tube suction or stripping test, to evaluate moisture susceptibility of designed mixes.

Table 57: Study Findings (continued)

State	Recycled Materials & Application	Study Results
VA	RAP in HMA	*(Diefenderfer et. al., 2014). "I-81 In-Place Pavement Recycling Project"* ❖ Active fillers (e.g. cement) can improve resistance to moisture and improve the early strength of bitumen stabilized asphalt materials. ❖ On higher volume roads, an asphalt concrete overlay is generally placed over in-place recycling HMA layer, but functional treatments (e.g. chip seals) are used on lower volume roadways. ❖ During construction, cold central-plant and cold in-place recycling HMA layers generally meet or exceed 98% of the modified Proctor density requirements based on AASHTO T 180. ITS and M_R laboratory testing indicated that the performance of CCPR and CIR are similar. Dynamic modulus testing indicated that the CCPR material might have a better performance at higher temperatures. ❖ The field performance tests demonstrated that the section of pavement rehabilitated by the three, in-place recycling methods (FDR, CCPR, CIR) continues to perform well after nearly three years of high volume, interstate traffic.
	RAP in Base	*Hoppe et al. 2015. "Feasibility of RAP Use as Road Base and Sub-base Material"* ❖ RAP in base and subbase is technically viable. There is a trend of using up to 50% RAP content by weight in virgin aggregate, because of the concern on lower shear strengths and excessive permanent deformations as RAP content increases. ❖ RAP for use in base and subbase layers can be characterized by performance-related parameters, such as grading, resilient modulus, shear strength, and permanent deformation and durability (i.e., frost susceptibility and abrasion). ❖ No leaching concerns on un-stabilized RAP used as base or subbase material. Use of chemical stabilization agents may require environmental assessment on a case-by-case basis.

Table 58: Technical Data and Specifications

<table>
<tr><th>State</th><th>Item</th><th>Details</th></tr>
<tr><td>AK</td><td>RAP in HMA</td><td>◆ Max 15% in wearing course; max 25% in lower courses</td></tr>
<tr><td>AL</td><td>RAP In HMA</td><td>
◆ The allowable use of RAP in:
■ ALDOT 327, Plant Mix Bituminous Base: RAP≤ 25%, RAP+RAS≤ 25%
■ ALDOT 327-E, Permeable Asphalt Treated Base: RAP≤ 10%, RAS not allowed
■ ALDOT 420, Open Grades Friction Course: RAP≤ 10%, RAS not allowed;
■ ALDOT 423, Stone Matrix Asphalt & Superpave
• surface layers: RAP ≤ 20% (with no more than 15% containing chert gravel), RAP+RAS≤ 20%
• all other layers: RAP≤ 25%, RAP+RAS≤ 25%
■ allowable to all Superpave ESAL range mixes that require PG 67-22 liquid binder: RAP≥25 %, or RAP+RAS≤35 % (mixes in base and binder layers)
■ unallowable to surface Superpave ESAL mixes that require PG 76-22 liquid binder: RAP≥25 %, or RAP+RAS≥25 %.
◆ Required test for RAP≥25 %: AASHTO T 319, AASHTO T 240, AASHTO T 315, ALDOT 361
◆ Additional requirements on stockpiles when RAP≥25 %:
<table>
<tr><th colspan="2">Additional RAP Stockpile Requirements for RAP Used in a Job Mix Fomula with Increased RAP Content</th></tr>
<tr><td>Control Parameter</td><td>Standard Deviation</td></tr>
<tr><td>Asphalt Content</td><td>0.5%</td></tr>
<tr><td>%Passing #200 Sieve</td><td>1.0%</td></tr>
<tr><td>Sieve with 50% RAP Passing</td><td>5.0%</td></tr>
<tr><td colspan="2">*Based on a minimum of 10 tests.</td></tr>
</table>
◆ Mix design
• job-mix formula approved by the Materials and Tests Engineer, checked by the Division Materials Engineer
• new job-mix formula for new source and new materials; no new job-mix formula for changed liquid asphalt binder source or changed anti-stripping agent, but one-point check (the Air Void, VMA, Stability, Flow, and TSR) is required.
</td></tr>
</table>

Table 58: Technical Data and Specifications (continued).

