Quantify the Energy and Environmental Effects of Using Recycled Asphalt and Recycled Concrete for Pavement Construction

Phase I Final Report

Prepared for

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Prepared by

National Technology Development, LLC

NTD

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The objective of this study is to quantify the energy and environment impacts from using recycled materials for highway construction. Specifically, when recycled asphalt pavement is re-used for producing hot mix asphalt or when recycled concrete aggregate is used in concrete, how much energy will be utilized and how much are the greenhouse emissions. This study quantified the impact of using recycled asphalt pavement (RAP) in hot mix asphalt and recycled concrete aggregate in concrete on energy consumption and greenhouse gas emission. For RAP, the impact on energy consumption and greenhouse gas emission is affected by a few factors, such as moisture content in RAP, hot mix asphalt discharge temperature and RAP content. A mathematical model was developed to determine the impact. For recycled concrete aggregate for concrete production, impact on energy consumption and greenhouse gas emission is largely affected by transporting distances. A simple model was also developed for recycled concrete aggregate.</td></tr>
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ABSTRACT

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KEY WORDS

Recycled Asphalt Pavement, Recycled Concrete Aggregate, Energy, Greenhouse Gas Emission

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SUMMARY

The State of New York has a state and local highway system that annually handles over 100 billion vehicle miles. This total system encompasses over 110,000 highway miles. Sustainable development is defined as a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. There is a need for a straightforward method of integrating sustainable roadway practices into a common standard. Current standards and decision tools do not adequately address all four sustainability components: engineering performance, cost, environment and society. For instance, while pavements are heavy users of recycled material they are not intently built to minimize emissions, energy use and environmental impact. Traditionally, the cost analysis for a material only includes engineering performance and economy. However, it has become obvious that energy and environment should also be included in the analysis. Currently there is a lack of quantitative evaluation of energy and environment impacts. A quantitative characterization of energy and environment impacts for using recycled materials is needed to facilitate the comprehensive analysis.

This study quantified the impact of using recycled asphalt pavement (RAP) in hot mix asphalt and recycled concrete aggregate in concrete on energy consumption and greenhouse gas emission, respectively. For RAP, the impact on energy consumption and greenhouse gas emission is affected by a few factors, such as moisture content in RAP, hot mix asphalt discharge temperature and RAP content. A mathematical model was developed to determine the impact. For recycled concrete aggregate for concrete production, impact on energy consumption and greenhouse gas emission is largely affected by transporting distances. A simple model was also developed for recycled concrete aggregate.

1 BACKGROUND

Introduction

The State of New York has a state and local highway system that annually handles over 100 billion vehicle miles. This total system encompasses over 110,000 highway miles. Other than funds spent by local governments, the New York State Department of Transportation (NYSDOT) each year spends about 15 billion dollars on transportation. This presents a significant investments and the contribution to the sustainability of the infrastructure and society by the transportation sectors could also be significant.

There is a need for a straightforward method of integrating sustainable roadway practices into a common standard. Current standards and decision tools do not adequately address all four sustainability components: engineering performance, cost, environment and society. For instance, while pavements are heavy users of recycled material they are not intently built to minimize emissions, energy use and environmental impact. Traditionally, the cost analysis for a material only includes engineering performance and economy. However, it has become obvious that energy and environment should also be included in the analysis. Currently there is a lack of quantitative evaluation of energy and environment impacts. A quantitative characterization of energy and environment impacts for using recycled materials is needed to facilitate the comprehensive analysis.

Objective

The objective of this study is to quantify the energy and environment impacts from using recycled materials for highway construction. Specifically, when recycled asphalt pavement is re-used for producing hot mix asphalt or when recycled concrete aggregate is used in concrete, how much energy will be utilized and how much are the greenhouse emissions.

2 LITERATURE REVIEW

The team reviewed literatures, including basic definition of energy and greenhouse gas emission, status of the use of recycled asphalt and recycled concrete for transportation infrastructure, and the approaches to quantify energy consumption of greenhouse gas emission.

(1) Energy definition

According to Halstead et al. (Halstead 1981), the energy related to a construction material consists of four types of energy: calorific energy, processing energy, transport (hauling) energy, and construction energy.

- Calorific energy is the heat energy released when a fuel or other product is completely burned.
- Processing energy is the energy required to manufacture or otherwise process a unit of material.
- Transport energy is the energy used as fuel for transporting materials from the place of their origin or manufacture to the point of their use.
- The construction energy is the energy used as fuel in operating construction equipments.

(2) Greenhouse Gas Emission

According to EPA, gases that trap heat in the atmosphere are often called greenhouse gases. Some greenhouse gases such as carbon dioxide occur naturally and are emitted to the atmosphere through natural processes and human activities. Other greenhouse gases (e.g., fluorinated gases) are created and emitted solely through human activities. The principal greenhouse gases that enter the atmosphere because of human activities are:

- Carbon Dioxide (CO_2): Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and also as a result of other chemical reactions (e.g., manufacture of cement).
- Methane (CH_4): Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and

other agricultural practices and by the decay of organic waste in municipal solid waste landfills.

- Nitrous Oxide (N_2O): Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.

Global warming potential (GWP) is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is a relative scale which compares the gas in question to that of the same mass of carbon dioxide. The GWP can be represented by the following formula: $GWP=CO_2 + 21CH_4 + 310N_2O$, in accordance with the Intergovernmental Panel on Climate Change (Wikepedia).

(3) Recycled Materials for Transportation Infrastructure Construction

Transportation sectors, including construction of highway and bridges, accounts for significant energy consumption and greenhouse gas emission, as shown in Figure 2-1. Table 2-1 shows the energy consumption for hot mix asphalt and Portland cement concrete, based on the study by Halstead (Halstead 1981, Table 20). The study assumed 765 tons per mile-in of HMA surface and 782 ton per mile-in of PCC and 132 MJ per gallon of fuel. For instance, 1,605 gallons of fuel are used for a one mile-in of HMA (Halstead 1981). This is equivalent to 1605/765*132=277 MJ/ton for HMA. Using recycled materials for construction typically has impact on the life cycle costs. In the meantime, the use of recycled materials inevitably affects the energy consumption and greenhouse gas emission. This study focuses on the use of recycled asphalt pavement (RAP) in hot mix asphalt (HMA) and recycled concrete aggregate (RCA) in concrete.

Table 2-1 Energy Consumption by HMA and PCC (*after Halstead W. 1981*)

Material	Construction, Btu/ton	Transportation Long Distance, MJ/ton	Processing, MJ/ton	Calorific, MJ/ton	Total MJ/ton
HMA	277	794	67	1764	2899
PCC	42	731	10203	0	1795

Recycled Asphalt Pavement

For RAP used in HMA, the existing asphalt pavement has to be grinded, transported to a plant for further processing, blended, and heated. The process of including RAP in HMA is shown in Figure 2-2.

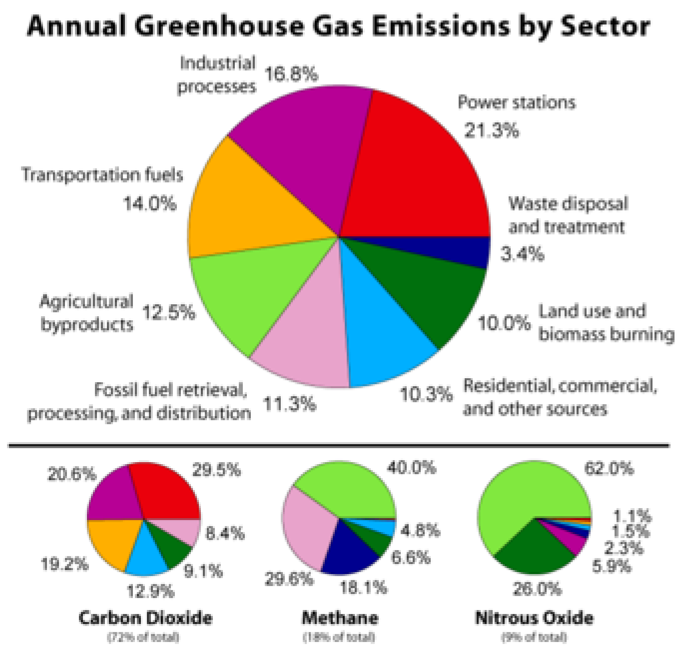

Figure 2-1. Greenhouse Gas Emission Breakdown (*after Wikipedia*)

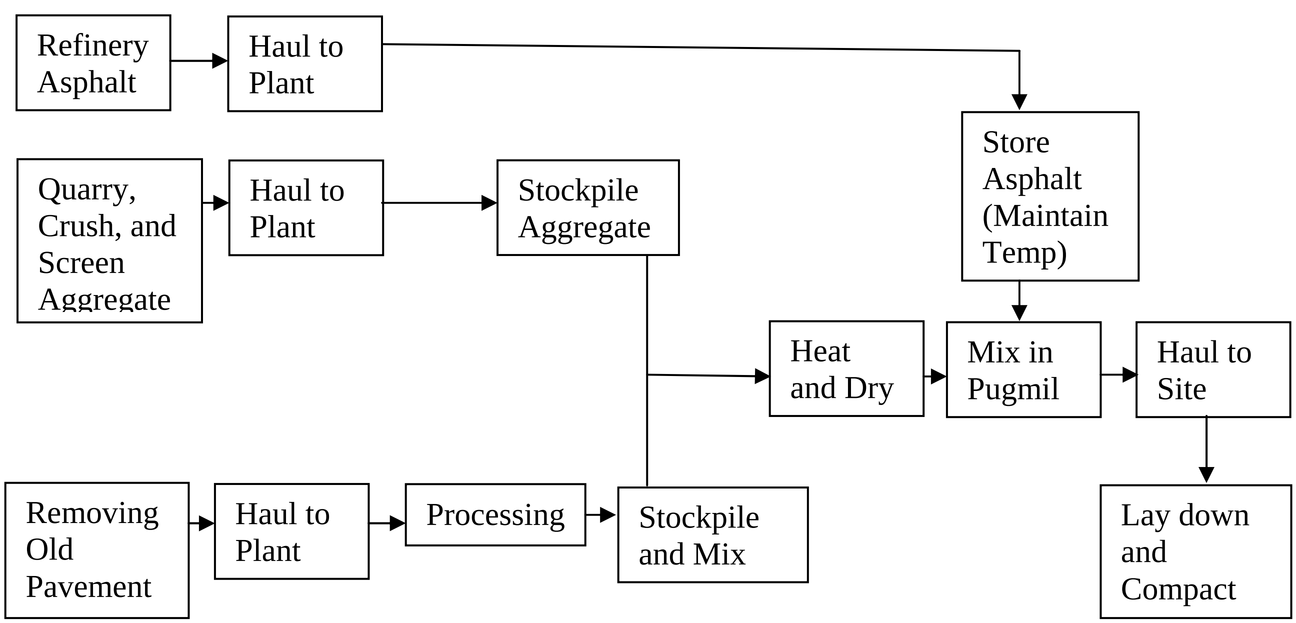

Figure 2-2. Flow Chart of HMA Construction (*after Hastead 1981)*

When heated, RAP may give off gaseous hydrocarbons. To minimize these emissions, HMA plants generally heat RAP indirectly (usually it is added after the aggregate is heated and thus heats up through contact with the already-hot aggregate).

