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# Life Cycle Cost Evaluation of Lab-Scale Modified Asphalt Mixture Production

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## *Abstract*

*This paper compares the life cycle costs (LCC) of various asphalt mixture technologies added with polymeric substances that modify either the binder or the whole mix and evaluates the hotspot of each mix type with the scope of cradle-to-gate from the raw materials purchase to the production of 7 kg samples. The polymer-modified binder yields the largest total cost of IDR 12,197, followed by the polymer-modified warm and hot asphalt mixture with a difference of up to 3% and 14.5%, and the standard hot mix gives the lowest result (IDR 9,344) of 23.4% smaller than the largest. Raw material price holds the major contribution with approximately 82.7%, while electricity consumption accounts for 30%. Oven heating contributes the most to the calculated impact from the lab production by 40 to 60%, followed by the mixing activity by a 10 – 30% difference. Conclusively, the LCC of bituminous mixture production is heavily influenced by raw materials price and electricity consumption, and the standard hot mix asphalt generates the lowest total cost, despite having a higher cost than the warm mix in the production stage.*

***Keywords:*** *Life Cycle Cost, Cradle-to-Gate, Asphalt, Production*

## Abstrak

Riset ini membandingkan *life cycle cost* (LCC) dari beberapa jenis teknologi campuran aspal yang ditambahkan dengan bahan polimer yang digunakan untuk memodifikasi bitumen dengan campuran aspal serta mengevaluasi tinjauan kritis dari tiap jenis campuran dengan lingkup berupa *cradle-to-gate* dari tahap akuisisi bahan baku hingga produksi 7 kg sampel untuk masing-masing tipe. Penggunaan bitumen modifikasi polimer menghasilkan harga terbesar yakni IDR 12,197, diikuti oleh aspal campuran hangat dan panas modifikasi polimer dengan perbedaan hingga 3% dan 14.5%, serta metode produksi campuran aspal panas standar menghasilkan nilai terkecil (IDR 9,344) sebesar 23.4% dibandingkan nilai terbesar. Harga bahan baku memberi kontribusi terbesar hingga mencapai 82.7% sementara konsumsi listrik berkontribusi sebanyak 30%. Tahap pemanasan dalam oven memberi kontribusi terbesar untuk dampak dari proses produksi di lab mencapai 40 hingga 60%, diikuti oleh kegiatan pencampuran dengan selisih 10 - 30%. Dapat disimpulkan bahwa LCC dari campuran aspal sangat terpengaruh oleh harga bahan baku serta konsumsi energi listrik, serta campuran aspal panas standar menghasilkan LCC terendah, walaupun menghasilkan nilai yang lebih tinggi pada tahap produksi sampel dibandingkan campuran aspal hangat.

