Quantifying energy consumption and greenhouse gas emissions of construction projects: A case study of Semarang - Bawen road project

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Abstract. Roads have significant impacts on the environment, economy and society, and the choice of pavement thus has broad implications. All phases of road development, from construction to operations, consume a vast amount of resources and produce waste and emissions. This study aims to examine energy consumption and greenhouse gas (GHG) emissions of a road construction project using Life Cycle Assessment (LCA) approach. Semarang-Bawen section road project was used as a case study, which uses Asphalt Concrete-Wearing Course (AC-WC) and Asphalt Concrete-Binder Course (AC-BC) layers for flexible pavement, and concrete slabs for rigid pavement. The methods used to estimate energy consumption and GHG emissions refers to the Intergovernmental Panel on Climate Change (IPCC) procedure, i.e. the Energy Use and GHG Emissions for Pavement Construction, and Fuel Conversion Method. The results show energy consumption of the project for the flexible and rigid pavements are 1193.79 GJ and 952.056 GJ, respectively. This indicates that the flexible pavement contributes to CO₂ emissions greater than the rigid one. The flexible pavement has a total emission of 89257.96 kgCO₂/km, while the rigid pavement is of 70464.53 kgCO₂/km. Based on these results it can be concluded that rigid pavement is considered more environmentally friendly than flexible pavement.

1. Introduction

Roads are one of important components of the infrastructure development of a country, including Indonesia. Roads are one of the transport infrastructures which plays a major role in people's lives and promotes public welfare [1]. Road construction and regular maintenance work require materials which can be produced through a process that is very carbon intensive and consume lots of energy [2]. Road construction is heavily dependent on natural materials, such as soil, stone, limestone, cement and asphalt. A significant number of studies have found that the conventional installation of asphalt pavements can contribute to vast amount of energy consumption and carbon emissions that are not favourable to environmental conservation and sustainable construction [3]. The use of non-renewable materials and natural resources can be a problem for future generations. Development programs that pay attention to social, economic, and environmental aspects have been launched by many countries and have become a joint agreement as sustainable development. Efforts leading to sustainable road development in Indonesia are based on the principles of sustainable road development used by other countries [4].

Roads have a major effect on the climate, economy and society, and pavement options also have wide consequences. All phases of road production, from construction to operations, consume vast amounts of environment products and resources and generate waste and emissions [5]. During the paving construction process significant volumes of energy consumption and particulate emissions are generated. Roads are constructed in multiple layers, consisting of subgrade, subbase, base and surface layers. Together these layers make up the pavement. The paving may be constructed from a wide range of materials and mixtures of gravels, cement, asphalt, concrete or strengthened soils. The types
of materials and thickness of the pavement layers shall be determined by the projected traffic level. There are three primary types of pavements, i.e. flexible pavement (asphalt), rigid pavement (portland cement concrete) and hybrid pavement (both flexible and rigid layers exist in the same pavement) [6].

Despite growing exposure to sustainable development, the feasibility study is gradually emphasizing environmental considerations and future impacts of prospective projects. Greenhouse gas (GHG) emissions have become essential environmental standards after the Kyoto Protocol initiated a more coordinated international initiative to limit GHG emissions in 1997. As one of the main sources of GHG emissions, the construction industry has started to implement GHG pollution evaluations to evaluate project viability or sustainable development goals. Most studies have, however, centred on measuring GHG pollution from buildings. There has been relatively little attention paid to estimating GHG emissions from civil engineering systems, such as pavement. A potential explanation for this is the absence of sufficient knowledge in the early stages of the civil engineering project [7].

This study aims to examine energy consumption and GHG (CO₂) emissions of a road construction project with flexible and rigid pavements using Life Cycle Assessment (LCA) approach. Semarang-Bawen road project section Km. 11 + 500 - Km. 34 + 000 was used as a case study for this purpose, allowing a comparison to be made between the flexible and rigid pavements in terms of energy consumption and GHG (CO₂) emissions.

