LIFE CYCLE ASSESSMENT OF EMISSIONS AND ECOLOGICAL RESOURCES OF LOW-VOLUME ROAD MIXTURES

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ABSTRACT

The rising prices of the asphalt cement materials and the increased awareness of environmental impacts of asphalt mixtures has resulted in a need to search for alternatives that can reduce the cost of those mixtures and decrease emissions and resource consumption generated during their production without compromising performance. This paper evaluates the environmental impacts of using mixtures designed with lower asphalt binder content for use in low-volume roads. To achieve this objective, ecologically based life cycle assessment was conducted on low-volume pavement sections with asphalt mixtures designed with lower asphalt binder and a conventional Hot Mix Asphalt mixture. This comprehensive evaluation does not include only emissions and energy consumption, but it also includes ecological resource consumption. Several metrics were used to evaluate the resource intensity of pavement mixtures; including, cumulative mass, energy, industrial exergy, and ecological exergy consumption, and renewability index. By utilizing this comprehensive ecologically based LCA model, low volume road mixtures were evaluated holistically by considering the impacts on ecosystem goods and services.

1. INTRODUCTION

The rising prices of the asphalt cement materials, global warming, and the increased awareness of environmental impacts of asphalt mixtures has resulted in a need to search for alternatives that can reduce the cost of those mixtures and decrease emissions generated during their production and construction, without compromising performance. One such alternative is the use of asphalt treated mixtures. Asphalt treated mixtures are hot mix asphalt (HMA) mixtures consisting of crushed rock or natural gravel mixed with low percentages (2.5 - 4.5) of paving grade asphalt cement [1]. Those mixtures cost less than typical HMA mixtures because they can be produced with less expensive aggregates and lower percentages of asphalt cement binder. Asphalt treated mixtures can be used in construction of asphalt layer of a pavement structure.

State agencies specifications for asphalt treated mixtures are similar to those required for HMA binder and wearing course mixtures. This has adversely affected the economic competitiveness of those mixtures and resulted in limiting their use in pavement construction. However, a new design methodology for asphalt treated mixtures that are durable, stable, and cost effective was recently developed [2]. The new generation of asphalt treated mixtures designed using the developed methodology has similar performance as conventional low-volume HMA ones; yet they are approximately 16% cheaper. In addition, those mixtures results in reducing the environmental impacts of low-volume HMA, as lower quantities of asphalt binder are used in their production.

The objective of this study is to develop a hybrid Eco-LCA model to evaluate 1 km functional unit of low-volume roads not only from emissions and energy consumption, but also from ecological resource consumption perspective using various environmental performance metrics. This way, a more comprehensive evaluation between alternative designs that include ecological resources is sought. The rest of the paper is organized as follows. First, a brief background of life cycle assessment is presented. Next, the research methodology is described. After that, the analysis results are presented. Finally, the findings are summarized and future work is pointed out.

2. ECOLOGICALLY BASED LIFE CYCLE ASSESSMENT

LCA is an important assessment methodology that aims to quantify the environmental impacts of a product or a process over its life cycle; from raw material extraction, manufacturing, and use stage to final disposal. It primarily consists of goal and scope definition, life-cycle inventory analysis, life-cycle impact assessment, and interpretation. Based on the interpretation of the results, potential improvements are analyzed. Since there is no standard way of conducting impact assessment, many studies often analyze inventory analysis results. The scope of inventory analysis depends heavily on the LCA approach that is chosen.