**Kata kunci:** *Life Cycle Cost*, *Cradle-to-Gate*, Campuran Aspal, Produksi

## Introduction

Numerous modifications have been implemented to asphaltic mixtures for road constructions to enhance their properties against ever-increasing traffic loading, particularly in Indonesia, where the average annual traffic growth from 2019 to 2021 was estimated to reach 3% (Badan Pusat Statistik, 2022). One of the most popular modification methods is using polymeric products. There is a large variety of polymers used for asphalt mixes, among which are elastomeric products such as rubber (natural and crumb) and styrene-butadiene-styrene (SBS), as well as thermoplastic products such as ethylene vinyl acetate (EVA), polyethylene (PE), polypropylene (PP), polyester, and polyethylene terephthalate (PET). The application of these products can either be through the modification of the bitumen itself to form the polymer-modified binder (PMB) before being applied to form the asphaltic mixture, commonly addressed as the wet mix method, or by pouring the polymer into the whole mixture during the blending stage, known as the dry mix method (Brasileiro et al., 2019). The modification of the asphaltic mixture by means of the aforementioned polymers and mixing techniques has been outlined in numerous research, all of which can be performed on the most standardised type of bituminous mixture known in the Indonesian national standard called hot mix asphalt produced at 155-170$^o$C, as well as the warm mix asphalt produced at 120-135$^o$C with various effect (Dirjen Bina Marga, 2018). Crumb rubber, for instance, has been widely used to modify the rheological properties of an asphalt binder, particularly in an attempt to create warm mix asphalt products produced at the temperature of 120-140$^o$C, with the result of increased elastic recovery and stiffness of the binder, leading to a higher quality mixture for road structures. SBS is the most popular type of polymer incorporated to modify bituminous binder, with the most notable brand under Shell (Shell Bitumen, n.d.). Current reports show enhanced rheological properties of the crumb-rubber, SBS, or polyethylene-modified binder in the form of increased molecular weight that improves its complex viscosity and reduces phase angle, leading to elevated elastic recovery, stiffness, thermal cracking resistance, and fatigue life with a decent opportunity to use warm mix asphalt technologies; nonetheless, chemical stabilising agents are required to improve the compatibility with the polymer and binder, and exceeding polymer content by typically more than 6% is found to cause segregation between polymeric-rich phase and bitumen-rich phase (Hao et al., 2017; Nizamuddin et al., 2021; Okhotnikova et al., 2019; Porto et al., 2019; Ratajczak & Wilmański, 2020; Wang, 2021; Wang et al., 2018, 2020). On the other hand, the application of polymeric products in the dry mixture scale often comes in the fibrous form, reportedly increasing the stiffness, fatigue life, rutting resistance, thermal cracking resistance, tensile strength, and binder absorption to prevent bleeding in road structures, also with a possibility to incorporate the warm mix asphalt and recycled asphalt technologies (Apostolidis et al., 2020; Daniel, 2020; Daniel et al., 2019, 2021; Fazaeli et al., 2016; Gao et al., 2021; Gibson & Li, 2015; Giustozzi et al., 2015; Ho et al., 2016; Jaskuła et al., 2017; Poulikakos et al., 2017). Besides the fibrous form, the polymer can be incorporated by a granular shape, with an example being the granular-shaped EVA reported to enhance stiffness, tensile strength, rutting resistance, and crack resistance of hot and warm bituminous mixtures (Daniel et al., 2022; Montanelli & srl, 2013).

In addition to improving mechanical properties and durability, several projects have documented the environmental impact and cost that follows the modification in asphalt concrete mixtures to create a cost-benefit analysis. Life cycle assessment (LCA) is deemed a powerful method to evaluate the impact of a product, mainly a bituminous mixture in this case, during its whole life cycle, albeit depending on data available in the interest region (Arendt et al., 2020; Karaman Öztaş, 2018). There are several stages that can be considered in a typical LCA evaluation that form its scope and boundary, from the raw material acquisition, known as a cradle stage, to the demolition of the structure, known as a grave stage, with a possibility to extend the life of the material by recycling it to create another cradle stage (Cristobal-Garcia et al., 2016; Horne et al., 2009; JRC Science Hub, 2016; Klopffer & Grahl, 2014). The environmental impact obtained from LCA can be further analysed to give a monetary value using a process known as Life Cycle Cost Assessment (LCCA). LCCA has been widely applied in construction projects globally, both in building and road projects. Numerous case studies, including in Indonesia, have presented the possibility of measuring the entire cost until the end of life, some of which were in combination with Building Information Modelling (BIM) and artificial neural network systems (Dutta, 2014; Kadek et al., 2023; Li & Madanu, 2009; Liang et al., 2019; Maisham et al., 2019; Mearig & Morris, 2018; Menufandu et al., 2017; Petrović et al., 2021; Rasane & Ambre, 2019;

Reyes et al., 2022; US Department of Transportation, 1998). Previous research of the authors has addressed the impact of lab-scale production of several types of asphalt concrete mixture, from warm mix asphalt and hot mix asphalt, to evaluate the impact of polymer addition to the mixture regarding its mechanical properties, with an emphasis on the environmental impact (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023). This study will proceed from the previous project with a calculation of the life cycle cost within the same scope as its predecessor to further characterise the impact of the mixture variation and exemplify the effect of incorporating different materials on the production treatment, and hence, the outcome. This research is done as an attempt to evaluate the hidden cost of the environmental impact assessed through each phase of the production stage on the lab scale, as opposed to the previous outcomes stated herein, in which the impact was mainly measured in the field that treated the production stage as one combined process.