2. Literature Review

Table 1 shows several studies on consumption of energy also GHG emissions on road works which have been carried out. In Indonesia a research was done by collecting data on fuel consumption used at various stages of road flexible pavement, which refers to Intergovernmental Panel on Climate Change (IPCC) procedures. This research observed three stages of the process cycle, i.e. hot asphalt mixture production stage, material transportation stage, and asphalting work stage. The results show that the aggregate drying process is the most dominant process consumed energy, and emitted emissions of all stages [8]. Another research was carried out analysing the energy consumption and GHG emissions during the construction phase of a rigid pavement of the Cisumdawu toll road, with an observed road length of 800 m. This research found that the production and construction phases are the most energy consuming stages and produce the highest GHG [9]. An effort has been done to track and measure the carbon footprint of flexible pavement, from the production and distribution of materials raw material, and factory operations in road construction projects. The highest CO₂e emissions were produced by the plant used for laying asphalt concrete and material transportation [10]. Research on quantitative estimates of GHG emissions from road construction projects, complete assessments and life cycle measurements in the construction process for rigid and flexible pavements. The findings showed that production and transportation of materials contributed to the highest GHG emissions [11].

In other countries, research has been carried out to compare the implications on environment of asphalt pavement and reinforced concrete pavement using the LCA method from the material extraction stage, the production phase, the use phase, and the final disposal phase. Asphalt tends to have higher energy demand, lower production demands for materials and fertilizers and lower environmental emissions for the original development of similar paving designs [12]. Short life cycle inventory evaluation of continuous reinforced concrete pavement (CRCP) and asphalt pavement in relation to energy consumed by each type of road construction pavement. For CRCP, energy is used mainly in the production of cement and reinforcing steels, while energy use exists for asphalting during asphalt mixing, aggregate drying and bitumen production [13]. Based on project case studies in China, the research findings suggested a new inventory analysis approach for the evaluation of GHG pollution from portland cement pavement. The construction process of concrete pavement is carried out in three phases, i.e. the production of raw materials, the manufacture of concrete, and the construction at the site. The results show that the highest GHG emissions occur in the production phase, followed by the manufacturing phase, and the construction phase [14]. Another work is to use a life cycle assessment method to determine the environmental effects of maintenance of pavements. The categories of environmental impacts considered in the LCA can include global warming, human
health, quality of ecosystem, acidification, land use, and etc. In this research, assessment of the impact is limited to carbon dioxide (CO$_2$) emissions for global warming potential (GWP). The results show that the preservation of the pavement brings significant environmental benefits to the reduction of CO$_2$ emissions due to the improved surface condition of the pavement, although the emissions generated at the construction stage [15].

The research findings of energy consumption of road projects may vary due to differences in construction technology, construction equipment and raw materials, and relatively large variability in sources of data base which leads to a lack of consistency of the results [16]. Although many studies have been carried out on this subject, each of the energy and emission studies has limitations depending on the nature and quality of the data used. This is also due to differences in system boundaries including energy inputs, so that the results cannot easily be compared [17], making this area of research is therefore still an interesting subject to study.

### Table 1. Research on LCA of road pavement.

| Research Scope                                                                 | System Boundary                                                                 | Output                                                                                           | Reference |
|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|-----------|
| Applying EIO-LCA model and analysis uncertainty in input and environmental outcomes of CRCP and hot mix asphalt (HMA) pavements | Materials production, construction, end-of-life phases | Energy, Toxics Release Inventory (TRI) chemical emissions (H$_2$SO$_4$), hazardous waste, pollutant emissions to air (SO$_2$, NO$_2$, particulars) | [12]      |
| Using SETAC-EPA model for assessing the energy consumption of CRCP and HMA pavement | Process materials, construction | Energy consumption |                                                                                                    | [13]      |
| Estimating energy consumptions and CO$_2$ emissions of HMA calculated based on IPCC guidelines. | Process of mixing, transportation and application at project sites | Consumption of energy and emissions of GHG |                                                                                                    | [8]       |
| Analysis of life cycle inventory impact of concrete pavement construction on environment | Production of raw material, concrete production and pavement construction phase | GHG emissions |                                                                                                    | [14]      |
| Consumption of energy and GHG emissions of a rigid pavement at the construction stage | Material, transportation and construction | Consumption of energy and emissions of GHG |                                                                                                    | [9]       |
| Assessment of carbon footprint of flexible pavement                          | Off site and on-site construction project activities | GHG emissions in term of CO$_2$e |                                                                                                    | [10]      |
| Estimates of GHG emissions from local road construction projects, rigid and flexible pavements | Production of raw materials, transportation, and construction | GHG emissions |                                                                                                    | [11]      |
| Environmental effect of asphalt pavement preservation at stage of construction and operation | Production of materials, construction, use phase and end-of-life phases | CO$_2$ emissions |                                                                                                    | [15]      |