State	Item	Details
Al	RAP in HMA	◆ **Processing** • RAP used in 3/8 inch {9.5 mm} Section: 100 % of the RAP passes the 1/2 inch {12.5 mm} sieve • RAP used in ALDOT 801 and 802 (no gravel in ALDOT 327 PATB, ALDOT 420 and ALDOT 423 mixes): the maximum size for the mix specified • RAP used in ALDOT 327 PATB and ALDOT 420 mixes: 100 % of the RAP retained on the No. 4 {4.75 mm} sieve ◆ **Construction Requirements:** • equipment; wet weather and temperature limitations; preparation of underlying surface; preparation of mixtures; transporting mixture; placing the mixture; compacting; joints.
	RCA in PCC	◆ **Processing** ■ Wash and eliminate coatings on coarse aggregate for Portland cement concrete and cover aggregate for bituminous treatment. ■ Coating check: Material shall pass the No. 200 {75 µm} sieve and be checked by visual inspection using a petrographic microscope. ■ The amount of deleterious substances shall not exceed these limits: (see table below) ■ Aggregate that has an adherent coating will not be acceptable.

Maximum Allowable Deleterious Materials in Coarse Aggregates		
Type of deleterious materials	Bitumen Surface Treatment and Concrete Class A, B, and D	All other uses
Coal and lignite	0.25%	0.25%
Clay lumps	0.25%	0.25%
Material passing the No.200 sieve	1.0%	2.0%
Flat or elongated particles (5:1 ratio)	10%	10%

■ Aggregate that has an adherent coating will not be acceptable.

Type of Deleterious Materials	Bitumen Surface Treatment and Specific Concrete Mixtures	All Other Uses
Flat or elongated particles (3:1 ratio)	20%	20%
Other local deleterious substance (Shale ,Mica, Marcasite, etc.)	2%	2%
Reactive Silica	8%	8%

Table 58: Technical Data and Specifications (continued).

State	Item	Details
AL	**RCA in PCC**	■ Three options for designing concrete mixes with limestone aggregates that contain more than 8.0% silica: • Class F fly ash replacing 20% cement by weight; • Ground Granulate Blast Furnace Slag replacing 50% cement by weight (for concrete placed at ambient temperatures of 45 ºF {7 ºC} or above); or • Class C fly ash and microsilica replacing 30% and 5% cement by weight. ■ Restriction of the amount of absorption for gravel aggregates: • gravel for use in bituminous plant mixes and bridge superstructure concrete (except prestressed concrete): absorption ≦2.0% and passing the 3/4 inch {19.0 mm} sieve and retained on the No. 4 {4.75 mm} sieve • require a 15 minute vacuum saturation period prior to the 15-19 hour soaking period ■ The maximum allowable deleterious materials in coarse aggregate used in concrete (mininmum 28-Day compressive strength of 3000 psi, ALDOT 501.02) applies only to concrete used for bridge substructures, box culverts, retaining walls and concrete safety barriers.
	FS	◆ The stockpile must be approved by the Materials and Tests Engineer before it may be used.
	DM	◆ **Source** ■ DM from maintaining navigable route of waterways are not used, since the grain size tends to be very fine-grained, uniform in size and generally cannot be processed to meet required gradation. ■ DM from mining operations of waterways are used.
CT	**RAP in HMA**	◆ **Processing** ■ 100% RAP pass the two in (50 mm) sieve. Additional crushing and sizing may be required if the RAP aggregate exceeds the maximum sieve size for the mix type in CTDOT 828. ■ From pavements previously constructed: • certification for binder substantially free of solvents, tars and other contaminants • label stockpile with a sign reading "ConnDOT RAP" and separate it from all other materials • The request for approval of the RAP material include: o certification for source, stockpile location; and o estimation for quantities to be used. ■ From unknown source: • certification for the component of RAP meeting the specification requirements of CTDOT M.04.01-1a through c and for the binder in the RAP substantially free of solvents, tars and other contaminants • separate stockpiled RAP from all other RAP materials at all times

Table 58: Technical Data and Specifications (continued).