## Research Methods

This study attempted to evaluate the cost due to the production of four types of bituminous mixtures at a lab scale. The scope used in this research was cradle-to-gate from the purchase of the raw material to the fabrication of 5 cylindrical samples with 100-mm diameter for each type of asphalt concrete mix, or approximately 7kg per each type. The asphaltic mixture fabricated in this study comprised the hot mix asphalt using polymer-modified binder (PMB) produced at 180ºC (**case 1**), the EVA-modified hot mix asphalt fabricated at 160ºC (the use of 5% and 6% EVA w/t are regarded as **case 2** and **case 3**), the EVA-modified warm mix asphalt fabricated at 130ºC (the use of 5% and 6% EVA w/t are regarded as **case 4** and **case 5**), and the standard hot mix asphalt at 160ºC (**case 6**). The production protocol for each case is explained as follows.

Firstly, all the raw materials were heated according to their intended production temperature. For case 1, the materials were directly subjected to the temperature of 180ºC. For case 2 – case 3 and case 6, the materials were heated at 160ºC. Meanwhile, for case 4 – case 5, only the binder was heated at 160ºC before being mixed with zeolite to achieve the desired viscosity when blended with the aggregates, which were put at 130ºC simultaneously. The oven heating stage was kept at 45 minutes for all specimens before being put into the mixer. The mixing phase started with subjecting the aggregates to a 2-minute mixing process first prior to pouring EVA (case 2 - case 5) shortly before pouring the binder into the mixer. The whole mixing process lasted for less than 5 minutes for each specimen. Finally, the sample was collected from the mixer and put into a standard cylindrical-shaped Marshall mould of 100mm diameter for the compaction phase. The specimen was compacted according to the national standard (Bina Marga 2018 Rev. 2) with 75 blows applied to each surface of the cylindrical sample. All activities described herein were subjected to a simplified emission measurement system in the compound, where air quality sensors under the brand name of Dienmern 502-03 were mounted on top or close to the emission sources, such as on top of the mixing bowl and compaction machine, as explained in the previous papers from the authors (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023). The room was isolated during the recording to ensure no external source interfered with the process. Table 1 and Table *2* capture the total amount of raw material used for the production of the asphalt mix specimens, including the energy use.

The outcomes of this activity have been described in environmental impact assessment results already published in national publications previously, summarised in Table 3-Table *5*.

The results from Table 3 were then added with the outcome of voltage and electric current measurements using digital multimeters attached to the oven cable over the whole duration to raise from the room temperature to the desired point, conducted to accurately characterise the effect of three different heating temperatures, namely 130, 160, and 180ºC, on the electricity consumption during the production. The total electrical current and voltage were then multiplied to convert them to the total electricity consumption by modifying Ohm's law, expressed in Eq. 1.

$$E = \sum_{t=0}^{t} I \cdot V \cdot t \qquad \text{Eq. 1}$$

Where E denotes the power consumption in Watt-Hour, I is the measured electrical current in Ampere, the electrical voltage (in Volt) is denoted by V, and t denotes the duration of the equipment usage, in this case the oven.

**Table 1.** Previous research – Total material quantity (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023)

| Material | Unit | Total use | | |
|---|---|---|---|---|
| | | Case 1 | Case 2 | Case 3 |
| Coarse aggregate | gr | 2,570.54 | 2,540.58 | 2,540.58 |
| Fine aggregate | gr | 3,592.17 | 3,550.30 | 3,550.30 |
| Filler | gr | 428.42 | 423.43 | 423.43 |
| Zeolite | gr | 0 | 0 | 0 |
| Bitumen 60/70 | gr | 0 | 390.86 | 390.86 |
| PMB PG76 | gr | 395.47 | 0 | 0 |
| EVA | gr | 0 | 97.71 | 117.26 |
| Energy use | kWh | 0.97 | 0.75 | 0.75 |