2.1. **Sustainable Road Construction**

Indonesia has proven its concern on environmental issues through Law no. 23/1997 on environmental management, with the main goal is to realize sustainable development. Indonesia also ratified the Kyoto Protocol through Law no. 17/2004. At The Conference of Parties (COP) in Copenhagen, Denmark in 2009 Indonesia is committed to reducing emissions by 26% by 2020 [9]. The Ministry of Public Works and Public Housing Regulation No. 5/2015 on General Guidelines for the Implementation of Sustainable Construction in the Implementation of Infrastructure in the Field of Public Works and Settlements, states that road operators must implement principles of sustainable...
construction by meeting the technical reliability requirements and sustainable principles, i.e. the social, economic, and environmental aspects must be considered in the use of resources, keeping the natural resources for future generations [18].

2.2. Life Cycle Assessment (LCA)
Since the 1980s, the use of LCA has gained consideration in environmental evaluation of specific goods and processes. Unlike processes and services in other industries, however, the LCA continues to be in the early stages of infrastructure implementation. Despite the growing number of LCA literature on highways, there is no agreement about what kind of pavement has environmental efficiency advantages [19].

The LCA studies generally consist of four phases, i.e. the purpose and scope of the definition, life cycle inventory (LCI), impact assessment and interpretation of results [20]. The LCI involves the collection of data and calculations to measure the input and output of materials and energy from a system, and the impact assessment evaluates the significance of potential environmental impacts based on LCI [21]. In road construction, both flexible pavement and rigid pavement stages of the LCA consist of:

- **Material Production.** The stage in which the process of making a product from raw materials. Generally, it uses asphalt mixing plant to produce hot asphalt mixes, and batching plant to produce concrete mixes, wheel loaders, dump trucks and mixer trucks.
- **Construction.** The process of assembling an infrastructure to support human life.
- **Maintenance.** The process to maintain road pavement conditions to serve traffic loads and the environment. The maintenance is in the form of routine, periodic, upgrading, and reconstruction.
- **End-of-Life.** There are two possibilities in this last stage of the life cycle. The first is that there is no waste and emissions generated at this stage, because the previous pavement becomes a new sub-pavement. The second possibility is waste and pollution production as the old pavement is demolished and dumped into landfills.

2.3. Flexible Pavement
The flexible pavement refers to road with an asphalt surface. It consists of a road structure which includes asphalt-bound and unbound materials. In general, this pavement is made from various layers, such as hot mixed asphalt layer, unbound road base, unbound sub base and subgrade [6]. Figure 1 shows a typical cross section of a road with a flexible pavement structure consisting of three pavement layers [22].

![Figure 1. A typical flexible pavement structure.](image)
2.4. Rigid Pavement

The rigid pavement, also called cement concrete pavement, is a pavement that uses cement as a binder so that the level of stiffness is relatively high, compared to asphalt pavement. Its structure consists of hydraulic cement concrete surface layers, foundation layer (base), and if needed, the sub base course layer [6]. Figure 2 shows a typical cross section of a road with a rigid pavement structure (reinforced concrete) consisting of three layers, i.e. sub grade, sub base course, and concrete slab [23].

