Carbon footprint estimation of an asphalt mixture containing PET-waste bottles

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Abstract*– This study quantifies the carbon footprint of an asphalt mixture that incorporates polyethylene terephthalate (PET) waste as a partial replacement for conventional asphalt mixture. A life cycle assessment (LCA) approach was employed to assess greenhouse gas emissions associated with raw material extraction, production, transportation and construction processes. The results indicate that the incorporation of PET waste reduces the carbon emissions of the asphalt mixture compared to conventional formulations. This reduction is primarily attributed to lower energy demand and reduced dependence on petroleum-based fuels. The findings highlight the potential of PET-modified asphalt as a more sustainable alternative for pavement applications, contributing to waste reduction and climate change mitigation. These results support the integration of recycled plastics into road construction as an effective strategy to reduce the environmental impact of asphalt production.

Keywords—carbon footprint, life cycle analysis, asphalt mixture, PET, waste materials in infrastructure

I. Introduction

Climate change is one of the most complex challenges facing humanity today [1]. It has been identified that one of the main contributors to this problem is the burning of fossil fuels, which releases large amounts of carbon dioxide and other pollutants that exacerbate the greenhouse effect [2]. The greenhouse effect is a natural mechanism that keeps the temperature of the planet within habitable limits. However, the excessive accumulation of gases such as carbon dioxide, methane and others alter the mechanism, causing global warming, which has been increased by human activities [3]. Specifically, the transportation sector is considered one of the largest contributors because of its dependence on fossil fuels [4]. In addition to this, the construction of asphalt-based transportation roads plays an important role in this problem [5].

The use of asphalt in paving contributes to global warming primarily because the production of asphalt releases a considerable amount of carbon dioxide (CO_2) and other greenhouse gases. Manufacturing asphalt requires refining oil, a process that consumes a lot of energy and generates significant CO_2 emissions [6]. Additionally, during paving, the asphalt must be heated to high temperatures, which consumes large amounts of energy, typically from fossil fuels [7].

Currently, there are various regulations to estimate the contribution of the production of asphalt mixtures to global warming, among them are the ISO-14040 and ISO-14064 standards for life cycle analysis and carbon footprint estimation, respectively. The application of both regulations allows not only to quantify the greenhouse gases associated with specific activities, but also to identify opportunities for improvement for the analyzed processes and apply changes whenever feasible, to improve their environmental performance [8,9].

Understanding these impacts is essential to developing effective mitigation and adaptation strategies. For example, a recent initiative has been the use of various waste materials as another component in asphalt mixtures. This has proven to have benefits, not only on an environmental level, but also on a mechanical level [10]. However, it is necessary to understand the effect that the incorporation of waste would have on the carbon footprint of the resulting material. Therefore, the objective of this research is to study the life cycle of waste plastics (polyethylene, PET, specifically) as an additive in hot asphalt mixtures by means of the determination of its carbon footprint, applying ISO-14040 and 14064 standards.

II. Background

Asphalt mixtures are mainly composed of aggregates and bitumen, a petroleum product. The production process consists of several stages, each of which contributes to the overall carbon footprint. First, it is considered that transportation of raw materials to the asphalt plant and transportation of finished product to construction sites contribute to GHG emissions [11]. The distance traveled and the mode of transportation (truck, rail or ship) influence the magnitude of these emissions. Additionally, during mixture production the raw materials are heated and mixed in the asphalt plant. Then, the energy needed for heating, usually derived from fossil fuels, is a major source of emissions, including carbon, volatile organic compounds (VOCs) and particulates [12]. Also, construction activities require energy-intensive machinery, further increasing the carbon footprint [13]. Lastly, regular maintenance and rehabilitation of asphalt roads involves additional material production and application processes, which contribute to long-term GHG emissions [14].

