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Carbon Footprint of Road Pavement Rehabilitation: Case Study in Sungai Petani, Kedah

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Abstract

Global warming is the consequence of long-term incline in the amount of greenhouse gases in the upper layers of the atmosphere. The emission of these gases is caused by human activities that are intensely harmful to the environment (such as land use changes, deforestation, and burning of fossil fuels). This study aims to calculate the carbon footprint of a highway and evaluate its road pavement rehabilitation. The area of this study is the PLUS Malaysia Berhad expressways in Sungai Petani, Kedah, Malaysia. The impacts of carbon emissions are assessed by performing life cycle assessment (LCA) on the materials and machineries used in road pavement rehabilitation, and boundaries refer to a partial LCA conducted from the gate to the site. Results show that the pavement material emitted the highest carbon footprint was quarry dust 3247.91 tons of CO_{2e}, followed by cement, stone aggregate, and bitumen emit 251.15, 130.74, and 0.11 tons of CO_{2e} respectively. The milling machinery emitted the highest carbon footprint, producing 478.14 tons fossil CO_{2e}, due to its highest engine capacity of 448.8 kW/h and long usage of 108 hours, followed by the lorry DBM, lorry ACWC, and dump truck at 459.47, 352.50, 314.64 tons fossil CO_{2e}, respectively. The results of this study can be integrated with transportation planning to control environmentally harmful transport activities in Malaysia.

Keywords: Carbon footprint, road pavement rehabilitation, life cycle assessment, pavement materials, machineries

INTRODUCTION

Since the industrial revolution, human activities have been increasingly altering the global carbon cycle, and an emerging concern from such phenomenon is the growing concentration of atmospheric carbon dioxide [1]. Wiedmann and Minx (2008) defined “carbon footprint” as “a measure of the exclusive total amount of carbon dioxide emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product”[2];Moss, Lambert, and Rennie (2008) provided a more suitable definition of carbon footprint: the total mass of greenhouse gases directly and indirectly emitted by an individual or a company throughout the full lifecycle of a product[3]. Carbon dioxide (CO_2) is considered a dominant factor of climate change, andCO_2 gas emissions account for nearly three-fourths of the global emissions of greenhouse gases (GHGs) [4].

Global warming is the consequence of the long-term accumulation of GHSs in the upper layers of the atmosphere. The emission of these gases is caused by human activities that are intensely harmful to the environment (such as land use changes, deforestation, and burning of fossil fuels) [5]. Environmentally harmful activities vary from industry to industry, but the built environment is generally considered the dominant contributor to GHG emissions, accounting for almost 50% of the global carbon dioxide emissions [6]. Therefore, GHG emissions must be reduced by at least 50% to stabilize global concentrations by 2100 [7].

Life cycle assessment (LCA) shows the benefit of the contributions made by each step in the life cycle of a process or product; the life cycle begins from the acquisition of the raw materials up to their disposal at the end of useful life [8]. The European Commission (2007) guidelines define a carbon footprint as a subset of a complete LCA [9]. These guidelines also help users to uncover trade-offs across environmental impacts, which could otherwise remain unnoticed, and are critical to ensuring proper decision making [10]. The environmental footprint of a pavement is measured by the aggregation of impacts over its life cycle, beginning from the extraction of the raw materials and culminating in various end-of-life scenarios. When individual components or entire life-cycle phases are omitted from the LCA framework [11].

A number of emission estimation methods and research frameworks for assessing environmental impact have been presented in the field of road engineering. Park et al., (2003) assessed the environmental impacts of highways in a life cycle [12]; Fox et al., (2011) applied the results obtained by a carbon mangagement systrem to road projects in Scotland [13]; Tsai and Chang (2012) developed a framework for developing sustainable items for highway design [14]; Avetisyan et al., (2011) established an optimization-based methodology that enables a construction firm to assess its equipment needs while accounting for GHG emissions [15].

Several efforts have been made to gain insight in to the GHGs generated by materials or machines used for road construction. Avetisyan et al., (2011) and Kim et al., (2011) evaluated the GHGs resulting from construction machineries [15, 16]. GHGs emissions from machineries and construction materials are the major contributors to the impact of the road on global warming, specifically when dealing with road transport infrastructure LCA. These two elements jointly account for more than 80% of the GHGs total emissions. A number of authors reported a higher relevance of pavement materials, ranging from 59% to 97% of the total emissions [17, 12], whereas others report higher values for off-road machineries, ranging from 76% to 95% depending on the scope of the particular assessment analysis [18, 19].

Although the evaluation of carbon emission in different regions has been adopted, the LCA model of one country is difficult to apply to another country because of the differences in construction techniques, pavement materials, and the validity and applicability of the data [20]. Therefore, local researchers in Malaysia must propose their own estimation method based on the local circumstances. The main focus of this study is to analyze the carbon footprint for the road pavement rehabilitation for expressways in Sungai Petani, Kedah. The specific aim is to identify the type of pavement material and machinery used at the rehabilitation site in terms of CO_2 emission.