RAP is typically added cold and thus may require longer HMA plant heating times. This can sometimes reduce plant output by as much as half. This can be overcome by preheating RAP, but the added energy, equipment and emissions concerns often make preheating undesirable.

Recycled Concrete Aggregate

Concrete generated from the demolition and crushing of concrete structures typically results in similar elements as the original concrete: coarse and fine aggregates, mortar, steel reinforcements and possibly deleterious materials, depending on its source. Deleterious materials are typically introduced into recycled concrete during the demolition or collection process. For example, recycled concrete generated from road demolition operations may include subbase soil materials and elements of asphalt pavement. Recycled concrete generated from the demolition of building structures may contain reinforcement steel, commingled wood, gypsum (plaster), glass and other structural elements.

(4) Past Studies on Energy and GWP Effects by the Use of Recycled Pavement Materials

Leadership in Energy and Environmental Design (LEED)

LEED provides a suite of guides for environmentally sustainable construction, based on a rating system. It considers and gives credits to sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation and design process. Recycled materials and energy/environment are important components of this rating system. However, the rating system is somewhat subjective, without providing detailed guidelines for what the credits are based on. For example, re-use of existing materials get a blanket two points without considering further details. Although LEED is not intended for transportation industry, it is the pioneer activity towards the sustainability of infrastructure construction.

Greenhighway System Rating

NYSDOT's Green LITES and University of Washington's Green Highway Rating are two notable highway rating and certification programs. A "green" highway rating system is to provide a way to update current state and federal highway best management practices to include advanced recycling techniques, extended environmental mitigation and extensive energy reduction. Such a system would classify the various parts of the highway construction process and then rate them based on their environmental sustainability. This approach would be beneficial to the design and construction of new surface transportation systems as well as the maintenance of existing transportation infrastructure. Again, the energy and environment, as well as the use of recycled materials, are significant components of this green highway rating system. Currently, there is a lack of analytical quantification of the energy consumption and greenhouse gas emission to be incorporated into the green highway rating system.

Other Studies

Athena Institute (2006) did a study for Cement Association of Canada on a life cycle perspective on concrete and asphalt roadways and embodied primary and global warming potential. The report compared the energy consumption and greenhouse gas emission of concrete pavement and asphalt pavement. It is noted that the energy used in this study only considered the energy consumption to produce either HMA or PCC, not a total energy for construction. RAP, up to 20%, was considered in the analysis, as an alternative. However, the RAP was simply used to replace new HMA, without considering the difference of energy and GWP between HMA and RAP. Therefore, the analysis in the report is not precise.

Tables 2-2 and 2-3 list the energy and GWP for hot mix asphalt and PCC by Athena Institute.

Table 2-2 Primary Energy and GWP for PCC

	Canada	Quebec	Ontario
Primary Energy (GJ/Ton)	808	751	877
GHG Emission (Kg/Ton)			
Carbon dioxide (CO_2)	119	113	118
Methane (CH_4)	0.027391	0.025217	0.184783
Nitrous oxide (N_2O)	0.000087	0.000001	0.000087
GWP (kg CO2 equiv.)	120	113	123

Table 2-3 Primary Energy and GWP for HMA

	Canada	Quebec	Ontario
Primary Energy (GJ/Ton)	3310	2787	3268
GHG Emission (Kg/Ton)			
Carbon dioxide (CO_2)	59	57	56
Methane (CH_4)	0.140435	0.128696	0.134783
Nitrous oxide (N_2O)	0.000087	0.000087	0.000043
GWP (kg CO2 equiv.)	62	60	59

COLAS Group analyzed the contribution made by road construction to energy consumption and greenhouse gas emission (COLAS Group 2003). Hot mix asphalt with different percentages of RAP was included in the analysis, as shown in Tables 2-4 and 2-5. Recycled concrete aggregate was not considered in the report.

The results from different studies are quite different. One of reasons is that these studies are sponsored by either HMA or PCC industry with the intent to promote their products. Scrutiny has to be taken to use these data. In addition, no study gives consideration to the asphalt binder from RAP. According to NYSDOT mix design, a portion of asphalt binder in RAP substitutes new asphalt binder in HMA.

Copple et al. studied the energy saving by the use of recycled concrete in new concrete (Copple 1981). They reported that, when compared to using concrete with virgin aggregate, using concrete with RCA save 10% energy, based on a 15-mile hauling distance for virgin aggregate.

Table 2-4 COLAS Analysis of HMA Energy Consumption (MJ/Ton)

Materials	Binder, Asphalt or Cement	Aggregate	Manufacture	Transport	Lay	Total
PCC	200	32	14	67	6	319
HMA	279	38	275	75	9	680
HMA+10%RAP	250	35	275	73	9	642
HMA+20%RAP	157	33	275	64	9	538
HMA+30%RAP	137	30	275	58	9	510
HMA+50%RAP	98	25	275	47	9	454

Table 2-5 COLAS Analysis of HMA Greenhouse Gas Emission (Kg/Ton)

Materials	Binder	Aggregate	Manufacture	Transport	Lay	Total
HMA	16	9.4	22	5.3	0.6	54
HMA+10%RAP	15	8.6	22	4.9	0.6	51
HMA+20%RAP	9	7.8	22	4.3	0.6	44
HMA+30%RAP	8	7	22	3.9	0.6	41
HMA+50%RAP	6	5.2	22	3.1	0.6	37

The information collected above was used directly or indirectly to obtain the input to quantitatively estimate the effects of the use of recycled materials on energy and greenhouse gas emission.

3 QUANTIFICATION OF IMPACT ON ENERGY AND GRENHOUSE GAS EMISSION

Recycled Asphalt Pavement

(a) Generalization/Modeling of Energy Consumption to Dry RAP

One of the challenges of adding RAP in HMA plant is the difficulty in drying/heating RAP. Due to the moisture and asphalt in RAP, adding high percentage of RAP often slows down HMA production. In HMA plant, RAP is added at the mid-term and virgin aggregates are “superheated” to dry/heat RAP. Table 3-1 shows the superheated temperatures of virgin aggregate to heat RAP, depending on RAP content, moisture content in RAP, and HMA discharge temperature [Alaska Pavement Summit, 2007].

Table 3-1 needs to be generalized for the purpose of modeling. The generalization can be done through either nonlinear regression or artificial neural network. To facilitate the implementation of this study, the nonlinear regression approach was employed.

Observations were first made on the effects of RAP percentage, moisture content in RAP, and discharge temperature of combined aggregates and RAP, as shown in Table 3-2.

(1) Effects of RAP Content on Temperature of Superheated Virgin Aggregates

Figure 3-1 shows the relationship between the RAP content and the increase of virgin aggregates at 0% moisture content in RAP and discharge temperature of HMA of 240°F. As seen in Figure 3-1, increasing the RAP content also increased the temperature needed for virgin aggregates. The relationship could be modeled as a binomial relationship. The relationship between RAP content and increased temperature is expressed in Equation (1):

$$\Delta T_{Agg}=0.03\,P_{RAP}^{2}+2.6214P_{RAP}-0.6 \quad (1)$$

where ΔT_{Agg}=Increase of Temperature of Virgin Aggregate, °F,

P_{RAP}=RAP content, %.

Table 3-1 Aggregate Temperatures (°F) to Heat/Dry RAP

		Recycled Mix Discharge Temperature			
	Reclaimed Material Moisture Content, %	240°F/116°C	260°F/127°C	280°F/138°C	300°F/149°C
10% RAP 90% Agg	0	269	291	313	335
	1	274	296	318	340
	2	279	301	323	345
	3	284	306	328	350
	4	289	311	333	355
	5	294	316	338	360
20% RAP 80% Agg	0	292	317	342	367
	1	303	328	353	378
	2	314	339	364	389
	3	325	350	375	400
	4	336	361	386	411
	5	347	372	397	422
30% RAP 70% Agg	0	324	352	330	408
	1	343	371	599	427
	2	362	390	418	446
	3	381	409	437	465
	4	400	428	456	484
	5	419	447	475	503
40% RAP 60% Agg	0	366	397	430	463
	1	424	426	459	492
	2	453	455	488	521
	3	482	484	517	550
	4	511	513	546	579
	5	540	542	575	608
50% RAP 50% Agg	0	420	460	500	540
	1	464	504	544	588
	2	508	548	588	628
	3	552	592	632	672
	4	596	636	676	716
	5	640	680	720	760

Table 3-2 Effects of RAP Percentage, Moisture Content, and Discharge Temperature on Aggregate Temperature

	Increase of Aggregate Temperature, °F		
Add RAP Percentage, %	**For same moisture content and discharge temperature,**	**Per 1% increase moisture in RAP,**	**Per 20°F increase of discharge temperature,**
10	29	5	22
20	52	11	25
30	84	19	28
40	156	29	N/A
50	180	44	40

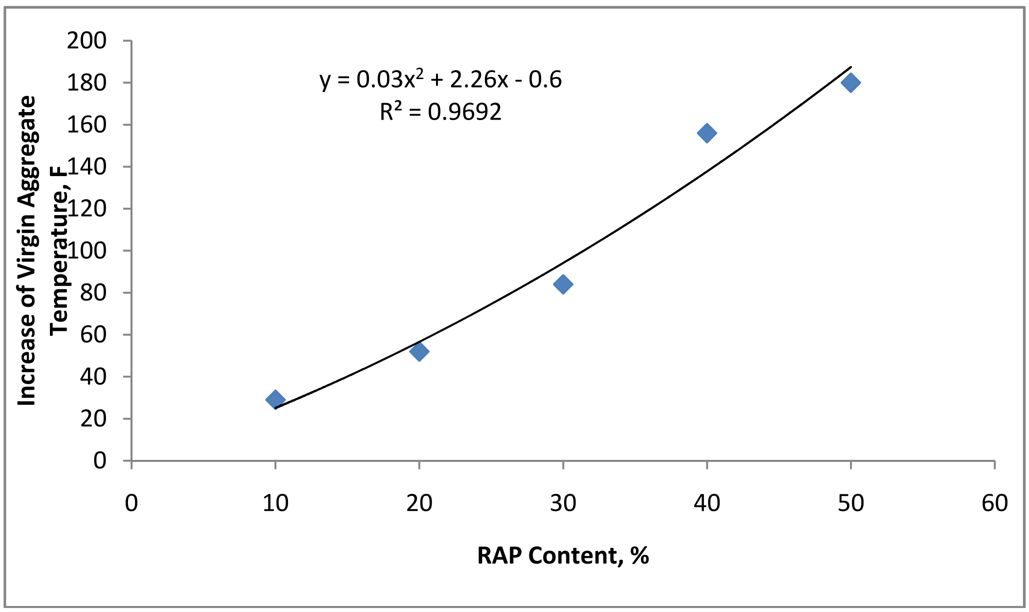

Figure 3-1. Relationship between RAP Content and Increase of Virgin Aggregate Temperature

(2) Effects of RAP Content and Moisture Content in RAP

The moisture in RAP takes more energy to evaporate. As shown in Figure 3-2, the relationship between RAP content and increased aggregate temperature for 1% increase of moisture content, is nonlinear. The relationship is expressed in Equation (2):

$$\Delta T_{Agg}=0.0143\,P_{RAP}^2+0.1029P_{RAP}+2.8 \quad (2)$$

where ΔT_{Agg}=Increase of Temperature of Virgin Aggregate per 1% increase of moisture content in RAP, °F,

P_{RAP}=RAP content, %.

