ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS OF HIGH RAP CENTRAL PLANT HOT RECYCLING TECHNOLOGY USING LIFE CYCLE ASSESSMENT：CASE STUDY

Yong Lu[1,2*], Hao Wu[1,2], Aihua Liu[1,2], Wuyang Ding[1,2] and Haoran Zhu[1,2]

1 JSTI Group Co., Ltd, 2 National Engineering Laboratory for Advanced Road Materials

No.2200, Chengxin Road, Jiangning Science Park, Nanjing, China

Tel: 86-025-86576835

**Corresponding author: ly1365@jsti.com*

ABSTRACT: Traditional LCA of central plant hot recycling shows that, the higher RAP added, the less energy consumed. This conclusion is mainly based on the calculation of reduced raw material. However, when the content of Reclaimed asphalt pavement mixture (RAP) reaches some level, it is needed to take measures such as using additive or improved construction method for maintain the performance of asphalt pavement. For the situation of high RAP central plant hot recycling technology has become more and more widely used, in order to evaluate its effect of energy saving and emission reduction, this paper investigate and compare the life cycle energy consumption and greenhouse gas emissions with the method of LCA, with considering the matters of RAP addition, asphalt-recycling agent, warm agent and transport distance. The study results indicate that, it is not appropriate say that the higher RAP added, the less energy used. Raw material transportation distance is the key factor of energy consumption and greenhouse gas emissions, while asphalt-recycling agent is the least factor. Besides, with theoretical calculation of different warm mix method, the result show that mechanical foaming is more energy saving than the organic additive warm agent, while being used in high RAP central plant hot recycling.
Keywords: High RAP central plant hot recycling; LCA; Warm agent; Transport distance

1 INTRODUCTION

Against the background of accelerating global warming due to the effect of greenhouse gases, efforts to reduce greenhouse gas emissions are being made worldwide. Among public works, road construction, which involves numerous processes, leads to greenhouse gas emission. Construction industry, in particular, is one of the high energy consumption industries in which the problem of a lack of efficient energy conservation in construction projects has been identified. Owing to the increase in project scales in recent times, the construction stage of public works requires mechanized construction and involves a significant amount of energy consumption and emission of environmental pollutants. Efficient use of fuel and material resources, reduction in greenhouse gas emissions and control of environmental impacts have become important to the construction industry, including pavement engineering. Life cycle assessment（LCA） is one important way of estimating the scale and environmental impacts of resource use and emissions to the environment (1,2). In several productive fields, recycling techniques represent one of the most promising strategies to achieve economic and environmental sustainability goals. Also in the pavement industry, recycling has gained increasing importance for the production of new asphalt mixtures.

The results of this life cycle assessment (LCA) contribute information on the relative environmental impacts of reclaimed asphalt pavement methods and choice to regulatory and market decision makers in China.

In fact, it allows the optimization of the materials in terms of costs and natural resources saving

(3, de la Roche et al. 2013). Many laboratory studies concerning the evaluation of performance of recycled mixtures with high RAP content have been carried out (4 Aurangzeb et al. 2012; 5, Frigio et al. 2014; 6, Stimilli et al. 2013). However, it is widely recognized that mixtures prepared in reclaimed asphalt pavement could perform excellent natural resources saving and is good to achieve economic and environmental sustainability goals when large amounts of RAP are incorporated in the new mixture. In fact, in the case of high content RAP mixtures the production process requires particular sequences to improve the performance of mixtures. The warm mix agent or warm mix method has to be used at the stage of the production process to avoid the excessive smoke during large amount RAP healing process, in addition of being benefit for the main properties of a flexible pavement (compact ability, stiffness, cracking aptitude and fatigue) (7). Moreover, recycling agent is utilized in reclaimed asphalt mixtures to improve such properties. Meanwhile, different transportation distance has influence on energy consumption and greenhouse gas emission. In this sense, many aspects related to the reclaimed asphalt pavement with large amount of RAP, can alter the energy consumption and greenhouse gas emission. So that combination of different factors with reclaimed asphalt pavement is necessary to assess by LCA methods for widely demonstrate the actual use of recycling technology with large amount of RAP in the new mixtures.

