Measuring Carbon Footprint of Flexible Pavement Construction Project in Indonesia

Jati Utomo Dwi Hatmoko¹,*, Arif Hidayat¹, Apsari Setiawati¹, and Stefanus Catur Adi Prasetyo¹

¹Civil Engineering Department, Diponegoro University, Semarang - Indonesia

Abstract. Road infrastructure in Indonesia is mainly dominated by flexible pavement type. Its construction process, however, has raised concerns in terms of its environment impacts. This study aims to track and measure the carbon footprint of flexible pavement. The objectives are to map the construction process in relation to greenhouse gas (GHG) emissions, to quantify the GHG emissions in terms of carbon dioxide equivalents (CO₂e) as generated by the process of production and transportation of raw materials, and the operation of plant off-site and on-site project. Data collection was done by having site observations and interviews with project stakeholders. The results show a total emissions of 70.888 tonnes CO₂e, consisting of 34.248 tonnes CO₂e (48.31%) off-site activities and 36.640 tonnes CO₂e (51.687%) on-site activities. The two highest CO₂e emissions were generated by the use of plant for asphalt concrete laying activities accounted 34.827 tonnes CO₂e (49.130%), and material transportation accounted 24.921 tonnes CO₂e (35.155%). These findings provide a new perspective of the carbon footprint in flexible pavement and suggest the urgent need for the use of more efficient and environmentally friendly plant in construction process as it shows the most significant contribution on the CO₂e. This study provides valuable understanding on the environmental impact of typical flexible pavement projects in Indonesia, and further can be used for developing green road framework.

1 Introduction

The construction industry is one of important sectors in national infrastructure development. While it supports national economy, a series of construction activities is potentially harmful to the environment. In 2010, the construction sector contributed 18% directly or indirectly to greenhouse gas emissions [1]. In 2007, China’s construction sector accounted for nearly 50% of total energy use in which major energy-producing contributors were; materials, heating, fuels, and electricity supply [2]. As the largest CO₂ emitter since 2013 China’s emissions even showed an upward trend as a quadratic polynomial [3].

One of the construction sectors that produce significant greenhouse gas emissions is road construction, which will continue to increase along with the growth of the road length built by the government. Road infrastructure in Indonesia is dominated by flexible pavement which allegedly produces high greenhouse gas emissions due to changes in land conditions and functions, and the consumption and exploitation of resources. This is in line with a study in the Netherland which compared emissions from different types of pavement and that found that flexible pavement emits carbon emissions higher than rigid pavement and brick roads mostly from production and construction activities [4]. Life cycle assessment on flexible pavement construction activities showed that it generated twice higher carbon emissions than that of rigid pavement construction activities [5].

The carbon emissions have been closely linked to global warming and will leave carbon footprint. Although it has now become one of main environmental indicators [6], however it has been defined differently, e.g. [7-11]. One of the most cited common definitions of Carbon footprint is; a measure of the whole sum of CO₂ emissions resulted directly or indirectly from activities of individual, organization, process, industry sectors over the life cycle of a product (goods and services) [12]. The importance of relating the environmental aspects, in terms of energy consumption and carbon emissions, with the decision of pavement design has been promoted as opposed to typically cost consideration [13].

This study aims to track and measure the carbon footprint of flexible pavement construction. The objectives are to map the construction process in relation to greenhouse gas (GHG) emissions, to quantify the GHG emissions in terms of carbon dioxide equivalents (CO₂e) as generated by the process of production and distribution of raw materials, and the operation of plant in the project.

2 Highway Pavements

The highway pavement is a section of highway which is hardened by a certain construction layer. It has a certain
thickness, strength, and stiffness, and stability in order to be able to channel the traffic load on it to the ground safely. Other factors, such as environmental condition, temperature, seepage and properties of materials also influence the behaviour of the pavement [14].

Flexible pavement is one type of road pavement that uses asphalt as a binder. Typical layers of flexible pavement include sub-grade, sub-base, and base courses, binder course, and surface course and have the function to carry and transfer traffic loads to the sub-grade (Fig. 1). Based on temperature during mixing and compacting, asphalt concrete is divided into hot mix, warm mix, and cold mix. This study focuses on hot mix asphalt concrete as it is the most commonly works method and is considered to meet pavement requirements. A typical cross section of the flexible pavement is shown in Fig. 2.