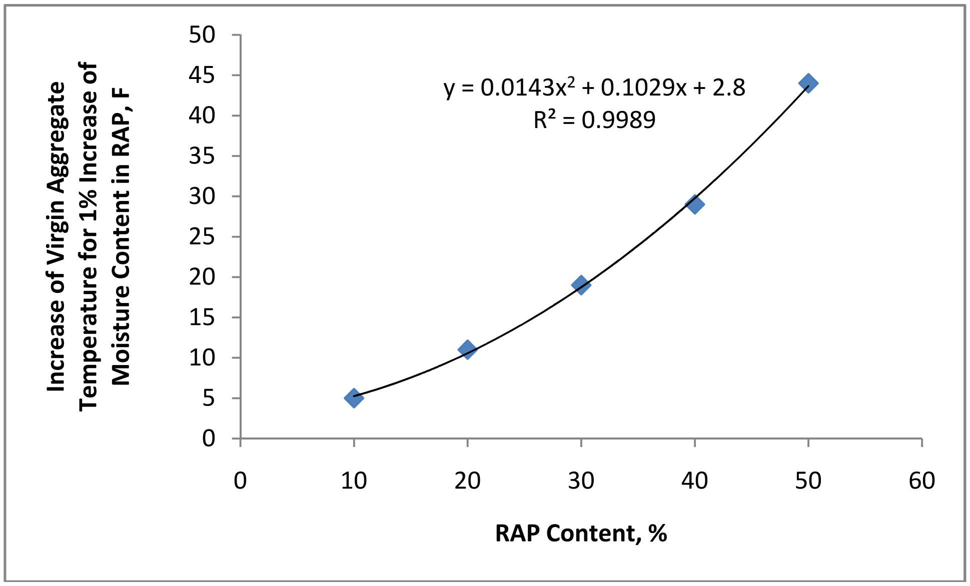

Figure 3-2. Relationship between RAP Content and Increase of Aggregate Temperature for 1% Increase of Moisture Content in RAP

(3) Effects of RAP Content on Discharge Temperature

As the HMA discharge temperature increases, the temperature of virgin aggregates needs to be increased. As shown in Figure 3-3, the relationship between RAP content and increased aggregate temperature for 20°F increase of discharge temperature, is nonlinear. More energy is needed to heat/dry RAP at high RAP content. The relationship between RAP content and increased temperature per 20°F increase of discharge temperature is expressed in Equation (3):

$$\Delta T_{Agg}=0.0068\,P_{RAP}^2+0.0355P_{RAP}+21.27 \quad (3)$$

where ΔT_{Agg}=Increase of Temperature of Virgin Aggregate per 20°F increase of discharge temperature, °F,

P_{RAP}=RAP content, %.

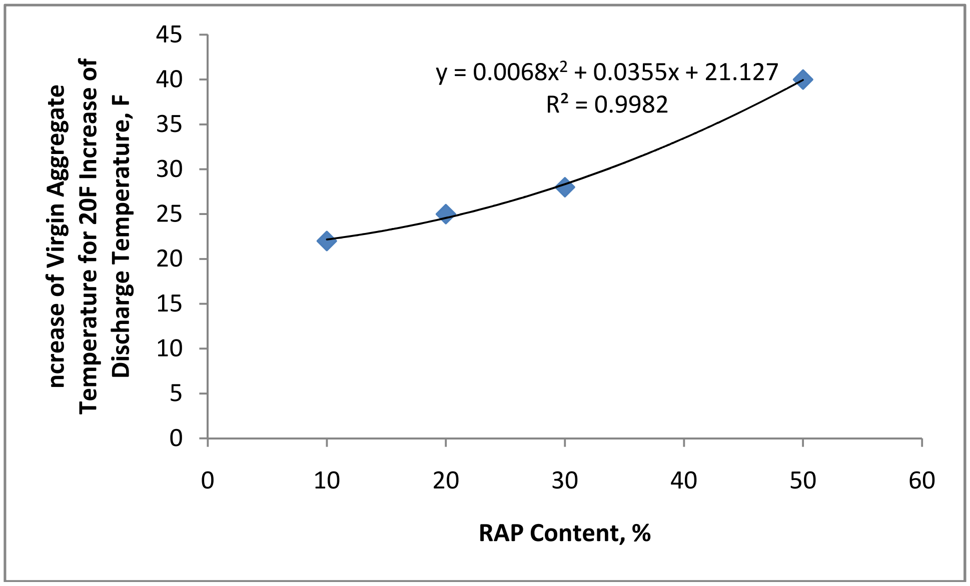

Figure 3-3. Relationship between RAP Content and Increase of Aggregate Temperature for 20F Increase of Discharge Temperature

Combining the effects of RAP content, moisture content, and discharge temperature, Equation (4) is developed to determine the required increase of aggregate temperature:

$$\Delta T_{Agg}=(-0.0516+0.0143P_{moi}+0.00034T_{dis})\,P_{RAP}^{2}+(2.1954+0.1029\,P_{moi}+0.00177\,T_{disc})P_{RAP}+2.8\,P_{moi}+1.0635T_{dis}-254.124 \quad (4)$$

where ΔT_{Agg}= Increase of Temperature of Virgin Aggregate due to RAP, °F,

P_{moi}=Moisture content, %

T_{dis}=Discharge Temperature, °F

P_{RAP}=RAP content, %.

To quantify the energy consumption to heat RAP, Equation (5) is used:

$$\Delta H=M_{Agg}\,c_p(T_f-T_i)= M_{Agg}\,c_p\Delta T_{Ag}= M_{RAP}\,c_p\Delta T_{Ag}(100-P_{RAP})\,/P_{RAP} \quad (5)$$

where ΔH=Energy to heat up RAP, BTUs,

M_{Agg} =Mass of Aggregate, lbs, = M_{RAP} (100-P_{RAP}) /P_{RAP}

M_{RAP} =Mass of RAP, lbs

c_p=specific heat of aggregate, 0.22BTUs/lbs/°F

T_f=Final temperature of aggregate, °F

T_i=Initial temperature of aggregate, °F

The energy to heat RAP can be developed as the following model, named "NTD model":

$$\Delta H_{RAP} = M_{RAP}\, c_p(100-P_{RAP})\,/P_{RAP}\,[(-0.0516+0.0143P_{moi}+0.00034T_{dis})\,P_{RAP}^2$$

$$+(2.1954+0.1029\,P_{moi}+0.00177\,T_{disc})P_{RAP}+2.8\,P_{moi}+1.0635T_{dis}-254.124] \qquad (6)$$

(b) Modeling of Energy to Heat Virgin Aggregates

For the purpose of comparing the energy impact of using RAP, the energy to heat/dry aggregate of the same mass and moisture content has to be determined. The energies to heat/dry virgin aggregate with moisture consist of the following [Hunt 2008],

(1) Energy to heat moisture:

$$M_{agg}P_{moi}(212-T_{amb})C_{water}/100 \qquad (7)$$

where M_{agg} =Mass of Aggregate, lbs

P_{moi}=Moisture content, %

T_{amb}=Ambient temperature, °F

C_{water}=specific heat of water, 1BTUs/lbs/°F.

(2) Energy to evaporate water:

$$M_{agg}P_{moi}LH/100 \qquad (8)$$

where LH=Latent heat to evaporate water, 970BTUs/lbs

(3) Energy to remove vapor:

$$M_{agg}P_{moi}(T_{dis}-212)C_{vap}/100 \qquad (9)$$

where C_{vap}=Specific heat of vapor, 0.5BTUs/lbs/°F

(4) Energy to heat aggregate:

$$M_{agg}(T_{dis}-T_{amb})C_{agg} \qquad (10)$$

where C_{vap}=Specific heat of aggregate, 0.22BTUs/lbs/°F

The total energy to heat aggregates with moisture is:

$$\Delta H_{Agg}=M_{agg}P_{moi}(212-T_{amb})C_{water}/100+M_{agg}P_{moi}LH/100+M_{agg}P_{moi}(T_{dis}-212)C_{vap}/100 + M_{agg}(T_{dis}-T_{amb})C_{agg} \quad (11)$$

In addition, the energy consumption to heat/dry aggregate has to consider the heating efficiency. Typically, an energy efficiency of 87.5% is used [Hunt 2008]. Therefore, after accounting for energy efficiency, the final model to heat/dry aggregate becomes:

$$\Delta H_{Agg}=M_{agg}P_{moi}(212-T_{amb})C_{water}/100+M_{agg}P_{moi}LH/100+M_{agg}P_{moi}(T_{dis}-212)C_{vap}/100 + M_{agg}(T_{dis}-212)C_{agg}/0.875 \quad (12)$$

(c) Quantify Energy Impacts of Heating/Drying RAP

The difference of ΔH between RAP and aggregate of same mass and moisture content can be quantified to obtain the impact of using RAP on energy and/or CO_2. Table 3-3, 3-4, and 3-5 shows the energy consumption to heat/dry RAP and virgin aggregates of the same mass per ton of HMA and moisture content for mix discharge temperatures of 280, 300, and 320°F, respectively. The difference in percentage indicates using higher percentage saves heating energy while using low percentage RAP consumes more heating energy, when compared to no RAP in HMA, as illustrated in Figures 3-4, 3-5, and 3-6 for discharge temperatures of 280, 300, and 320°F, respectively.