In this paper, the research focuses on life cycle assessment on recycling technology. Due to LCA concept, milling, production and transportation of materials, mixing and paving, etc. such production process are divided to calculate energy consumption and greenhouse gas emission in every stage. As well as, many factors including different content of RAP such as 10 wt. %, 30 wt. %, 50 wt. % in whole mixture (10 wt. % is defined as that the asphalt mixture has 10% content RAP at weight in the whole mixture), milling and repaving, in particular, based on 50 wt. %RAP, three warm mix methods and three content of recycling agent are considered to compare the energy consumption and greenhouse gas emission with combination of different factors.

2 METHODOLOGY

2.1 *Indicators*

In order to evaluate the environmental benefits of high RAP central plant hot recycling, depletion of minerals (resource saving and recycling), depletion of fossil fuels (energy consumption), global warming potential (GHG emission) were selected as indicators to evaluate the environmental benefits of asphalt pavement construction and maintenance. The energy consumption data during the construction were directly investigated, and were converted to the unified energy unit according to the conversion coefficient of average low calorific value. The GHG emission including carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) was calculated through the energy consumed. They were converted to equivalent CO2 emission using global warming potential (GWP); the conversion coefficients of CH4 and N2O were 25 and 298 at a time horizon of 100 years, respectively (8). Other impact category indicators, for example, acidification, photo oxidant formation and so on, were not considered at this initial stage, because sufficient inventory data is still unavailable in China till now. Only the energy consumption and GHG emission are insufficient to indicate the advantage of materials recycling and the value of natural resources. The materials recycled were calculated for evaluation of the technology.

2.2 *Functional Unit*

For comparison of different asphalt mixtures, the energy consumption and GHG emission of per ton mixture is adopted as the functional unit. For comparison of different pavement maintenance techniques, per unit area pavement is used.

2.3 *System Boundary*

As the case study mainly focuses on the influence with RAP content, Recycling Agent content, warm mix technology and transportation distance to energy consumption and CO2 emission, meanwhile there is not adequate data and calculation models for service life of pavement at present, only the processes directly related to pavement construction are analyzed in this paper, including the production and transportation of asphalt, aggregate and other raw materials, mixing and paving. While the indirectly related processes as infrastructure construction, production of machines and service life of pavement are excluded. Meanwhile, some raw materials with small addition which have little influence on the final results are negligible. According to the cut-off rule suggested by ISO 14040, the constituent parts with a proportion to the total results less than 1% by mass will be ignored, but the total proportion ignored should not exceed 5%. Figure 1 shows the system boundary analyzed in this research.

3 LIFE CYCLE IMPACT ASSESSMENT RESULTS

3.1 *Production of raw materials*

The raw materials of asphalt pavement include aggregate, asphalt, recycle agent and warm mix agent. Recycle agent has the same ingredient with asphalt, so the energy consumption and GHG emission is regarded as the same as asphalt. The energy consumption and GHG emission of aggregate refers to Chinese Life Cycle Database (CLCD) (9). Global warming potential (GWP) was characterized using factors reported by the Intergovernmental Panel on Climate Change in 2007(10-12). The database of European Bitumen Association provides the basic LCI data for virgin asphalt (8). Table 1 shows energy consumption and GHG emission of some raw materials.

Table 1 Energy Consumption and GHG Emission of Some Raw Materials

Raw materials		Energy consumption	GHG Emission
		MJ/t	kg/t
RAP		3.08E+1	2.09E+0
Virgin asphalt		2830	1.89E+02
Warm mix agent	Organic additives	54.63	5.02 E+0
	Mechanical foaming	/	/
Recycle agent		/	/
Aggregates		31.82	2.40E+00

Referring to CLCD, the type of equipment is selected as the standard transportation mode. The energy consumption and GHG emission are shown in Table 2.