Nowadays, there are various research focused on quantifying GHG emissions of asphalt mixtures to evaluate the effect of more green processes or the use of waste materials on the carbon footprint. For example, Gettu and Buttlar [10] identify the extraction and processing of raw materials as the most critical phase that impacts the carbon footprint of asphalt mixtures. The study emphasizes the environmental burden associated with the extraction of crude oil and the production of binding materials. It suggests that optimizing material use and incorporating recycled materials can significantly reduce the carbon footprint.

For example, recent research evaluates greenhouse gas (GHG) reduction potentials through improved waste management and resource efficiency in Taiwan. It uses a waste input-output (WIO) model to simulate different circular economy scenarios, such as increased recycling and alternative waste treatments, such as waste conversion to solid waste fuel (SRF). The study finds that recycling plastics significantly reduces GHG emissions compared to incineration and landfilling, demonstrating the environmental benefits of better recycling practices [15].

Also, another study compared the environmental impacts of reusing and recycling plastic waste. It found that reusing plastic materials significantly reduces the carbon footprint compared to recycling, mainly because reuse avoids energy-intensive processes such as collecting, sorting, cleaning and reprocessing. The study also emphasized the importance of developing systems to encourage reuse rather than recycling to maximize carbon footprint reduction [16].

Victory [17] present a review that evaluates the environmental performance of asphalt mixtures containing various recycled materials, such as crumb rubber, recycled PVC particles, and reclaimed asphalt pavement (RAP). The study highlights that the incorporation of these materials can significantly reduce the carbon footprint of asphalt mixtures. For example, the use of crumb rubber particles and recycled PVC in stone mastic asphalt mixtures improves performance and reduces environmental impact. Similarly, the author reports that the use of recycled steel slag and concrete aggregates reduces demand for virgin materials and reduces GHG emissions. The use of RAP also contributes to substantial carbon footprint reductions by minimizing the need for virgin materials and energy-intensive production processes.

In this sense, Godoi et al. [18] used a life cycle assessment methodology to estimate the carbon footprints of asphalt mixtures with increasing RAP content. They found that asphalt mixtures containing up to 93% RAP and produced at lower temperatures could reduce the carbon footprint by 55 to 64% compared to conventional mixtures. This reduction is due in part to decreased energy requirements to heat and process RAP. However, the authors recognized that high RAP contents might cause a lower rutting performance and a consequent reduction of service life.

Related to the previous, Pouranian and Shishehbor [19] evaluate the environmental and economic benefits of various technologies and materials used in asphalt mixtures, such as warm mix asphalt (WMA), crumb rubber modifier (CRM), and reclaimed asphalt pavement (RAP). The study finds that combinations such as WMA + RAP and WMA + CRM offer significant reductions in greenhouse gas emissions and energy consumption, although comprehensive economic analyzes are needed for full sustainability assessments.

Then, it is highlighted that the use of waste materials in infrastructure not only contribute to circularity but might have the potential to reduce carbon footprint associated to construction projects.

III. Methodology

The purpose of this research is to estimate the carbon footprint related to asphalt mixtures by means of a cradle to ground LCA study. Then, the results allow to compare the GHG emissions of a conventional mixture and a mixture that includes waste PET as an additive. The materials and methods are described as follows.

A. Case study description

The study focuses on the production and construction of a lane of asphalt mixture according to the description given in Table 1.

TABLE I
Case study description

Characteristics	Value
Length of the lane (m)	22,0
Width of the lane (m)	2,05
Thickness of asphalt layer (m)	0,100
Amount of asphalt mixture required per lane (kg)	12 135

Additionally, two different scenarios were considered: scenario 1 is a conventional asphalt mixture and scenario 2 is an asphalt mixture that contains 1% of PET obtained from waste plastic bottles. Details regarding materials and mixture design are given further in the text. Both scenarios were analyzed according to the scope described in Figure 1.