METHODOLOGY

LCA is a commonly used analytical tool for systematically evaluating the environmental aspects of products, processes, or service systems throughout their life cycle. LCA evaluation includes all of the processes associated with a product, from its "cradle raw material extraction" to its "grave-disposal." In this study, LCA is being applied in the road industry for measuring and comparing the key lifetime environmental impacts of asphalt products and laying processes.

This study generated practical results for the application of LCA pavement rehabilitation in Malaysia in accordance with ISO 14040 [21]. The LCA stepwise approach involves guideline goal and scope definition, inventory analysis, life-cycle impact assessment, and interpretation. The system boundary plays a crucial role in LCA [22], as shown in Figure 1.

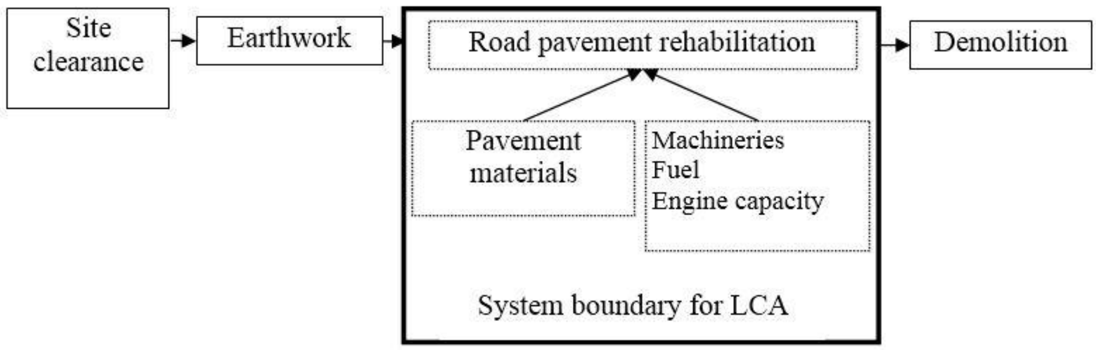


Figure 1: LCA system boundary for road pavement rehabilitation

This study focuses on the machineries and materials used in rehabilitation phases that cover input and output in terms of quantities of materials and fossil fuel consumption for machineries. The input and output flowchart (Figure 2) identifies the machinery type, the pavement materials type (i.e., dense bitumen macadam (DBM), asphaltic concrete binder course (ACBC), and asphaltic concrete wearing course (ACWC)), and fuel consumptions.