Table 2 Energy Consumption and GHG Emission of equipment during production process of mixture

Production process	Types	Energy consumption	GHG emission
		MJ/t	kg/t
Mixing	Xi`an Construction Machine J3000	2.56E+2	1.98E+1
Transportation	30t	5.438E-1	4.030E-2
Paving	Vogele1800	1.651E+1	1.223E+0
Compaction	Steel roller	3.785E+0	2.805E-1
	Tire roller	5.441E+0	4.033E-1
Others	/	8.445E+0	6.259E-1

“Others” means energy consumption and GHG emission of loader and screening machine, because of low values, in this paper, their values are the average by survey data.

kg/t is the unit of GHG emission which means during the production process 1 ton asphalt mixture would produce mass of GHG emission in weight.

3.2 *Mixture Production*

Typical pavement asphalt mixtures were chosen for analysis, such as Sup-20(dense-graded HMA using Superpave method) with base asphalt by asphalt-aggregate ratio of 4.8% (asphalt content of 4.58%). Compared with new asphalt pavement, the construction process adds the milling process. In the mixing process, the reclaimed asphalt pavement (RAP) is mixed with new asphalt and aggregate. The production of raw materials includes the mill and transport of RAP to the plant. The heating temperature of new aggregate is increased for heating RAP to the mixing temperature. Therefore, the fuel consumption of the plant is about 1kg t-1 higher than the typical new HMA based on collected data. The hot in-plant recycling mixture is typically used for the 8cm thick bottom course in China, and the asphalt-aggregate ratios of both RAP and virgin asphalt mixtures are designed as 4.8%.

The paper focused on hot in-plant recycling mixture with different amount of RAP, such as the weight of 10%, 30% and 50%. Besides, warm technology as organic additives and machine foaming, different content of recycle agent and milling and repaving and so on, different factors among hot in-plant recycling technology are considered to comparing the energy consumption and GHG emission.

The production of asphalt mixture usually uses batch asphalt mixing plant in China. Nearly twenty experienced asphalt pavement construction companies were investigated for the accurate and reliable energy data. Average energy consumption is taken as a representative value in this research.

Currently, installation of auxiliary building asphalt mixture recycling equipment is mainly technology. Under this background, the energy consumption and GHG emission is assessment. Due to survey, the average fuel oil amount is approximately 6.0kg/t, within the moisture content of RAP is 3-5%, heating to the temperature 900C to 1100C. During the hot in-plant recycling production, the heating temperature of new aggregate is higher than conventional asphalt mixture, so the energy consumption is higher than conventional batching plant with about 1kg/t.

3.3 *Paving and Compaction*

The speed of asphalt paver should be adapted to the production of mixing plant, thickness and width of pavement. The paving speed of reclaimed asphalt mixture is usually lower than other asphalt mixture, and typical construction speeds of 2.5m ·min^{-1} and 3 m ·min^{-1} were selected for SUP pavements. The energy consumption of paving and compaction was calculated according to the power of machines and production efficiency. The average result is taken as the representative value.

3.4 *Summarization of Data*

To describe clearly the combination of different factors in hot in-plant recycling mixture with high content RAP. Table 3 listed every process in construction and the content of raw materials.

Table 3 Different factors combination for LCA assessment

Construction process		Milling and re-paving	RAP content(In weight)			RAP content, 50%, warm mix recycling	
			10%	30%	50%	Organic additive	Mechanical foaming
Temperature reduction		/	/	/	/	30^{0}℃ or 0	30^{0}℃ or 0
Raw materials production	Virgin asphalt	4.8%					
	aggregate	/	/	/	/	/	/
	Recycling agent	/	3%、5%、7%、9% weight in old asphalt			/	/
	Warm mix agent	/	/	/	/	3%weight in asphalt	Water is 1.5% weight in asphalt.
	RAP (80km)	/	10%	30%	50%	50%	50%
Raw materials transportation distance		50km, 100km, 150km, 200km, 250km					
Mixture mixing							

Mixture transportation	80km	
Pavement construction	Paving	
	Compacting	
	Others	

Based on the analysis and calculation results, the energy consumption and GHG emission of reclaimed asphalt pavement are shown in Table 4.

