How sustainable are flexible and rigid pavement? A Life Cycle Impact Assessment (LCIA) approach

J U D Hatmoko* and L Lendra1,2

1Department of Civil Engineering, Diponegoro University, Indonesia
2Department of Civil Engineering, Palangka Raya University, Indonesia

Email: *jati.hatmoko@ft.undip.ac.id

Abstract. The number of road construction projects continues to grow, potentially causing more impacts on the environment. This research analyses the impacts of road construction projects of flexible and rigid pavement by adopting the Life Cycle Impact Assessment (LCIA) approach, and by means of the Eco-Indicator 99 (EI99). The impact values at the production, construction and maintenance stages for the flexible pavement are 86.60 kPt (49.34%), 65.40 (37.26%) and 23.50 kPt (13.39%), while for the rigid pavement equals 47.70 kPt (60.46%), 31.20 (39.54%) and 0 kPt (0%), respectively. It is smaller than the flexible pavement, i.e. 175.50 kPt and 78.9 kPt, respectively. The results of the EI99 show the impact values of the flexible pavement from the aspects of human health, ecosystem quality, and resources are 11.99 kPt (6.83%), 2.17 kPt (1.24%), and 161.40 kPt (91.93%), while for the rigid pavement of 29.49 kPt (37.43%), 37.80 kPt (4.79%), and 45.54 kPt (57.78%), respectively. The total impact value of the three aspects of the rigid pavement is 78.9 kPt, which is smaller than, and worth 45% of the flexible pavement of 175.50 kPt. It can be concluded that the rigid pavement can be considered more sustainable than flexible pavement.

1. Introduction

The construction industry plays a very important role in the national infrastructure growth. A variety of construction activities, while benefiting the national economy, have the potential to cause adverse environmental impacts. In the construction sector, road construction is one of the major emitters of greenhouse gasses and continues to grow along with the road developments by the government [1]. The construction of concrete road (rigid pavement) continues to grow and is progressively becoming the main type of roadways for heavy traffic loads, due to its long service life and less frequent maintenance requirements compared to the asphalt road (flexible pavement) [2]. The asphalt road is slowly being replaced by the concrete road as it breaks down faster [3]. In terms of structural strength and maintenance costs, the rigid pavement is superior to the asphalt roads [4]. There has been a question, however, on the environmental impacts from the construction process of these two types of pavement. The used of different materials in a project may impact on the energy consumption of the construction process, and ultimately can have impacts on the environment, including global warming.

The concept of sustainable construction exists and becomes a necessity in the midst of the phenomenon of global warming and the issue of environmental damage that is afflicting humanity. Based on Global Status Report 2017, buildings and construction combined compensate for 36% of the final electricity usage and 39% of energy-related emissions of carbon dioxide (CO₂) with the inclusion of upstream power production [5]. The idea of sustainable construction is seen as one of the strategies
for mitigating environmental degradation and lowering carbon emissions, which is the key source of global warming in the construction industry. This research aims to analyse the environmental impacts of road construction projects of flexible and rigid pavement by adopting the Life Cycle Impact Assessment (LCIA) approach, and by means of the Eco-Indicator 99 (EI99).

2. Literature Review
2.1. Sustainable Development
Sustainable development is an attempt to fulfil all basic needs and to create resources to satisfy the human expectations for a better life. There are three pillars that support the nature of sustainability, i.e. social aspects, environmental aspects and economic aspects, which interact with one another [6] [7], as shown in Figure 1.

![Figure 1. Supporting pillars for sustainability.](image)

The Indonesian government's contribution to rising global change is accomplished by reducing emissions by 26 percent by 2020. This was then updated separately in 2015, with an emission reduction goal of 29% by 2030. One of the follow-up duties in the construction industry is the issuing of Ministry of Public Works Regulation no. 11/2012 concerning the National Action Plan for Mitigation and Adaptation to Climate Change in 2012-2020, and the regulation no. 02/ PRT/M/2015 concerning Green Buildings for reducing greenhouse gas (GHG) emissions sourced from buildings. Emissions reducing strategies must be implemented in all sectors and regions [8]. Road operators must also implement a sustainable construction approach by meeting the requirements of technical reliability and sustainable principles in accordance with Ministry of Public Works and Public Housing (PUPR) regulation no. 5/2015, concerning General Guidelines for the Implementation of Sustainable Construction in the Implementation of Infrastructure in the Field of Public Works and Settlements [9].