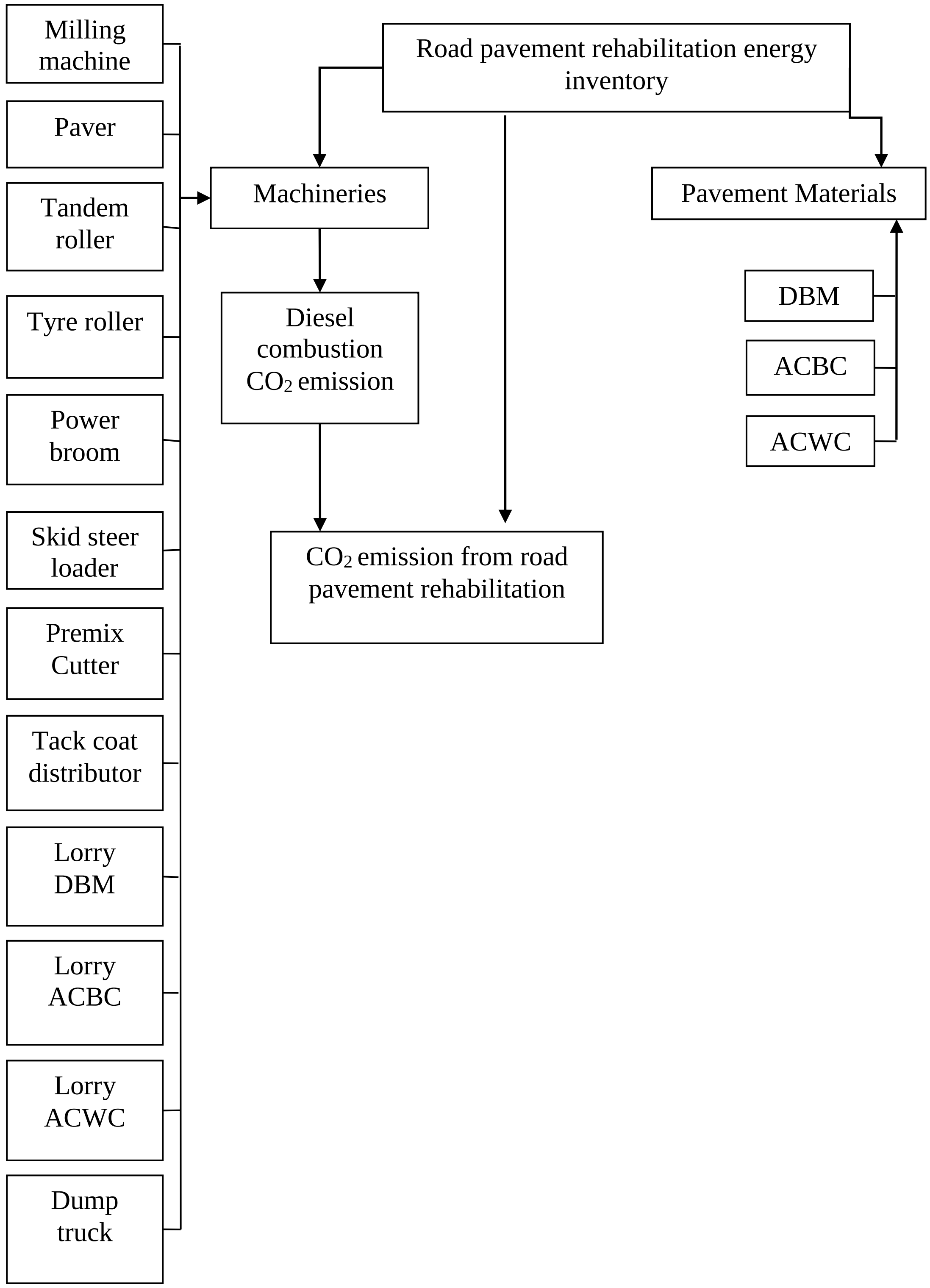


Figure 2: Framework of input and output adopted in the road pavement rehabilitation at Sungai Petani, Kedah

A. Goal and Scope Definition
This study focuses on estimating the carbon footprints of fuel used by machineries in pavement rehabilitation and the impact of materials used in pavement layers. This study area is a geographic location in Kedah, Malaysia, specifically a rehabilitation site along Sungai Petani Utara to Sungai Petani Selatan in section Northern 2 and North–South Expressway for the road length from 99.60 km to 103.00 km.

B. Inventory Analysis
Life cycle inventory (LCI) consists of the relevant inputs and outputs for a given product or system that are identified and quantified throughout its life cycle [23]. The LCI contains the data collected for materials and machineries used in each phase for pavement rehabilitation and calculation procedures. Data collection is the key initial step in designing a carbon emission model, as the data will be the basis for the study. The data were obtained from the respective project officers via interviews and from their daily logbooks. The data include the pavement material quantities in three layers. Table 1summarizes the percentage of pavement materials for the DBM, ACBC, and ACWC layers.

Table 1: Percentage of pavement materials for layers

	Material	**Proportion (% by wt. of aggregate)**	**Source**
DBM	40.0 mm agg.	26.0	Kuad quarry
	25.0 mm agg.	18.0	Kuad quarry
	10.0 mm agg.	14.0	Kuad quarry
	Quarry dust	40.0	Kuad quarry
	Cement	2.0	CIMA berhad
	Bitumen	3.5 - 4.5 (by wt. of mixture)	Petronas
ACBC	28.0 mm agg.	24.0	Kuad quarry
	20.0 mm agg.	18.0	Kuad quarry
	10.0 mm agg.	16.0	Kuad quarry
	Quarry dust	40.0	Kuad quarry
	Cement	2.0	Cement industries
	Bitumen	4.5 - 6.5 (by wt. of mixture)	Petronas
ACWC	28.0 mm agg.	24.0	Kuad quarry
	20.0 mm agg.	18.0	Kuad quarry
	10.0 mm agg.	16.0	Kuad quarry
	Quarry dust	40.0	Kuad quarry
	Cement	2.0	Cement industries
	Bitumen	4.5 - 6.5 (by wt. of mixture)	Petronas

The types of machineries used during the work at the site and the usage time duration of the machineries are shown in Table 3. The engine rating of the machineries and the fuel source used throughout the rehabilitation works were main information considered in this study. Table 2 shows the rating of the engine capacity for calculating the intensity rate of fossil fuel consumption of each machine.

Table 2: Rating of the machinery engine capacity

Machinery	Engine capacity (kW/h)
Milling machine	448
Power broom	28.5
Premix cutter	9.5
Skid steer loader	61.1
Lorry dump truck	208.1
Paver	100
Tandem roller	55.4
Tyre roller	63
Tack coat distributor	80
Lorry DBM	246
Lorry ACBC	246
Lorry ACWC	246

Table 3: Total duration of the machinery operation for each layer

Task	Type of machinery	Duration usage (hour)
Milling works	Milling machine	108
	Power broom	9
	Premix cutter	4
	Skid steer loader	77
	Lorry dump truck	153
DBM	Paver	78
	Tandem roller	38
	Tyre roller	38
	Power broom	13
	Premix cutter	7
	Tack coat distributor	16
	Lorry DBM	189
ACBC	Paver	47

	Tandem roller	23
	Tyre roller	22
	Power broom	10
	Premix cutter	7
	Tack coat distributor	9
	Lorry ACBC	93
ACWC	Paver	52
	Tandem roller	24
	Tyre roller	23
	Power broom	8
	Premix cutter	10
	Tack coat distributor	9
	Skid steer loader	36
	Lorry ACWC	145

The fuel used in the processes was brought by lorry trucks from the supply source, which is 380 km away. This detail is regarded as the fuel transportation inventory value. A total of 1000 L of fuel for associated works was transported each week.