Table 4 Energy Consumption and GHG Emission of Different Maintenance Measures

Construction process			Energy and emission	Milling and re-paving	RAP content (In weight)			RAP content, 50%, warm mix recycling	
					10%	30%	50%	Organic additive	Mechan-ical foaming
Raw materials production	Virgin asphalt		Energy consumption(MJ t^{-1})	136.46	122.81	95.52	68.23	68.23	68.23
			GHG(kg t^{-1})	9.11	8.20	6.38	4.56	4.56	4.56
	aggregate		Energy consumption(MJ t^{-1})	30.29	27.26	21.20	15.14	15.14	15.14
			GHG(kg t^{-1})	2.28	2.06	1.60	1.14	1.14	1.14
	Recycle agent content	3%	Energy consumption(MJ t^{-1})	/	0.36	1.09	1.82	1.82	1.82
			GHG(kg t-1)	/	0.02	0.07	0.12	0.12	0.12
		5%	Energy consumption(MJ t-1)	/	0.61	1.82	3.03	3.03	3.03
			GHG(kg t^{-1})	/	0.04	0.12	0.20	0.20	0.20
		7%	Energy consumption(MJ t^{-1})	/	0.85	2.55	4.24	4.24	4.24
			GHG(kg t^{-1})	/	0.06	0.17	0.28	0.28	0.28
		9%	Energy consumption(MJ t^{-1})	/	1.09	3.27	5.45	5.45	5.45
			GHG(kg t^{-1})	/	0.07	0.22	0.36	0.36	0.36
	Warm mix agent		Energy consumption(MJ t^{-1})	/	/	/	/	39.51	/
			GHG(kg t^{-1})	/	/	/	/	3.63	/
	RAP (80km)		Energy consumption(MJ t^{-1})	/	11.73	35.18	58.63	58.63	58.63
			GHG(kg t^{-1})	/	0.80	2.39	3.98	3.98	3.98
Raw materials transportation distance	50		Energy consumption(MJ t^{-1})	27.19	24.47	19.03	13.61	13.63	13.61
			GHG(kg t^{-1})	2.02	1.81	1.41	1.01	1.01	1.01
	100		Energy consumption(MJ t^{-1})	54.38	48.94	38.07	27.22	27.26	27.22
			GHG(kg t^{-1})	4.03	3.63	2.82	2.02	2.02	2.02
	150		Energy consumption(MJ t^{-1})	81.57	73.81	58.28	42.75	42.75	42.75
			GHG(kg t^{-1})	6.05	5.47	4.32	3.17	3.18	3.17
	200		Energy consumption(MJ t^{-1})	108.76	97.88	76.13	54.45	54.53	54.45
			GHG(kg t^{-1})	8.06	7.25	5.65	4.04	4.04	4.04
	250		Energy consumption(MJ t^{-1})	135.95	122.36	95.17	68.06	68.16	68.06
			GHG(kg t^{-1})	10.08	9.07	7.06	5.04	5.04	5.04
Mixture mixing (no heating reduction with warm mix technology)			Energy consumption(MJ t^{-1})	256.00	256.00	256.00	256.00	256.00	256.00
			GHG(kg t^{-1})	19.80	19.80	19.80	19.80	19.80	19.80
Mixture mixing (heating reduction with warm mix technology)			Energy consumption(MJ t^{-1})	256.00	256.00	256.00	256.00	204.80	204.80
			GHG(kg t^{-1})	19.80	19.80	19.80	19.80	15.84	15.84
Mixture transportation distance(80km)			Energy consumption(MJ t^{-1})	43.50	43.50	43.50	43.50	43.50	43.50
			GHG(kg t^{-1})	3.22	3.22	3.22	3.22	3.22	3.22
Pavement construction	Paving		Energy consumption(MJ t^{-1})	16.51	16.51	16.51	16.51	16.51	1.22
			GHG(kg t^{-1})	1.22	1.22	1.22	1.22	1.22	1.22
	Compacting		Energy consumption(MJ t^{-1})	9.23	9.23	9.23	9.23	9.23	0.68
			GHG(kg t^{-1})	0.68	0.68	0.68	0.68	0.68	0.68
	Others		Energy consumption(MJ t^{-1})	8.45	8.45	8.45	8.45	8.45	0.63
			GHG(kg t^{-1})	0.63	0.63	0.63	0.63	0.63	0.63