2.2. Life Cycle Impact Assessment (LCIA)
Life Cycle Impact Assessment (LCA) is a method used in the life cycle stage from the material up to the product stage is used by consumers [10]. The ISO 14040 Standard divides the process of LCA in four stages, i.e.: (1) The goal and scope definition; (2) Life Cycle Inventory (LCI) analysis; (3) Life Cycle Impact Assessment (LCIA); and (4) interpretation of results [10] [11].

The LCIA has been adopted in previous studies, e.g. evaluation on the environmental impacts of mining and mineral processing, material and equipment transportation, construction, maintenance, and reconstruction of a 35-km long dual road in Abu Dhabi [12]; estimation of the asphalt and concrete impact on from the production process to the disposal(cradle to grave boundary system) by using the ReCiPe and SimaPro software [13]; calculation the effect of using polyurethane bounded pavement to determine whether it satisfies the energy efficiency, environmental protection and sustainable development requirements [14]; assessment of energy and environmental life cycles for renewable materials and urban road surface technologies focused on the use of bitumen mixtures (hot mix asphalt and wet asphalt mixtures) with recycled materials (reclaimed asphalt pavement, crumb rubber and used plastics) [15]; valuation of the environmental impact of recycled aggregates by process separation into
raw matter, transport and recycling aggregates, and identification of materials used at each point and amount of energy consumption for environmental impact evaluation [16]; assessment of the energy use and environmental effects of asphalt pavement from used tires during the life cycle and end of material production, construction and maintenance [17].

In addition, the LCA approach was implemented for building a Triple-Bottom-Line (TBL) model for sustainable assessment of the environmental and socio-economic impacts of pavements mixtures constructed with Warm Asphalt mix (WMA) to compare with traditional Hot Mix Asphalt (HMA) [18]; impact assessment of substances emitted from the concrete manufacturing cycle in six areas of environmental effects, i.e. global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidizing manufacturing [19], and examining the environmental impact of the increasing use of recycled materials in asphalt pavement construction and maintenance [20].

2.3. Eco-Indicator 99
Eco-Indicator 99 (EI99) denotes the impacts on the environment of materials or process based on data from the LCA. The higher value of the indicator indicates the greater impact on the environment. EI99 helps manufacturers or project managers to evaluate a company's environmental effects over its life cycle [21]. Three types of impacts are defined in EI99, as follows:

1. Impact on human health: articulated as the number of years lost, also the number of years living with disabilities. The index is Disability Adjusted Life Years (DALYs). The impact of these aspects includes climate change, depletion of ozone layer, effects of carcinogenic and respiratory, and ionizing radiation.

2. Impact on ecosystem quality: the endpoint indicator used in this aspect is the Potentially Disappeared Fraction of species (PDF), which is the loss of a species in a certain area over a certain period of time (PDF.m2.years). Effects in this category include: ecotoxicity, acidification, eutrophication, and land-use.

3. Impact on resources: future excess energy requirement for extraction of minerals and fossil fuels, with a surplus MJ unit. The impact of this aspect is minerals and fossil fuels.

2.4. Types of Pavement of Road Infrastructure
Typically, the main types of pavement of road infrastructure are flexible pavement, rigid pavement and composite (both flexible and rigid layers in the same pavement). The designer must be able to choose the appropriate pavement type, and ensure the road can serve users to travel on the pavement that is safe, durable, quiet, smooth, economical, and using sustainable materials [22]. Road network in Indonesia is characterized by flexible pavement, which is assumed to contain high GHG emissions due to shifts in land settings and functions as well as resource use and utilization [1].

