Lowland Technology International 2018; 20 (2): 117-124
International Association of Lowland Technology (IALT): ISSN 1344-9656
Special Issue on: Green Technology for Sustainable Infrastructure Development

Research Paper

Environmental impact evaluation of road pavements using life cycle assessment tool

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ARTICLE INFORMATION

Article history:

Received: 9 February, 2017
Received in revised form: 11 April, 2017
Accepted: 20 July, 2017
Publish on: 07 September, 2018

Keywords:

Climate change
Greenhouse gas emissions
Environmental impact assessment
Life cycle assessment
Road construction

ABSTRACT

The acquisition of road construction materials, building processes, rehabilitation, demolition, and disposal of road surfaces adversely impact the environment. In Thailand, the rapid expansion of road transportation networks has raised concerns regarding environmental degradation. Alternative road pavement materials need to be assessed from a life cycle assessment perspective to promote sustainable global development. An environmental impact evaluation was undertaken for two major road types - concrete and asphaltic concrete (AC) pavements - using life cycle impact assessment, with relevant data obtained from related government documents and reports. Results indicated that AC pavement had a higher impact on climate change than concrete pavement, while concrete pavement exhibited a higher impact on terrestrial acidification, human toxicity, metal depletion, and fossil depletion than AC pavement. Building material acquisition and construction contributed the major impact on climate change at 93.2% and 83% for concrete and AC roads, respectively. The mitigation options for reducing the impact of climate change impact were utilization of a mixture of 35 to 50% fly ash with cement instead of cement only in concrete pavement process and implementation of recycling in rehabilitation phase for AC pavement. The findings can be applied to support future decision-making processes for the sustainable development of road construction projects.

1. Introduction

Road transportation networks are the major infrastructure systems for most countries, with advantages of flexibility, low cost, and various routes. In Thailand, more than 80% of public transport relies on road transportation (Anastasiou et al., 2015). In developing countries, road construction has continuously expanded resulting in serious environmental issues including global warming, fossil fuel depletion, human toxicology, metal depletion, and terrestrial acidification. Several road construction processes contribute to adverse environmental impact, including construction materials acquisition, building processes, rehabilitation, demolition, and disposal of road surfaces. The environmental impact depends on the type and activity

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Note: Discussion on this paper is open until March 2019

data of each road type. In Thailand, there are 210,074 kilometers of road comprising 72.01%, 18.36%, and 9.63% of asphaltic concrete (AC), concrete, and dirt respectively. One advantage of AC pavement (flexible pavement) is the lower capital cost compared to concrete (rigid pavement); however, the former requires more maintenance and repairs during its service lifespan. In contrast, concrete pavement has higher mechanical strength and durability, resulting in lower repair and maintenance costs (Araújo et al., 2014; Valipour et al., 2014). Therefore, concrete pavement has attracted increased interest with more frequent construction.

Life cycle assessment (LCA) is a tool which evaluates the environmental impacts of products throughout their entire life cycle (from cradle to grave). LCA has been utilized worldwide to compare different types of road surfaces, including Swiss road pavements (Balaguera et al., 2018; Farina et al., 2017; Barandica et al., 2013; Loijos et al., 2013; Vidal et al., 2013; Santero et al., 2011) and asphalt pavement at London Heathrow Airport Terminal 5 (Barandica et al., 2014). Road construction has a major environmental impact on global warming and climate change caused by the increasing levels of greenhouse gases (GHGs) in the atmosphere. Road construction in Korea emitted carbon dioxide (CO_2) at 120.1 tCO_2/m, 29.6 tCO_2/m, and 7.5 tCO_2/m for bridges, tunnels, and roads, respectively (Department of Highways and Ministry of Transport, 2012). Raw construction material acquisition plays a major role in GHG emissions (Department of Highways and Ministry of Transport, 1992). The LCA of new roads in Spain reported that GHG emissions ranged from 8,880 to 50,300 tCO_2eq/km; the road construction phase was the highest with the maintenance phase playing a secondary role (Dumitrescu et al., 2014). The GHG emissions from rigid pavement were higher than those from flexible pavement (Ecoinvent, 2007). In Thailand, few researches have reported the assessment of environmental impact, especially global warming caused by road construction.

The main objective of this research was to compare the environmental impact between concrete pavement and AC pavement as a life cycle assessment. The impact assessment was performed for raw material acquisition and construction, rehabilitation, and demolition phases. The evaluation of GHG reduction from rigid and flexible road pavements using simple scenario was reported.