![Figure 2. A typical rigid pavement structure.](image)

3. Research Method

This research used the Semarang - Bawen road project as a case study for flexible and rigid pavements. The observed flexible pavement is located at Km. 16 + 650 - Km 17 + 375, and the rigid pavement is located Km. 11 + 990 - Km. 12 + 980. The analysis was carried out on the surface layers of the pavements, i.e. the AC-WC and AC-BC layers for the flexible pavement, and the concrete slab layer for the rigid pavement. The calculation of energy usage uses energy conversion method based on fuel consumption, while the GHG emissions analysed in this study are only Carbon Dioxide (CO$_2$). The formula refers to the Guidelines for National Greenhouse Gas Inventories Volume 2 guide [24] [25]. The analytical method used for estimating energy consumption is the conversion of fuel usage to a standard energy unit (Joule). To get the amount of energy consumption in each production of 1 Mg (tons) of pavement material, the calculation uses equation 1.

$$\text{Energy Consumption (MJ/ton)} = \frac{\text{Fuel Consumption (liter)} \times \text{Calorific Value (MJ/liter)}}{\text{Total Production (ton)}}$$  \hspace{1cm} (1)

The estimated amount of CO$_2$ emissions per tonne of pavement material production, referring to the equation in the IPCC guidelines, as described in equation 2.

$$\text{GHG Emissions (kgCO}_2\text{/ton)} = \frac{\text{Energy Consumption (MJ)} \times \text{Emission Factor (kgCO}_2\text{/MJ)}}{\text{Total Production (ton)}}$$  \hspace{1cm} (2)

To calculate the estimate energy consumption using equation 3.

$$E = K_B \times C_v$$  \hspace{1cm} (3)

where: $E =$ energy consumption (MJ); $K_B =$ fuel consumption (liter); $C_v =$ calorific value (MJ/liter)
Calculation of CO$_2$ emissions per ton of material production using equation 4.

\[ \text{GHG} = K_B \times F_E \]  \hspace{1cm} (4)

where: \( \text{GHG} \) = greenhouse gas (kgCO$_2$); \( K_B \) = fuel consumption (liter); \( F_E \) = emission factor (kgCO$_2$/liter)

Data was collected in the construction site through observation of the construction process and interviews with engineers on site, and through literature research. The data collected is used to assess the life cycle of the materials following the stages, below:

1. Estimating the need for asphalt mixture in flexible pavement and concrete mixture in rigid pavement.
2. Calculating the fuel and energy consumption of equipment used at each stage of the life cycle on the pavement, starting from the stage material production to the end-of-life stage. Estimation of fuel consumption is done by converting units of fuel demand by multiplying fuel consumption by the conversion rate from Table 2 of fuel conversion, which refers to the guidelines of the IPCC.
3. Calculating emissions at each stage of the life cycle of road pavement, starting from the material production stage to the end-of-life stage. This is done by multiplying the fuel demand by the emission factor from the fuel conversion table, which refers to the guidance of the IPCC.
4. Comparing the results of the calculation of fuel consumption, energy consumption and emissions between the flexible pavement and the rigid pavement used in the Semarang - Bawen Road improvement project.

**Table 2. Energy conversion factor [24].**

| Type of Fuel | Density (kg/ltr) | Calorific Value (MJ/ltr) | Emission Factor (kgCO$_2$/ltr) |
|--------------|------------------|--------------------------|-------------------------------|
| Crude Oil    | 0.847            | 35.83                    | 2.63                          |
| Diesel       | 0.837            | 35.99                    | 2.67                          |

4. Results

The stages of the analysis in this study are described as follows: (1) Collecting data in the form of flexible and rigid pavement technical data, such as: job mix formula, quantity of asphalt mixed material, quantity of concrete mix material, heavy equipment data, heavy equipment fuel consumption data, distance of asphalt mixing plant (AMP) and concrete batching plant to the location project, as well as the distance of the location of the extraction of aggregate and bitumen material to the AMP and concrete batching plant; (2) Analysis of estimated fuel consumption; (3) Analysis of estimated energy consumption; and (4) Analysis of CO$_2$ GHG emissions.