C. Impact assessment

At the impact assessment stage, the magnitude and significance of the environmental impacts of the products or systems are evaluated on the basis of the LCI analysis (LCIA) [23]. The goal of this step is to examine the product or system from an environmental perspective by considering impact categories and category indicators based on the LCI results. LCIA also provides information for the life-cycle interpretation phase. LCIA involves the translation of the environmental pollutants identified during data collection to environmental impacts. Emission Factors (EF_S) is applied to estimate carbon for specific materials [24]. An emission factors are considered the calculating of energy required to produce the materials. In this study, the LCIA used the EF_S to estimate carbon footprints for pavement materials; it can be calculated by multiplying the carbon dioxide equivalents (CO_{2e}) factor to the mass of the material. Table 4 shows the source of CO_{2e}.

Table 4: Material source of CO_{2e}factor

Material	CO_{2e} factor (kg/ton)	Source
Stone aggregate	20.82	Barrett 2002[25]
Quarry dust	750	Metz 2005[26]
Bitumen	0.22	IPCC 2006[27]
Cement	1160	Das and Kandpal 1999[28]

However, the LCIA for machineries utilizes the model developed by the Department for the Environment, Food, and Rural Affairs (DEFRA) of the United Kingdom. This model is the best tool for emission calculation, and it has been peer-reviewed and tested by experts and industry leaders [29]. In the carbon emission model by the DEFRA, the GHG emission assessment involves three LCIA steps[30]. The first step is identifying the fuel mass consumption of the machinery, which can be calculated by multiplying the operation hours of the machinery by the rating of the engine (kW) and fuel mass consumption rate, as in:

$$FMC = D_o \times E_R \times FMR \times 1 \text{ Liter} \quad (1)$$

where:

FMC = Fuel mass consumption (liters)
D_o= Duration usage of operation (hours)
E_R = Rating of engine (kW)
FMR = Fuel mass consumption rate
=0.24 kg/kWh (as recommended by DEFRA)

The second step is calculating the carbon footprint of the embodied energy (EE) by multiplying the FMC (L) with CO_{2e} factor, as in:

$$CF_{EE} = FMC \times CO_{2Df} \quad (2)$$

where:

CF_{EE} = Carbon footprints of embodied energy (tons fossil CO_{2e})
CO_{2Df}= Carbon dioxide equivalent factor of diesel
= 0.0031761 tCO_{2e} (as recommended by the DEFRA)

The last step is calculating the total carbon footprints with the summation of EE and carbon footprint resulting from fuel transport, as in:

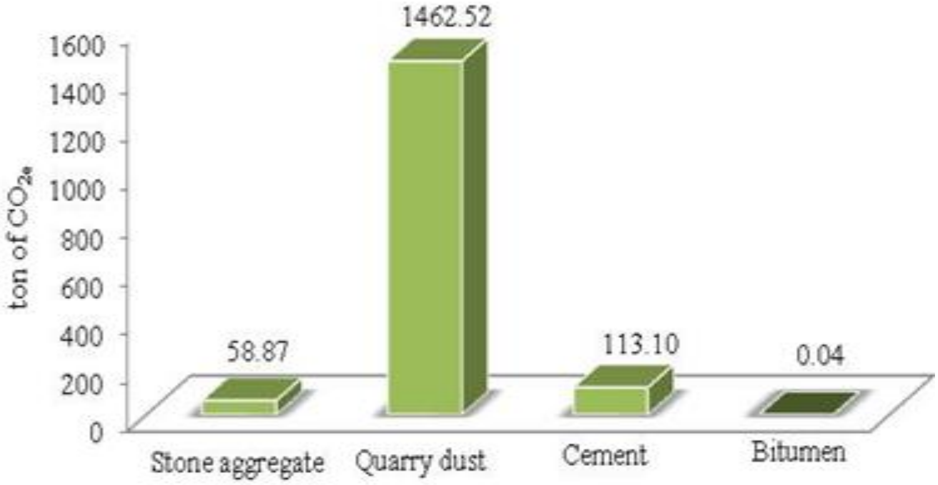
$$CF = CF_{EE} + CF_T \quad (3)$$

where:

CF= Total carbon footprint
CF_{EE}= Carbon footprint of embodied energy (tons fossil CO_{2e})
CF_T = Carbon footprint due to transportation (tons fossil CO_{2e}).

RESULT AND DISCUSSION

Embodied energy (EE) is an accounting methodology that aims to evaluate the sum of the energy necessary to create a product during its entire life cycle [31]. In this case, EE is the sum of the energy input of fuels from the supply source, during transport to the site, and when being used to operate the machinery at the construction site. Thus, the carbon footprint produced is associated with the EE and transportation values [32]. The carbon footprint of the materials in the pavement rehabilitation depended on the quantities of materials and the emission factor for materials. Figure 3 shows the CO_2 emission for each pavement layer.