2. Typical Road Pavements

The environmental impact of the two main types of road pavements constructed in Thailand was evaluated. Road classification was split into flexible pavement (AC) and rigid pavement (concrete). Typical cross-sections of these pavements are shown in **Fig. 1**. Asphaltic concrete pavement has four layers, including the top AC layer, base course, sub-base course, and subgrade soil, while rigid pavement has three layers, including the top concrete slab, sub-base course, and subgrade soil. However, the thicknesses of each layer for concrete and AC pavements vary depending on the traffic loading. A typical road cross section frequently used in many areas of Thailand was selected, with lane width at 3.5 meters and shoulder width 2.5 meters, comprising a two-lane road 12.0 meters wide. Typically, an AC road is composed of 15 cm selected materials, 15 cm soil aggregate sub-base, 20 cm soil aggregate type base (or soil cement base), and 10 cm concrete base/AC. Materials used for these layers are shown in **Table 1**.

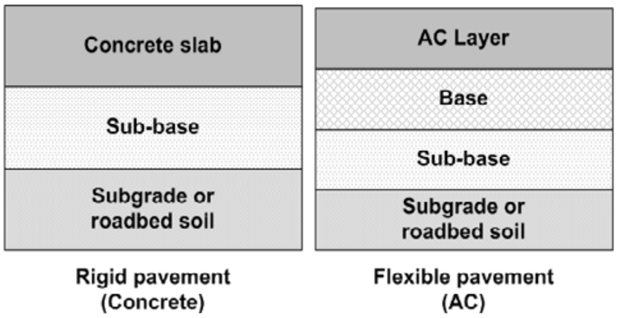

Fig. 1. Schematic representation of typical pavement cross-sections.

Table 1. General pavement materials used in Thailand.

Pavement layers	Asphalt pavement	Concrete pavement
Surface layer	AC 60/70 hot-mix asphalt	Portland cement concrete
Base course	1. Crushed rock 2. Soil cement 3. Cement modified crushed rock 4. Pavement recycling materials	1. Sand cushion 2. Crushed rock cushion
Sub-base course	1. Selected materials 2. Soil aggregate	
Subgrade soil	1. Soil embankment 2. Sand embankment	1. Soil embankment 2. Sand embankment

3. Materials and Methods

3.1 Framework and Scope

The scope of this study encompassed all phases of the entire life cycle of road construction, including materials acquisition, the construction process, usage (including maintenance for AC), and end of life of the road surface. The functional unit to compare environmental impacts was defined as 1 km of road distance. The framework for the evaluation of the environmental impacts from road construction is shown in **Fig. 2**.

Firstly, the materials and energy used in the construction, use/rehabilitation and demolition phases of various types of road including rock, cement, asphalt and diesel were collected. Secondly, the inventory data for each road were balanced in terms of both mass and energy. The environmental impacts of the roads were then evaluated using SimaPro software and the ReCiPe midpoint approach. Finally, the results for both concrete roads and AC pavements were analyzed and compared. Improvement of the hot spot process was proposed to reduce the environmental impacts.

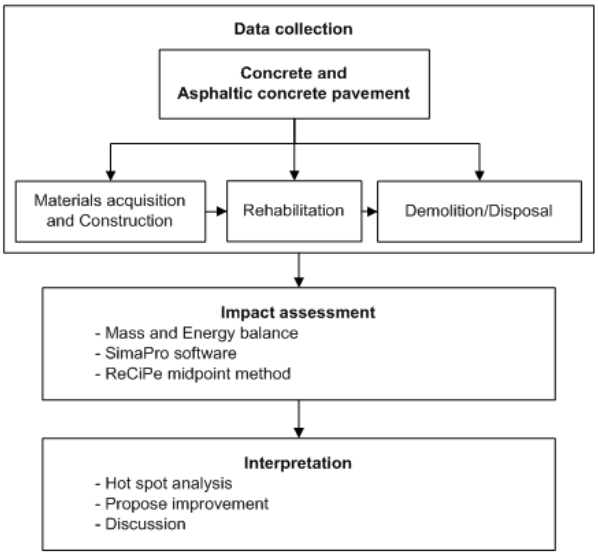

Fig. 2. Framework for evaluation of the environmental impacts.