| No  | Sequence of Work | Description |
|-----|------------------|-------------|
| 1   | Sub-base Course  | Mixing and loading the aggregate in a Dump Truck using Wheel Loader in Base Camp. Transporting aggregate to the job site by Dump Truck and overlaid it using Motor Grader. Overlay aggregate wetted with Water Tank Truck before compacted using Tandem Roller and pneumatic tandem roller. During compacting, a group of workers will tidy up the edge of the expans and surface level using a tools. |
| 2   | Base Course      | Wheel Loader mixes and loads aggregate into Dump Truck in Base Camp. Dump truck transports aggregate to the job site and overlaid it with Motor Grader. Overlay aggregate wetted with Water Tank Truck before compacted using Tandem Roller and Pneumatic Tandem Roller. During compacting, a group of workers will tidy up the edge of the expans and surface level using a tools. |
| 3   | Asphalt Concrete - Base | Wheel Loader loads aggregate into AMP’s Cold Bin. Aggregates and asphalts are mixed and heated by AMP and to be loaded directly into the Dump Truck and transported to the job site. The AC-Base hot mix is overlaid by Finisher and compacted by Tandem Roller and Pneumatic Tandem Roller. During compacting, a group of workers will tidy up the edge of the expans and surface level using a tools. |
| 4   | Asphalt Concrete - Base Course | Wheel Loader loads aggregate into AMP’s Cold Bin. Aggregates and asphalts are mixed and heated by AMP and to be loaded directly into the Dump Truck and transported to the job site. During compacting, a group of workers will tidy up the edge of the expans and surface level using a tools. |
| 5   | Asphalt Concrete - Wearing Course | Wheel Loader loads aggregate into AMP’s Cold Bin. Aggregates are mixed and compacted by Tandem Roller and Pneumatic Tandem Roller. During compacting, a group of workers will tidy up the edge of the expans and surface level using a tools. |

Fig. 1. Typical layers of flexible pavement

Fig. 2. Cross-section of the flexible pavement

3 Construction Method of Flexible pavement

The stages of flexible pavement work include preparatory work, sub base and base course work, and surface course work. Preparatory work related to the survey, and preparation of body of the road. Sub-base and base work include spreading work using grader, and compaction work using roller and worked after the sub-grade meets the elevation and density requirements.

Surface course work includes prime coat work, and asphalt concrete work using asphalt finisher, dozer, and pneumatic tired roller. Table 1 shows the sequence of works of a flexible pavement project as observed from Salatiga Ring Road project from STA. 9 + 285 to STA. 9 + 385.

4 Carbon Emissions of Construction Resources

In the construction industry the CO2 emission varies along the project life cycle, however the density of the CO2 emissions is the highest in construction phase compared to operation and maintenance phases [15, 16]. Construction materials and the use of plant during construction phase have the potential to generate greenhouse gas emissions through the exploitation of materials in nature, and the use of fossil fuels during the production process. Plant refers to all heavy machinery and equipment utilised for construction works.

According to the Kyoto Protocol 2007 [17], there are six main greenhouse gases, namely carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFHCs) and sulphur hexafluoride (SF6). Internationally, the effect size of a process on the environment is gas emissions equalized with CO2 equivalent (CO2e). CO2e...
The material production includes the processing and laying for road sub-base, base, and surface courses. The operation of plant use for asphalt concrete production covers off-site and on-site project activities (Fig. 3). Off-site activities include material production and transportation, while onsite activities examine the site activities include material production and transportation, respectively. Material production stage includes the amount of CO2 emissions associated with the mining, processing, and production of materials construction. Material transportation stage includes the amount of CO2 emissions associated transportation of construction materials from the source or manufacture to the site. Plant use stage includes the amount of CO2 emissions associated with the fuels consumption during the construction of sub base and base course, and surface course. The carbon footprint measurement in this study covers off-site and on-site project activities (Fig. 3). Off-site activities include material production and transportation, while onsite activities examine the operation of plant use for asphalt concrete production and laying for road sub-base, base, and surface courses. The material production includes the processing of natural materials, such as coarse aggregate and fine aggregate, fillers and asphalt. Material transportation generates carbon emissions by bringing the natural materials from the sources to project site, using dump trucks for aggregate and filler, and tank truck for asphalt. The production of asphalt concrete operates AMP and wheel loader. While for asphalt concrete laying more plant were used, such as dump truck, motor grader, vibrator roller, water tanker, etc.

Carbon footprint can be classified as embodied carbon (EC) and operational carbon (OC) [20]. EC is emissions resulted from the production, transportation and construction stages. OC is carbon emissions resulted from the utilization of built facilities, which is normally believed to be higher than the EC. However, estimating the EC values are challenging due to variability of project characteristics, e.g. construction type, design, site condition, etc.