The results show that, hot in-plant recycle technology with different factors has different energy consumption and GHG emission. In this paper, aimed at different factors, the LCA assessment method is used to analysis hot in-plant recycle with high RAP. The factors are followed.

- RAP content, different contents of RAP, such as 0%(in other words, milling and repaving), 30%, 40%, 50%， four kinds of RAP contents are considered for analysis.
- Recycle agents, when the RAP content is 50wt.%, different contents of recycle agents are utilized.
- Warm mix technology, to ensure the performance and compaction of hot in-plant recycling mixture with high RAP, warm mix technology is usually method. Meanwhile, there are many kinds of warm mix technology, and during construction course, it usually no heating reduction method to make for the compaction.
- Distance, when the transportation distance of raw materials is different, it is obvious that the energy consumption and GHG emission is variant.

4 DISCUSSION

4.1 *The effect of RAP content*

The main difference among milling and repaving, hot in-plant recycle mixture with 10%, 30%, 50% amount RAP in the whole mixture is the difference of the content of RAP. RAP is waste mixture recycling. When the other situations are the same, with the more RAP used, the energy consumption and GHG emission is less. Based on the date in section 3.2 and table 2, the energy consumption and GHG emission of every construction process and total production can be calculated. The result is shown in Figure 2.

Results show that, based on some assumptions, with the increasing of the RAP content, the energy consumption and GHG emission is reduction. Actually, when the RAP content is increased, to ensure the reclaimed asphalt pavement performance, many improvement actions are used inevitably. These actions such as warm mix technology and recycle agent would have some energy consumption and CO2 emission. Thus these factors will be considered in the paper.

4.2 *The effect of recycle agent*

Under the above date base, different content of recycle agent, such as 3%, 5%, 7%, 9% accounted of old asphalt mass are taken into consideration to be added in reclaimed asphalt mixture. Then, the energy consumption and CO2 emission are calculated and be shown in Table 6.

Table 6 Energy Consumption and GHG Emission of Different Content of recycle agent

Construction process		Energy and emission	Milling and repaving	10%	30%	50%
Raw materials(Including recycle agent)	3%	Energy consumption(MJ t^{-1})	166.74	162.16	152.99	143.82
		GHG(kg t^{-1})	11.40	11.08	10.44	9.80
	5%	Energy consumption(MJ t^{-1})	166.74	162.40	153.72	145.03
		GHG(kg t^{-1})	11.40	11.09	10.49	9.88
	7%	Energy consumption(MJ t^{-1})	166.74	162.64	154.44	146.24
		GHG(kg t^{-1})	11.40	11.11	10.54	9.96
	9%	Energy consumption(MJ t^{-1})	166.74	162.89	155.17	147.46
		GHG(kg t^{-1})	11.40	11.13	10.58	10.04
Raw materials transportation (150km)		Energy consumption(MJ t^{-1})	81.57	73.81	58.28	40.79
		GHG(kg t^{-1})	6.05	5.47	4.32	3.03
Mixture mixing		Energy consumption(MJ t^{-1})	256.00	256.00	256.00	256.00
		GHG(kg t^{-1})	19.80	19.80	19.80	19.80
Mixture transportation(80km)		Energy consumption(MJ t^{-1})	43.50	43.50	43.50	43.50
		GHG(kg t^{-1})	3.22	3.22	3.22	3.22
Construction	Paving	Energy consumption(MJ t^{-1})	16.51	16.51	16.51	16.51