Three approaches have been mainly utilized in LCA studies; P-LCA, EIO-LCA, and hybrid LCA [3]. P-LCA was developed by the Society of Environmental Toxicology and Chemistry and the U.S. Environmental Protection Agency. This method divides the product studied to individual process flows in order to determine their environmental effects [4]. In P-LCA, every process that is included from the supply chain of the product analyzed needs to be properly inventoried. As the boundary of the study gets broader, inventory analysis gets much more complicated. Conversely, with narrowly defined boundaries, some important environmental impacts in the extended supply chain might be overlooked. Additionally, a process-based LCA enables very detailed analysis, but can be expensive, time-consuming, and can be inappropriate due to uncertainty in the available data. Also, it is difficult to involve all upstream suppliers for impacts assessment with P-LCA [5]. This issue creates a boundary problem which has been overcome by EIO-LCA. EIO-LCA combines the environmental data with the economic input-output matrix of the U.S. economy to form a comprehensive system boundary. This model quantifies the environmental impacts of the products or processes of direct and indirect suppliers at the level of U.S. economy [4]. Although this model was very successful in including the entire economic supply chain that would be mostly missed with P-LCA, analysis of specific processes is not as detailed as P-LCA [6]. In order to take advantage of both models, hybrid LCA models have been developed to combine both process and input-output life cycle assessment models to provide more comprehensive and powerful assessment methodology [7]. The combination of EIO-LCA and P-LCA enabled the researchers to analyze specific processes with details while considering the entire economy simultaneously.

Systems boundaries in the previous models include processes and the whole economy. Nevertheless, ecosystem goods and services are not within the scope of these LCA models. To include ecosystem goods and services, such as water, forest, land, carbon sequestration, pollination, biogeochemical cycles, rain, and wind, Eco-LCA model was developed by Zhang et al. [8]. Eco-LCA model emerged as an important tool that includes important ecological good and services described in Millennium Assessment framework [9]. This environmental assessment tool extends the system boundary to include not only national economy used in EIO-LCA, but also ecological good and services that provide resources for the industrial system.

Eco-LCA uses the same economic input-output data as EIO-LCA. It utilizes thermodynamic input-output analysis approach to account for the contribution of natural capital [10]. Through this approach, exergy analysis is performed to account for industrial systems within the economy, and emergy analysis is performed to account for ecological goods and services. Cumulative exergy flows between industry sectors is allocated based on the economic input-output tables. Eco-LCA mainly focuses on the consumption of ecosystem goods and services and it has the capability to aggregate the results based on various levels such as mass, energy, industrial exergy, and ecological exergy. These aggregation levels provide further insight regarding material and energy intensity of the products being analyzed. It also provides the ability to reach at different metrics that could be used for holistic assessments.

Several sustainability metrics help us to gain more insight during our analysis. For instance, Resource intensity is an important metric to consider while evaluating resource consumption. Resource intensity of different pavement designs is calculated by dividing total cumulative exergy consumption of each pavement design by its total economic output. It represents ECEC for providing ecological goods and services for each $1 of economic output and is represented in terms of sej/$. Thus, a smaller resource intensity value indicates a pavement design which shows less natural resource consumption per dollar of economic output. On the other hand, ECEC/ICEC ratio, which is also termed as efficiency ratio, reveals the magnitude of ecological links that are ignored by ICEC analysis. When these ecological links are taken into consideration, the ECEC/ICEC ratio will be higher in pavement design that utilizes higher proportion of non-renewable resources. In addition, renewability ratio indicates the ratio of renewable resources used to the total ecological resources consumed and offers a valuable indication of depletion of renewable resources. Similarly, loading ratio, defined as the ratio of cumulative consumption of non-renewable resources to those from renewable resources, indicates the relative dependence of a pavement on non-renewable resources [10]. Hence, a higher loading ratio for design option indicates that it consumes relatively more non-renewable resources than other design option. These ratios are important indicators to understand the degree of dependence on renewable and non-renewable resources for each pavement design.

3. RESEARCH METHODOLOGY

Three pavement sections with intermediate traffic volume were selected in this study. All sections had the same structure, which consisted of an asphalt surface layer and a base course layer. The thickness of the asphalt surface layer was selected to be 2 inches in all four sections. The asphalt binder used was an SBS elastomeric polymer-modified PG 70-22M binder. Table 1 presents the Job Mix Formula of the four wearing course mixtures evaluated.