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The method of this study is a case study method carried out by quantifying the CO2e emissions generated during the construction of flexible pavement including material production and transportation, and the plant operation. Material production stage includes the amount of CO2e emissions associated with the mining, processing, and production of materials construction. Material transportation stage includes the amount of CO2e emissions associated transportation of construction materials from the source or manufacture to the site. Plant use stage includes the amount of CO2e emissions associated with the fuels consumption during the construction of sub base and base course, and surface course. Data analysis techniques of this study is quantitative analysis by multiplying each factor causing CO2 emissions in construction with emission factor as presented in equations 1, 2, and 3.

\[ \text{CO2eMP} = V \times \text{EFMP} \]  
\[ \text{CO2eMT} = \text{TFCMT} \times \text{EFMT} \]  
\[ \text{CO2ePU} = \text{TFCPU} \times \text{EFPU} \]  

where CO2eMP, CO2eMT, and CO2ePU denote the carbon emissions equivalent for material production, material transportation, and plant use, respectively. \( V \) denotes the volume of materials. EFMP, EFMT, and EFPU denote the emission factor for material production (kg CO2/ton), material transportation (kg CO2/litre), and plant use (kg CO2/litre), respectively. TFCMT and TFCPU denote Total Fuel Consumption (litre) for material transportation and plant use, respectively.

### 5 Research method

The object of this study is Salatiga Ring Road project from STA. 9 + 285 up to STA. 9 + 385 with four 3.625-meter-width lanes and flexible pavement type (Fig. 2). Data collection was done by having regular site observations to flexible road projects, interviews with project stakeholders, as well as document analysis. Site observation was carried out to understand the construction methods (see Table 1), procedure, including the materials and equipment used in the project. Interview with project staffs enhanced the understanding of the common practice in the typical projects.

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### 6 Results and analysis

#### 6.1 CO2e emissions from off-site construction project activities

#### 6.1.1 CO2eEmissions of Material Production

For material production, the CO2e emission is calculated by multiplying the volume of each material with emissions factor as presented in Table 3. The total CO2e emission in material production for all road layers is 9.327 tonnes CO2e. Asphalt contributes the highest CO2e of 7.564 tonnes CO2e, followed by coarse aggregate contributes of 1.247 tonnes CO2e, fine aggregate contributes of 0.515 tonnes CO2e, and filler contributes 0 tonnes CO2e (Fig. 4).
Table 3 The CO₂e emissions in material production

| No | Components             | Materials | Volume (Kg) | Emissions Factor kg CO₂/ton | Total Emissions (Tonnes CO₂e) |
|----|------------------------|-----------|-------------|----------------------------|--------------------------------|
| 1  | Subbase course (t=15 cm) | Coarse agg. | 609         | 1.067                       | 0.650                          |
|    |                        | Fine agg.  | 203         | 1.067                       | 0.217                          |
| 2  | Base course (t=15 cm)   | Coarse agg. | 380.625     | 1.067                       | 0.406                          |
|    |                        | Fine agg.  | 126.875     | 1.067                       | 0.135                          |
| 3  | Prime coat             | Asphalt   | 1.951       | 11.91                       | 5.924                          |
| 4  | Tack coat              | Asphalt   | 0.525       | 11.91                       | 1.595                          |
| 5  | AC – Base (t=6 cm)     | Coarse agg. | 73.892      | 1.067                       | 0.079                          |
|    |                        | Fine agg.  | 53.998      | 1.067                       | 0.058                          |
|    |                        | Filler     | 0.004       | 1.067                       | 0.000                          |
|    |                        | Asphalt    | 0.006       | 11.91                       | 0.019                          |
| 6  | AC – Base course (t=6 cm) | Coarse agg. | 60.9        | 1.067                       | 0.065                          |
|    |                        | Fine agg.  | 70.644      | 1.067                       | 0.075                          |
|    |                        | Filler     | 0.005       | 1.067                       | 0.000                          |
|    |                        | Asphalt    | 0.006       | 11.91                       | 0.017                          |
| 7  | AC – Wearing course (t=4 cm) | Coarse agg. | 44.66       | 1.067                       | 0.048                          |
|    |                        | Fine agg.  | 28.42       | 1.067                       | 0.030                          |
|    |                        | Filler     | 0.002       | 1.067                       | 0.000                          |
|    |                        | Asphalt    | 0.003       | 11.91                       | 0.010                          |
|    | Total                  |            |             |                            | 9.327                          |

The CO₂e emissions in terms of plant operation are released during the process of compaction and asphaltting. The CO₂e emissions is calculated by multiplying the total of fuel consumption associated plant use in construction site and AMP with emissions factor as presented in Table 5. It shows the total CO₂e emission related to the plant operation is 36.64 tonnes CO₂e.