<table>
<tr><th>State</th><th>Item</th><th>Details</th></tr>
<tr><td>CT</td><td>RAP in HMA</td><td>
• The request for approval shall include:
○ a 5-pound (2.5-kg) sample of the RAP incorporated into the recycled mixture & a 5-pound (2.5-kg) sample of the extracted aggregate from the RAP;
○ viscosity test results; and
○ a statement that RAP material 100% passing the ½ inch (12.5 mm) sieve and free from contaminants such as joint compound, wood, plastic, and metals.

■ From existing roadway, contractor's RAP stockpile approved by the department, or department stockpile:
• for interstate projects, no alluvial gravel or local sand
• for shoulder construction, sand or gravel ≤20%
• for non-interstate projects, alluvial gravel ≤ 5 %
• for mainline or ramps, RAP = 0 ~40%
• for continuous mix type plants, RAP ≤40%
• for batch type plant, RAP ≤25%

◆ Applied in bituminous concrete
■ Comply with requirements in CTDOT M.04.01-1.
■ Limit use of RAP in 10% with no binder grade modification. The JMF should be approved by the Engineer.
■ If greater than 10% of total mix weight (mass), 5% increments up to a maximum of 30% is allowed in the percentage of RAP, provided a new JMF is approved by the Engineer.
• JMF shall include: Gradation and asphalt content of the RAP, percentage of RAP to be used, virgin aggregate source(s), total JMF content based on total mixture weight (mass), percentage of bitumen based on total mixture weight (mass), gradation of combined bituminous concrete mixture (including RAP), and grade of virgin added.

◆ In construction:
■ Indicate on the ticket the percent of RAP, the moisture content, and the net weight of RAP added to the mixture.
■ Make necessary adjustments to ensure bituminous concrete materials are free from moisture throughout.
■ Do not change the JMF and RAP percentage without prior approval of the engineer in daily construction.
</td></tr>
<tr><td>ME</td><td>RAP in HMA</td><td>
◆ Applied in HMA
The percentage for RAP can be reduced up to 10% from the amount list on the JMF but shall not exceed the amount listed in the JMF, or for the specific application, under any circumstance.
</td></tr>
</table>

Table 58: Technical Data and Specifications (continued).

<table>
<tr><th>State</th><th>Item</th><th>Details</th></tr>
<tr><td>ME</td><td>RAP in HMA</td><td>
◆ Applied in bituminous pavement
■ 100% of RAP should pass a 2-inch square mesh sieve.
■ It should be free of winter sand, granular fill, construction debris and other materials not generally considered bituminous pavement.

◆ Full-depth Reclamation (FDR) HMA
■ It should be rolled with a vibratory pod/tamping foot roller with a minimum 54 inch diameter single drum.
■ The remaining FDR material shall be compacted to a minimum density of 98% of the target density as determined in the control section.

◆ Plant
■ It should be capable of automatically compensating for the moisture content of the RAP.
■ The RAP shall be delivered to the mixer at a temperature of no less than 50°F.
■ If a drum type mixing plant is used, the RAP may be heated prior to being mixed with the emulsified asphalt to a temperature not to exceed 195°F.
■ The plant mixed recycled asphalt pavement shall be performed:
• between May 15th and September 15th inclusive in Zone 1 and between May 1st and September 30th inclusive in Zone 2;
• when the atmospheric temperature is 50°F and rising;
• when there is no standing water on the surface;
• during generally dry conditions, or when pulverizing, adding, mixing, and curing can be obtained using proper procedures, or when compaction can be accomplished as determined by the resident; and
• when the surface is not frozen and overnight temperatures are expected to be above 32°F.