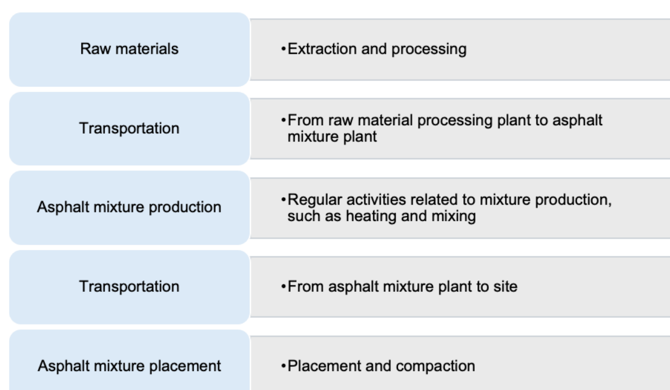

Fig. 1. Scope definition for the LCA analysis

B. Inventory and data collection

To proceed with the inventory, it was necessary to recover information from primary and secondary sources, as described below.

Primary sources:

In this case, the information was obtained by means of questionaries, e-mail and verbal communication. The data for the asphalt, fossil fuels and related materials was obtained from RECOPE, a local industry that oversees commercializing those products. The information regarding waste-PET manufacturing and processing were collected from a local plastic company. The data for the aggregates were collected from interviews and emails exchanged with the staff that operates the quarry. Lastly, the data for asphalt mixture production and placement was obtained from questionaries sent to the person in charge of the asphalt plant at the construction site. Other details were consulted by telephone and email.

Secondary sources:

The information that could not be collected from primary sources was obtained through secondary sources such as the Ecoinvent database, previous research that applies to the region and reports issued by the National Meteorological Institute of Costa Rica.

Subsequently, the modeling of the inventory data was carried out using a tool developed in an Excel spreadsheet. The tool considers all the stages and activities mentioned in Figure 1. Then, carbon footprint was calculated based on ISO 14064 (part 2) standard.

Tool development:

To configure the Excel-based tool, a review of existing carbon footprint tools, such as CCaLC2 [20] and CCLUB [21], was conducted. These tools served as a reference, as they also enable users to calculate the carbon footprint of products or processes and provide results disaggregated by life cycle stage.

The identification of emission sources and data collection for the greenhouse gas (GHG) inventory were carried out simultaneously with the development of the spreadsheet. Consequently, the tool was structured according to the stages defined in the cradle-to-site approach for asphalt mixtures. These stages include: (1) raw material production, (2) transportation of the raw material to the asphalt plant, (3) asphalt mixture production, (4) transportation of the mixture to the construction site, and (5) asphalt placement (Figure 1). Each stage was further subdivided into specific activities or unit operations relevant to that phase.

For the calculation methodology, ISO 14067:2018 was used as a guiding standard, complemented by the carbon footprint estimation methods proposed by Bo et al. [22] and Li et al. [23]. Lastly, the tool was populated with inventory data collected as described in the previous section.

C. Analysis

After collecting the data and quantifying carbon footprint, the results were analyzed. To do this, an analysis was carried out for each stage of the life cycle considering the effect of specific raw materials, such as recycled PET, aggregates and asphalt to the overall footprint. Then, a comparison between conventional mixture and a mixture containing plastic waste were carried out. Finally, conclusions and recommendations were obtained from these generated results, as indicated by the ISO 14040 standard.

IV. Analysis of Results

The 2 scenarios described were analyzed according to the case study description and the number of materials involved for each one. The carbon footprint was obtained for each scenario, represented by the emissions, in kilograms of carbon dioxide equivalent per functional unit. In this study, the functional unit corresponds to 1 ton of asphalt mixture. The carbon footprint for scenario 1 (original asphalt) is taken as a base for comparison. The results are shown in Table II.

TABLE II
CASE STUDY DESCRIPTION

Scenario	GHG emissions ($kgCO_2eq/ton_{mixture}$)	Difference (%)
Conventional asphalt mixture (Scenario 1)	356,31	-0,58
1% PET asphalt mixture (Scenario 2)	354,25	

According to the results, the decrease in GHG emissions may appear to be insignificant, since it is only 0,58%, which is approximately equivalent to 2 kg of carbon dioxide (equivalent).