		GHG(kg t^{-1})	1.22	1.22	1.22	1.22
	Compacting	Energy consumption(MJ t^{-1})	9.23	9.23	9.23	9.23
		GHG(kg t^{-1})	0.68	0.68	0.68	0.68
	Others	Energy consumption(MJ t^{-1})	8.45	8.45	8.45	8.45
		GHG(kg t^{-1})	0.63	0.63	0.63	0.63
Total	3%	Energy consumption(MJ t^{-1})	582.00	569.66	544.96	518.30
		GHG(kg t^{-1})	43.00	42.10	40.31	38.39
	5%	Energy consumption(MJ t^{-1})	582.00	569.50	544.50	519.50
		GHG(kg t^{-1})	43.00	42.09	40.28	38.47
	7%	Energy consumption(MJ t^{-1})	582.00	569.74	545.23	520.71
		GHG(kg t^{-1})	43.00	42.11	40.33	38.55
	9%	Energy consumption(MJ t^{-1})	582.00	569.98	545.95	521.93
		GHG(kg t^{-1})	43.00	42.12	40.38	38.63

Results showed that, the energy consumption and GHG emission of hot in-plant asphalt mixture with different content RAP is nearly the same while the amount of recycle agent is changed. Maybe it is because, the energy consumption and CO2 equivalent value has no primary date. Considering the chemistry composite is similar with asphalt, so the energy consumption and CO2 equivalent value of recycle agent is referred to asphalt. Besides the mass of recycle agent is a little account for asphalt, consequently, the mass of recycle agent could be ignored while compared with the mass of asphalt. That is to say, from the point of recycle agent, aimed to hot in-plant recycling technology with high RAP, the change of recycle agent has no harmful influence to energy consumption and GHG emission.

4.3 *The effect of warm mix technology*

Based on the section 3.2 assumptions, the energy consumption and GHG emission are calculated combined with two kinds of warm mix technology such as organic additives and mechanical foaming. So as to consider the actual construction operation, two kinds of situations including heating reduction (the temperature is reduced by 30 ^{0}C with 20% energy saving) and no heating reduction. The calculation result is shown in Figure 3.
Results showed that, the energy consumption and GHG emission is increased to ensure the construction workability of hot in-plant recycling with high RAP, that is to say, no heating reduction is considered while warm mix technology is used. Furthermore, warm mix technology with organic additive has more energy consumption and GHG emission. Yet the energy change of mechanical foaming is less which can be ignored. However, when heating reduction is considered, the warm mix technology with mechanical foaming can saving more energy consumption and GHG emission.

4.4 *The effect of Transportation distance*

So as to analysis in influence of transportation distance to energy consumption and GHG emission, five distances are taken into consideration including 50km, 100km, 150km, 200km and 250km under the situation of different RAP content and warm mix technology. The calculation result is shown in Figure 4 and Figure 5.
From table 8, Figure 4 and Figure 5, we can see that, the energy consumption and GHG emission has obviously change with the transportation for five kinds of asphalt mixture, including reclaimed asphalt with different content RAP, organic additive and mechanical foaming used in reclaimed asphalt with 50% RAP. Furthermore, the change trend is different with different transportation distance.
When the transportation distance is 50km, the reclaimed asphalt mixture with the amount of 50% RAP in the whole mixture that used organic additive has the most energy consumption and GHG emission. And with the increasing of transportation distance, the gap is gradually decreased. Above-mentioned asphalt mixture has less energy consumption and GHG emission than the reclaimed asphalt mixture with the amount of 10% RAP in the whole mixture at the distance of 150km. Even the same with reclaimed

asphalt mixture with the amount of 30% RAP in the whole mixture at the distance of 250km. that is to say, When the transportation distance is 150km, the reclaimed asphalt mixture with amount of 50% RAP in the whole mixture used organic additive has less energy consumption and GHG emission than reclaimed asphalt mixture with amount of 10% RAP in the whole mixture, but more energy consumption and GHG emission than reclaimed asphalt mixture with amount of 30% RAP in the whole mixture. And when the transportation distance is father, the reclaimed asphalt mixture with amount of 50% RAP in the whole mixture began to appear advantage of low RAP recycle asphalt mixture.