◆ Processing
■ All material must be no larger than 1 1/2 inch.
■ Material must be stockpiled, but not for longer than 48 hours.
</td></tr>
<tr><td>SD</td><td>RAP in HMA & Base</td><td>
◆ Applied in asphalt concrete
RAP shall conform to the following gradation:
<table>
<tr><th>Sieve Size</th><th>Percent Passing</th></tr>
<tr><td>1 1/2 inch</td><td>100</td></tr>
<tr><td>1 inch</td><td>95-100</td></tr>
</table>
◆ Applied in cold in-place recycling for HMA
RAP shall conform to the following gradation:
<table>
<tr><th>Sieve Size</th><th>Percent Passing</th></tr>
<tr><td>1 1/4 inch</td><td>100</td></tr>
<tr><td>1 inch</td><td>95-100</td></tr>
</table>
</td></tr>
</table>

Table 58: Technical Data and Specifications (continued).

State	Item	Details
SD	RAP in HMA & Base	◆ **Applied in granular base** ■ requirements for gradation ■ liquid limit, plasticity index, LA abrasion loss ◆ RAP is not typically allowed in Select Borrow. ◆ RAP is allowed in HMA ≦20% (Mainline HMA Mix). ◆ RAP is allowed in shoulders ≦40%. ◆ RCA is not allowed in drainage fabric, edge drains, or other similar drainage systems except in approach drains and transverse drains. ◆ **Processing:** ■ 100 percent passing a 1 1/4-inch sieve; ■ 75 percent or less of the aggregate passing a No. 4 sieve; and ■ asphalt content: 3% ~6.5%. ■ Department: Assess properties by visual inspection but may test questionable. ■ For the percent passing the 1 1/4-inch sieve, extraction of asphaltic material is not required in the test. ■ For the percent passing the No. 4 sieve and percent of asphalt content, extraction of asphaltic material is required in the test.
WI	RAP in Base	◆ Contractor can use RAP as 3-inch base, or 1 1/4-inch base without regard to the gradation requirements under WIDOT 305.2.2.1. ◆ **Construction** ■ For RAP base, stockpile material conforming to WIDOT 306.2 and place material as the plans or special provisions specify. Construct the base conforming to WIDOT 305.3. ■ Excess material becomes the contractor's property. ◆ **In asphaltic pavement base** ■ 100 percent passing a 1 1/4-inch sieve. ■ For shouldering or surfacing applications, RAP content must equal 45 ~ 55% (by weight). ◆ **In open graded base** Furnish crushed concrete conforming to WIDOT 301.2, except for gradation conform to the following: Sieve: 1-inch / 3/8-inch / No. 4 / No. 10 / No. 40 / No. 200 Percent passing (by weight): 90 - 100 / 45 - 65 / 15 - 45 / 0 - 20 / 0 - 10 / 0 - 5.0

Table 58: Technical Data and Specifications (continued).

<table>
<tr><th>State</th><th>Item</th><th>Details</th></tr>
<tr><td>OH</td><td>RAP in HMA</td><td>

◆ **Processing**

- From verifiable Department, Ohio Turnpike Commission projects:
  - Process and use RAP by one of the following two methods.
- From other sources or the unknown source:
  - Process and blend the RAP into a single uniform stockpile, test according to Level 3 Asphalt Mix Design requirements and obtain District approval for use.
  - Obtain written Laboratory approval for use of unusually large, old RAP stockpiles of unknown content and/or age. Include approved methods in the Quality Control Plan for ongoing processing and testing of piles. Ensure no foreign or deleterious material (OHDOT 703.04, OHDOT 703.05) in RAP.