3. Research Method
This research adopted a sustainable framework of the LCA method to find out how much environmental impact arising from flexible pavement and rigid pavement. Data was collected from a road construction project of Semarang - Bawen section Km. 11 + 500 - Km. 34 + 000, via site observation, observing project documents, followed by interviews with the consultant and the contractor to understand the construction process more thoroughly. This research applies the four basic stages of the LCA, i.e.: (1) The goal and scope definition; (2) Life Cycle Inventory (LCI); (3) Life Cycle Impact Assessment (LCIA); and (4) Interpretation of Results.

3.1. The Goal and Scope Definition
The goal is to analyse the environmental impact of flexible pavement and rigid pavement through the life cycle and make a comparison of the two to learn which type of pavement is friendlier to the environment. The scope consists of two parts, i.e.: (1) Functional Unit: road pavement with a length of
1 kilometre and width of 14 m (4 lanes 2 directions) for each type of pavement being compared; and (2) Boundary System: material production, construction, and maintenance.

3.2. Life Cycle Inventory (LCI)

The purpose of the LCI study is to identify and determine the extent and value of the system's environmental impacts by measuring the product's inputs (i.e. resources and energy) and outputs (i.e. emissions and waste) over its life cycle [23]. It is a quantitative analysis of energy consumption and emissions of products, processes or activities with the process of collecting and calculating input and output data in the entire system life cycle [14]. For this purpose, the data collected include: job mix formula, quantity of asphalt mix material, quantity of concrete mix material, heavy equipment data, fuel consumption data, the distance of AMP (Asphalt Mixing Plant) and concrete batching plant to the project location, and the distance of quarries of aggregate and bitumen to AMP and concrete Batching Plant.

3.3. Life Cycle Impact Assessment (LCIA)

The LCIA analyse the type and value of each impact produced by means of the EI99 using SimaPro software. The LCIA calculation phase is divided into four steps, i.e.: (1) classification: the appropriate impact aspect is assigned to the inventory items taken out from the inventory analysis; (2) characterization: the effect of each object shall be categorized into the effect group for each quantified dimension; (3) normalization: the environmental impacts given to the environmental aspect are divided into environmental impacts, locally or globally; and (4) weighting: the comparative importance among the impact aspects is determined [19]. Table 1 shows the characterization-normalization-weighting indicator with EI99, which will be used for calculation in the following stages:

- the normalization, i.e. the characterization value is multiplied by the normalization factor
- the weighting, i.e. the normalization value is multiplied by the weighting factor
- single score, i.e. classification the values of the impact category based on the activity or process

| Impact Category       | Unit     | Normalization | Weighting |
|-----------------------|----------|---------------|-----------|
| Carcinogens           | DALY     | 65.1          | 300       |
| Resp. Organics        | DALY     | 65.1          | 300       |
| Resp. Inorganics      | DALY     | 65.1          | 300       |
| Climate Change        | DALY     | 65.1          | 300       |
| Radiation             | DALY     | 65.1          | 300       |
| Ozone Layer           | DALY     | 65.1          | 300       |
| Ecotoxicity           | PDF.m2.yr| 1.95E-5       | 400       |
| Acidification / Eutrophication | PDF.m2.yr | 1.95E-4 | 400       |
| Land Use              | PDF.m2.yr| 1.95E-4       | 400       |
| Minerals              | MJ surplus| 1.95E-4     | 200       |
| Fossil Fuels          | MJ surplus| 1.95E-4     | 200       |

The environmental impacts are analysed based on the damage caused to three aspects, i.e. human health, ecosystem quality and resources. Each of these aspects has their respective impacts categories, as follows:

- Human Health: carcinogens, respiratory organics, inorganic respiration, climate change, radiation, and ozone layer.
- Ecosystem Quality: ecotoxicity, acidification, eutrophication and land use.
- Resources: minerals and fossil fuel.
3.4. Interpretation of Results
This phase is a combination of the results of the LCI and LCIA, which are then used to interpret, draw conclusions and recommendations in accordance with the goals and scopes identified earlier. The findings are recorded in the most detailed manner and incentives are regularly evaluated to reduce the effect of goods or services on the ecosystem [10].

4. Results
This section describes the results of the environmental impacts on the flexible pavement, rigid pavement, and the comparison of them.