6.2 CO₂e emissions from on-site construction project activities (asphalt concrete production and laying)

The CO₂e emissions in terms of plant operation are released during the process of compaction and asphaltting. The CO₂e emissions is calculated by multiplying the total of fuel consumption associated plant use in construction site and AMP with emissions factor as presented in Table 5. It shows the total CO₂e emission related to the plant operation is 36.64 tonnes CO₂e.
Table 5 CO$_2$e emissions for plant operation on on-site

| No | Components | Vol. (m$^3$) | Units | Plants | Operational Time (hour) | Fuel Consump (gal/hour) | Total Fuel Consump (litre) | Total Emissions (Tonnes CO$_2$e) |
|----|------------|-------------|-------|-------|-------------------------|------------------------|---------------------------|----------------------------------|
| (1) | Sub base course (t = 15 cm) | 580 | 5 | Wheel Loader | 0.061 | 35.380 | 2.08 | 278.908 | 0.742 |
| | | | | Dump Truck | 0.292 | 169.418 | 5.50 | 3531.518 | 9.394 |
| | | | | Motor Grader | 0.011 | 6.612 | 6.00 | 150.357 | 0.400 |
| | | | | Vibro | 0.017 | 10.092 | 10.50 | 401.611 | 1.068 |
| | | | | Water Tanker | 0.021 | 11.948 | 5.00 | 226.415 | 0.602 |
| | Base course (t = 15 cm) | 362.5 | 4 | Wheel Loader | 0.061 | 22.112 | 2.08 | 174.317 | 0.464 |
| | | | | Dump Truck | 0.292 | 105.886 | 5.50 | 2207.199 | 5.871 |
| | | | | Motor Grader | 0.011 | 4.132 | 6.00 | 93.973 | 0.250 |
| | | | | Vibro | 0.017 | 6.308 | 10.50 | 251.007 | 0.668 |
| | | | | Water Tanker | 0.021 | 7.468 | 5.00 | 141.509 | 0.376 |
| | Prime coat | 1885 | 3 | Asph. Sprayer | 0.335 | 5.613 | 1.50 | 319.10 | 0.085 |
| | | | | Air Compress | 0.000 | 0.631 | 0.26 | 0.631 | 0.002 |
| | Tack coat | 507.5 | 2 | Asph. Sprayer | 0.335 | 0.170 | 0.26 | 0.170 | 0.000 |
| | | | | Air Compress | 0.000 | 5.613 | 1.50 | 319.10 | 0.085 |
| | AC – Base (t = 6 cm) | 101.5 | 1 | Wheel Loader | 0.048 | 4.842 | 2.08 | 38.167 | 0.102 |
| | | | | AMP | 0.054 | 5.491 | 4.00 | 83.246 | 0.221 |
| | | | | Genset | 0.054 | 5.491 | 4.00 | 83.246 | 0.221 |
| | | | | ASP | 1.329 | 134.934 | 5.50 | 2812.701 | 7.482 |
| | | | | ASPH | 0.068 | 6.861 | 8.52 | 221.623 | 0.590 |
| | | | | Tandem Roll | 0.028 | 2.842 | 4.00 | 43.085 | 0.115 |
| | | | | Pneumatic Tyre | 0.021 | 2.121 | 4.00 | 32.160 | 0.086 |
| | | | | Wheel Loader | 0.048 | 4.150 | 2.08 | 32.714 | 0.087 |
| | | | | AMP | 0.054 | 4.707 | 4.00 | 71.354 | 0.190 |
| | | | | Genset | 0.054 | 4.707 | 4.00 | 71.354 | 0.190 |
| | | | | Dump Truck | 1.392 | 121.139 | 5.50 | 2525.138 | 6.717 |
| | | | | ASPH | 0.068 | 5.881 | 8.52 | 189.963 | 0.505 |
| | | | | Tandem Roll | 0.028 | 2.436 | 4.00 | 36.930 | 0.098 |
| | | | | Pneumatic Tyre | 0.021 | 1.818 | 4.00 | 27.565 | 0.073 |
| | | | | Wheel Loader | 0.002 | 0.110 | 2.08 | 0.869 | 0.002 |
| | | | | AMP | 0.002 | 0.122 | 4.00 | 1.846 | 0.005 |
| | | | | Genset | 0.002 | 0.122 | 4.00 | 1.846 | 0.005 |
| | | | | ASPH | 0.010 | 6.113 | 5.50 | 127.430 | 0.339 |
| | | | | Tandem Roll | 0.002 | 0.093 | 4.00 | 1.407 | 0.004 |
| | | | | Pneumatic Tyre | 0.002 | 0.128 | 4.00 | 1.934 | 0.005 |
| Total | | | | | | | | 36.64 |

The great volume of asphalt as well as great distance from AMP to site (approximately 80 km) have great impact on the fuel consumption, which linked to significant CO$_2$e emissions emitted.