Table 1 - Job Mix Formula for Asphalt Treated Mixtures

Mixture Designation	LS-70	LS-RAP	HMA
Aggregate blend	75% LS 25% CS	60% LS 20% RAP 20% CS	80% LS 20% CS
Binder type	PG70-22M	PG70-22M	PG70-22M
Binder content, %	3.0	3.0	4.4

The MEPDG software was used to compare the performance of pavement sections. All sections had the same structure, which consisted of 2 inches asphalt concrete layer and

10 inches of crushed limestone base course layer. In Section 1 and 2, the LS-70 and LS-RAP asphalt treated mixtures were used in the asphalt concrete layer, respectively. In addition, a typical HMA mixture was used in the control section, Section 3, as a conventional mixture. The MEPDG prediction of IRI showed that during the 20 years analysis period all sections had similar performance.

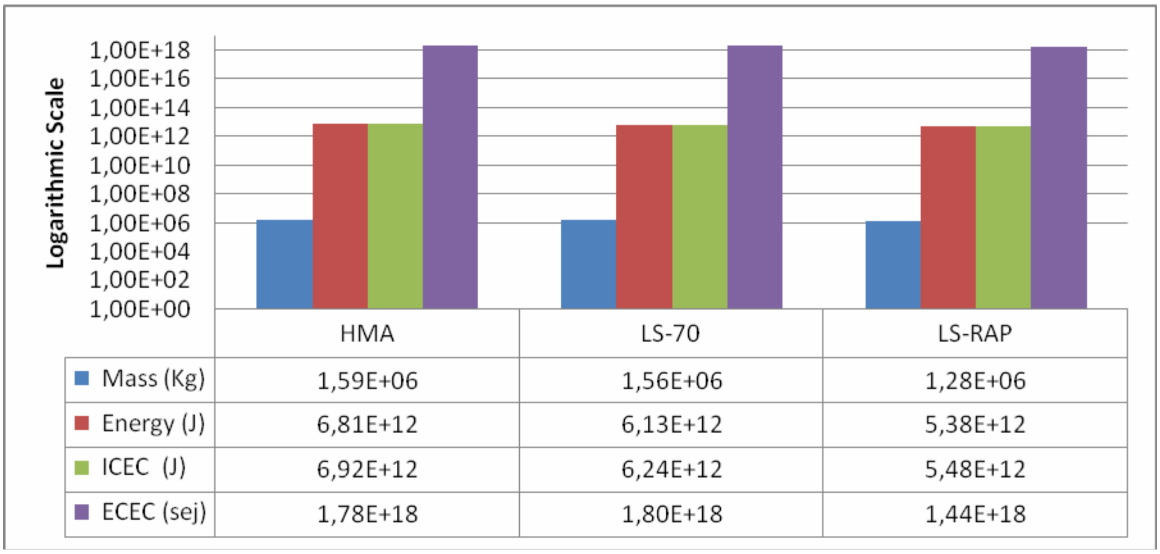
The volumes of the pavements are calculated by multiplying the width and depth of each section with length of the pavement, which is selected to be a two-lane low-volume road with a total width of 7.2 m and a length of 1 km. After calculation the life cycle inventory, Eco-LCA was used to calculate the resource consumption of the mixtures. The system boundary of the current LCA consists of ecological and economic systems, simultaneously. Cumulative consumption of ecological and industrial resources related to life cycle phases of materials extraction and processing of pavement materials, transportation of pavement materials, ready mixtures, and recycled asphalt, asphalt mixing, and placement of mixtures are included within the scope of the research. Materials and energy used for these life cycle phases are quantified, and then a hybrid LCA model is developed. The emissions during material transportation and mixing plant operations are utilizing process-based LCA methodology.