4.1. Consumption of Energy and Emissions in Flexible Pavement

The technical data of the flexible pavement includes 1000 m length and 14 m width of the road, 0.05 m and 0.09 m thickness of the AC-WC and AC-BC layers. Table 3 shows the material data for the structural components of the flexible pavement per 1 km. The results of the calculation of fuel consumption at the production, construction and maintenance stages, can be seen in Tables 4, 5 and 6 below.
Table 3. Material data for the structural components of 1 km flexible pavement.

| Pavement Layer | Aggregate (ton) | Filler (ton) | Asphalt (ton) | Total (ton) |
|----------------|----------------|-------------|---------------|-------------|
| AC-WC          | 1518.91 (93.65%) | 15.41 (0.95%) | 87.58 (5.40%) | 1621.9 (100%) |
| AC-BC          | 2749.34 (93.85%) | 27.83 (0.95%) | 152.33 (5.20%) | 2929.5 (100%) |
| Total          | 4268.25 (93.78%) | 43.24 (0.95%) | 239.91 (5.27%) | 4551.4 (100%) |

Table 4. Fuel consumption of flexible pavement in the production stage.

| Activity          | Heavy Equipment | Heavy Equipment Fuel Consumption | Material Quantity 1 Km of Flexible Pavement | Total Fuel Consumption (litre/km) |
|-------------------|-----------------|----------------------------------|---------------------------------------------|---------------------------------|
| Transportation:   |                 |                                  |                                             |                                 |
| Aggregate         | Dump Truck      | 0.00196 ltr/kg                   | Aggregate 4268250 kg                        | 8365.77                         |
| Asphalt           | Dump Truck      | 0.0045 ltr/kg                    | Asphalt 239910 kg                          | 1079.59                         |
| Asphalt Mixture   | Wheel Loader    | 0.677 ltr/m³                     | Aggregate 2371.25 m³                       | 1605.34                         |
| Production        | Generator Set   | 2.03 ltr/m³                      | Asphalt Mixture 1960.96 m³                 | 3980.75                         |
| Asphalt Mixture   | Dump Truck      | 4.752 ltr/m³                     | Aggregate 1960.96 m³                       | 9318.48                         |
| Transportation    |                 |                                  |                                             |                                 |

Table 5. Fuel consumption of flexible pavement in the construction stage.

| Process     | Heavy Equipment | Fuel Consumption (litre/km) |
|-------------|-----------------|----------------------------|
| Overlay     | Asphalt Paver   | 455.14                     |
| Compacting  | Tandem Roller   | 455.14                     |
|             | Tire Roller     | 455.14                     |

Table 6. Material and fuel consumption of flexible pavement in the maintenance stage.

| Material Consumption (ton) | Fuel Consumption (litre) |
|---------------------------|--------------------------|
| Asphalt                   | 71.97                    |
| Aggregate                 | 1280.47                  |
|                           | Production               | 7304.98                    |
|                           | Construction             | 409.62                     |

For this research, the data needed to calculate the energy consumption and emissions using the energy conversion method is data of fuel consumption at each stage of the flexible pavement life cycle which then is converted to energy. The total amount of fuel consumption, energy consumption and emissions of the flexible pavement can be seen in Table 7. It shows that the estimated fuel consumption for the maintenance phase for the design life is worth 30% of each stage of production and construction. The assumption of end of life in this study is to reuse the old pavement as a subbase layer of the new pavement, so that there is no waste of material and energy at the end of life stage of this flexible pavement.
Table 7. The calculation of fuel, consumption of energy and emissions of flexible pavement.

| LCA Stage   | Total Fuel Consumption (litre/km) | Total Energy Consumption (GJ/km) | Total Emissions (kgCO₂/km) |
|-------------|----------------------------------|---------------------------------|---------------------------|
| Production  | 24349.93                         | 867.00                          | 65014.31                  |
| Construction| 1365.42                          | 49.14                           | 3645.67                   |
| Maintenance | 7714.60                          | 277.65                          | 20597.98                  |
| End of life | 0.00                             | 0.00                            | 0.00                      |
| Total LCA   | 33429.95                         | 1193.79                         | 89257.96                  |

4.2. Consumption of Energy and Emissions of The Rigid Pavement

The technical data of the rigid pavement includes a road length of 1000 m, the width of 14 m, and the thickness of the concrete slab layer of 0.27 m. Tables 8 and 9 show the results of the calculation of fuel consumption at the production and the construction stages for rigid pavement.