4.1. Environmental Impacts of The Flexible Pavement
The flexible pavement being studied consists of two layers of asphalt pavement, i.e. asphalt concrete-wearing course (AC-WC) and asphalt concrete-binder course (AC-BC), each with a length of 1000 m and the width of 14 m. The AC-WC layer is 0.05 m thick, while the AC-BC layer is 0.09 m thick. Table 2 shows the results of the flexible pavement with the EI99 method in accordance with the LCIA characterization factor values. The total impact value of the three aspects of damage category, i.e. human health, ecosystem quality, and resources of the flexible pavement is 175.50 kPt, with the largest is related to resources (91.93%). For the LCIA approach, among the three stages, the largest impact value is at the production stage of 86.60 kPt (49.34%), followed by the construction, and the maintenance stage of 65.40 (37.26%) and 23.50 kPt (13.39%), respectively.

| Damage Category       | Impact Category     | Total (kPt) | Production | Construction | Maintenance |
|-----------------------|---------------------|-------------|------------|--------------|-------------|
| Human Health          | Carcinogens         | 0.27        | 0.16       | 0.07         | 0.04        |
|                       | Resp. Organics      | 0.06        | 0.03       | 0.02         | 0.01        |
|                       | Resp. Inorganics    | 9.20        | 6.27       | 1.86         | 1.06        |
|                      | Climate Change      | 2.41        | 1.48       | 0.64         | 0.29        |
|                      | Radiation           | 0.05        | 0.02       | 0.02         | 0.01        |
|                      | Ozone Layer         | 0.01        | 0.00       | 0.00         | 0.00        |
|                       | Sub total           | 11.99       | 7.96       | 2.61         | 1.41        |
|                      | (% of Total)        | (6.83%)     | (49.34%)   | (14.65%)     | (8.03%)     |
| Ecosystem Quality     | Ecotoxicity         | 0.80        | 0.53       | 0.17         | 0.10        |
| Acidification / Eutrophication | 1.47 | 1.01 | 0.28 | 0.17 |
| Land Use              | -0.09               | 0.10        | -0.17      | -0.03        |
|                       | Sub total           | 2.17        | 1.64       | 0.28         | 0.24        |
|                       | (% of Total)        | (1.24%)     | (75.2%)    | (12.8%)      | (11.0%)     |
| Resources             | Minerals            | 0.40        | 0.23       | 0.12         | 0.05        |
| Fossil Fuels          | 161.00              | 76.80       | 62.40      | 21.80        |
|                       | Sub total           | 161.40      | 77.03      | 62.52        | 21.85       |
|                       | (% of Total)        | (91.93%)    | (47.7%)    | (38.7%)      | (13.5%)     |
|                       | Total               | 175.50      | 86.60      | 65.40        | 23.50       |
|                       | (% of Total)        | (100%)      | (49.34%)   | (37.26%)     | (13.39%)    |

Table 3 shows the values of materials or processes which cause the environment impacts for the three stages of LCA, i.e. production, construction, and maintenance. It can be seen that the largest impact for the three stages is caused by material and process of asphalt, with impact values of 64.4 kPt, 65.10 kPt, and 19.30 kPt, respectively, and with percentages of more than 74%.
Table 3. Contributors to the environmental impact of the flexible pavement.

| Material / Process                  | Impact (kPt) | (%) |
|-------------------------------------|--------------|-----|
| Asphalt                             | 64.40        | 74.00 |
| Aggregate                           | 8.27         | 9.50  |
| Heavy fuel equipment                | 0.35         | 0.40  |
| Generator set                       | 1.75         | 2.00  |
| Transportation                      | 11.80        | 14.00 |
| **Total**                           | **86.60**    | **100** |

4.2. Environmental Impacts of The Rigid Pavement

The rigid pavement section observed for this study is of 1000 m length, the width of the road on the concrete slab is 14 m, and the thickness of the concrete slab layer is 0.27 m. Table 4 shows the EI99 results of the rigid pavement in accordance with the LCIA characterization factor values. It is assumed that there is no maintenance during the design life of the rigid pavement, as one of the benefits of the rigid pavement is the routine maintenance is minimal and there could be no maintenance at all if the materials and construction process conform to specifications. At the end of life, the concrete that has lost its structural function will be replaced overlaying with new concrete layer or reconstruction.