Table 3-3 Energy Analysis of Heating/Drying RAP and Virgin Aggregate (Per Ton of HMA) for Discharge Temperature of 280°F

RAP content	Moisture Content	Discharge Temperature	Ambient Temperature	Energy to heat/dry RAP	Energy to heat/dry Aggregate	Difference in Energy	Difference in Percentage
%	%	°F	°F	BTU	BTU	BTU	
10	1	280	60	30966	13705	17261	125.94%
10	2	280	60	33049	16347	16701	102.16%
10	3	280	60	35131	18990	16141	85.00%
10	4	280	60	37214	21632	15582	72.03%
10	5	280	60	39296	24274	15022	61.88%
20	1	280	60	43479	27410	16069	58.62%
20	2	280	60	47202	32695	14508	44.37%
20	3	280	60	50926	37979	12947	34.09%
20	4	280	60	54649	43264	11385	26.32%
20	5	280	60	58373	48549	9824	20.24%
30	1	280	60	55570	41115	14455	35.16%
30	2	280	60	61347	49042	12305	25.09%
30	3	280	60	67125	56969	10155	17.83%
30	4	280	60	72902	64896	8006	12.34%
30	5	280	60	78679	72823	5856	8.04%
40	1	280	60	65711	54821	10891	19.87%
40	2	280	60	73577	65390	8188	12.52%
40	3	280	60	81443	75959	5485	7.22%
40	4	280	60	89310	86528	2782	3.21%
40	5	280	60	97176	97097	79	0.08%
50	1	280	60	72373	68526	3847	5.61%
50	2	280	60	81986	81737	249	0.30%
50	3	280	60	91599	94949	-3350	-3.53%
50	4	280	60	101212	108160	-6948	-6.42%
50	5	280	60	110825	121371	-10547	-8.69%

Table 3-4 Energy Analysis of Heating/Drying RAP and Virgin Aggregate (Per Ton of HMA) for Discharge Temperature of 300°F

RAP content	Moisture Content	Discharge Temperature	Ambient Temperature	Energy to heat/dry RAP	Energy to heat/dry Aggregate	Difference in Energy	Difference in Percentage
10	1	300	60	39742	14734	25008	169.74%
10	2	300	60	41825	17399	24426	140.39%
10	3	300	60	43907	20064	23843	118.84%
10	4	300	60	45990	22729	23261	102.34%
10	5	300	60	48072	25394	22678	89.30%
20	1	300	60	52123	29467	22656	76.88%
20	2	300	60	55847	34798	21049	60.49%
20	3	300	60	59570	40128	19442	48.45%
20	4	300	60	63293	45458	17835	39.23%
20	5	300	60	67017	50789	16228	31.95%
30	1	300	60	64290	44201	20089	45.45%
30	2	300	60	70068	52197	17871	34.24%
30	3	300	60	75845	60192	15653	26.00%
30	4	300	60	81622	68187	13434	19.70%
30	5	300	60	87399	76183	11216	14.72%
40	1	300	60	74536	58935	15601	26.47%
40	2	300	60	82402	69595	12807	18.40%
40	3	300	60	90268	80256	10012	12.48%
40	4	300	60	98134	90917	7218	7.94%
40	5	300	60	106000	101577	4423	4.35%
50	1	300	60	81152	73669	7483	10.16%
50	2	300	60	90765	86994	3770	4.33%
50	3	300	60	100377	100320	57	0.06%
50	4	300	60	109990	113646	-3655	-3.22%
50	5	300	60	119603	126971	-7368	-5.80%

Table 3-5 Energy Analysis of Heating/Drying RAP and Virgin Aggregate (Per Ton of HMA) for Discharge Temperature of 320°F

RAP content	Moisture Content	Discharge Temperature	Ambient Temperature	Energy to heat/dry RAP	Energy to heat/dry Aggregate	Difference in Energy	Difference in Percentage
10	1	320	60	48518	15762	32756	207.81%
10	2	320	60	50601	18450	32151	174.26%
10	3	320	60	52683	21138	31545	149.23%
10	4	320	60	54766	23826	30940	129.86%
10	5	320	60	56849	26514	30334	114.41%
20	1	320	60	60767	31525	29243	92.76%
20	2	320	60	64491	36901	27590	74.77%
20	3	320	60	68214	42277	25938	61.35%
20	4	320	60	71938	47653	24285	50.96%
20	5	320	60	75661	53029	22632	42.68%
30	1	320	60	73010	47287	25724	54.40%
30	2	320	60	78788	55351	23437	42.34%
30	3	320	60	84565	63415	21150	33.35%
30	4	320	60	90342	71479	18863	26.39%
30	5	320	60	96119	79543	16576	20.84%
40	1	320	60	83361	63049	20311	32.22%
40	2	320	60	91227	73801	17426	23.61%
40	3	320	60	99093	84553	14540	17.20%
40	4	320	60	106959	95305	11654	12.23%
40	5	320	60	114825	106057	8768	8.27%
50	1	320	60	89930	78811	11119	14.11%
50	2	320	60	99543	92251	7292	7.90%
50	3	320	60	109156	105691	3464	3.28%
50	4	320	60	118769	119131	-363	-0.30%
50	5	320	60	128382	132571	-4190	-3.16%

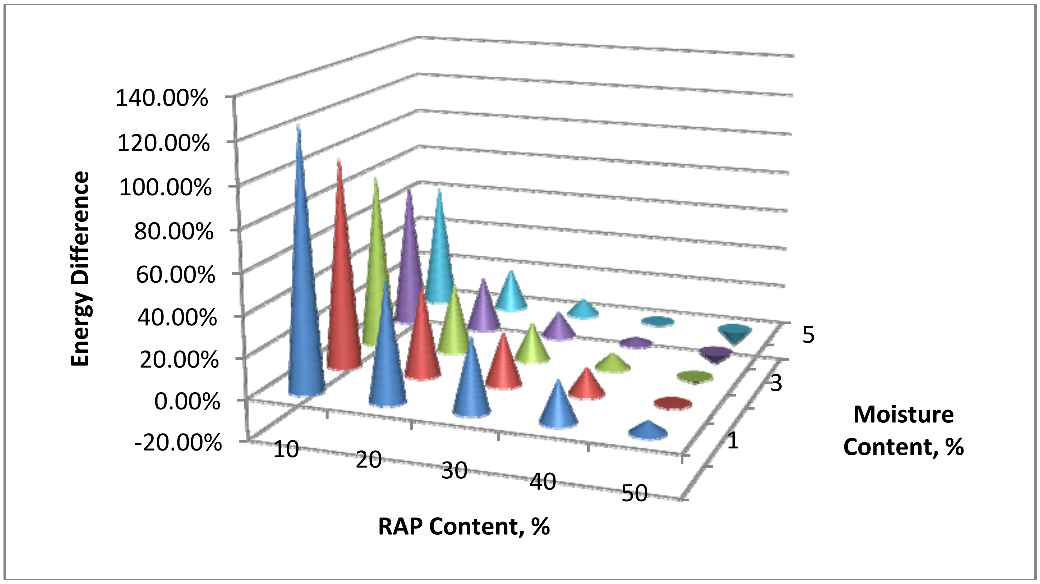

Figure 3-4. Effects of RAP Content and Moisture Contents on Energy Consumption at Discharge Temperature of 280°F

(Positive value indicates heating/drying RAP consume more energy than aggregates)

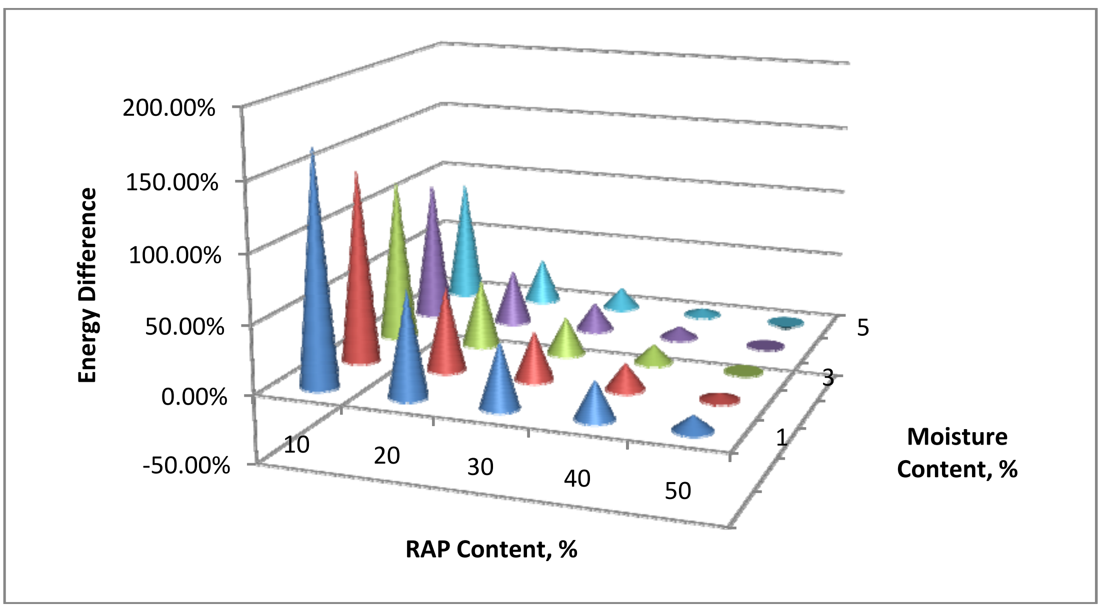

Figure 3-5. Effects of RAP Content and Moisture Contents on Energy Consumption at Discharge Temperature of 300°F

(Positive value indicates heating/drying RAP consume more energy than aggregates)

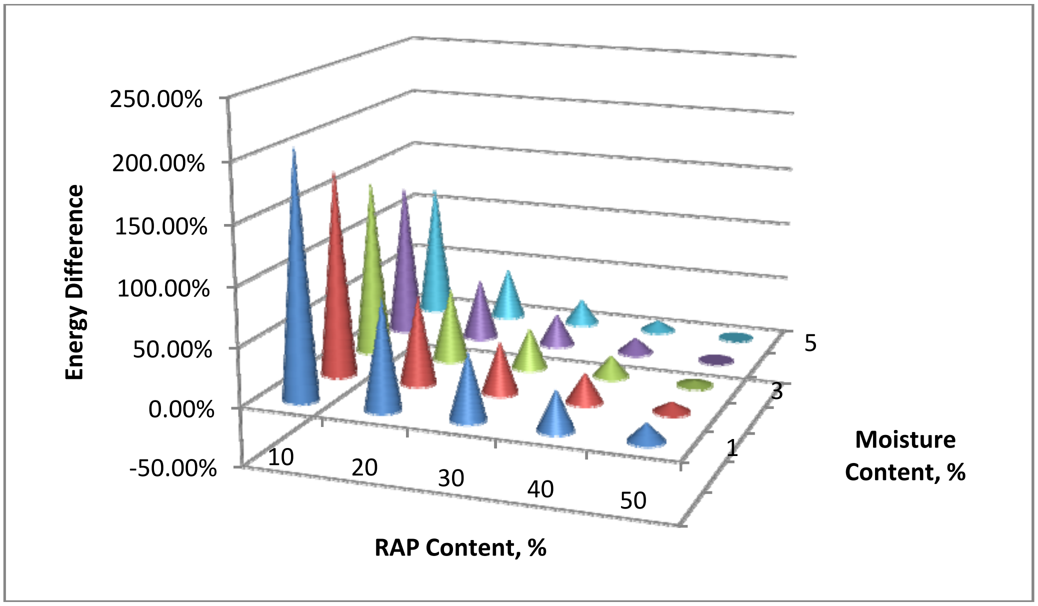

Figure 3-6. Effects of RAP Content and Moisture Contents on Energy Consumption at Discharge Temperature of 320°F

(Positive value indicates heating/drying RAP consume more energy than aggregates)

(d) Quantify Energy Impacts of Transporting RAP

Another potential impact of using RAP is the shorter hauling distance from the site to plant, when compared to transporting virgin aggregates. The average hauling distance from site to plant is 12.42 miles for RAP and 43.47 for virgin aggregates [Emery 2007]. The average energy for hauling material is 3,253 BTU/Ton/Mile [Miller 2001]. These values were used to determine the energy difference in hauling RAP and virgin aggregates.