3.2 Inventory and Data Sources

The inventory data of concrete and AC pavements were collected from the construction, use/rehabilitation, and demolition phases (**Fig. 2**). Data for construction materials and energy used were obtained from the handbook of standard highway design (EEA, 2013) and calculated from the planning and cost estimation handbook (Gschösser et al., 2012) expressed in units of road distance (**Table 2**). Data of raw material acquisition and production were sourced from the Ecoinvent database in SimaPro software (Huang et al., 2009).

The functional unit of concrete and AC roads was 1 km for 2 lanes. The rehabilitation material and fuel consumption were assumed to be 5% and 20% of the original surface layer for concrete and AC, respectively. For the demolition of concrete and AC pavement, the scenarios of both road types were assumed according to domestic practice (demolition and landfill).

Table 2. Materials and energy used for 1 km of concrete and AC pavement construction.

Type		Item	Amount	Unit
Concrete road				
	Base course	Soil work	37,804	ton
		Selected materials	5,538	ton
		Gravel	5,427	ton
		Sand	3,460	ton
	Surface	Cement	1,240	ton
		Granite	2,285	ton
		Sand	1,339	ton
		Steel bar	42	ton
		Water	575	m^3
	Energy	Diesel	1,500	L
Asphalt concrete road				
	Base course	Soil work	37,804	ton
		Selected materials	5,538	ton
		Gravel	5,427	ton
		Crushed granite	7,263	ton
	Surface	Asphalt	62	ton
		Granite	2,528	ton
		Prime coat	13	ton
		Tack coat	4	ton
	Energy	Diesel	2,500	L

The pollutants from fossil fuel combustion were also considered in the assessment. The major GHGs, including CH_4, CO, CO_2, N_2O, NMVOC, NO_x, PM10, and SO_2 were calculated according to the Intergovernmental Panel on Climate Change (IPCC) report and the European Environment Agency (EEA) guidelines (IPCC, 2006; Limsawasd, 2017).

3.3 Evaluation of Environmental Impacts

The environmental impacts of concrete pavement and AC pavement were evaluated by SimaPro software using the ReCiPe midpoint method (Liu et al., 2017). Five related impact categories were identified and the major impacts for each stage of the system, including climate change, terrestrial acidification, human toxicity, metal depletion and fossil depletion were quantified.

Climate change impacts of both direct and indirect greenhouse gases released from concrete pavement and AC pavement processes are quantified by multiplying activity data with climate change impact factor as equation [1].

$$CC = AD \times EF_{CC} \quad [1]$$

Where *CC* is the climate change impact expressed as kg CO_2eq unit, *AD* is the activity data of considered process (arbitrary unit), and EF_{CC} is the climate change impact factor which is defined according to the ReCiPe guideline (kg CO_2eq/arbitrary unit).

Terrestrial acidification impacts of concrete pavement and AC pavement are quantified by/as the related air emissions according to the ReCiPe guideline by multiplying activity data with terrestrial acidification impact factor as equation [2].

$$TA = AD \times EF_{TA} \quad [2]$$

Where TA is the terrestrial acidification impact expressed as kg SO_2eq unit, *AD* is the activity data of considered process (arbitrary unit), and EF_{TA} is the terrestrial acidification impact factor (kg SO_2 eq/arbitrary unit).

Human toxicity impacts of concrete pavement and AC pavement are quantified by multiplying activity data with human toxicity impact factor as equation [3].

$$HT = AD \times EF_{HT} \quad [3]$$

Where *HT* is the human toxicity impact expressed as kg 1,4-DBeq unit, *AD* is the activity data of considered process (arbitrary unit), and EF_{HT} is the human toxicity factor (kg 1,4-DBeq /arbitrary unit).

Metal depletion impacts are designated as the metal used compared to the global reservation which is quantified by multiplying activity data with metal depletion impact factor as equation [4].

$$MD = AD \times EF_{MD} \quad [4]$$

Where *MD* is the metal depletion impact expressed as kg Fe eq unit, *AD* is the activity data of considered process (arbitrary unit), and EF_{MD} is the metal depletion factor (kg Fe eq/arbitrary unit).

Fossil depletion impacts are indicated by the decrease of fossil fuel referred to the global reservation which is quantified by multiplying activity data with fossil depletion impact factor as equation [5].

$$FD = AD \times EF_{FD} \quad [5]$$

Where *FD* is the fossil depletion impact expressed as kg Oil unit, *AD* is the activity data of considered process (arbitrary unit), and EF_{FD} is the fossil depletion factor (kg Oil eq/arbitrary unit).