The total impact value of the three aspects of damage category, i.e. human health, ecosystem quality, and resources of the flexible pavement is 78.9 kPt, with the largest is related to resources (57.72%). For the LCIA approach, among the three stages, the largest impact value is at the production stage of 47.70 kPt (60.46%), followed by the construction stage of 31.20 (39.54%), respectively.

Table 4. The results of EI99 and LCIA of the rigid pavement.

| Damage Category       | Impact Category             | Total (kPt) | Production | Construct | Maintenance |
|-----------------------|-----------------------------|-------------|------------|-----------|-------------|
| Human Health          | Carcinogens                 | 0.55        | 0.25       | 0.30      | 0           |
|                       | Resp. Organics              | 0.02        | 0.01       | 0.01      | 0           |
|                       | Resp. Inorganics            | 17.40       | 10.10      | 7.26      | 0           |
|                       | Climate Change              | 11.40       | 5.98       | 5.44      | 0           |
|                       | Radiation                   | 0.12        | 0.06       | 0.06      | 0           |
|                       | Ozone Layer                 | 0.00        | 0.00       | 0.00      | 0           |
|                       | **Sub total**               | **29.49**   | **16.40**  | **13.07** | **0**       |
|                       |                             | (37.38%)    | (55.6%)    | (44.3%)   | (0%)        |
| Ecosystem Quality     | Ecotoxicity                 | 1.18        | 0.66       | 0.52      | 0           |
|                       | Acidification / Eutrophication | 2.66    | 1.64       | 1.02      | 0           |
|                       | Land Use                    | -0.05       | 0.05       | -0.10     | 0           |
|                       | **Sub total**               | **3.79**    | **2.35**   | **1.44**  | **0**       |
|                       |                             | (4.80%)     | (62.0%)    | (38.0%)   | (0%)        |
| Resources             | Minerals                    | 1.04        | 0.47       | 0.57      | 0           |
|                       | Fossil Fuels                | 44.50       | 28.40      | 16.10     | 0           |
|                       | **Sub total**               | **45.54**   | **28.87**  | **16.67** | **0**       |
|                       |                             | (57.72%)    | (63.4%)    | (36.6%)   | (0%)        |
|                       | **Total**                   | **78.90**   | **47.70**  | **31.20** | **0**       |
|                       |                             | (100%)      | (60.46%)   | (39.54%)  | (0%)        |
Table 5 shows that the largest impact value at the production stage is caused by cement with an impact value of 31.4 kPt (66% of the impact value of the production stage). Whereas at the construction stage, concrete mixture has the largest impact with the value of 28.50 kPt, which is equal to 91% of the impact values of this stage.

**Table 5. Contributors to the environmental impact of the rigid pavement.**

| Material / Process       | Impact (kPt) | Percentage (%) |
|--------------------------|--------------|----------------|
| Sand                     | 6.27         | 13.00          |
| Gravel                   | 5.35         | 11.00          |
| Cement                   | 31.40        | 66.00          |
| Water                    | 0.01         | 0.01           |
| Electricity (pump)       | 0.00         | 0.002          |
| Heavy fuel equipment     | 0.65         | 0.014          |
| Generator set fuel       | 1.46         | 3.06           |
| Transportation           | 2.60         | 5.50           |
| **Total**                | **47.70**    | **100**        |

**4.3. Comparison of Environmental Impacts between the Flexible and Rigid Pavement**

Table 6 and Figure 2 show the comparison of the total environment impact by damage categories between the flexible and rigid pavement. It can be seen that the total impact value of the three damage categories of the rigid pavement is 78.9 kPt, which is smaller than, and worth 45% of the flexible pavement of 175.50 kPt. However, among the three-damage category, the flexible pavement has less impact value for human health and quality of ecosystem than the rigid pavement.