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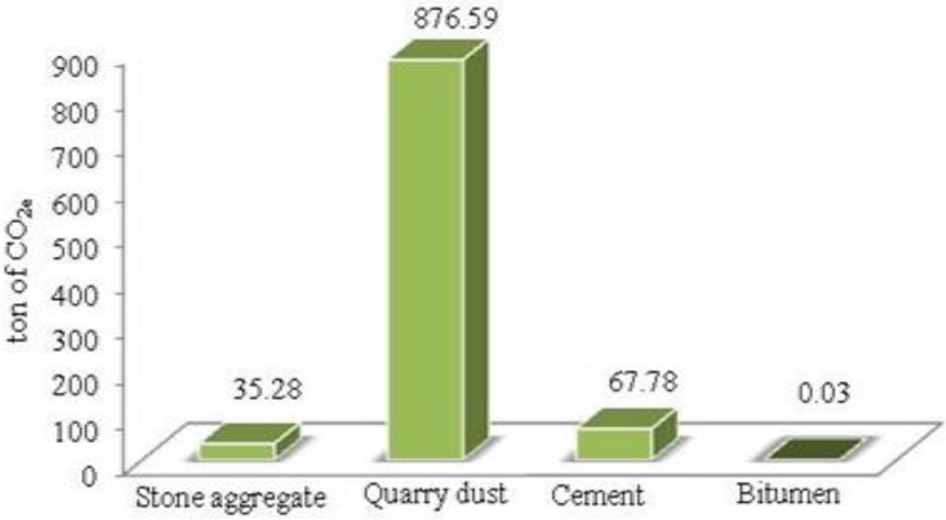

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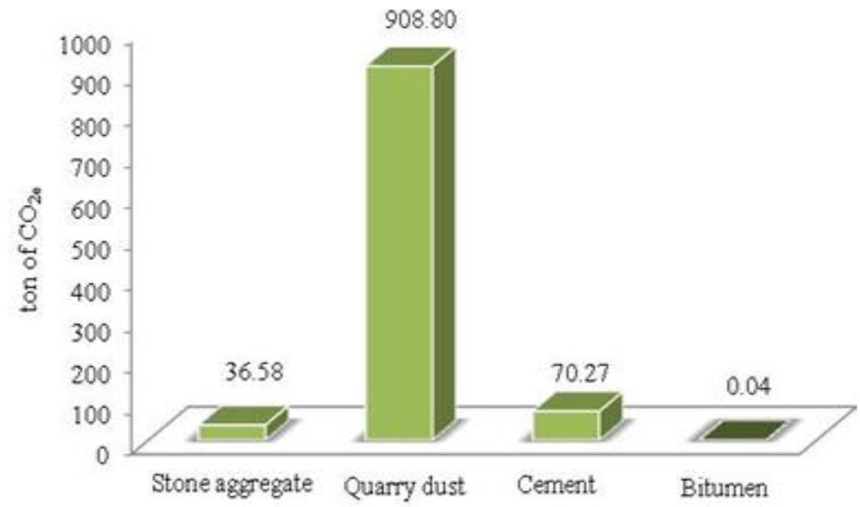


Figure 3: CO_2 emission of the pavement material used in (a) DBM, (b) ACBC, and (c) ACWC

The highest CO_2 emission is generated by quarry dust a total of 1462.52 tons of CO_{2e} in the DBM layer, because the CO_{2e} of quarry dust 750 kg/ton is higher than that of stone aggregate 20.82 kg/ton even though the stone aggregate quantity 2827.54 kg is higher than the quarry dust quantity 1950.02 kg. Meanwhile, the CO_{2e} of cement 1160 kg/ton is higher than that of quarry dust 750 kg/ton, but the carbon emission of quarry dust is higher because the quantity of cement is 97.50 kg lower than that of quarry dust 1950.02 kg. This is followed by the cement, stone aggregate, and bitumen, which emit 113.10, 58.87, and 0.04 tons of CO_{2e}, respectively. Bitumen has the lowest carbon emission, because the CO_{2e} factor of bitumen 0.22 kg/ton is the lowest among all materials. The result for the DBM layer CO_2 emission is shown in Figure 3(a).

Similarly, for the ACBC layer, the highest CO_2 emission 876.59 tons of CO_{2e} is generated by quarry dust, because the CO_{2e} factor of quarry dust 750 kg/ton is higher than that of stone aggregate 20.82 kg/ton even though stone aggregate quantity 1694.75 kg is higher than quarry dust quantity 1168.78 kg. The CO_{2e} of cement 1160 kg/ton is higher than of quarry dust 750 kg/ton, but the carbon emission of quarry dust is higher because the quantity of cement is 58.43 kg lower than that of quarry dust 1168.78 kg. This is followed by cement, stone aggregate, and bitumen, which emit 67.78, 35.28, and 0.03 tons of CO_{2e}, respectively. Bitumen has the lowest carbon emission, because the CO_{2e} factor of bitumen 0.22 kg/ton is the lowest among all materials. This result of CO_2 emission for ACBC layer is shown in Figure 3(b).
Similar to the DBM and ACBC layers, the highest CO_2 emission in ACWC is generated by quarry dust 908.81 tons of CO_{2e}, because the CO_2 equivalent factor of quarry dust 750 kg/ton is higher than that of stone aggregate 20.82 kg/ton even though stone aggregate quantity 1757.02 kg is higher than quarry dust quantity 1211.74 kg. The CO_2 equivalent of cement 1160 kg/ton is higher than that of quarry dust 750 kg/ton, but the carbon emission of quarry dust is higher because the quantity of