(e) Quantify Energy Impacts of Binder in RAP

In accordance with NYSDOT Superpave mix design method, the binder in RAP is considered to be part of total binder in HMA. Therefore, the binder in RAP plays a role in energy and CO_2 emission analysis. The analysis consists of two parts: processing energy and calorific energy. The processing energy of binder includes handling and heating binder. The calorific energy is the embodied energy in binder. A processing energy of 587,000 BTU/Ton and a calorific energy of 371,000,000 BTU/Ton were used for asphalt binder [Halstead 2001]. When compared to HMA without RAP, less virgin binder is needed in HMA with RAP and energy is saved. It is noted that the calorific energy of binder overwhelms other energies.

The difference in energy consumption between RAP and virgin aggregate can be determined after combining the drying/heating, transportation, and processing/calorific energies. It is noted that the energy/CO_2 determined in here is not the total energy/CO_2 for RAP. The energy/CO_2 for those activities which do not make difference between RAP and aggregates, such as crushing and stockpiling, are not included. Tables 3-6, 3-7, and 3-8 show the differences in energy between the use of one ton of RAP and virgin aggregates. A positive value indicates that energy is saved by using RAP in HMA. Figures 3-7, 3-8, and 3-9 illustrate the impacts on energy. It can be seen that using RAP in HMA saves energy at any RAP and moisture content. However, this saving is primarily from the calorific energy of asphalt binder in RAP.

Table 3-6 Difference in Energy (BTUs) Consumption between RAP and Virgin Aggregates for Discharge Temperature of 280°F, per Ton of HMA

Moisture Content, %	RAP Content, %				
	10	20	30	40	50
1	162431	343315	524621	707878	894613
2	162991	344876	526771	710581	898211
3	163551	346438	528921	713284	901810
4	164110	347999	531070	715987	905408
5	164670	349560	533220	718690	909007

Note: positive value indicates that aggregates consume more energy.

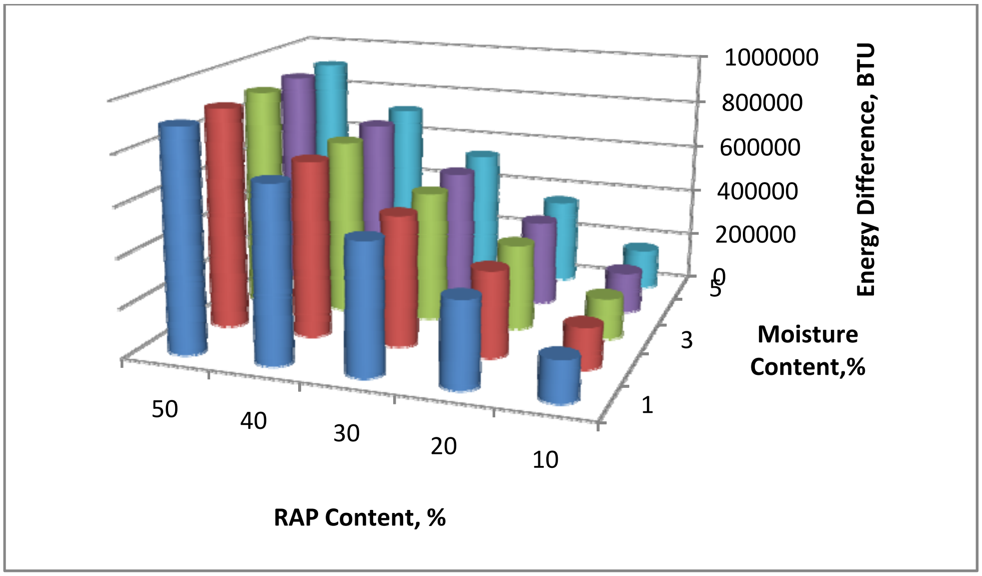

Figure 3-7. Difference in Energy Consumption between RAP and Virgin Aggregates at Discharge Temperature of 280°F, Per Ton of HMA

Note: positive value indicates that aggregates consume more energy.

Table 3-7 Difference in Energy Consumption (BTUs) between RAP and Virgin Aggregates for Discharge Temperature of 300°F, Per Ton of HMA

Moisture Content, %	RAP Content, %				
	10	20	30	40	50
1	154684	336728	518987	703167	890977
2	155266	338335	521205	705962	894690
3	155849	339942	523424	708756	898403
4	156431	341549	525642	711550	902116
5	157014	343156	527860	714345	905829

Note: positive value indicates that aggregates consume more energy.

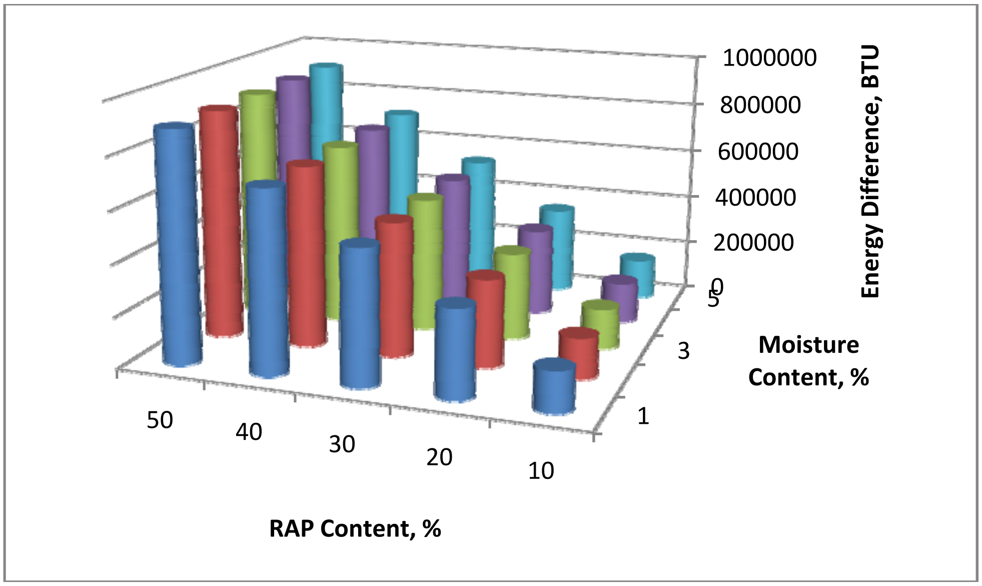

Figure 3-8. Difference in Energy Consumption Between RAP and Virgin Aggregates at Discharge Temperature of 300°F, Per Ton of HMA

Table 3-8 Difference in Energy Consumption (BTUs) between RAP and Virgin Aggregates for Discharge Temperature of 320°F, Per Ton of HMA

Moisture Content, %	RAP Content, %				
	10	20	30	40	50
1	146936	330142	513353	698457	887342
2	147541	331794	515639	701343	891169
3	148147	333447	517926	704228	894996
4	148752	335099	520213	707114	898823
5	149358	336752	522500	710000	902650

Note: positive value indicates that aggregates consume more energy.

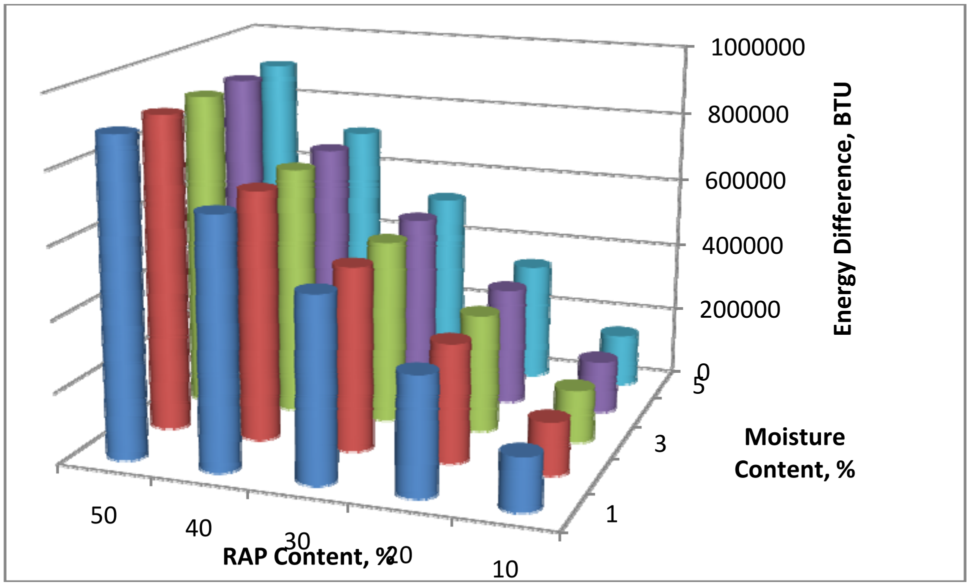

Figure 3-9. Difference in Energy Consumption between RAP and Virgin Aggregates at 320°F, Per Ton of HMA

(f) Impacts on Greenhouse Gas Emission

The impacts of using RAP in HMA on CO_2 emission is backcalculated from the energy analysis. The energy is provided by burning fuel or natural gas, except for the calorific energy in asphalt binder. Therefore, the difference in energy between RAP and virgin aggregates was used to determine the quantity of fuels used to provde these energies, excluding calorific energy. An average of 140,000 BTU/Gallon is used for fuel in this analysis [Hunt 2008]. Burning each gallon of fuel releases about 22.3 lbs of CO_2 [EPA 2005]. The results of CO_2 emission between one ton of RAP and aggregates are shown in Tables 3-9, 3-10, and 3-11 and illustrated in Figures 3-10, 3-11, and 3-12 for discharge temperatures of 280, 300, 320°F, respectively. Note that a positive number indicates using RAP in HMA reduces CO_2 emission. It can be seen that at low RAP content, using RAP increases CO_2 emission while the opposite is true for high RAP content. The reduction of CO_2 emission from using RAP is primarily from the shorter hauling distance for RAP materials.

Table 3-9 Difference in CO2 Emission (lbs) Between RAP and Virgin Aggregate at Discharge Temperature of 280°F, Per Ton of HMA

Moisture Content, %	RAP Content, %				
	10	20	30	40	50
1	-0.7	1.5	3.8	6.4	9.5
2	-0.6	1.7	4.1	6.8	10.1
3	-0.5	2.0	4.5	7.2	10.7
4	-0.5	2.2	4.8	7.7	11.3
5	-0.4	2.5	5.2	8.1	11.8

Note: positive value indicates that using RAP reduces CO2 emission.

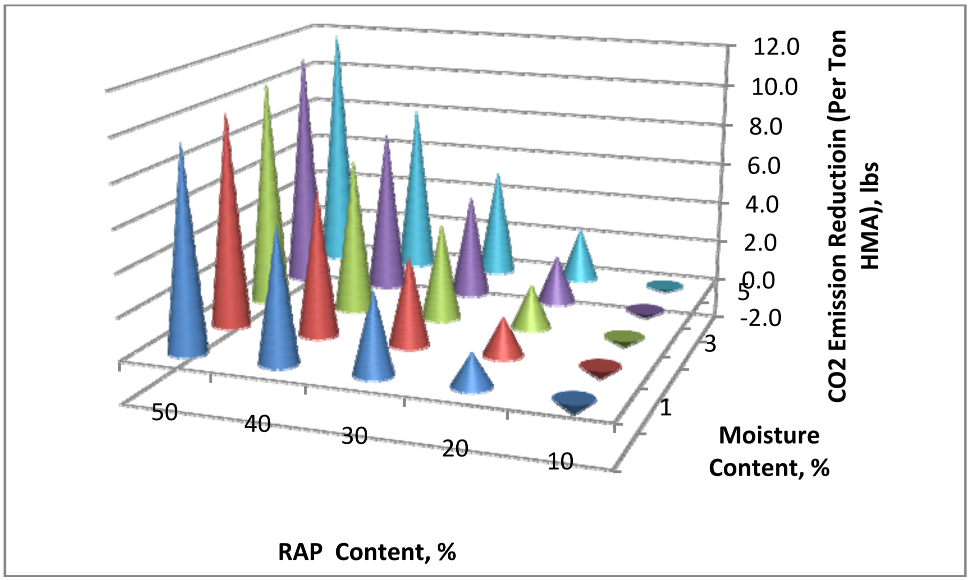

Figure 3-10. Difference in CO2 Emission between RAP and Virgin Aggregate at Discharge Temperature of 280°F, Per Ton of HMA

Note: positive value indicates that using RAP reduces CO2 emission.