**Table 6. Total environmental impact by damage category.**

| Damage Category         | Flexible Pavement (kPt) | Rigid Pavement (kPt) |
|-------------------------|-------------------------|----------------------|
| Human Health            | 11.99 (6.83%)           | 29.49 (37.43%)       |
| Ecosystem Quality       | 2.17 (1.24%)            | 3.78 (4.79%)         |
| Resources               | 161.40 (91.93%)         | 45.54 (57.78%)       |
| **Total**               | 175.50 (100%)           | 78.90 (100%)         |

Table 7 compares the environmental impact between the flexible pavement and the rigid pavement for the LCA stages of production, construction, and maintenance. It can be seen that the total impact value of all the LCA stages of the rigid pavement is smaller than the flexible pavement, i.e. 175.50 kPt and 78.9 kPt, respectively. This total result is also consistent with the result of each individual stage of production, construction, and maintenance, where the impact value of the rigid pavement is also smaller than the flexible one.
Figure 2. Comparison of the single score value of environmental impacts between flexible pavement and rigid pavement.

Table 7. Comparison of the environmental impact based on the LCA stages.

| LCA Stage   | Flexible Pavement (kPt) | Percentage (%) | Rigid Pavement (kPt) | Percentage (%) | Smaller Environmental Impact Value |
|-------------|-------------------------|----------------|----------------------|----------------|-----------------------------------|
| Production  | 86.60                   | 49.34          | 47.70                | 60.46          | Rigid Pavement                    |
| Construction| 65.40                   | 37.26          | 31.20                | 39.54          | Rigid Pavement                    |
| Maintenance | 23.50                   | 13.39          | 0                    | 0              | Rigid Pavement                    |
| Total       | 175.50                  | 100            | 78.90                | 100            | Rigid Pavement                    |

5. Discussion

This research found that for the flexible pavement, the production stage is the stage with the largest environmental impact value of 86.60 kPt (49.34%), followed by the construction, and the maintenance stages of 65.40 (37.26%) and 23.50 kPt (13.39%), respectively. This largest impact is mainly caused by fossil fuels and asphalt material and the related processes. These findings are supported by a research which stated that the main energy consumption at the production stage occurs during the mixing and drying of asphalt aggregates [24]. This means that the production stage is the most critical stage when it comes to managing the environmental impact of the flexible pavement.

This research also found that for the rigid pavement, the production phase has the greatest environmental impact of 47.7 kPt (60.46%), followed by the construction phase of 31.2 kPt (39.54%). The biggest impact is caused by the fossil fuels of 44.50 kPt, the cement material at the production stage of 31.40 kPt (66% of the impact value of the production stage), and the concrete mixing process at the construction stage of 28.50 kPt (91% of the impact values of this stage). These research findings are consistent with a study which found that for the rigid pavement, the material contributed 92.80% of the total amount of environmental impact [4], while another research states that the three biggest impacts of the rigid pavement is caused by material, fuel and transportation [25].
The effect on human health and the environment is very similar between the two forms of pavement, but in both instances, asphalt production is still higher. The effect of asphalt production on the resources is approximately 100 mPt greater than the influence of concrete production [13].

Both the flexible and rigid pavement have the biggest impact in the production stage, followed by construction and maintenance. It is almost similar with an empirical results in the life cycle of the fast lane transportation project, demonstrating that the construction process has the biggest environmental effect (62.7%), followed by the demolition (35.8%) and the maintenance phase (1.7%) [26].

This research found that the total environmental impact on the rigid pavement is 78.9 kPt, which is smaller than, and equals 45% of the total impact of the flexible pavement of 175.50 kPt. This indicate that the rigid pavement can be considered more environmentally friendly, hence also more sustainable. These findings explain why more countries are now replacing the flexible pavement with the rigid pavement [2]. Not only because the concrete pavement is structurally superior to the asphalt pavement, has long service life and very minimal maintenance [3] [4], but also due to better environmental performance as suggested by the findings of this research.