Method 1-Standard RAP Limits		
Asphalt Mix Applications	Percentage RAP by Dry Weight of Mix, Max.	Total Virgin Asphalt Binder Content, Min
Heavy Traffic Polymer Surface Course	10%	5.2
Medium Traffic Surface Course	20%	5.0
Light Traffic Surface Course	20%	5.2
Intermediate Course	35%	3.0
Base Course 301	50%	2.7
Base Course 302	40%	2.0

Method 2-Extended RAP Limits		
Asphalt Mix Applications	Percentage RAP by Dry Weight of Mix, Max.	Total Virgin Asphalt Binder Content, Min
Heavy Traffic Polymer Surface Course	10%	5.0
Medium Traffic Surface Course	25%	4.8
Light Traffic Surface Course	25%	5.0
Intermediate Course	40%	3.0
Base Course 301	55%	2.5
Base Course 302	45%	1.8

- Determine the final RAP gradation and asphalt binder content on a minimum of four separate stockpile (or roadway for concurrent grinding) samples, all agreeing within a range of 0.4% for asphalt binder content and 5 % passing the No. 4 (4.75 mm) sieve.

</td></tr>
</table>

Table 58: Technical Data and Specifications (continued).

<table>
<tr><th>State</th><th>Item</th><th>Details</th></tr>
<tr><td rowspan="2">OH</td><td>RAP In HMA</td><td>◆ Plant
■ Provide enough space for handling at a hot mix facility.
■ Provide a clean, graded base for stockpiles that does not collect water. Test blended RAP and RAS stockpiles to assure uniform gradation and asphalt binder content.
■ Ensure uniform stockpile properties match the JMF submitted RAP and RAS properties, unless the uniform stockpile will be processed into the asphalt plant using plant cold feed in line processing.
■ Record in the JMF submittal both the uniform stockpile and in line processed RAP properties.
■ Give each stockpile a unique identification, distinguishing if RAS piles are from un-used manufactured shingle waste or used roofing tear-off shingles. Provide in the plant lab RAP and RAS properties for each uniform, blended stockpile cross referenced with its identification.
■ Provide the date the stockpile processing was completed and the estimated size in tons. Stockpiles and processing methods are subject to inspection and approval by the DET at any time.</td></tr>
<tr><td>FS</td><td>◆ Mix design
■ Conform to the requirements of OHDOT 703.05 for gradation. Use fine aggregate that is fine enough to stay in suspension within the mixture to ensure proper flow.
■ Meet the requirements of the Division of Surface Water Policy 400.007 “Beneficial Use of Non-Toxic Bottom Ash, Fly Ash and Spent Foundry Sand and Other Exempt Wastes,” and all other regulations.
• The following requirements should be met:
<table><tr><td>Leachate</td><td>Selenium</td><td>Phenol</td><td>Cyanide</td><td>Fluoride</td></tr><tr><td>Maximum content (mg/L)</td><td>1</td><td>10.5</td><td>0.6</td><td>12.0</td></tr></table>• The solution must be analyzed for the following parameters: acidity, alkalinity, aluminum, arsenic, barium, cadmium, chlorides, chromium, copper, fluoride, iron, lead, manganese, mercury, pH, selenium, specific conductance, sulfates, total dissolved solids, vanadium and zinc.
• At a minimum, annual tests must be performed on the materials.
◆ The applications of nontoxic FS are stabilization/solidification of other waste, soil blending ingredient, landfill, structural fill, pipe bedding, borrow pits and surfacing.</td></tr>
</table>

Table 58: Technical Data and Specifications (continued).