Despite the modest reduction observed at the analyzed scale, the use of PET in asphalt mixtures presents important environmental and practical benefits. Incorporating recycled PET contributes to the circular economy by diverting plastic waste from landfills and reducing the demand for virgin materials. Additionally, when applied at larger project scales or across multiple road segments, the cumulative effect or emissions reduction could become more significant. Moreover, PET-containing mixtures has shown potential to improve pavement performance [24-26], which may result in longer service life and lower maintenance needs, which are factors that can further reduce the environmental impact over the full life cycle.

The global carbon footprint of each scenario can be divided into the individual carbon footprint for each phase involved in the LCA. Figure 2 shows the contribution of each stage of the life cycle to the carbon footprint of each mixture.

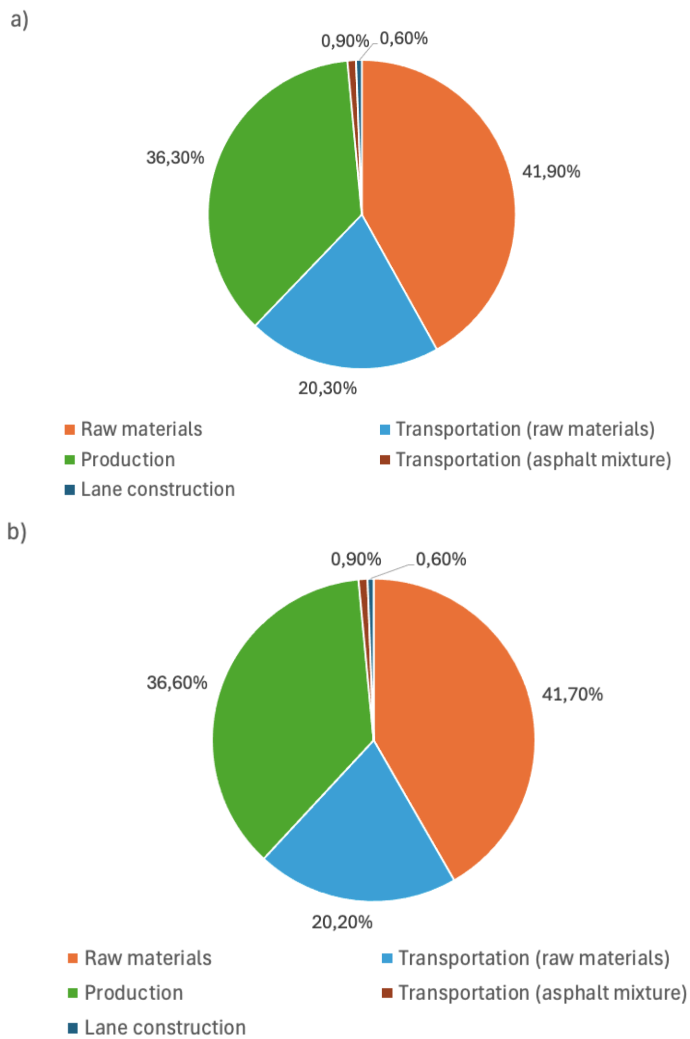

Fig. 2 contribution of each stage to the global carbon footprint of asphalt mixture placement a) conventional mixture (scenario 1) and b) PET-mixture (scenario 2)

In the case of scenario 1 (Figure 2.a), the raw material production phase generates the greatest contribution to the total carbon footprint, representing 41.9% of emissions. This stage includes the extraction and production of aggregates, extraction and distillation of oil, transportation of asphalt from the United States to Costa Rica and storage of the material in RECOPE. Scenario 2 (Figure 2.b) exhibits a similar trend.

The production of the asphalt mixture is the second stage that contributes the most to the carbon footprint in both scenarios with 36,3% (scenario 1) and 36,6% (scenario 2), which is attributed to the consumption of diesel and other fuels.