5 CONCLUSIONS

This research investigated the energy consumption and GHG emission of high RAP central plant hot recycle technology under different factors including RAP content, recycle agent content, warm mix technology and the raw materials transportation. Such effect factors are actually problems during construction production process. By this study, the preliminary findings show many different results, instead that generally it is think that with the increasing of RAP content, it would appear more and more energy consumption and GHG emission. The following conclusions were drawn:
(1) The transportation distance is more significant influence factor than warm mix technology for energy consumption and GHG emission. warm mix technology which take more energy consumption appear less with the more transportation.
(2) Without warm mix technology, with the increasing of RAP content, the energy consumption and GHG emission are more and more. In fact, during the construction production process of high RAP central plant hot recycling technology, warm mix technology is commonly method to improve the compaction and performance of reclaimed asphalt mixture.
(3) The energy consumption and GHG emission effect of recycle agent which added into high RAP central plant hot recycling asphalt mixture could be ignored, yet the content change of recycle agent make no difference to energy consumption and GHG emission.
(4) To ensure construction workability and compaction of high RAP central plant hot recycling asphalt mixture, warm mix technology is utilized and no heating reduction during every construction process. In this situation, when the transportation distance is less than 150km, the reclaimed asphalt mixture with amount of 50% RAP in the whole mixture has no advantage over the mixture with low amount of RAP.

6 ACKNOWLEDGEMENTS

The research activities described in this paper was sponsored in part by the Research Project of Jiangsu DOT under Grant No. 2015T01. This support is greatly acknowledged. Data analysis and opinions are those of the authors and do not necessarily reflect those of the sponsoring agency.

7 REFERENCES

1. Wang, T., J. Harvey and A. Kendall. Reducing greenhouse gas emissions through strategic management of highway pavement roughness. Environmental Research Letters [J], Vol. 9, No. 3, 2014, pp. 1-10.
2. http://www.ce.berkeley.edu/~horvath/palate.html.
3. Aurangzeb, Q., Al-Qadi, I. L., Abuawad, I. M., Pine, W. J. & Trepanier, J. S. 2012. Achieving Desired Volumetrics and Performance for High Rap Mixtures. Trans Res Rec 2294:34-42.
4. de la Roche, C., Van de Ven, M., Planche, J.P., Van den Bergh, W., Grenfell, J., Gabet, T. et al.2013. Hot Recycling of Bituminous Mixtures. In M.N. Partl, H.U. Bahia, F. Canestrari, C. de laRoche, H. Di Benedetto, H. Piber & D. Sybilski (eds) State-of-the-Art-Reports 9: Advances inInter laboratory Testing

and Evaluation of Bituminous Materials:361-428. Springer.
5. Frigio F., Pasquini, E. & Canestrari, F. 2014. Laboratory Study to Evaluate the Influence of Reclaimed Asphalt Content on Performance of Recycled Porous Asphalt. JOTE 43(6).
6. Stimilli A., Ferrotti G., Graziani A. & Canestrari F. 2013. Performance evaluation of cold recycled mixture containing high percentage of reclaimed asphalt. RMPD, 14:149-61.
7. Leon, J. G., Jensen, P. H. Environmental aspects of warm mix asphalt produced with chemical additives.5th Eurasphalt&Eurobitume Congress, Istanbul. 2012.
8. IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2 Energy, 2006, Page 1.21-1.24.
9. Chinese Life Cycle Database (CLCD), Sichuan University & IKE.
10. Temren, Z., Sonmez, I. A study on energy consumption and carbon footprint of asphalt and concrete mixtures[C]. 5th Eurasphalt&Eurobitume Congress, Istanbul, 2012.
11. http://www.arra.org/.
12. https://www.fhwa.dot.gov/.