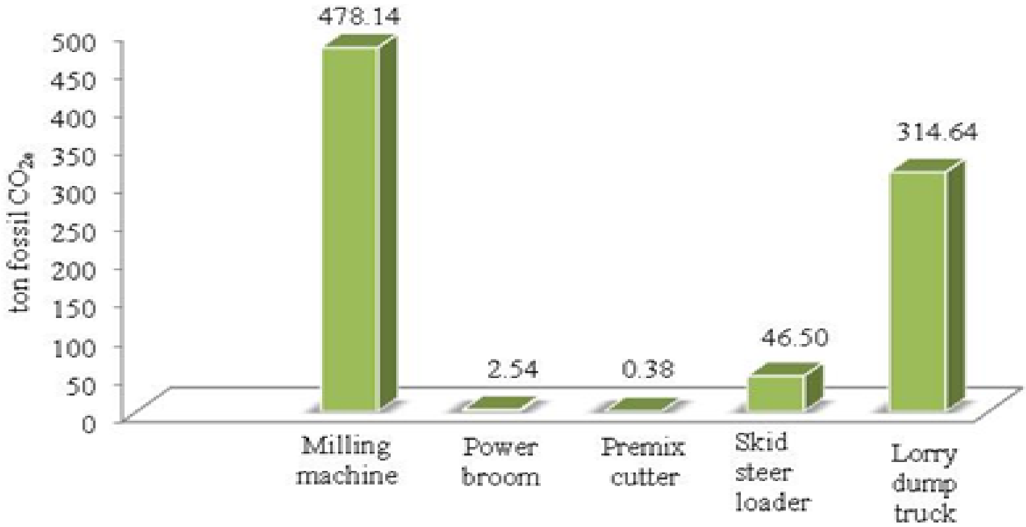
cement is 60.58 kg lower than that of quarry dust 1211.74 kg. This is followed by the cement, stone aggregate, and bitumen, which emit 70.27, 36.58, and 0.04 tons of CO_{2e}, respectively. The carbon emission of bitumen is the lowest because its CO_2 equivalent factor 0.22 kg/ton is the lowest among all materials. This result of CO_2 emission for ACWC layer is depicted in Figure 3(c). Therefore, these findings suggest that the highest emission of carbon footprints is generated by quarry dust in the three layers of road pavement due to large amount used of the material.

The carbon footprints of machineries in road pavement rehabilitation originates from different types of machineries used on the different layers, such as milling work, the DBM layer, the ACBC layer, and the ACWC layer. The produced carbon footprint is associated with the EE and transportation values. Table 5 shows the total carbon footprint emitted from pavement rehabilitation.

Table 5: Total carbon footprint emitted at the pavement rehabilitation site of Sungai Petani, Kedah

Task	Type of machinery	Carbon footprint (tons fossil CO_{2e})		
		Embodied	**Transport**	**Total**
Milling works	Milling machine	36.88	441.26	478.14
	Power broom	0.20	2.34	2.54
	Premix cutter	0.03	0.35	0.38
	Skid steer loader	3.59	42.91	46.50
	Lorry dump truck	24.27	290.37	314.64
Total		**64.97**	**777.23**	**842.20**
DBM	Paver	5.95	71.14	77.09
	Tandem roller	1.60	19.20	20.80
	Tyre roller	1.82	21.83	23.65
	Power broom	0.28	3.38	3.66
	Premix cutter	0.05	0.61	0.66
	Tack coat distributor	0.98	11.67	12.65
	Lorry DBM	35.44	424.03	459.47
Total		**46.12**	**551.86**	**597.98**
ACBC	Paver	3.58	42.86	46.44
	Tandem roller	0.97	11.62	12.59
	Tyre roller	1.06	12.64	13.70
	Power broom	0.22	2.60	2.82
	Premix cutter	0.05	0.61	0.66
	Tack coat distributor	0.55	6.57	7.12
	Lorry ACBC	17.44	208.65	226.09
Total		**23.87**	**285.55**	**309.42**

ACWC	Paver	3.96	47.42	51.38
	Tandem roller	1.01	12.13	13.14
	Tyre roller	1.10	13.21	14.31
	Power broom	0.17	2.08	2.25
	Premix cutter	0.07	0.87	0.94
	Tack coat distributor	0.55	6.57	7.12
	Skid steer loader	1.68	20.06	21.74
	Lorry ACWC	27.19	325.31	352.50
Total		**35.73**	**427.65**	**463.38**