4. Results and Discussion

The characterized impacts associated with 1 km of concrete road and AC road are shown in **Tables 3** and **4**. The material acquisition and construction phases of both road types were the major contributors for all environmental impact categories. Concrete roads showed higher total environmental impact than AC roads, except for the climate change category. AC roads showed a higher impact on climate change than concrete roads due to rehabilitation, while concrete roads exhibited a higher contribution to climate change from the demolition phase.

Table 3. Characterized impacts for 1 km of concrete road (analyzed by ReCiPe midpoint).

Impact category	Unit	Raw material acquisition and Construction	Rehabilitation	Demolition	Total
Climate change	kg CO_2 eq	1,775.41	84.53	69.94	1,929.88
Terrestrial acidification	kg SO_2 eq	5.67	0.04	0.50	6.21
Human toxicity	kg 1,4-DB eq	225.11	0.48	11.26	236.85
Metal depletion	kg Fe eq	218.41	0.10	3.14	221.65
Fossil depletion	kg Oil eq	131.47	6.07	33.86	171.40

Table 4. Characterized impacts for 1 km of AC road (analyzed by ReCiPe midpoint).

Impact category	Unit	Raw material acquisition and Construction	Rehabilitation	Demolition	Total
Climate change	kg CO_2 eq	1,690.57	338.11	8.92	2,037.60
Terrestrial acidification	kg SO_2 eq	0.78	0.16	0.01	0.95
Human toxicity	kg 1,4-DB eq	9.65	1.93	3.33	14.91
Metal depletion	kg Fe eq	1.96	0.39	0.07	2.42
Fossil depletion	kg Oil eq	121.35	24.27	0.48	146.10

Estimation of CO_2 emission from road construction projects in Spain based on four case studies ranged from 0.55 to 3.66 $kTCO_2$/km. Furthermore, land use and land-use change (LULUC) should be considered in CO_2 emission and sequestration evaluation (Goedkoop et al., 2009).

Terrestrial acidification and fossil depletion impacts were influenced by raw material acquisition and the construction phase of concrete and AC roads. Diesel consumption showed a high contribution to fossil depletion for both concrete and AC roads. Impacts from steel production were strongly related to human toxicity and metal depletion categories. Asphalt used in AC was a principal contributor to many impacts, including human toxicity, metal depletion, and fossil depletion, while diesel showed the most impact on terrestrial acidification. To improve road pavement sustainability, raw materials and energy consumption must be critically assessed and evaluated. A rehabilitation strategy using hot-mix asphalt containing 30% of reclaimed asphalt pavement (RAP) was reported as most suitable (Office of the National Economic and Social Development Board, 2011). Partial life cycle assessment of road construction (only on the construction and/or maintenance phase), using modified hot mixed asphalt (with hydrated lime) in the maintenance phase, reported the environmental footprint of major environmental categories as lower than using classical hot mixed asphalt, with 43% less primary energy (Santos et al., 2017).

Figure 3 depicts the climate change impact associated with all phases of concrete pavement. For concrete roads, the raw material acquisition and construction phase showed the major contribution to climate change at 93.2%, with 3.08% and 3.67% for the rehabilitation and demolition phases, respectively. Climate change impact from surface pavement was 62.4% from cement and 5.66% from steel acquisition. Raw material acquisition and construction phase of concrete pavement showed the highest global warming impact which was mainly from cement production (1,081.34 kg CO_2eq) and diesel combustion (579.63 kg CO_2eq) as shown in **Fig. 4.**

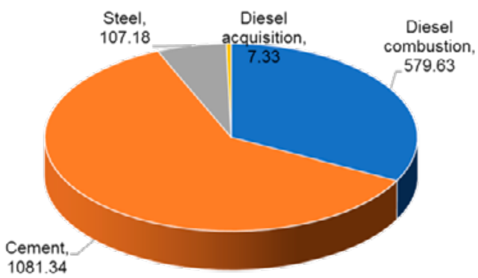

Fig. 4. Climate change impact contribution of construction phase for concrete road (kg CO_2eq).