6. Conclusion
The aim of this research is to analyse the environmental impacts of road construction projects of the flexible pavement and rigid pavement based on LCIA approach, by means of the Eco-Indicator 99 (EI99). For the LCIA approach, the impact values at the production, construction and maintenance stages for rigid pavement are 86.60 kPt (49.34%), 65.40 (37.26%) and 23.50 kPt (13.39%), while for rigid pavement respectively 47.70 kPt (60.46%), 31.20 (39.54%) and 0.00 kPt (0%), respectively. The results of the EI99 indicate the impact value of the aspects human health, ecosystem quality, and resources for flexible pavement are 11.99 kPt (6.83%), 2.17 kPt (1.24%) and 161.4 kPt (91.93%), respectively, while for the rigid pavement 29.49 kPt (37.43%), 37.8 kPt (4.79%), and 45.54 kPt (57.78%), respectively. The total impact value of the three aspects of the rigid pavement is 78.9 kPt, which is smaller than, and worth 45% of the flexible pavement of 175.50 kPt. Based on the results of the LCIA approach and the EI99, it can be concluded that for the project under review, the rigid pavement can be considered more sustainable than the flexible pavement. As every project is unique, however, various factors may influence the results of even similar research, including the design life of the project. Further research could investigate how the design life of a project may impact on the environmental performance.

Acknowledgment
The authors appreciate Yudi Hidayat and Drajad Adhiprasetyo for supporting site survey and collecting data for this research. This research was financially supported by The Faculty of Engineering, Diponegoro University, Indonesia through Strategic Research Grant 2020.

References
[1] Utomo DHJ, Hidayat A, Setiawati A, Catur APS. Measuring Carbon Footprint of Flexible Pavement Construction Project in Indonesia. Hadiyanto, Sudarno, Maryono, editors. E3S Web of Conference. EDP Sciences; 2018;31:07001 .doi.org/10.1051/e3sconf/20183107001
[2] Shaban AM, Alsabbagh A, Waife S, Sukasawang N. Effect of Pavement Foundation Materials on Rigid Pavement Response. IOP Conf. Ser. Mater. Sci. Eng. IOP Publishing; 2020 Jan 17;671:012085. doi.org/10.1088/1757-899X/671/1/012085
[3] Handayani FS, Pramesti FP, Wibowo MA, Setyawan A. Estimating and Reducing the Release of Greenhouse Gases in Local Road Pavement Constructions. International Journal on Advanced Science, Engineering and Information Technology. Insight Society; 2019 Oct 31;9(5):1709. doi.org/10.18517/ijaseit.9.5.9705
[4] Mulyana A, Wirahadikusumah R. Analisis Konsumsi Energi dan Emisi Gas Rumah Kaca pada
Tahap Konstruksi Studi Kasus: Konstruksi Jalan Cisumdawu (Analysis of Energy Consumption and Greenhouse Gas Emissions during the Construction Stage Case Study: Cisumdawu Road Construction). *Jurnal Teknik Sipil ITB*. 2017;24:269–80.

[5] Abergel T, Dean B, Dulac J. *Towards a zero-emission, efficient, and resilient buildings and construction sector*. United Nations Environment Programme; 2017.

[6] Lawalata GM. *Prinsip-Prinsip Pembangunan Jalan Berkelanjutan* (Principles of Sustainable Road Development). *Jurnal Transportasi*. 2013;13:115–24

[7] Beatley T. *The Sustainable Urban Development Reader*. Routledge; 2004 Jan 22. doi.org/10.4324/9780203501627

[8] Agung WM, Uda SAKA, Zhabrinna. Reducing carbon emission in construction base on project life cycle (PLC). Hajek P, Han AL, Kristiawan S, Chan WT, Ismail M b., Gan BS, et al., editors. *MATEC Web of Conferences*. EDP Sciences; 2018;195:06002. doi.org/10.1051/matecconf/201819506002

[9] Lawalata GM. *Pemeringkatan Jalan Hijau untuk Mendukung Implementasi Program Konstruksi Jalan Berkelanjutan* (Green Road Ratings to Support the Implementation of the Sustainable Road Construction Program). *Jurnal HPJI*. 2019;5:21–30.