State	Item	Details
OH	RCA in PCC	◆ Source ■ RCA source must be from an ODOT project.. Do not use non-ODOT sources. ■ Do not inter-mingle concrete from different ODOT concrete sources. ■ Do not use RCA as a fine aggregate or produce a coarse aggregate material with more than 5% passing the No. 16 sieve, in the concrete. ◆ **Processing coarse RCA** ■ Remove steel, joint sealant, soil and other contaminants. Use necessary crushing, screening, washing and beneficiation methods to remove all fines and impurities and produce coarse aggregate with consistent quality and properties. ■ Meet quality requirements of 703.02-B, except: • percent of wear, Los Angeles test, maximum 50%; • amount passing the No. 200 (75µm) sieve, maximum 1.5%; • chloride content (AASHTO T 260), maximum 0.6 lbs. /yd^3 in new concrete; • specific gravity variability, maximum* 0.100; • absorption variability, maximum* 0.8%; * Stockpile aggregates that have specific gravity and absorption values that fall outside the limits of variability separately. ■ Use only material passing 703.13. Test each coarse aggregate gradation and each different source of RCA by the Department. ■ Meet the gradation requirements of mix design in 1117.04 and 1117.05. ■ Use only coarse RCA with absorption of 7.0% or less. ■ Provide coarse RCA with an asphalt content of 1.0% or less. ■ Stockpile material and do not use until RCA is tested and approved. ODOT will take quality assurance samples of stockpiles to verify the quality and consistency of the RCA. ◆ **Mix design** ■ Proportion the mix so that the nominal maximum aggregate size is 1 inch and the combination of aggregates are workable, finishable and well graded, and within the percent retained on each sieve. ■ When sieve recommendations are not satisfied: ▪ No single sieve requiring a minimum of 8% retained will be below 5% retained and no more than two below sieves will be allowed. ▪ When the percent retained on each of two adjacent sieve sizes is less than 8%, the total percent retained on either of these sieves and the adjacent sieve (that is not below 8%) shall be at least 13%. ▪ A single sieve may retain up to 22%. ■ Use combined RCA and virgin aggregate to obtain a well graded mix.

Table 58: Technical Data and Specifications (continued).

State	Item	Details
OH	**RCA in PCC**	■ The cementitious content ≥520 lbs/yd^3. Use fly ash, GGBF slag, and combined pozzolans at the limits defined in 499. ■ Establish maximum water–cementitious (W/C_m) ratio conforming to 499.03 and Supplement 1026. ■ Use a water reducing admixture (705.12) to achieve an acceptable level of consistency, workability and finishability. • Meet the Modulus of Rupture of 600 psi in 7 days and 700 psi in 28 days. Base the strength on the average of three 6"x 6" beam tests results. • Achieve a minimum compressive strength at 28 days of 5500 psi. • Provide concrete with 6 ± 2% air. • Design the mix to mitigate any material-related distresses found during the pavement survey (1117.02). • To mitigate for ASR, use 20% type F fly ash; 30% GGBF slag, or; a combination of both materials up to 50%, not exceeding the maximum content for either material.
OH	**RCA in PCC**	◆ **Construction** ■ Stockpile the RCA in increments of no more than 5,000 tons and test the absorption and specific gravity to make batch adjustments prior to use. Don't use RCA with an absorption exceeding 7%. ■ Maintain moisture above SSD during concrete production by stockpile soaking. Test the moisture content of all aggregates at the beginning of each day's production and retest at least every 1000 yd^3 of concrete. ■ Test gradation daily to maintain gradation within specification limits. ■ Adjust the amount of water added at the mixer, based on the moisture in the aggregate and the moisture the aggregate will absorb. Do not exceed the maximum established water cementitious ratio. ■ Use an approved set-retarding admixture conforming to OHDOT 705.12, when the concrete temperature exceeds 75ºF (24ºC). ■ Test the air content, slump, unit weight and temperature on the first three loads. If consistent to the engineer's satisfaction, extend testing to every five loads of concrete or as directed by the engineer. ■ Make beams for strength specimens twice a day at the engineer's direction. Perform air, slump, yield and temperature tests when strength specimens are made. ■ Insure that the pavement obtains 600 psi modulus of rupture before subjecting the pavement to traffic. Do not allow moisture runoff from RCA stockpiles to enter streams or groundwater. ■ Establish a slump range approved by the engineer for the mix for each method of placement and control the mixes within the established range. Remove wash water from the mixer prior to batching concrete. ■ If the specific gravity changes by more than 0.02 from the original design, adjust the design weight to conform to the new specific gravity.

Table 58: Technical Data and Specifications (continued).