7 Discussions

Table 6 summarizes the results of the research that the total emissions of this project is 70.888 tonnes CO$_2$e. It can be seen that the highest CO$_2$e emissions were generated by the use of plant for on-site activities 36.640 ton CO$_2$e (51.687%), particularly for asphalt concrete laying activities accounted 34.827 (49.130%). The CO$_2$e emission of material transportation is the second highest accounted 24.921 (35.155%). Both asphalt concrete laying activities and material transportation indeed operate plant, particularly dump trucks, intensively during construction works, which obviously will generate significant amount of CO$_2$e. This condition is

Figure 5 shows that operation of dump trucks contributes the highest CO$_2$e emissions of 29.803 tonnes CO$_2$e, which leaves a significant gap compared with other types of plant.
worsened by the great distance to transport materials (fine aggregate) from the quarry to project site, and asphalt from the AMP location to project site. 

Table 6. Summary of CO₂e emission of Flexible Pavement

| Material Production | CO₂e emission off-site project (ton CO₂e) | CO₂e emission on-site project (ton CO₂e) | Total CO₂e emissions (ton CO₂e) |
|---------------------|------------------------------------------|------------------------------------------|------------------------------|
| Material Transport  |                                          |                                          |                              |
| Asphalt Concrete production | 1.813 | 34.827 | 36.640 |
| Asphalt Concrete Laying | (2.557%) | (49.130%) | (51.687%) |
|                      | 9.327 | 24.921 | 24.921 |
|                      | (13.157%) | (35.155%) | (35.155%) |

In this context, where great distance of transporting materials contributes significantly to the amount of CO₂e emissions, it is very important to manage plant and resource allocation to get optimum results. The AMP should be located as near as possible to the site to reduce time travel as well as reducing the carbon emissions. Closer distance will also minimize risks of travelling, such as traffic jam, accident, while at the same time maintaining the quality of hot asphalt from the AMP. In addition, with the significant contribution of plant operation of carbon emissions, there is also an urgent need for the use of more efficient and environmentally friendly plant in the construction process.

As coarse and fine aggregates are dominant materials in the flexible pavement, the use of recycled materials is one option to reduce the amount of energy and carbon emissions. Recycling will minimize the need for material extraction from nature, processing and production which eventually will contribute to reducing carbon emissions. This has been addressed by several studies, e.g. [21-23].

The results of this research provide a new perspective in comparison to the results of a study in China [24]. Using similar method to estimate carbon emissions from construction steps, i.e. production of materials, transportation of materials, and on-site construction activities, they found that most CO₂e emissions (over 80%) were contributed by production of raw materials. On-site activities and transporting materials generated only 10% and 3% of the total CO₂ emissions. While Wirahadikusuma et al [25] found that aggregate drying process at the AMP contributed most on energy consumption (68%) and carbon emissions (70-75%).

As each project is unique, the difference can be caused by distance of sources of materials, types of plant used, construction method, site condition, etc. These factors may explain why various results may be obtained from various researches. Nonetheless, the findings of this research provides a new perspective of the carbon footprint in flexible pavement in Indonesia, and suggest opportunities for developing research areas related to road pavement technology which is more environmentally friendly. On top of that, use of more efficient plant, recycled materials, and better management will help reducing carbon emission from the construction sector to tackle global warming.

8 Conclusions

This research has successfully tracked and measured the carbon footprint of flexible pavement, using Salatiga Outer Ring Road STA. 9 + 285 to STA. 9 + 385 with four 3.625-meter-width lanes as the case study. The total emissions of this project is 70.888 tonnes CO₂e, consisting of 34.248 tonnes CO₂e (48.31%) off-site activities and 36.640 tonnes CO₂e (51.687%) on-site activities. The two highest CO₂e emissions were generated by the use of plant for on-site activities for asphalt concrete laying activities accounted 34.827 tonnes CO₂e (49.130%), and material transportation accounted 24.921 (35.155%).

The findings of this research provide new information and portray pictures of carbon footprint sources and quantification model of carbon emissions in flexible pavement project. It has also provided a case study which may help stakeholders including government in formulating policies for national green road development. To gain more comprehensive understanding on the carbon footprint, it is recommended for future research to include also emissions at the operational and maintenance stages, as well as sub grade compaction work. In addition, as one case study may have limitation for generalization, more number of flexible pavement projects may provide more evidence and more comprehensive results.

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