Table 8. Fuel consumption of the rigid pavement production stage.

| Activity          | Heavy Equipment  | Heavy Equipment Fuel Consumption | Material Quantity for 1 km Rigid Pavement | Total Fuel Consumption (litre/km) |
|-------------------|------------------|----------------------------------|-------------------------------------------|----------------------------------|
| Transportation:   |                  |                                  |                                           |                                  |
| Sand              | Dump Truck       | 0.00208 ltr/kg                   | 3179000 kg                                | 6612.32                          |
| Gravel            | Dump Truck       | 0.00137 ltr/kg                   | 3825000 kg                                | 5420.25                          |
| Cement            | Bulk Truck       | 0.00436 ltr/kg                   | 1512000 kg                                | 6592.32                          |
| Concrete Mix      | Wheel Loader     | 0.677 ltr/m³                     | 4395.71 m³                                | 2975.90                          |
| Production        | Generator Set    | 0.875 ltr/m³                     | 3780 m³                                  | 3307.50                          |
| Concrete Mix      | Mixer Truck      | 0.377 ltr/m³                     | 3780 m³                                  | 1425.06                          |

Table 9. Rigid pavement fuel consumption in the construction stage.

| Process          | Equipment        | Fuel Consumption (litre/km) |
|------------------|------------------|-----------------------------|
| Moving bars      | Pick Up          | 78.52                       |
| Pouring          | Mixer Truck      | 0.80                        |
| Vibrating        | Concrete Vibrator| 171.60                      |
| Cutting          | Concrete Cutter  | 54.60                       |

Similar to the flexible pavement, the calculation of estimated consumption of energy and emissions in this study was carried out using a fuel conversion table. The results of the calculations can be seen in Table 10, assuming there is no maintenance during the design life of the rigid pavement, as one of the advantages of rigid pavement is the very minimal routine maintenance. It is assumed that at the end of life of the rigid pavement, the concrete slab that has lost its structural function and will be replaced by other new concrete slab by overlaying or reconstruction. The old concrete slab serves as a new concrete subbase.
Table 10. The calculation of fuel, consumption of energy and emissions of rigid pavement.

| LCA Stage | Total Fuel Consumption (litre/km) | Total Energy Consumption (GJ/km) | Total Emissions (kgCO₂/km) |
|-----------|----------------------------------|---------------------------------|----------------------------|
| Production| 26333.35                         | 941.00                          | 69829.49                   |
| Construction| 305.52                         | 11.06                           | 635.04                     |
| Maintenance| 0.00                             | 0.00                            | 0.00                       |
| End of life| 0.00                             | 0.00                            | 0.00                       |
| Total LCA| 26638.87                         | 952.06                          | 70464.53                   |

5. Discussion
Tables 7 and 10 show a comparison of the results of the fuel and energy consumption, also the emissions for the flexible and the rigid pavements. It can be seen that at the production stage, apparently the flexible pavement consumes less fuel and energy of 24349.93 litres/km and 867.00 GJ and produces less emissions of 65014.31 kgCO₂/km compared to the rigid one. For flexible pavement, it is known that the asphalt production of AMP consumes the most dominant energy and generate greenhouse gas emissions [8]. The highest CO₂e emissions are typically generated by the use of plant for on-site activities, i.e. for asphalt overlaying activities accounted for 34,827 tons of CO₂e (49.130%), and material transportation accounted for 24,921 (35.155%) [10].

At the construction stage, the rigid pavement consumes less fuel and energy than the flexible one, of 305.52 litres/km and 11.06 GJ, and produces less emissions of 635.04 kgCO₂/km. Whereas in the maintenance and end of life stages, the flexible pavement consumes more fuel and energy of 7714.60 litres/km and 277.65 GJ, respectively and produces fewer emissions of 20597.98 kgCO₂/km. Typically, the consumption of energy and GHG emissions of rigid pavement mostly in the stages of production and construction indeed, while the processing of materials requires the most energy and emits emissions [9].