Table 3-10 Difference in CO2 Emission (lbs) Between RAP and Virgin Aggregate at Discharge Temperature of 300°F, Per Ton of HMA

Moisture Content, %	RAP Content, %				
	10	20	30	40	50
1	-2.0	0.5	2.9	5.6	9.0
2	-1.9	0.7	3.2	6.1	9.5
3	-1.8	1.0	3.6	6.5	10.1
4	-1.7	1.2	3.9	7.0	10.7
5	-1.6	1.5	4.3	7.4	11.3

Note: positive value indicates that using RAP reduces CO2 emission.

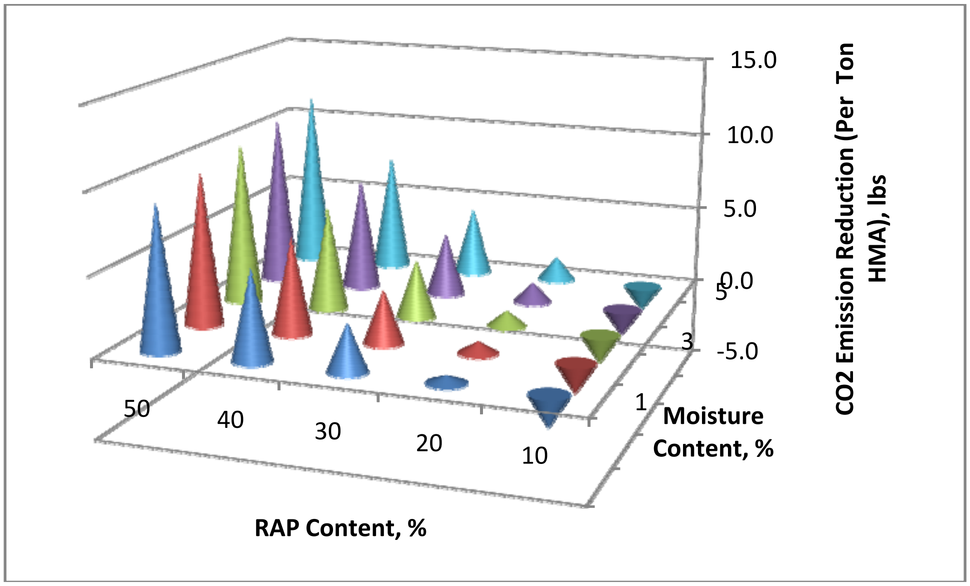

Figure 3-11. Difference in CO2 Emission between RAP and Virgin Aggregate at Discharge Temperature of 300°F, Per Ton of HMA

Note: positive value indicates that using RAP reduces CO2 emission.

Table 3-11 Difference in CO2 Emission (lbs) Between RAP and Virgin Aggregate at D ischarge Temperature of 320°F, Per Ton of HMA

Moisture	RAP Content, %

Content, %	10	20	30	40	50
1	-3.2	-0.6	2.0	4.9	8.4
2	-3.1	-0.3	2.4	5.3	9.0
3	-3.0	-0.1	2.7	5.8	9.6
4	-2.9	0.2	3.1	6.3	10.2
5	-2.8	0.5	3.4	6.7	10.8

Note: positive value indicates that using RAP reduces CO2 emission.

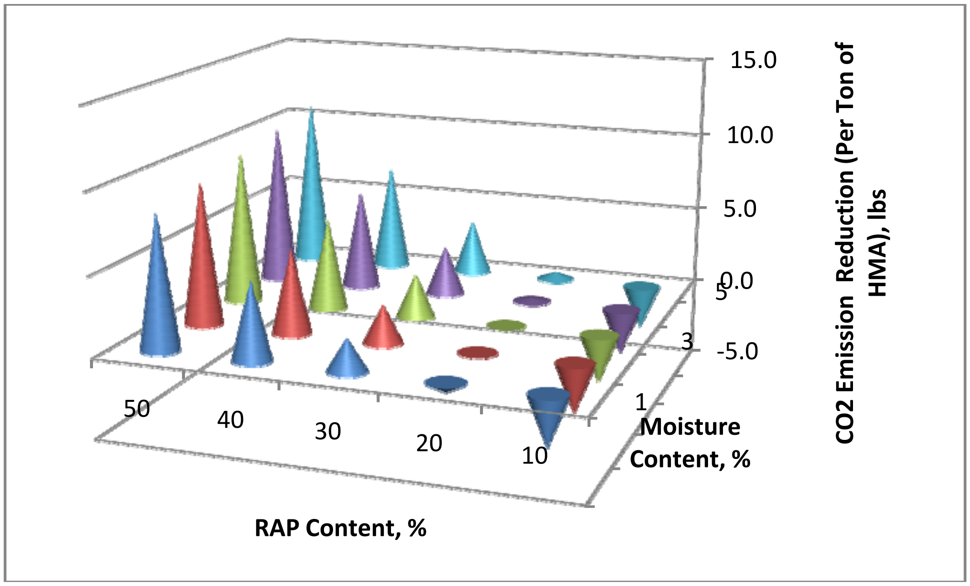

Figure 3-12. Difference in CO2 Emission between RAP and Virgin Aggregate at Discharge Temperature of 320°F, Per Ton of HMA

Note: positive value indicates that using RAP reduces CO2 emission.

Recycled Concrete Aggregate

During the past quarter, the team worked on quantifying the impact of using recycled concrete in concrete on energy and greenhouse gas emission. Approximately 200 million tons of waste concrete are produced each year through C&D projects. Currently, an estimated 50 to 60 percent of waste concrete is recycled, while the remainder is landfilled [EPA 2003]. When structures are demolished, the waste concrete can be crushed and reused in place of virgin aggregate. For recycled concrete aggregates to be used in concrete, the process includes breaking out old concrete, trucking broken concrete to recycling site (or moving crusher to the site), crushing, and trucking crushed concrete to concrete plant. For concrete production with virgin aggregates, the process includes quarrying, crushing, and trucking to concrete plant.

(a) Energy Analysis

Copple (1981) compared the energy for production of recycled aggregate and virgin aggregate for concrete. Energy requirements which are common to both types of concrete as well as energy requirements unique to each type of concrete were considered. Energy requirements which are unique to conventional mixes include production of virgin aggregates, and hauling of virgin aggregates. Energy requirements unique to recycled aggregate concrete include trucking broken concrete to recycling plant (or moving crusher to the job site), crushing and screening of concrete, and transporting old concrete to crusher and from crusher to plant if machines are at different sites. Results indicate that energy savings are realized for recycled aggregate concretes even when virgin aggregates must be hauled only a few miles. The energy savings increase with the increase of hauling distances, as shown in Figure 3-13. It is noted that the disposal of old concrete, if not used, also consumes energy. Copple (1981) used the following assumptions (1) a haul distance of 3 miles from old concrete site to crusher, (2) crusher and concrete plant are at the same site, and (3) a distance of 10 miles to disposal site. The energy for breaking old concrete was not included. In addition, a detailed analysis of energy consumption is needed.

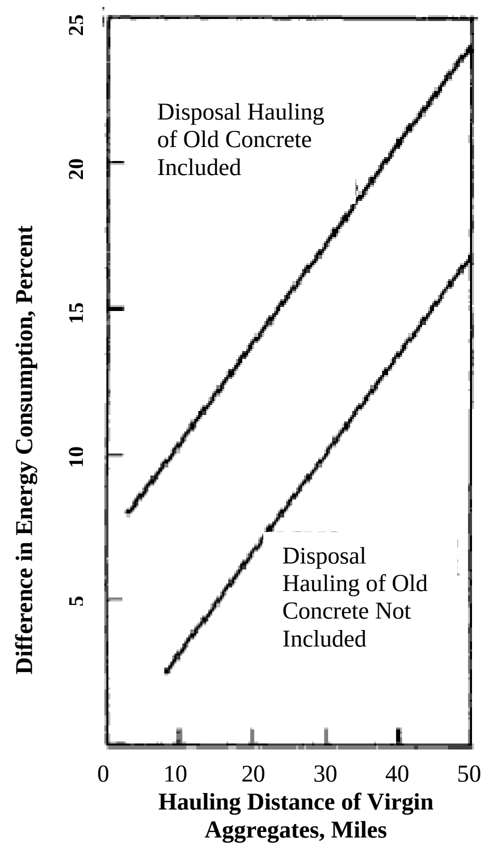

Figure 3-13. Difference in Energy Consumption between Recycled Concrete Aggregates and Virgin Aggregates (after Copple)

The energy consumption was compared between the use of virgin aggregates and recycled concrete aggregates for concrete production. For recycled concrete aggregates, the energy for removing old concrete pavement was based on the following assumptions:

- Production rate: 2,500 S.Y for eight hours for a nine-inch pavement [WisDOT];
- Energy consumption by the machine: 9 gallons diesel per hour [Horvath, 2003];
- Fuel energy for the machine: 14,000 Btu per gallon diesel [Hunt 2008].

It was found that the energy for removing the old concrete was 8.5 MJ per ton. Other energy consumption for processing and transporting the recycled concrete aggregate and virgin aggregate (sand and uncrushed gravel for concrete production) are shown in Table 3-12.

Table 3-12 Analysis of Energy Recycled Concrete and Virgin Aggregates

RECYCLED CONCRETE		VIRGIN AGGREGATES	
Process	**Energy Consumption, MJ per ton**	**Process**	**Energy Consumption, MJ per ton**
Remove old concrete	8.5	***Quarry and screen***	15.8 [Halstead 1981]
Transport to recycling plant, distance d1	3.43 per mile [Miller 2008]	***Transport from quarry to concrete plant, distance d3***	3.43 per mile [Miller 2008]
Crush and sort	10.8[Hamlyn]		
Transport to concrete Plant, distance d2	3.43 per mile [Miller 2008]		
Subtotal	=19.3+3.43×(d1+d2)	**Subtotal**	=15.8+3.43×d3
Transport broken concrete, if not used, to landfill, distance d4: 3.43 × d4			

The difference in energy consumption between disposal of old concrete and beneficial utilization as recycled concrete aggregate, is 3.43×([d3+d4–(d1+d2)]-3.5 for each ton. A positive value indicates energy saving. It can be seen that the energy savings depend on the transportation distance. If the summation of the distance from quarry site to concrete plant and distance from old concrete site to disposal site is larger than the summation of distance from old concrete site to crushing plant and distance from crushing plant to concrete plant, then the energy saving is possible. Tables 3-13 through 3-17 show the impact of using recycled concrete aggregate on energy for different d1 and d2, as illustrated in Figures 3-14 through 3-18.