4. ANALYSIS RESULTS

4.1. Cumulative Resource Consumption

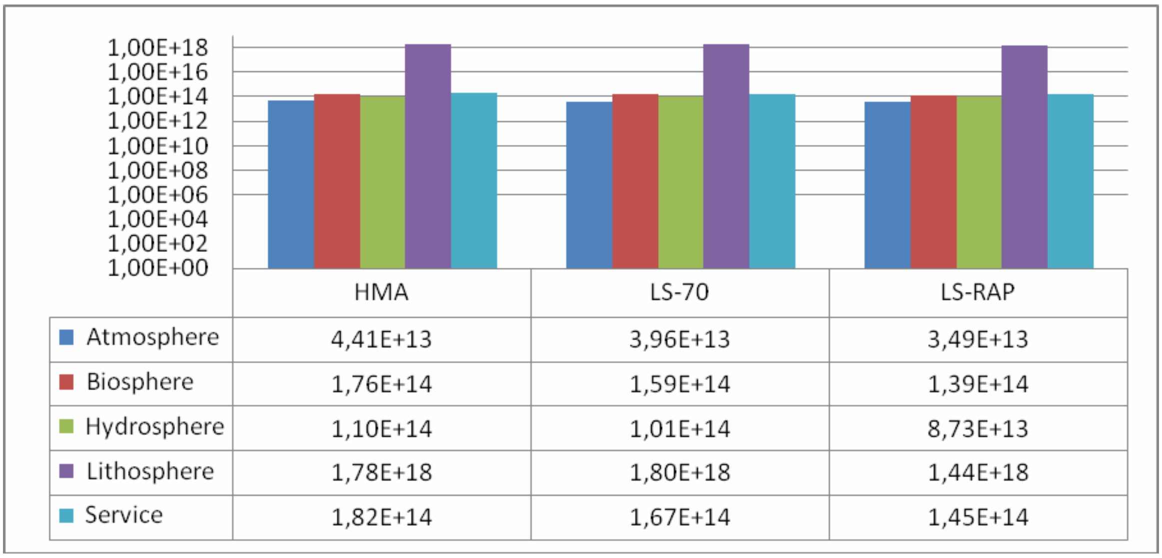
In this study, cumulative resource consumption of each pavement design is represented in terms of mass, energy, industrial, and ecological exergy. As can be seen from Figure 1, HMA pavement is found to have higher resource consumption in terms of mass, energy, industrial exergy. It was expected since the HMA has utilized the highest amount of petrochemical based bitumen, and non-metallic minerals. On the other hand, the total ecological exergy consumption value is found to be higher for LS-70 even though it consumed less limestone and bitumen compared to HMA. This result was due to the fact that LS-70 consumed higher amount of crushed stone which has a higher transformity value when compared to other pavement materials. Since ECEC calculations are based on the transformity values of each material, the dominance of high transformity crushed stone resulted in higher ECEC for LS-70. Based on resource consumption values, the material production phase has the highest resource consumption values in terms of industrial and ecological exergy utilization. This result can be attributed to high energy and material demand of material production phase. Consequently, the LS-70 and LS-RAP mixtures have utilized less material, energy and industrial exergy than HMA.

Figure 2 shows ECEC of the three pavements by ecosphere. The highest ECEC was obtained in the lithosphere for all pavement mixtures, since highly consumed metallic and non-metallic ores and crude oil are direct inputs from this ecosphere. Due to the fact that LS-70 pavement utilized higher amount of high transformity sand which has a higher value than limestone and bitumen, the total lithosphere ECEC inputs are found to be higher for LS-70 when compared to other designs. Since the total atmospheric emissions were highest for HMA, the exergy value of atmosphere was higher for this mixture.



	HMA	LS-70	LS-RAP
🟦 Mass (Kg)	1,59E+06	1,56E+06	1,28E+06
🟥 Energy (J)	6,81E+12	6,13E+12	5,38E+12
🟩 ICEC (J)	6,92E+12	6,24E+12	5,48E+12
🟪 ECEC (sej)	1,78E+18	1,80E+18	1,44E+18

Figure 1 – Cumulative Resource Consumption by Aggregation Metrics



	HMA	LS-70	LS-RAP
🟦 Atmosphere	4,41E+13	3,96E+13	3,49E+13
🟥 Biosphere	1,76E+14	1,59E+14	1,39E+14
🟩 Hydrosphere	1,10E+14	1,01E+14	8,73E+13
🟪 Lithosphere	1,78E+18	1,80E+18	1,44E+18
🟦 Service	1,82E+14	1,67E+14	1,45E+14