The transportation of raw materials from its distribution area to the asphalt mixing plant corresponds to 20,3% and 20,2% of the total emissions for scenario 1 and 2, respectively. The fact that each type of material comes from different areas increases emissions compared to the transportation of the asphalt mixture alone, that reaches a 0,9% for both scenarios. Lastly, the construction stage represents 0,6% of the total footprint in both cases, this is a stage where the least amount of fuel is required due to the short time required to place the mixture.

Lane construction

Based on the dimensions described in Table I and the information collected from the company in charge of the construction, the carbon footprint for the entire project was determined (Table III) considering a mass of 12,135 tons of asphalt mixture to build each section. As specified above, scenario 1 is taken as a basis for comparison. The percentage difference of scenario 2 with respect to scenario 1 is observed in column 3 of Table III.

TABLE III
CARBON FOOTPRINT RELATED TO THE LANE CONSTRUCTION FOR THE SCENARIOS UNDER STUDY

Scenario	GHG emissions ($kgCO_2eq/ton_{lane}$)	Difference ($kgCO_2eq$)
Conventional asphalt mixture (Scenario 1)	4 324	-25,0
1% PET asphalt mixture (Scenario 2)	4 299	

According to Table III, there is a difference of 25 $kgCO_2eq$ when recycled PET is used within the final product, compared to a mixture without any waste material. These results correspond to the construction of the lane that were built for experimental purposes, so the dimensions are expected to be smaller than that of a real construction of a highway for public use. This would imply greater dimensions and savings, in terms of GHG emissions, if recycled PET is used as an additive in a larger project.

Then, to study a scenario that is closer to reality, the construction of 1 km of road is analyzed (Table IV). The results show the difference in kilograms of carbon dioxide between each scenario. A total of 1 132 $kgCO_2eq$ would be avoided of being released to the environment when using PET, and this value would increase as the size of the project increases.

TABLE IV
CARBON FOOTPRINT OF A 1 LANE OF 1 KILOMETER LENGTH AND 2,05 METERS WIDE FOR THE SCENARIOS UNDER STUDY

Scenario	GHG emissions ($kgCO_2eq/km$)	Difference ($kgCO_2eq$)
Conventional asphalt mixture (Scenario 1)	196 178	-1 132
1% PET asphalt mixture (Scenario 2)	195 047	

The results shown in this research and in previous studies determine that recycled PET generates a decrease in the carbon footprint when used as a polymeric additive in asphalt mixtures. Then, the greater the amount of recycled PET that is used, the lower global carbon footprint is expected. However, even if the use of waste materials appears to be a good alternative for climate change mitigation, it is necessary to consider that the designed project needs to meet all the established quality and performance standards, meaning that the final design must consider both. This is the reason why other researchers have tested different percentages of recycled PET. For example, Rojas [27] built a cycle path that contains a 6% of recycled PET. In addition to this, a reduction in the production temperature was set to obtain a warm asphalt mixture. Rojas indicates that it is possible to produce the mixture with recycled PET at 130 °C, which generates greater decreases in the carbon footprint, compared to a hot mix asphalt.

In the present research no procedural modification was applied within production, such as a reduction in time in any operation or a decrease in temperature when mixing. Only the material change was made, so the differences between the carbon footprint of scenario 1 and 2 are due to the implementation of this recycled polymer. In this way, it would be expected that, if a change in temperature were applied to produce a warm asphalt mixture, like Rojas [27], maintaining the current study conditions, lower GHG emissions are expected.

By not modifying any process that would generate a greater difference in the carbon footprint between scenario 1 and 2, apart from the incorporation of recycled PET, an actual decrease in GHG emissions was shown in scenario 2. Even if the reduction is non-significant, it is necessary to consider that a material that could be treated as waste is being given a second use as an important component of an asphalt mixture.