[10] ISO. *Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006)* vol 44. British Standard; 2006.

[11] Araújo JPC, Oliveira JRM, Silva HMRD. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. *Transp Res D Transp Environ*. Elsevier BV; 2014 Oct;32:97–110. doi.org/10.1016/j.trd.2014.07.006

[12] Hasan U, Whyte A, Al Jasmi H. Life cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach. *J. Clean. Prod*. Elsevier BV; 2020 Jun;257:120531. doi.org/10.1016/j.jclepro.2020.120531

[13] Ivel J, Watson R, Abbassi B, Abu-Hamattreh ZS. Life cycle analysis of concrete and asphalt used in road pavements. *Environ. Eng. Res*. Korean Society of Environmental Engineering; 2019 Mar;25(1):52–61. doi.org/10.4491/eer.2018.399

[14] Cong L, Guo G, Yu M, Yang F, Tan L. The energy consumption and emission of polyurethane pavement construction based on life cycle assessment. *J. Clean. Prod*. Elsevier BV; 2020 May;256:120395. doi.org/10.1016/j.jclepro.2020.120395

[15] Praticò FG, Giunta M, Mistretta M, Gulotta TM. Energy and Environmental Life Cycle Assessment of Sustainable Pavement Materials and Technologies for Urban Roads. *Sustainability*. MDPI AG; 2020 Jan 18;12(2):704. doi.org/10.3390/su12020704

[16] Park W-J, Kim T, Roh S, Kim R. Analysis of Life Cycle Environmental Impact of Recycled Aggregate. *Appl. Sci*. MDPI AG; 2019 Mar 12;9(5):1021. doi.org/10.3390/app9051021

[17] Wang T, Xiao F, Zhu X, Huang B, Wang J, Amirkhanian S. Energy consumption and environmental impact of rubberized asphalt pavement. *J. Clean. Prod*. Elsevier BV; 2018 Apr;180:139–58. doi.org/10.1016/j.jclepro.2018.01.086

[18] Kucukvar M, Noori M, Egilmez G, Tatari O. Stochastic decision modeling for sustainable pavement designs. *Int. J. Life. Cycle. Assess*. Springer Science and Business Media LLC; 2014 Feb 25;19(6):1185–99. doi.org/10.1007/s11367-014-0723-4

[19] Kim T, Tae S. Proposal of Environmental Impact Assessment Method for Concrete in South Korea: An Application in LCA (Life Cycle Assessment). *Int. J. Environ. Res. Public Health*. 
[20] Huang Y, Bird R, Heidrich O. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *J. Clean. Prod.* Elsevier BV; 2009 Jan;17(2):283–96. doi.org/10.1016/j.jclepro.2008.06.005

[21] Louzguine DV, Inoue A, Saito M, Waseda Y. *Eco-indicator 99 Manual for Designers.* The Hague: Ministry of Housing, Spatial Planning and the Environment Communications Directorate; 2000.

[22] Thives LP, Ghisi E. Asphalt mixtures emission and energy consumption: A review. Renewable and Sustainable Energy Reviews. Elsevier BV; 2017 May;72:473–84. doi.org/10.1016/j.rser.2017.01.087

[23] Chang Y, Ries RJ, Lei S. The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model. *Energy and Buildings.* Elsevier BV; 2012 Dec;55:790–8. doi.org/10.1016/j.enbuild.2012.10.019

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

[25] Cass D, Mukherjee A. Calculation of Greenhouse Gas Emissions for Highway Construction Operations by Using a Hybrid Life-Cycle Assessment Approach: Case Study for Pavement Operations. *J. Constr. Eng. M. Asce.* American Society of Civil Engineers (ASCE); 2011 Nov;137(11):1015–25. doi.org/10.1061/(asce)co.1943-7862.0000349

[26] Li H, Deng Q, Zhang J, Olubunmi Olanipekun A, Lyu S. Environmental Impact Assessment of Transportation Infrastructure in the Life Cycle: Case Study of a Fast Track Transportation Project in China. *Energies.* MDPI AG; 2019 Mar 15;12(6):1015. doi.org/10.3390/en12061015