**Table 2 (Cont).** Previous research – Total material quantity (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023)

| Material | Unit | Total use | | |
|---|---|---|---|---|
| | | Case 4 | Case 5 | Case 6 |
| Coarse aggregate | gr | 2,570.54 | 2,570.54 | 2,570.54 |
| Fine aggregate | gr | 3,592.17 | 3,592.17 | 3,592.17 |
| Filler | gr | 428.42 | 428.42 | 428.42 |
| Zeolite | gr | 2.91 | 2.91 | 0 |
| Bitumen 60/70 | gr | 390.86 | 390.86 | 390.86 |
| PMB PG76 | gr | 0 | 0 | 0 |
| EVA | gr | 97.71 | 117.26 | 0 |
| Energy use | kWh | 0.63 | 0.63 | 0.75 |

**Table 3.** Previous research - Measured environmental impact of several types of bituminous mixtures production modified with polymer (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023)

| Environmental impacts | Unit | HMA with PMB **(Case 1)** | HMA with polymer 5% **(Case 2)** |
|---|---|---|---|
| Global Warming Potential | kg CO$_2$-eq | 2.76 | 2.65 |
| Freshwater aquatic ecotoxicity potential | kg 1.4DB-eq | 0.37 | 0.32 |
| Human Toxicity Potential | kg 1.4DB-eq | 167.03 | 125.21 |
| Photochemical Oxidation Potential | kg C$_2$H$_4$-eq | 0.00081 | 0.00061 |

The whole measurement setup is shown in Figure 1 with an interval of 5 minutes for each reading. Meanwhile, the data of the mixer and compaction machine were obtained directly from the manufacturer.

**Table 4. (Cont.)** Previous research - Measured environmental impact of several types of bituminous mixtures production modified with polymer (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023)

| Environmental impacts | Unit | HMA with polymer 6% **(Case 3)** | WMA with polymer 5% **(Case 4)** |
|---|---|---|---|
| Global Warming Potential | kg CO$_2$-eq | 2.73 | 2.52 |
| Freshwater aquatic ecotoxicity potential | kg 1.4DB-eq | 0.34 | 0.343 |
| Human Toxicity Potential | kg 1.4DB-eq | 143.06 | 157.75 |
| Photochemical Oxidation Potential | kg C$_2$H$_4$-eq | 0.00069 | 0.00078 |

**Table 5. (Cont.)** Previous research - Measured environmental impact of several types of bituminous mixtures production modified with polymer (Daniel, Canny, et al., 2023; Daniel, Rifqon, et al., 2023)

| Environmental impacts | Unit | WMA with polymer 6% **(Case 5)** | Standard HMA **(Case 6)** |
|---|---|---|---|
| Global Warming Potential | kg CO$_2$-eq | 2.57 | 2.37 |
| Freshwater aquatic ecotoxicity potential | kg 1.4DB-eq | 0.348 | 0.4 |
| Human Toxicity Potential | kg 1.4DB-eq | 161.56 | 160.53 |
| Photochemical Oxidation Potential | kg C$_2$H$_4$-eq | 0.00081 | 0.00078 |

The system considered for the life cycle cost analysis follows Figure 2, in which only the life cycle impact given inside the boundary was taken into account based on the given database and measured data (Table 3-Table *5*) added with the purchasing cost of each materials and unit electric energy price, whereas the purchasing and whole life cycle costs of the equipments used in the production stage were not part of this calculation. This approach was taken by judging from the usage duration of each equipment in this research, which did not exceed 3 minutes per sample, as compared to their average lifespan, providing a negligible effect on the outcome.