Figure 2 – Cumulative Ecological Exergy Consumption by Ecospheres

In addition, Figure 3 presents the relative percentage contribution of cumulative exergy consumption by different life cycle phases. For all pavement designs, the material extraction and processing phases are found to have largest ICEC due to high industrial inputs from the ecosystem and energy consumption for processing of raw materials. The HMA design shows the highest percentage contribution rate for ICEC since the highest amount of mineral and binder content were used in this pavement design. On the other hand, LS-RAP has shown the lowest ICEC value because of the fact that the use of the reclaimed asphalt significantly reduced the amount of binder and virgin aggregate requirement for this design. In addition to material extraction and processing, the transportation phase showed second highest contribution in term of industrial exergy consumption. Since the construction phase has consumed less amount of energy compared to other life cycle phases, it shows the lowest ICEC value (see Figure 3). One another important point is that the relative contribution of transportation, mixing, and construction phases on ICEC has increased along with the decreasing percentage contribution of materials phase on ICEC for all mixtures.

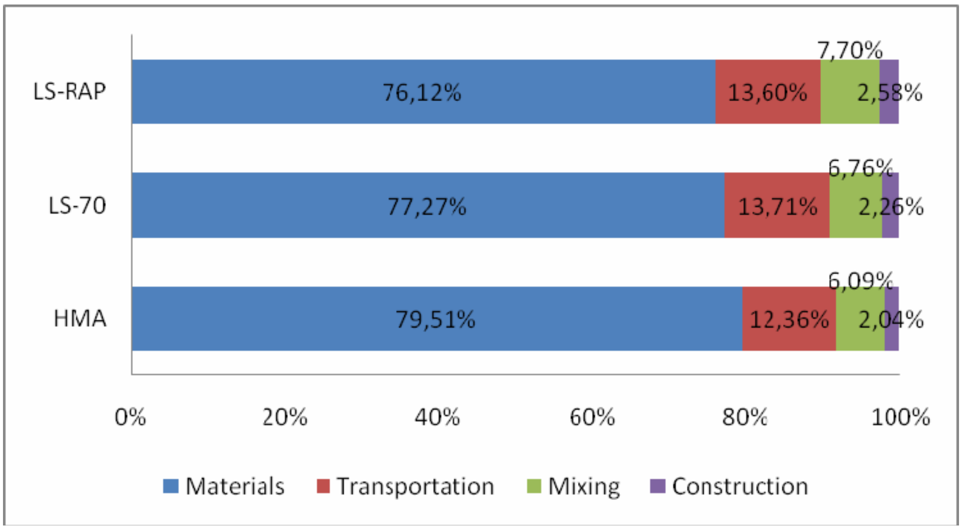
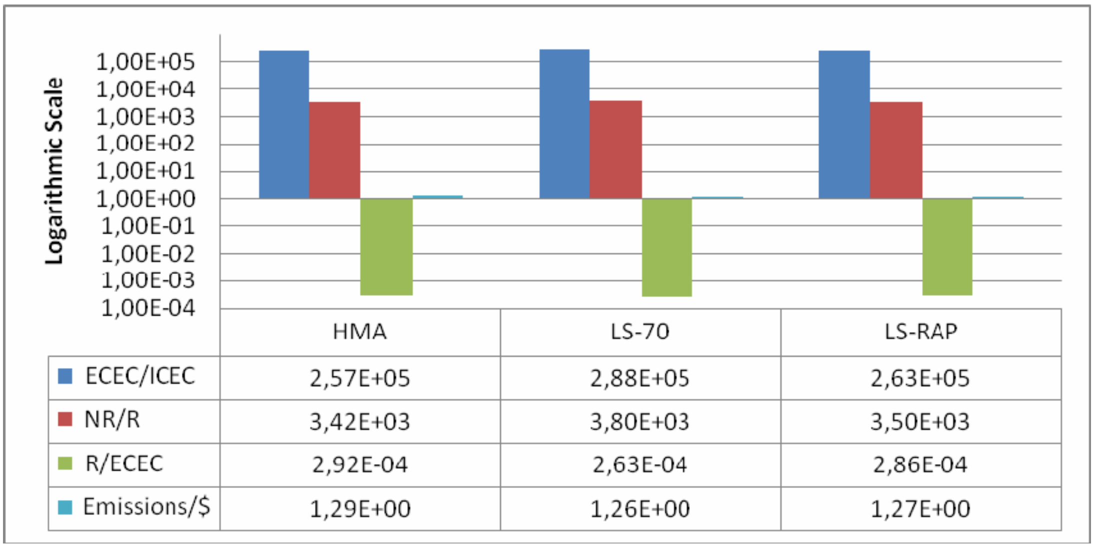