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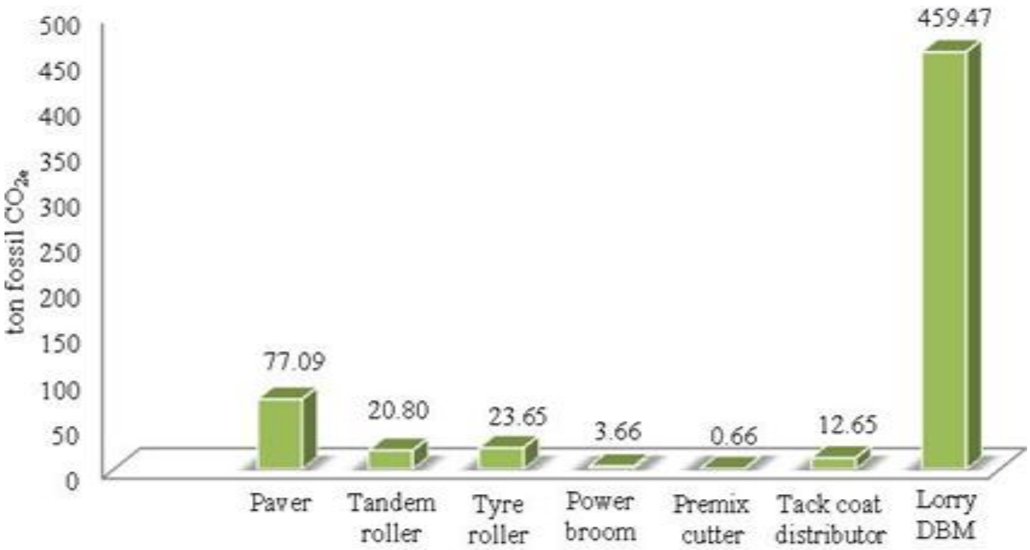

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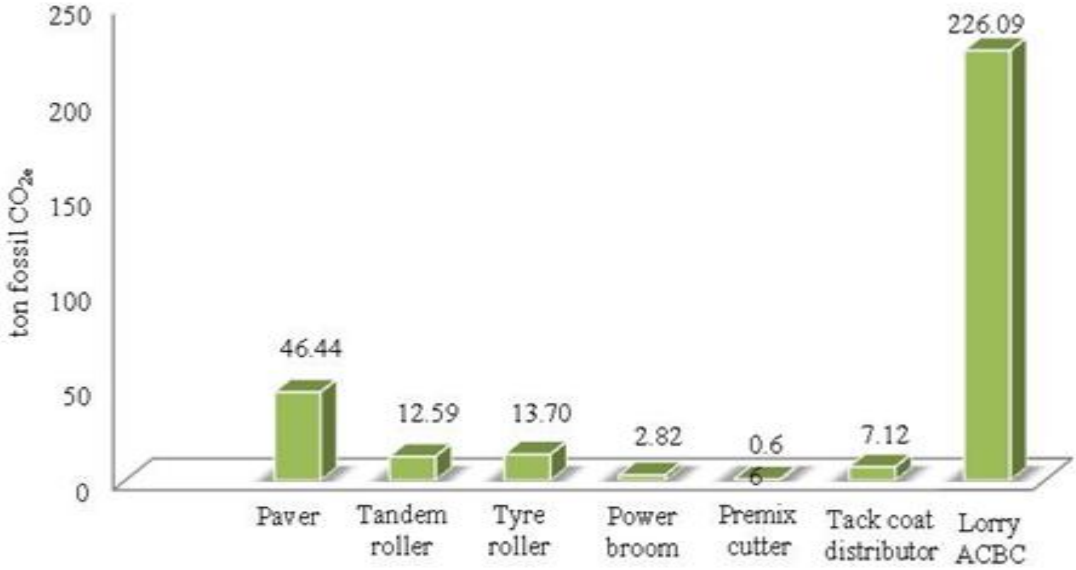

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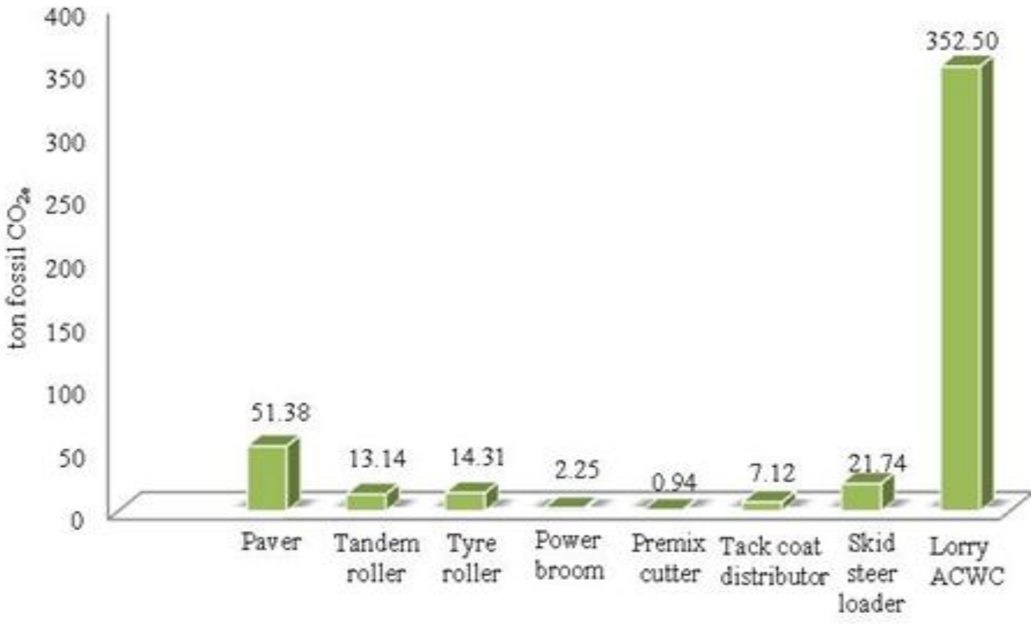