**Figure 1.** Electrical charge voltage and current measurement at the oven

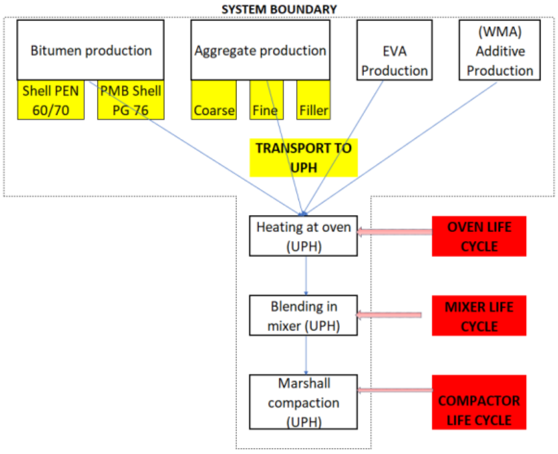


**Figure 2.** Product system and boundary of the study

All the gathered data were converted to the impact cost based on several assumptions. Firstly, the environmental impact cost calculation was based on the Dutch impact database (Nationale Milieu Database, 2022) with the currency conversion of EUR-IDR created from the currency of June 26th, 2023 (www.XE.com). Moreover, the material procurement cost was taken from the actual bulk purchasing price, and the electricity cost was taken from the standard national electricity price issued for 2023 (Kompas.com, 2023). All the conversion factors are shown in Table 6 and the unit prices are shown in Table *7*. The amount of environmental impact cost from the LCA result displayed in Table 3-Table *5* will be multiplied by the conversion factor shown in Table 6 and Table *7* to convert the impact to the cost analysis using Eq. 2.

$$\begin{aligned} &Total\ Impact\ (from\ LCA) \\ &= Measured\ Impact \\ &\times Characterisation\ Factor \\ &\times Conversion\ factor\ (Currency) \end{aligned} \qquad \text{Eq. 2}$$

**Table 6.** Conversion table for life cycle cost analysis (Nationale Milieu Database, 2022)

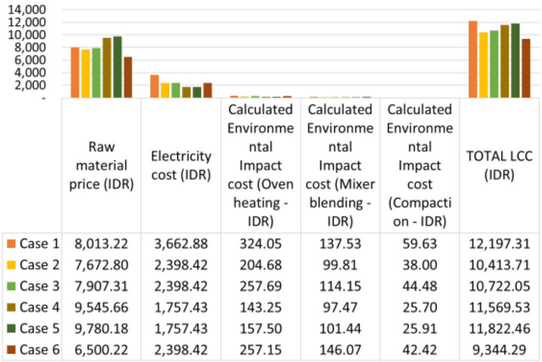
| Unit Environmental impacts | Conversion (EUR) | Currency EUR -> IDR |
|---|---|---|
| Environmental impact cost (Global Warming Potential – kg $CO_2$-eq) | 0.123 | 16,408.45 (*XE Conversion factor, June 26th, 2023*) |
| Environmental impact cost (Freshwater aquatic ecotoxicity potential – kg 1.4DB-eq) | 0.03 | |
| Environmental impact cost (Human Toxicity Potential – kg 1.4DB-eq) | 0.09 | |
| Environmental impact cost (Photochemical Oxidation Potential - kg $C_2H_4$-eq) | 2 | |

**Table 7.** Unit price data for life cycle cost analysis (Kompas.com, 2023)

| Unit Environmental impacts | Unit price in IDR Data taken in June 26th, 2023 |
|---|---|
| 2023 Electricity cost/ kWh | 1,115 |
| Raw material price – coarse aggregates/ $m^3$ | 650,000 |
| Raw material price – fine aggregates/ $m^3$ | 500,000 |
| Raw material price – filler/ $m^3$ | 650,000 |
| Raw material price – EVA polymer/ kg | 60,000 |
| Raw material price – zeolite/ kg | 23,000 |
| Raw material price – PMB/ 155 kg | 2,600,000 |
| Raw material price – 60/70 bitumen/ 155 kg | 2,000,000 |

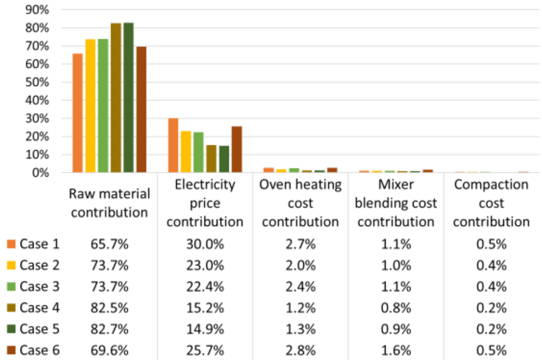
## Result and Discussion

The outcomes of the cost analysis of all types of specimens are presented in Figure 3 to Figure 6.