Figure 3 – Cumulative Industrial Exergy Consumption Percentage by Life Cycle Phase

4.2. Sustainability Metrics

Several environmental performance metrics including ECEC/ICEC, NR/R, R/ECEC, and Emissions/$ are used in order to evaluate different low volume road mixtures. As Figure 4 shows, the LS-70 design showed higher dependency on non-renewable ecological resource. The ECEC/ICEC value was found to be higher for LS-70, as well as NR/R and R/ECEC. Although the WMA used higher amounts of material, energy, and industrial exergy, the LS-70 design is found to be a less sustainable alternative. As mentioned earlier, the LS-70 mixture consumed more crushed stone which has the highest transformity value. All the aforementioned sustainability metrics are based on ecological resource consumption, which is calculated by transformity values. Therefore, the highest ECEC of LS-70 mixture makes this design less sustainable. On the other hand, when mass, energy, and industrial exergy are considered, the HMA mixture is found to be less favorable in terms of sustainability. In addition, the total emissions against per dollar output represent the emissions intensity, and this metric is found to be higher for HMA when compared to LS-70 and LS-RAP. This result was expected since the HMA consumed the largest amount of material and energy during overall life cycle period.



	HMA	LS-70	LS-RAP
🟦 ECEC/ICEC	2,57E+05	2,88E+05	2,63E+05
🟥 NR/R	3,42E+03	3,80E+03	3,50E+03
🟩 R/ECEC	2,92E-04	2,63E-04	2,86E-04
🟦 Emissions/$	1,29E+00	1,26E+00	1,27E+00

Figure 4 – Sustainability Metrics

4.3. Atmospheric Emissions

When the total atmospheric emissions are analyzed, it is found that the life cycle phases including mixing and transportation have shown the highest amount of emissions. The total air emissions are found to be largest for conventional HMA due to its higher transportation and mixing fuel consumption. Additionally, higher ecological resource consumption of HMA has resulted in higher total emissions since more material and energy required for processing of raw materials including minerals and petrochemical based bitumen. On the contrary, LS-RAP design shows the lowest transportation related emissions since the transportation fuel requirement was minimized by recycled material use. Also, this design shows lowest total atmospheric emissions for material processing phase due to lower requirement for new virgin materials. On the other hand, it was found that the mixing phase has had the highest total air emissions for all HMA, LS-70 and LS-RAP pavements.

The quantification of CO_2 emissions has a critical importance due to global warming potential of this atmospheric pollutant. As can be seen from Figure 5, the life cycle phases of mixing and transportation of pavement materials represent the most significant life cycle phases in terms of total CO_2 emissions. The conventional HMA design shows the highest total CO_2 emissions due to its higher mineral, binder, and fuel consumption. LS-RAP has shown lower dependency on new virgin materials and binder content. Therefore, this design has emitted less amount of CO_2 gas by reducing the processing, transportation and mixing related emissions. In this study, the construction phase has involved the energy consumption related environmental impacts. Since this phase has utilized lower energy compared to other life cycle phases, the CO_2 emissions are found to be lower.