(d)

Figure 4: CO_2 emission of the machineries used in (a) milling machine, (b) DBM, (c) ACBC, and (d) ACWC

In milling work, five different machineries are used, namely, milling machine, power broom, premix cutter, skid steer loader, and lorry dump truck, as shown in Figure 4(a). The carbon footprint from the milling machine 478.14 tons fossil CO_{2e} is the highest among all of the machines because it has the greatest engine capacity 448 kW/h. Moreover, the duration usage for the milling machine is 108 hours, causing greater carbon emission. The lowest carbon footprint 0.38 tons fossil CO_{2e} is emitted by the premix cutter because it has the lowest engine capacity 9.5 kW/h and the shortest duration usage 4 hours. For the DBM layer, the highest carbon footprint 459.47 tons fossil CO_{2e} is from the lorry DBM and the lowest 0.66 tons fossil CO_{2e} is from the premix cutter. The duration usage and engine capacity of the lorry DBM are 189 hours and 246 kW/h, respectively, which are the highest among all of the machines. Therefore, the lorry DBM emits more carbon. The premix cutter has the lowest carbon emission because its duration usage and engine capacity are 7 hours and 9.5 kW/h, respectively. The carbon footprints from the different types of machineries used in pavement rehabilitation in the DBM layer are shown in Figure 4(b).

For the ACBC layer the highest carbon footprint 226.09 tons fossil CO_{2e} is from the lorry ACBC and the lowest 0.66 tons fossil CO_{2e} is from the premix cutter. The duration usage and engine capacity of the lorry ACBC are 93 hours and 264 kW/h, respectively, which are the highest among all machines, causing the lorry ACBC to emit the most carbon. Meanwhile, the premix cutter has the lowest carbon emission because its duration usage and engine capacity are 7 hours and 9.5 kW/h, respectively. The carbon footprints from the different types of machineries used in the pavement rehabilitation in the ACBC layer are shown in Figure 4(c).

For the ACWC layer, the highest carbon footprints 352.50 tons fossil CO_{2e} is from the lorry ACBC and the lowest 0.94 tons fossil CO_{2e} is from the premix cutter. The duration usage and engine capacity of the lorry ACWC are 145 hours and 246 kW/h, which are the highest among all machines, causing the lorry ACWC to emit the most carbon. Meanwhile, the premix cutter has the lowest carbon emission because its duration usage and engine capacity are 10 hours and 9.5 kW/h, respectively. The carbon footprints from the different types of machineries used in the pavement rehabilitation in the ACWC layer are shown in Figure 4(d).

Comparing the results with CO_2 emission estimations of pavement rehabilitation works in previous studies is difficult because, to our knowledge, few studies have conducted emission estimations of road pavement rehabilitation. In a study in India, the emission from the materials used in highway construction, which included pavement, culverts, bridges, underpass, and road over bridges, for a total length of 386 km was 33531.12 tons. The length of highways and the quantities of materials are different, so the results would vary [33]. The total carbon footprint of the onsite rehabilitation works is 5842.87 tons.

While the CO_2 in onsite construction of four projects was estimated to be 97222, 69190, 97104, and 43134 tons for the length of 97.455, 23.698, 41.140, and 50.578 km, respectively, in China [34]. Another study used CHANGER to find that the carbon footprint of road construction for three projects were 29932, 359750, and 8541.2 tons for the length of 28, 250, 52.4 km in the United Kingdome, the United Arab Emirates, and India, respectively [35]. Furthermore, a case study during a highway construction for five tunnels in western China estimated that the highest CO_2 emission was 9639.5 tons for 3.25 km and the lowest was 3467.9 tons for 1.34 km [36].

In the present study, the largest contributors to CO_2 emission are the milling machine 478.14 tons fossil CO_{2e} and milling work task 842.20 tons fossil CO_{2e}, for the length of 3.4 km, whereas another study found the largest contributor to CO_2 emission were the dump truck machine 587.75 tons for 10.13 km in a road pavement construction in Korea and earthwork 1013.89 tons [37].

CONCLUSION

In summary, the carbon footprint hotspot was centered on quarry dust for the three layers pavement and the milling machine had the highest carbon emission in this road pavement rehabilitation, due to the large amount used of material and highest engine capacity of milling machine. This identified hotspot improves our understanding of the contribution of energy and carbon emissions, especially for pavement rehabilitation tasks that utilizes different types of machineries. The highway construction in Malaysia must realize the importance of mitigating carbon emission. More local studies should be conducted to obtain highly comprehensive findings on carbon emission and environmental impacts of using materials and machineries in pavement rehabilitation.

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