<table>
<tr><th>State</th><th>Item</th><th>Details</th></tr>
<tr><td>UT</td><td>RAP in HMA</td><td>

◆ **Mix design**

- RAP ≤ 25% of the total weight of the hot mix and asphalt binder ≤ 25% of the total binder.
- RAP aggregate is required to meet the requirement as follows with exception of Sand Equivalent:

<table>
<tr><th colspan="4">Aggregate Properties Required for HMA</th></tr>
<tr><th>Test Method</th><th>Test No.</th><th>75 Design Gyrations and Greater</th><th>Less Than 75 Design Gyrations</th></tr>
<tr><td>One Fractured Face</td><td>AASHTO T 335</td><td>95% minimum</td><td>85% min (1 inch and ¾ inch)
90% min (½ inch and ⅜ inch)</td></tr>
<tr><td>Two Fractured Face</td><td>AASHTO T 335</td><td>90% minimum</td><td>80% min (1 inch and ¾ inch)
90% min (½ inch and ⅜ inch)</td></tr>
<tr><td>Fine Aggregate Angularity</td><td>AASHTO T 304</td><td>45 minimum</td><td>45 minimum</td></tr>
<tr><td>Flakiness Index</td><td>UDOT MOI 933 (Based on ⅜ inch sieve and above)</td><td>17% maximum</td><td>17% maximum</td></tr>
<tr><td>L.A. Wear</td><td>AASHTO T 96</td><td>35% maximum</td><td>40% maximum</td></tr>
<tr><td>Sand Equivalent</td><td>AASHTO T 176 (Pre-wet method)</td><td>60 minimum</td><td>45 minimum</td></tr>
<tr><td>Plasticity Index</td><td>AASHTO T 89 and T 90</td><td>0</td><td>0</td></tr>
<tr><td>Unit Weight</td><td>AASHTO T 19</td><td>Minimum 75 lb/ ft^3</td><td>minimum 75 lb/ ft^3</td></tr>
<tr><td>Soundness (sodium sulfate)</td><td>AASHTO T 104</td><td>16% maximum loss with five cycles</td><td>16% maximum loss with five cycles</td></tr>
<tr><td>Clay Lumps and Friable Particles</td><td>AASHTO T 112</td><td>2% maximum</td><td>2% maximum</td></tr>
<tr><td>Natural Fines</td><td>N/A</td><td>0%</td><td>10% maximum</td></tr>
</table>

◆ **Test (optional)**

- Do not adjust the asphalt binder grade: RAP ≤15% by weight and RAP asphalt binder content ≤15% of the total asphalt binder content by weight.
- Adjust asphalt binder grade according to AASHTO M 323: Asphalt binder = 15 ~ 25% of the asphalt binder weight.
- Select one grade softer than the grade specified. Don't lower than PG XX-34.
- Provide test reports indicating the PG grade and quantity of the recovered asphalt binder that is consistent throughout the stockpile.

</td></tr>
</table>

Table 58: Technical Data and Specifications (continued).

State	Item	Details
VA	**RAP in HMA**	

◆ **In asphalt mixture**

- Asphalt surface, intermediate and base mixtures containing RAP shall use the PG grade of asphalt cement as indicated in Table II–14A.
- The final asphalt mixture shall conform to the requirements for the type specified. Do not contact open flame during the production process.
- Mixture is handled, hauled, and stored if contamination can be minimized. It is stockpiled and used if the variable asphalt contents and asphalt penetration values don't adversely affect the consistency of the mixture.
- Ensure that the maximum top size introduced into the mix is two inches. Introduce smaller size into the mix if the reclaimed particles are not broken down or uniformly distributed throughout the mixture during heating and mixing.
- The mixture being produced should conform to the approved job-mix formula and volumetric properties specified in Table II-14.