|  | Raw material price (IDR) | Electricity cost (IDR) | Calculated Environmental Impact cost (Oven heating - IDR) | Calculated Environmental Impact cost (Mixer blending - IDR) | Calculated Environmental Impact cost (Compaction - IDR) | TOTAL LCC (IDR) |
|---|---|---|---|---|---|---|
| ■ Case 1 | 8,013.22 | 3,662.88 | 324.05 | 137.53 | 59.63 | 12,197.31 |
| ■ Case 2 | 7,672.80 | 2,398.42 | 204.68 | 99.81 | 38.00 | 10,413.71 |
| ■ Case 3 | 7,907.31 | 2,398.42 | 257.69 | 114.15 | 44.48 | 10,722.05 |
| ■ Case 4 | 9,545.66 | 1,757.43 | 143.25 | 97.47 | 25.70 | 11,569.53 |
| ■ Case 5 | 9,780.18 | 1,757.43 | 157.50 | 101.44 | 25.91 | 11,822.46 |
| ■ Case 6 | 6,500.22 | 2,398.42 | 257.15 | 146.07 | 42.42 | 9,344.29 |

**Figure 3.** Total calculated life cycle cost of various asphalt mixtures lab-scale production



|  | Raw material contribution | Electricity price contribution | Oven heating cost contribution | Mixer blending cost contribution | Compaction cost contribution |
|---|---|---|---|---|---|
| ■ Case 1 | 65.7% | 30.0% | 2.7% | 1.1% | 0.5% |
| ■ Case 2 | 73.7% | 23.0% | 2.0% | 1.0% | 0.4% |
| ■ Case 3 | 73.7% | 22.4% | 2.4% | 1.1% | 0.4% |
| ■ Case 4 | 82.5% | 15.2% | 1.2% | 0.8% | 0.2% |
| ■ Case 5 | 82.7% | 14.9% | 1.3% | 0.9% | 0.2% |
| ■ Case 6 | 69.6% | 25.7% | 2.8% | 1.6% | 0.5% |

**Figure 4.** Contribution of each phase to the total calculated  life cycle cost

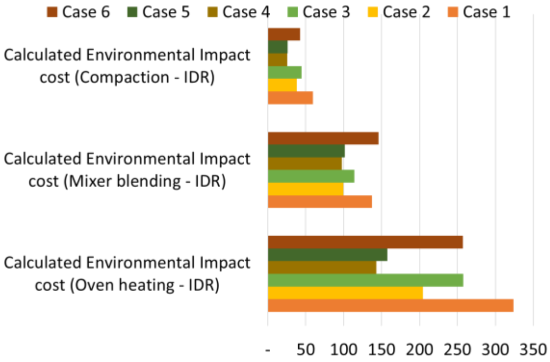


**Figure 5.** Calculated environmental impact cost from lab-scale sample production

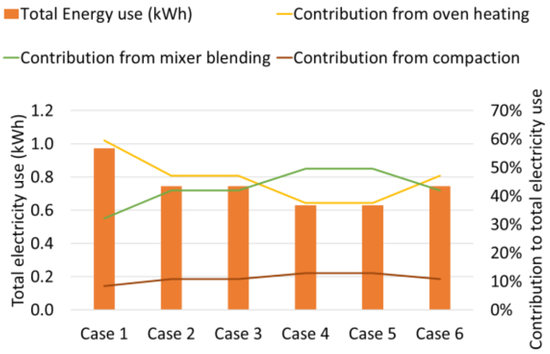


**Figure 6.** Calculation of electricity use

Figure 3 and Figure 4 comprise the total cost needed for the small scope of the laboratory-scale production of the bituminous mix, and the raw materials price generates the most significant contribution by up to 82.7% of the total cost with a large margin to the electricity consumption and other stages that contribute only up to 30% and less than 3% of the total cost, respectively. The production of bituminous mixture specimens using polymer-modified binder (case 1) concludes the largest cost, hugely attributed to a higher binder price and high electricity cost from a higher temperature in the oven heating stage. It is also apparent that the raw material cost for both types of WMA specimens (case 4 - case 5) spikes due to the extra materials used, namely zeolite and EVA polymer. Meanwhile, the total electricity cost of both the hot mix asphalt samples produced at 160°C (case 2 – case 3. case 6) and warm mix asphalt samples produced at 130°C (case 4 and case 5) experienced 34,5% and 52% reduction compared to that of the hot mix asphalt with PMB product produced at 180°C (case 1), and further explanation is illustrated in Figure 5 and Figure 6. Both graphs indicate the significance of the emission cost due to oven heating and electricity consumption relative to the other stages in the laboratory. Evidently, the environmental impact cost due to oven heating is approximately two and six times larger than the mixing and compaction stages, respectively, and the heating contributes around 46% to the total electricity demand in the laboratory on average with the range of 40 – 60%, slightly followed by the mixer blending with the estimated average contribution of 42% for every type of fabricated specimen with the range of 30 – 50%. It can also be seen that the temperature difference of 20°C between the production using PMB (case 1) and the standard HMA using polymer (case 2 – case 3) yields a decrease in total electricity consumption by 23%. In contrast, the lower temperature of WMA production by 30°C (case 4 – case 5) only generates 15% lower consumption compared to the standard HMA (case 6).