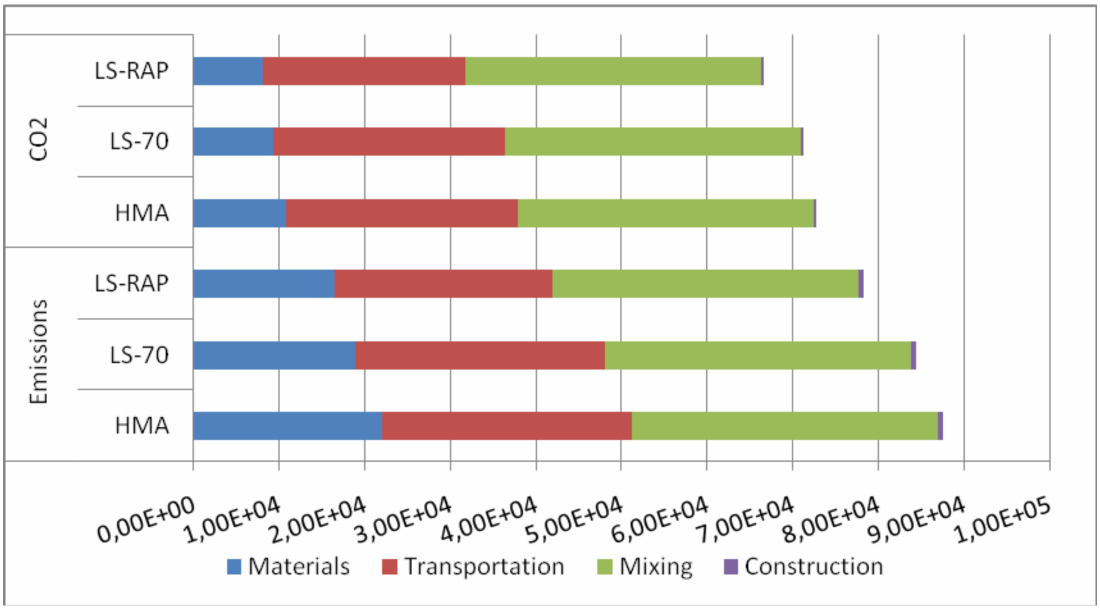


Figure 5 – Total Emissions and CO_2 Emissions by Life Cycle Phase (kg)

CONCLUSION

In this study, several low volume road mixtures were evaluated by using a comprehensive LCA methodology considering the impacts on ecosystem goods and services. Life cycle inventory data were collected for all pavement designs and their dollar amounts were calculated. The impacts on ecosystem were calculated in terms of cumulative mass, energy, industrial exergy, and ecological exergy. The emissions associated with plant operations and transportation of pavement materials was also included. Manufacturing of raw materials and their processing, transportation of materials to mixing plant, mixing plant operations, transportation of mixes to construction site, and pavement placement were included within the scope of the study. Based on the results summarized above, the following points are highlighted:

- LS-70 and LS-RAP mixtures have utilized less material, energy and industrial exergy than HMA. On the other hand, the dominance of high transformity crushed stone resulted in higher ECEC for LS-70 design. The highest ECEC was obtained in the lithosphere for all pavement mixtures, since highly consumed metallic and nonmetallic ores and crude oil were direct inputs from this ecosphere.

- For all pavement designs, material extraction and processing phases are found to have largest ICEC due to high industrial inputs from ecosystem, and energy consumption for processing of raw materials. HMA design shows the highest percentage contribution rate for ICEC since the highest amount of mineral and binder content were used in this mixture.

- The efficiency ratio was found to be higher for LS-70, as well as the loading and the renewability ratios. The LS-70 mixture consumed more crushed stone which has higher transformity value. Therefore, this mixture is found to be less sustainable when transformity values are considered. On the contrary, the HMA design used higher mass, energy, and industrial exergy.

- The conventional HMA design shows the highest total CO_2 emissions due to its higher mineral, binder, and fuel consumption. LS-RAP has shown lower dependency on new virgin materials and binder content. Therefore, this design emitted less amount of CO_2 gas by reducing the processing, transportation and mixing related emissions. Also, the emission intensity is found to be higher for HMA when compared to LS-70 and LS-RAP. Again, it was expected result since the HMA consumed the largest amount of material and energy during overall life cycle period.

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