Table 3-13 Energy Saving, MJ (d1=5; d2=5)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	13.65	47.95	82.25	116.55
	10	30.8	65.1	99.4	133.7
	15	47.95	82.25	116.55	150.85
	20	65.1	99.4	133.7	168
	25	82.25	116.55	150.85	185.15
	30	99.4	133.7	168	202.3

Note: positive values indicate energy saving;

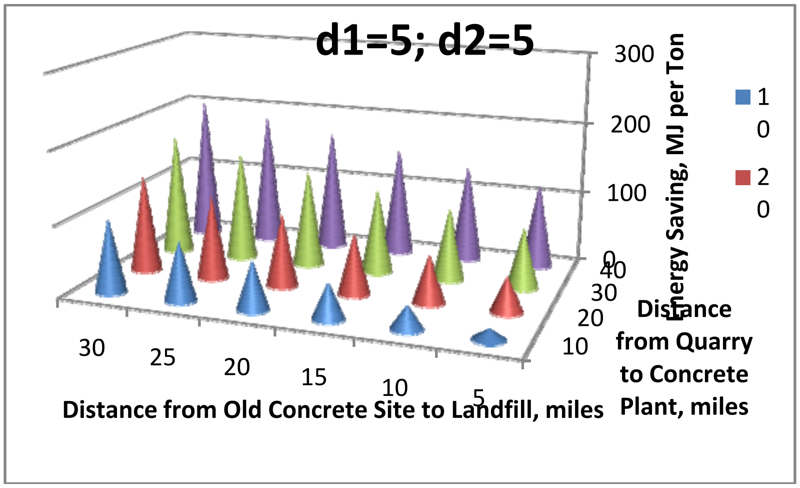

Figure 3-14. Energy Analysis for d1=5; d2=5

Table 3-14 Energy Saving, MJ, (d1=5; d2=10)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	-3.5	30.8	65.1	99.4
	10	13.65	47.95	82.25	116.55
	15	30.8	65.1	99.4	133.7
	20	47.95	82.25	116.55	150.85
	25	65.1	99.4	133.7	168
	30	82.25	116.55	150.85	185.15

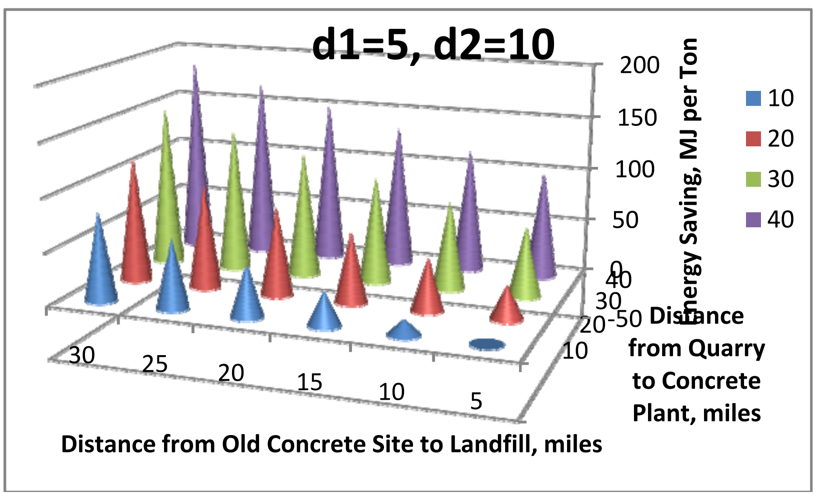

Figure 3-15. Energy Analysis for d1=5; d2=10

Table 3-15 Energy Saving, MJ, (d1=10, d2=10)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	- 20.65	13.65	47.95	82.25
	10	-3.5	30.8	65.1	99.4
	15	13.65	47.95	82.25	116.55
	20	30.8	65.1	99.4	133.7
	25	47.95	82.25	116.55	150.85
	30	65.1	99.4	133.7	168

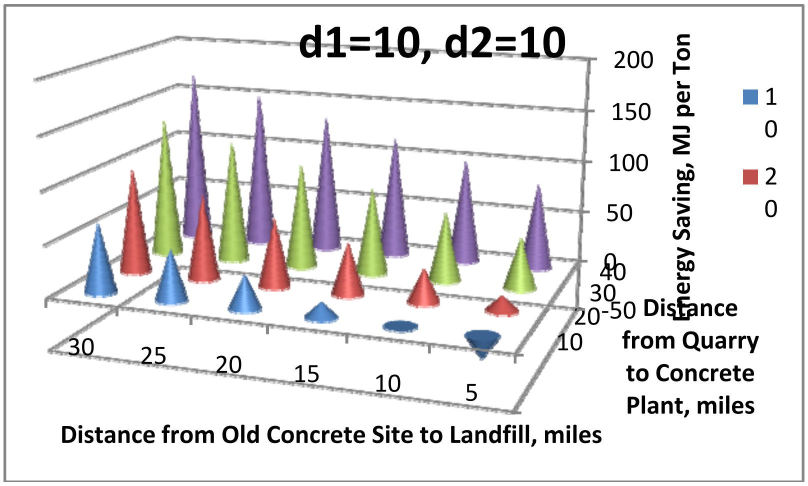

Figure 3-16. Energy Analysis for d1=10; d2=10

Table 3-16 Energy Saving, MJ, (d1=10, d2=15)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	-37.8	-3.5	30.8	65.1
	10	-20.6	13.65	47.95	82.25
	15	-3.5	30.8	65.1	99.4
	20	13.65	47.95	82.25	116.55
	25	30.8	65.1	99.4	133.7
	30	47.95	82.25	116.55	150.85

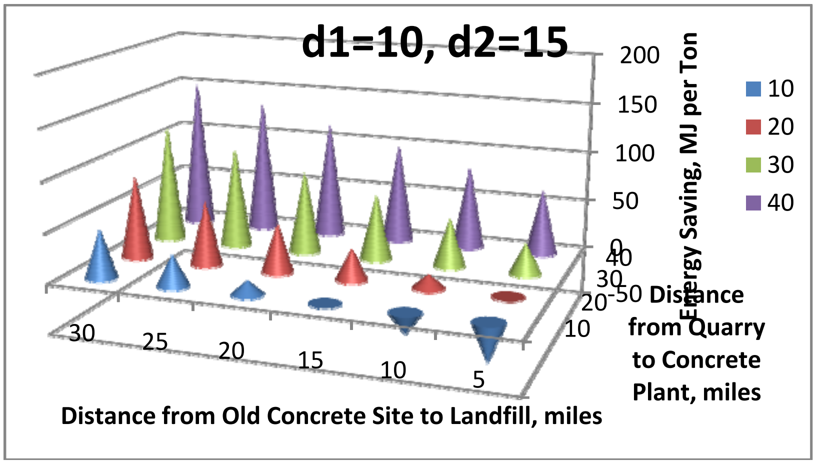

Figure 3-17. Energy Analysis for d1=10; d2=15

Table 3-17 Energy Saving, MJ, (d1=15, d2=15)

		From Quarry to Concrete Plant, Miles, d3			
		10	20	30	40
From Removal Site to landfill, Miles, d4	5	-54.9	-20.65	13.65	47.95
	10	-37.8	-3.5	30.8	65.1
	15	-20.6	13.65	47.95	82.25
	20	-3.5	30.8	65.1	99.4
	25	13.65	47.95	82.25	116.55
	30	30.8	65.1	99.4	133.7

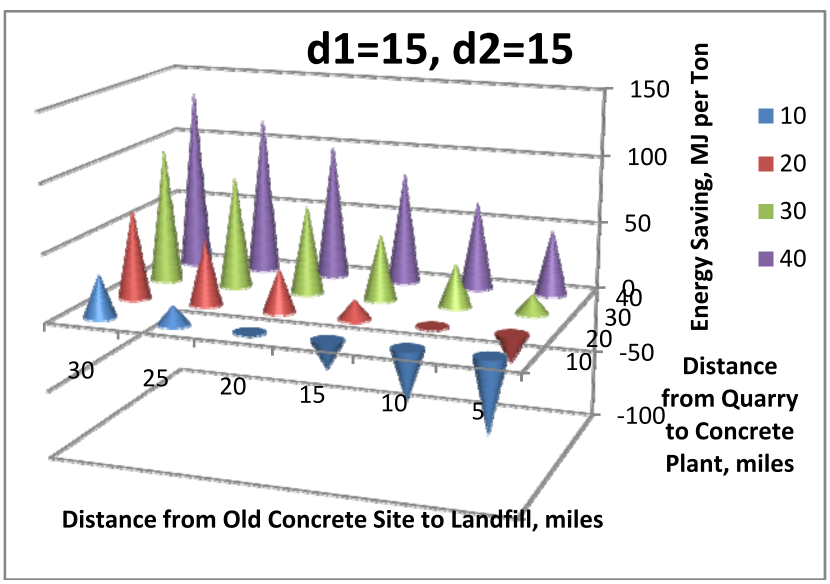

Figure 3-18. Energy Analysis for d1=15; d2=15

(b) Greenhouse Gas (GHG) Emission

The GHG benefits of recycling are calculated by comparing the difference in emissions associated with producing and transporting a ton of virgin aggregate versus producing and transporting a comparable amount of recycled inputs (i.e., crushed concrete). The GHG emissions associated with these steps result from the consumption of fossil fuels used in the production and transport of aggregate (combustion energy), as well as the upstream energy (pre-combustion energy) required to obtain these fuels. The calculation of avoided GHG emissions for concrete aggregate was broken up into two components: process energy and transportation energy emissions. According to EPA, a gallon of gasoline is assumed to produce 22.2 pounds of CO_2 [EPA 2005]. It is noted that the absorption of CO_2 by the recycled concrete is not considered. Tables 3-18 through 3-22 show the impacts of using recycled concrete aggregate on greenhouse gas emission for different d1 and d2, as illustrated in Figure 3-19 through 3-23.