For all the LCA stages, the total energy consumption of the flexible pavement is 1193.79 GJ, while the rigid pavement is 952.056 GJ, showing that the flexible pavement contributes greater CO₂ emissions than the rigid pavement. As for the total emissions, the flexible pavement has a total emission of 89257.96 kgCO₂/km, greater than the rigid pavement of 70464.53 kgCO₂/km.

This research found that there is a significant difference of the results of energy consumption and emissions per stage between the flexible pavement and the rigid pavement. This study assumes that the rigid pavement is without maintenance, although in fact there could be maintenance work that is carried out even at the minimum level. Assuming an equivalent pavement design, the flexible pavement seemed to have a higher energy input, and lower emissions than the rigid one. For the construction of 1 km long road with two typical lanes requires energy of 7.0×10⁵ MJ for flexible pavement, and 5.0×10⁶ MJ for rigid pavement [12]. The Swedish Environmental Research Institute (IVL) reports that concrete pavement requires 37% more energy in comparison to asphalt pavement [26], this dissimilar results occurred because of significant differences in system boundaries between the two studies [13].

6. Conclusion
This research aims to examine the consumption of energy and GHG emissions of a road construction project using Life Cycle Assessment (LCA) approach using a road project of Semarang - Bawen section as a case study. The research found that the energy consumption for the flexible pavement is greater than the rigid pavement, which is 1193.79 GJ and 952.056 GJ, respectively. For emissions, the flexible pavement contributes to greater CO₂ emissions than the rigid pavement. Flexible pavement has a total emission of 89257.96 kgCO₂/km while rigid pavement is 70464.53 kgCO₂/km.

Based on the results of the case study of all LCA stages, it can be concluded that the rigid pavement can be considered more environmentally friendly and hence is more sustainable than
flexible pavement, because it consumes less fuel, less energy and produce less \( \text{CO}_2 \) emissions. These results are true for the project of the case study, and hopefully may represent other similar projects in general. It should be noted, however, as every project is actually unique with all various factors which might impact on the project, various results may be expected. Based on the limitation of this study, further research can be done by calculating the energy consumption in the mining process and the processing of raw materials in the quarry, as well as the calculation of consumption of energy and emissions produced in the maintenance and end of life stages of the rigid pavement.

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References

[1] Isya M, Rani HA, Utama FP. Effect of Green Road Concept on Waste Management on Road Construction in The Banda Aceh City. IOP Conf. Ser. Mater. Sci. Eng., 2019 Jan 16;469:012061. doi.org/10.1088/1757-899x/469/1/012061

[2] Santos J, Ferreira A, Flintsch G. A life cycle assessment model for pavement management: road pavement construction and management in Portugal. Int. J. Pavement Eng., 2014 Aug 13;16(4):315–36. doi.org/10.1080/10298436.2014.942862

[3] Zhang Z, Gao X, Wang J, Ji X. Prediction model for energy consumption and carbon emission of asphalt surface construction. IOP Conf. Ser.: Earth Environ. Sci., 2019 Nov 9;330:022052. doi.org/10.1088/1755-1315/330/2/022052

[4] Lawalata GM. Sustainable Road Development Principles. Jurnal Transportasi. 2013;13:115–24

[5] Kucukvar M, Tatari O. Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements. Transp Res D Transp Environ. 2012 Jan;17(1):86–90. doi.org/10.1016/j.trd.2011.05.006

[6] Thives LP, Ghisi E. Asphalt mixtures emission and energy consumption: A review. Renew. Sust. Energ. Rev., 2017 May;72:473–84. doi.org/10.1016/j.rser.2017.01.087

[7] Kim B, Lee H, Park H, Kim H. Framework for Estimating Greenhouse Gas Emissions Due to Asphalt Pavement Construction. J. Constr. Eng. Manag., 2012 Nov;138(11):1312–21. doi.org/10.1061/(asce)co.1943-7862.0000549

[8] Wirahadikusumah RD, Sahana HP. Estimasi Konsumsi Energi dan Emisi Gas Rumah Kaca pada Pekerjaan Pengaspalan Jalan. Jurnal Teknik Sipil. 2012 Apr 1;19(1):25. doi.org/10.5614/jts.2012.19.1.3