Recommended Performance Grade of Asphalt Cement			
Mix Type	Percentage of RAP in Mix		
	%RAP<25.0%	25%<%RAP≦30%	25%<RAP≦35%
SM-4.75A,SM-9.0A, SM-9.5A,SM-12.5A	PG 64S-22	PG 64S-22	
SM-4.75D,SM-9.0D, SM-9.5D,SM-12.5D	PG 64S-22	PG 64S-22	
IM-19.0A	PG 64S-22	PG 64S-22	
IM-19.0D	PG 64S-22	PG 64S-22	
BM-25.0A	PG 64S-22		PG 64S-22
SM-25.0D	PG 64S-22		PG 64S-22

◆ **In asphalt concrete mixture**

Type E (polymer modified, VDOT 211.04) designated mixtures shall not contain more than 15% reclaimed asphalt pavement (RAP) material (by weight) or 3% recycled asphalt shingles (RAS) by weight.

◆ **In stone matrix asphalt concrete**

Specified Performance Grade of Asphalt and Use of RAP	
Mix type & PG	Allowable RAP Percentage in Mix
SMA-9.5(64H-22), SMA-12.5(64H-22), &SMA-19.0(64H-22)	0 to 20
SMA-9.5(64E-22), SMA-12.5(64E-22), &SMA-19.0(64E-22)	0 to 15

Table 58: Technical Data and Specifications (continued).

State	Item	Details
VA	**RAP in HMA**	◆ RAP is not permitted in thin hot mix asphalt concrete overlay.
WY	**RAP in HMA**	◆ Limit usage to 20% or less in HMA.

2.2 CONCLUSIONS

The main conclusions of the survey, based on responses from 16 state DOTs, include:

1. RAP has been used by all the states that responded to the survey. RCA has also been used by several states, while FS is less in use and DM is not used in any highway applications. The main sources of recycled materials are bridges and highways, recycling plants in-state, and demolished buildings or structures. Only a small amount of the recycling materials come from old pavements, recycling plants out-of-state or legal contractors.

2. Environmental concerns of using these materials include metal and organic contaminants, low or high pH level and HMA plant fumes. Yet, environmental effects are not the primary obstacle; technical challenges may be considered as a barrier for the wide use of the recycled materials.

3. The requirements in the state specifications include: source, processing, mix design, tests, plant requirements and construction methods. These may include limitations on the percentage of recycled material, gradation, stockpile processing, mechanical tests, leaching tests, plant equipment requirement, and quality control methods.

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APPENDIX

Recycled Material Availability Synthesis Study

Survey on the State of Practice of Recycled Materials in Highway Applications

Currently the use of recycled materials in highway applications in the US is expanding. However, their use is often limited due to regulatory, environmental and technical restrictions. University of Maryland currently sponsoring this research study to document the state-of-the-art practice of employing selected recycled materials, and develop the technical requirements for their safe use in alternative highway applications.

The following four recycled materials are the focus of this survey in order to document the state of practice by your agency and within your region:

- Recycled Concrete Aggregate (RCA);
- Reclaimed Asphalt Pavement (RAP);
- Dredged Materials (DM);
- Foundry Sand (FS).

Contact Information

Name & Position: ....
Agency: ....
Address: ....
....
Telephone: ....
Email: ....

Recycled Material Availability Synthesis Study

1. **Recycled Materials used by your agency in highway construction (check all that apply)**
   □ RCA □ RAP □ FS □ DM.
2. **What was the source?**

   □From Bridge/ Highway structures □Demolished buildings/other structures
   □From plants within your state □From plants outside your state
   □Other (please specify): ____
3. **In which applications was the recycled material used? Please check all that apply.**

   □GAB (Granular aggregate base) □FASB (Foam asphalt stabilized base)
   □Drainage/Fill materials □Select Borrow
   □HMA (Hot mix asphalt) □PCC (Portland cement concrete)
   □Other ___________________________________

4. **Please identify technical challenges you experienced with such materials.**

   ____
   ____
   ____

5. **What are the environmental concerns in regards to the use of recycled materials? Please check all that apply.**

   □Elevated concentrations of metal/organic contaminants
   □High/low pH levels;
   □Other____

We would appreciate it if you can provide additional information for any of these four recycled materials in your state and including:

i) **Key references & studies**

   ____
   ____
   ____
   ____

ii) **Technical data & specifications.**

   ____
   ____
   ____
   ____
   ____