Table 3-18 Greenhouse Gas Emission Reduction, lbs, (d1=5; d2=5)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	2.05	7.20	12.35	17.50
	10	4.63	9.78	14.93	20.08
	15	7.20	12.35	17.50	22.65
	20	9.78	14.93	20.08	25.23
	25	12.35	17.50	22.65	27.80
	30	14.93	20.08	25.23	30.38

Note: positive indicate CO2 reduction;

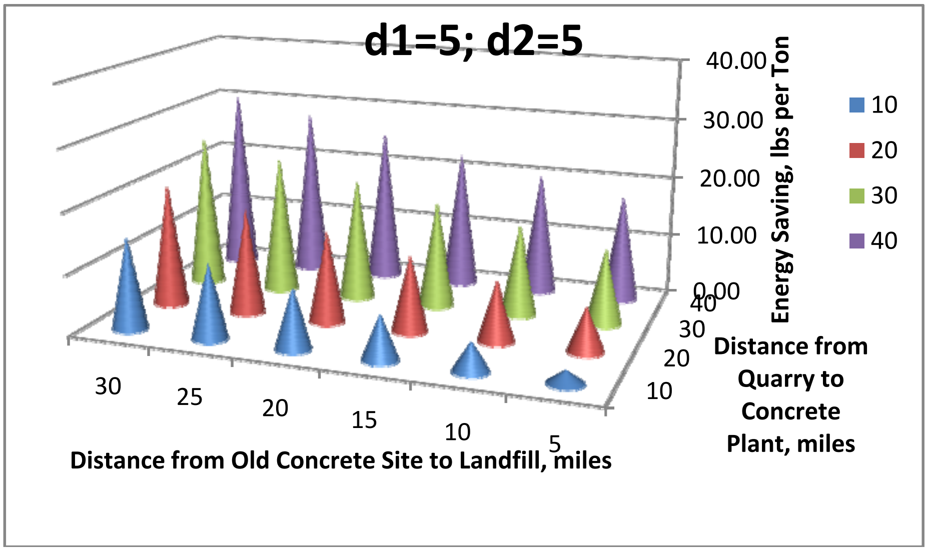

Figure 3-19. Greenhouse Gas Emission Analysis for d1=5; d2=5

Table 3-19 Greenhouse Gas Emission Reduction, lbs, (d1=5; d2=10)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	-0.53	4.63	9.78	14.93
	10	2.05	7.20	12.35	17.50
	15	4.63	9.78	14.93	20.08
	20	7.20	12.35	17.50	22.65
	25	9.78	14.93	20.08	25.23
	30	12.35	17.50	22.65	27.80

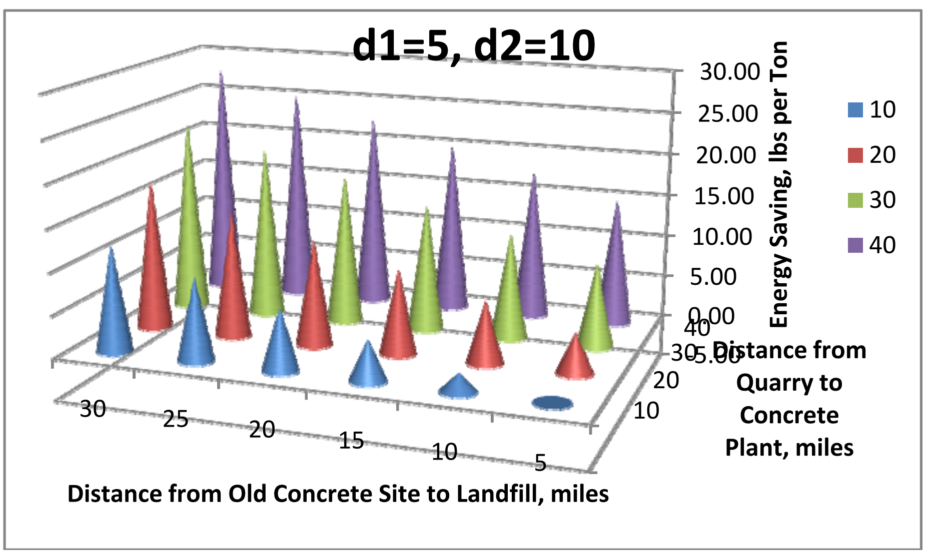

Figure 3-20. Greenhouse Gas Emission Analysis for d1=5; d2=10

Table 3-20 Greenhouse Gas Emission Reduction, lbs, (d1=10; d2=10)

		From Quarry to Concrete Plant, Miles, d3			
		10	20	30	40
From Removal Site to landfill, Miles, d4	5	-3.10	2.05	7.20	12.35
	10	-0.53	4.63	9.78	14.93
	15	2.05	7.20	12.35	17.50
	20	4.63	9.78	14.93	20.08
	25	7.20	12.35	17.50	22.65
	30	9.78	14.93	20.08	25.23

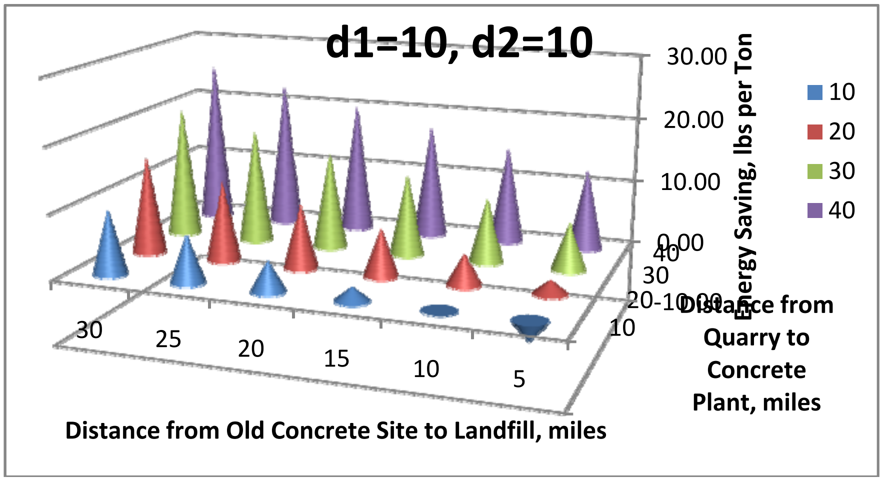

Figure 3-21. Greenhouse Gas Emission Analysis for d1=10; d2=10

Table 3-21 Greenhouse Gas Emission Reduction, lbs, (d1=10; d2=15)

		From Quarry to Concrete Plant, Miles, d3			
		10	20	30	40
From Removal Site to landfill, Miles, d4	5	-5.68	-0.53	4.63	9.78
	10	-3.10	2.05	7.20	12.35
	15	-0.53	4.63	9.78	14.93
	20	2.05	7.20	12.35	17.50
	25	4.63	9.78	14.93	20.08
	30	7.20	12.35	17.50	22.65

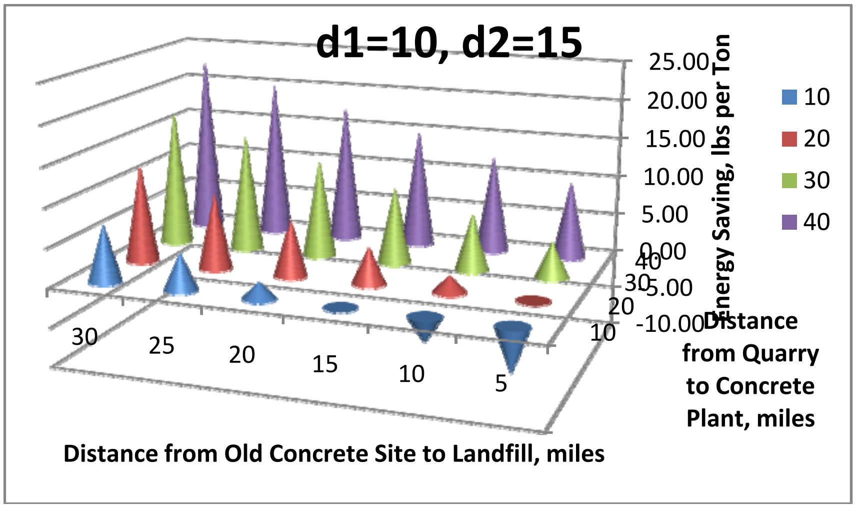

Figure 3-22. Greenhouse Gas Emission Analysis for d1=10; d2=15

Table 3-22 Greenhouse Gas Emission Reduction, lbs, (d1=15; d2=15)

		From Quarry to Concrete Plant, Miles, d3			
		10	**20**	**30**	**40**
From Removal Site to landfill, Miles, d4	**5**	-8.25	-3.10	2.05	7.20
	10	-5.68	-0.53	4.63	9.78
	15	-3.10	2.05	7.20	12.35
	20	-0.53	4.63	9.78	14.93
	25	2.05	7.20	12.35	17.50
	30	4.63	9.78	14.93	20.08

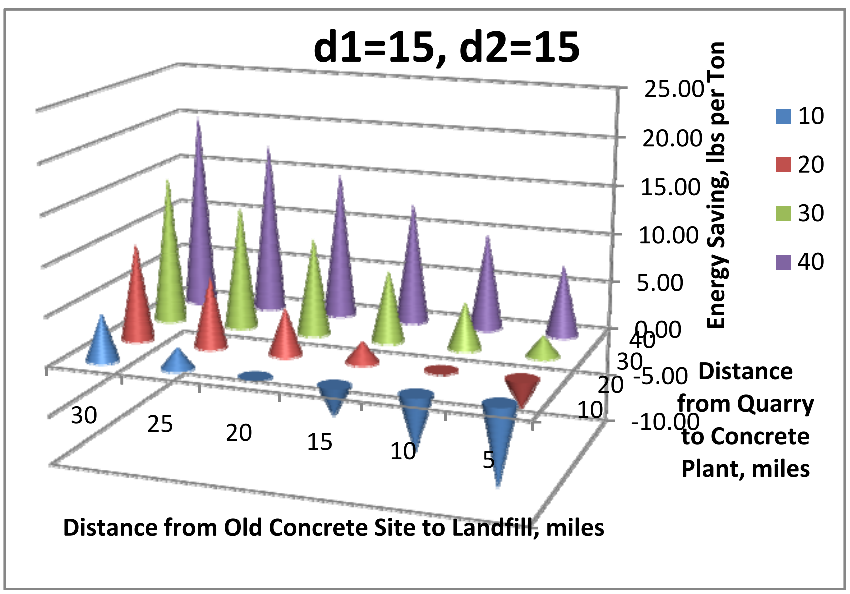

Figure 3-23. Greenhouse Gas Emission Analysis for d1=15; d2=15

4 FINDINGS AND RECOMMENDATIONS

Findings

The following findings can be made for the Phase I study:

(1) When recycled asphalt pavement (RAP) is used in hot mix asphalt (HMA), the impacts on energy consumption and greenhouse gas emission are affected by RAP content, moisture in RAP, and HMA discharge temperature.

(2) It can be seen that using RAP in HMA saves energy at any RAP and moisture content. However, this saving is primarily from the calorific energy of asphalt binder in RAP.

(3) At low RAP content, using RAP in HMA increases CO2 emission while the opposite is true for high RAP content. However, the reduction of CO_2 emission from using RAP is primarily from the shorter hauling distance for RAP materials.

(4) When the recycled concrete aggregate (RCA) is used for concrete production, the impacts on energy consumption and greenhouse gas emission largely depend on transporting distances.

(5) If the summation of the distance from quarry site to concrete plant and distance from old concrete site to disposal site is larger than the summation of distance from old concrete site to crushing plant and distance from crushing plant to concrete plant, the energy saving can be realized.

Recommendations

In this study, the quantification of impacts on energy consumption and greenhouse gas emission is based on initial material production. It is noted that the inclusion of recycled materials also affects the engineering performance of HMA or concrete and therefore, the service lives of infrastructure. The life cycle analysis of energy consumption and greenhouse gas emission will be different from the findings in this study. It is strongly recommended that life cycle analysis be conducted for recycled pavement materials.

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