[9] Mulyana A, Wirahadikusumah R. Analysis of Energy Consumption and Greenhouse Gas Emissions in the Construction Phase Case Study: Construction of Cisumdawu Road. Jurnal Teknik Sipil ITB. 2017;24:269–80

[10] Utomo Dwi Hatmoko J, Hidayat A, Setiawati A, Catur Adi Prasetyo S. Measuring Carbon Footprint of Flexible Pavement Construction Project in Indonesia. Hadiyanto, Sudarno, Maryono, editors. E3S Web Conf., 2018;31:07001. doi.org/10.1051/e3scconf/20183107001

[11] Handayani FS, Prameshi FP, Wibowo MA, Setyawan A. Estimating and Reducing the Release of Greenhouse Gases in Local Road Pavement Constructions. Int J Adv Sci Eng Inf Technol. 2019 Oct 31;9(5):1709. doi.org/10.18517/ijaseit.9.5.9705

[12] Horvath A, Hendrickson C. Comparison of Environmental Implications of Asphalt and Steel Reinforced Concrete Pavements. Transp. Res. Rec., 1998 Jan;1626(1):105–13. doi.org/10.3141/1626-13

[13] Zapata P, Gambatese JA. Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction. J. Infrastruct. Syst., 2005 Mar;11(1):9–20. doi.org/10.1061/(asce)1076-0342(2005)11:1(9)

[14] Ma F, Sha A, Yang P, Huang Y. The Greenhouse Gas Emission from Portland Cement Concrete
Pavement Construction in China. Int. J. Environ. Res. Public Health. 2016 Jun 24;13(7):632. doi.org/10.3390/ijerph13070632

[15] Wang H, Al-Saadi I, Lu P, Jasim A. Quantifying greenhouse gas emission of asphalt pavement preservation at construction and use stages using life-cycle assessment. Int J Sustain Transp. 2019 Jan 11;14(1):25–34. doi.org/10.1080/15568318.2018.1519086

[16] Fei L, Zhang Q, Xie Y. Study on energy consumption evaluation of mountainous highway based on LCA. Int. J Sustain. Sci., 2017 Jun;69:012036. doi.org/10.1088/1755-1315/69/1/012036

[17] Dixit MK, Culp CH, Fernandez-Solis JL. Embodied Energy of Construction Materials: Integrating Human and Capital Energy into an IO-Based Hybrid Model. Environ. Sci. Technol., 2015 Jan 15;49(3):1936–45. doi.org/10.1021/es503896v

[18] Lawalata GM. Pemeringkatan Jalan Hijau untuk Mendukung Implementasi Program Konstruksi Jalan Berkelanjutan. Jurnal HPJP. 2019;5:21–30

[19] Inyim P, Pereyra J, Bienvenu M, Mostafavi A. Environmental assessment of pavement infrastructure: A systematic review. J. Environ. Manage., 2016 Jul;176:128–38. doi.org/10.1016/j.jenvman.2016.03.042

[20] Environmental management. Life cycle assessment. Principles and framework. BSI British Standards; doi.org/10.3403/01139131u

[21] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: An overview. Energy Build., 2010 Oct;42(10):1592–600. doi.org/10.1016/j.enbuild.2010.05.007

[22] Wang Y, Chong D. Determination of Optimum Pavement Construction Alternatives to Minimize Life-cycle Costs and Greenhouse Gas Emissions. Construction Research Congress 2014. 2014 May 13. doi.org/10.1061/9780784443517.070

[23] AASHTO. 1993. AASHTO Guide for Design of Pavement Structures (Washington, DC: American Association of State Highway and Transportation Officials)

[24] Intergovernmental Panel on Climate Change. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories ed S Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Hayama, Kanagawa: Institute for Global Environmental Strategies (IGES))

[25] Kim B, Lee H, Park H, Kim H. Framework for Estimating Greenhouse Gas Emissions Due to Asphalt Pavement Construction. J. Constr. Eng. Manag., 2012 Nov;138(11):1312–21. doi.org/10.1061/(asce)co.1943-7862.0000549

[26] Stripple H. 2001. Life Cycle Assessment of Road A Pilot Study for Inventory Analysis (Gothenburg, Sweden: IVL)