Approximately 6% of anthropogenic CO_2 emission is from cement industrial (IPCC, 2005). Cement industrial has intended to use natural supplement cementing materials to reduce the impact. Concrete containing zeolite amount 10% to 30% reduced global warming potential from 60.3% to 64.3% as compared to convention concrete (Valipour et al., 2014). The investigation of using supplementary cementing materials and recycled concrete aggregates (RCA) and fly ash (FA) in concrete to reduce the global warming impact reported that the optimum mix was the combination of both RCA and FA rather than individual incorporation (Kurad et al., 2017). Sustainable design of the concrete mixture can also reduce CO_2 emission and energy consumption. An LCA study for emissions and energy reduction in concrete pavement mixture design by adding 40% fly ash to the total cementitious content resulted in a 9,935 MT reduction in CO_2 equivalent and reduced the cost of materials by 0.67 million dollars (Smith and Durham, 2016).

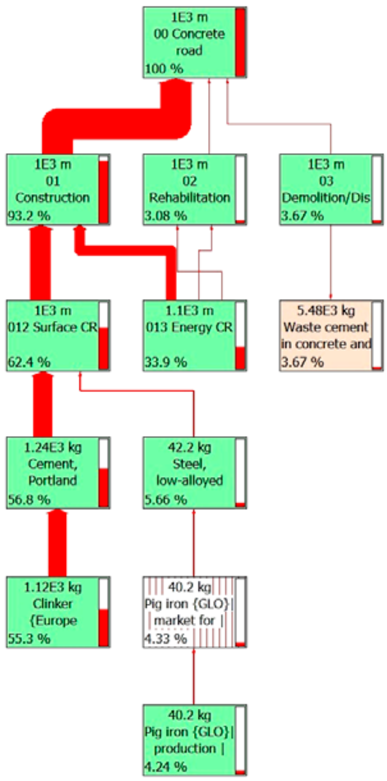

Fig. 3. Climate change impact contribution of concrete road.

Climate change impact assessment of supplementation of 35% to 50% fly ash to cement scenario was reported in **Table 5.** It was found that the climate change impact was reduced by 25% of the total climate change impact compared to conventional concrete. The reduction in raw material acquisition and construction and rehabilitation phases were 26% and 31%, respectively. This result suggested that mixing of waste or natural materials with cement significantly reduces climate change impact. This agreed well with Wang et al. (2017) and Anastasiou et al. (2015). Moreover, reducing greenhouse gas emissions from power plants can decrease the climate change burden, because electricity is used for material production and acquisition, such as cement and steel (Schlegel et al., 2016).

Table 5. Reduction of climate change impact for concrete road.

Life cycle phase	Impact ($kgCO_2eq$)	Reduction
Raw material acquisition and Construction	1,317.61	26%
Rehabilitation	58.69	31%
Demolition	69.94	-
Total	1,146.24	25%

Figure 5 shows the climate change impact associated with all phases of asphaltic pavement. The raw material acquisition and the construction phases showed major contributions at 83%, with 16.6% and 0.438% for the rehabilitation and demolition phases, respectively. Climate change impact from asphaltic surface pavement was mainly 96.8% from energy consumption and 2.8% from asphalt acquisition.

The major contribution of climate change impact of AC pavement was also from the raw materials and acquisition phase in which diesel consumption was the highest contributor to the impact as 1,628.52 kg CO_2eq (**Figure 6**). The mitigation option for reducing the climate change impact from AC pavement has been investigated. The study of life cycle assessment of asphalt pavements using reclaimed asphalt pavement (RAP), warm mix asphalt (WMA) and cold in-place recycling (CIR) has been reported. The use of a combination of RAP and WMA resulted in getting a reduction of up to 12% for CO_2eq, 15% for energy consumptions, and 15% for water used during the lifecycle. Moreover, a reduction of 9% of CO_2eq could be achieved by CIR technology (Giani et al., 2015). Greenhouse emission and energy consumption from using RAP content in asphalt binder mixtures showed significant reduction with an increase in RAP content (Aurangzeb et al., 2014). However, greenhouse gas emission from the production and construction of rubberized asphalt mixtures was similar to that from hot mix asphalt, but its CO and CH_4 emissions were significantly lower (Wang et al., 2018). The scenario of using 100% recycled spent surface materials in rehabilitation phase was evaluated. It was found that a greenhouse gas reduction of 2.7% could be achieved for the phase and 0.4% of total emission (**Table 6**).