Conversely, the impact costs of the modified warm mix asphalts from both the mixing and compaction stages are found to be lower than in the other cases, directly proportionate to the decrease in electricity consumption. This indicates that the warm mix additive, which reduces binder viscosity, contributes to more effortless blending with the aggregates and lowers the necessary compaction effort compared to the hot mix asphalt samples. It is also apparent that the use of additives on both hot and warm mix asphalt specimens required neither additional electricity in every stage nor longer production duration, thus introducing no notable difference to the standard mixture in terms of the required electrical energy. Nonetheless, the decreased electricity consumption, as well as easier mixing and compaction efforts, are compensated by the price of the raw material, thereby making the production of polymer-modified WMA specimens (case 4 – case 5), which uses extra zeolite as the warm-mix additive, incline to become IDR 11,822 for 7kg of specimens, only 3% lower than the production of the mixture using PMB of IDR 12,197 (case 1). On the other hand, cases 2-3 and case 6 generate the lowest total LCC by IDR 10.413, IDR 10.722, and IDR 9.344, respectively, or being 12% to 23.4% smaller than the highest outcome (case 1). This indicates that the standard mixing temperature of 160$^o$C does not necessarily yield a higher total cost than the lower one in cases 2 and 3, which is mainly due to the additives employed for the warm mix asphalt (case 2 – case 3), and the raw material price for the PMB product and the highest production temperature at 180$^o$C (case 1). Nonetheless, judging from the previous studies about the effect of polymer on mechanical properties and environmental impact of the asphalt concrete mix (Daniel, Canny, et al., 2023; Daniel et al., 2022; Daniel, Rifqon, et al., 2023; Montanelli & srl, 2013), it is apparent that the inclusion leads into improved performances, which in turn, will possibly lead to higher service life. Consequently, further research needs to address the long-term behaviour of the pavement structure, including the generated impact cost, the emission from the users, lifespan, demolition, and further opportunity for recycling the materials.

## Conclusion

This paper presents the comparison of life cycle costs generated from the production of several asphalt mixture technologies modified with polymeric substances through wet and dry methods with the scope of cradle-to-gate from the purchasing of raw materials to the production of 7 kg samples of each type of mixture. It is found that the application of the polymer-modified binder (case 1) with the highest material heating temperature and purchasing cost yields the highest life cycle cost, followed by the warm (case 4 – case 5) and hot mix asphalt (case 2 – case 3) modified with the polymer using the dry mix method with a difference of up to 3% and 14.5%, respectively. Meanwhile, case 6 (standard hot mix asphalt) records the lowest cost by 23.4% smaller than case 1. The cost of raw material purchasing holds the most significant proportion to this result with up to 82.7%, while the electricity consumption costs up to 30%. In addition, the impact of oven-heating activities accounts for the largest proportion within the range of 40 to 60% of the total measurement, slightly followed by the mixing activity by a difference of 10 – 30% to the heating process. Lastly, using extra additives for the warm mix asphalt samples increases the total production cost to only 3% less than case 1, whereas the standardised approach (case 6) yields the lowest cost by 23.4% smaller than case 1. Conclusively, the life cycle cost up to the sample production stage of bituminous mixtures is highly influenced by the raw materials price and electricity consumption from the high heating temperature, also related to the highest fraction of environmental impact cost. However, the standard method (case 6) still reaches the lowest cost due to the absence of extra materials compared to other cases, even with the lower production temperature (case 2 – case 3).

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