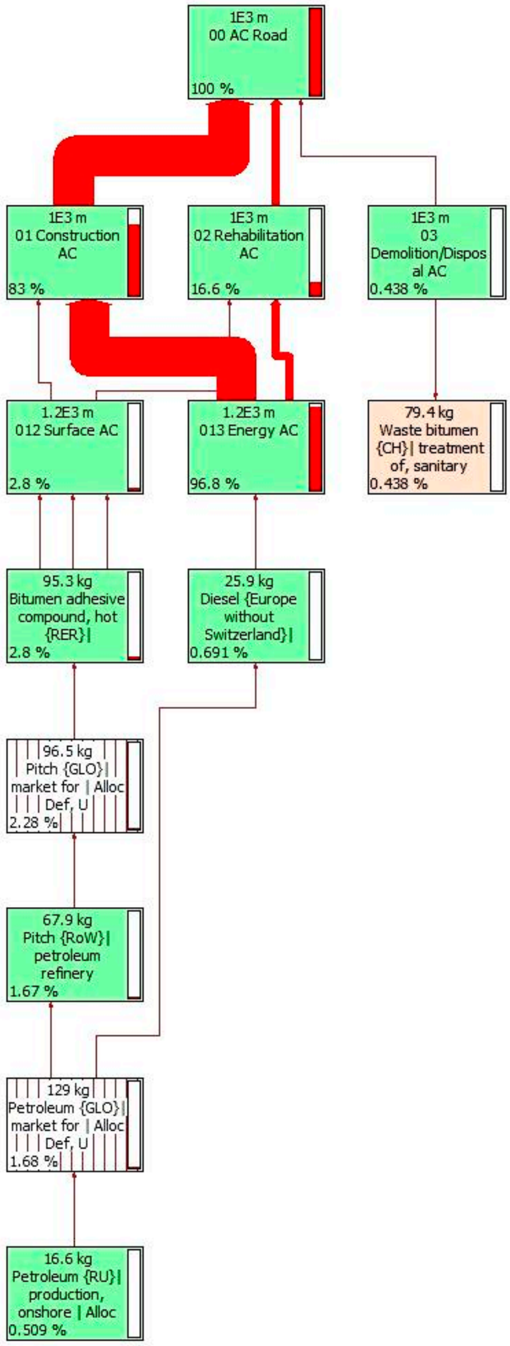

Fig. 5. Climate change impact contribution of AC road.

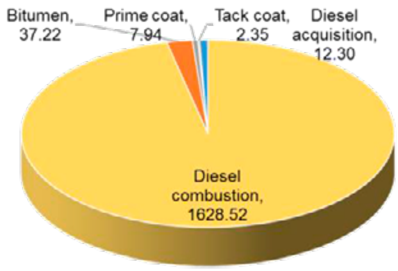

Fig. 6. Climate change impact contribution of construction phase for AC road.

Table 6. Reduction of climate change impact for AC road.

Life cycle phase	Impact ($kgCO_2eq$)	Reduction
Raw material acquisition and Construction	1,690.57	-
Rehabilitation	329	2.7%
Demolition	8.92	-
Total	2,028.60	0.4%

Reducing climate change impact, improving cement production efficiency by supplementing waste and natural cementing materials with cement while decreasing diesel consumption is an appropriate way to reduce the impacts for AC road construction. Limitations of this study were the omission of other road transportation components, such as bridges and tunnels, from the evaluation. However, an estimation of materials-induced CO_2 emission from road construction in Korea reported that bridges showed the largest contribution to CO_2 emission, followed by tunnels and road-only because of the usage amount of main construction materials (Department of Highways and Ministry of Transport, 2012). Utilization of RAP can reduce gaseous emissions from the construction phase due to reduction in raw material extraction. Using 50% RAP reduced energy consumption by 3% and decreased gas emissions by 14% for CO_2, 23% for SO_2 and approximately 15% for CH_4, N_2O (Seo and Kim, 2013).

5. Conclusions

A comparison of life cycle assessments for two road pavement types - concrete and AC - was conducted for a one-kilometer road length. For both road pavements, the raw material acquisition/construction phase played a major role in all environmental impact categories. AC roads exhibited higher climate change impact from the raw material acquisition/construction and rehabilitation phases, while concrete roads showed a higher environmental impact on terrestrial acidification, human toxicity, metal depletion, and fossil fuel depletion.

Acknowledgements

We would like to sincerely thank the School of Energy and Environment, University of Phayao for supporting research facility, and the Department of Highways, Ministry of Transport for providing valuable data.

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