In this study 9,3 kg of recycled PET is required in the production of 1 ton of asphalt mixture of scenario 2. If an average 500 mL PET bottle weights 25 g, 372 bottles would be required to manufacture 1 ton of mixture. Following this same logic, approximately 4 514 bottles were used for the section built for this study, and in the hypothetical case of the construction of 1 km lane of road, 204 819 bottles would be used. By implementing these changes, this large amount of material is prevented from ending up in landfills or circulating on the planet and at the same time, it helps mitigate climate change, contributing with circular economy.

V. Conclusions

The construction industry plays a significant role in global greenhouse gas (GHG) emissions, contributing to climate change and environmental degradation. Asphalt mixtures, commonly used in road construction, are a key component of this industry. Therefore, understanding the carbon footprint of asphalt mixtures is crucial to developing sustainable practices and reducing the environmental impact of road construction. This study allowed determining that the use of waste materials such as PET, helps reducing carbon footprint of infrastructure projects and prevents these materials to be free contaminants in the environment.

References

[1] D. J. Soeder, "Fossil Fuels and Climate Change," in *Fracking and the Environment*, Cham, Switzerland: Springer, 2020, pp. 155-185.

[2] E.L.F. Schipper, N.K. Dubash, & Y. Mulugetta, "Climate change research and the search for solutions: rethinking interdisciplinarity" *Climatic Change,* vol. 168, no. 18, 2021.

[3] A. K. Priya, M. Muruganandam, S. Rajamanichan, (…), "Impact of climate change and anthropogenic activities on aquatic ecosystem – A review," *Environmental Research*, vol. 238, p. 117233, 2023.

[4] J. P. Araújo, J. Oliveira, H. Silva, “The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements”, *Transportation Research Part D: Transport and Environment,* vol. 32, p. 97-110, 2014.

[5] K. Byungil, H. Lee, H. Park, H. Kim, “Framework for estimating greenhouse gas emissions due to asphalt pavement construction”, Journal *of construction engineering and management*, vol. 138, no 11, p. 1312-1321, 2012.

[6] H. AzariJafari, Yahia, M. B. Amor, “Life cycle assessment of pavements: reviewing research challenges and opportunities”, *Journal of Cleaner Production,* vol. 112, p. 2187-2197.

[7] J. Benjamin; W. Ryne. “Hot Mix Asphalt vs. Warm Mix Asphalt”. *South. Ill. University Edwardsv*, 2019.

[8] M. Espinoza, N. Campos, R. Yang, H. Ozer, J. P. Aguiar-Moya, A. Baldi, L. G. Loria, I. L. Al-Qadi. “Carbon footprint estimation in road construction: La Abundancia–Florencia case study”, *Sustainability*, vol. 11, no 8, p. 2276, 2019.

[9] D.M. Barbieri, B. Lou, F. Wang, I. Hoff, S. Wu, J. Li, H.R. Vignisdottir, R.A. Bohne, S. Anastasio, T. Kristensen, “Assessment of carbon dioxide emissions during production, construction and use stages of asphalt pavements”, *Transportation Research Interdisciplinary Perspectives*, vol. 11, p.100436, 2021.

[10] N. Gettu, W.G. Buttlar, “Critical Parameters Affecting the Carbon Footprint of Asphalt Mixes”. In: Banthia, N., Soleimani-Dashtaki, S., Mindess, S. (eds) *Smart & Sustainable Infrastructure: Building a Greener Tomorrow*. RILEM Bookseries, vol 48. Springer, 2024.

[11] A., Francisco “Greenhouse gas emissions associated with road transport projects: current status, benchmarking, and assessment tools”, *Transportation Research Procedia*, vol. 48, p. 2018-2030, 2020.

[12] F. Ma, A. Sha, R. Lin, Y. Huang, C. Wang. "Greenhouse Gas Emissions from Asphalt Pavement Construction: A Case Study in China", *International Journal of Environmental Research and Public Health* 13, no. 3, p. 351, 2016.

[13] P.F.F. Grael, L.S.B.L. Oliveira, D.S.B.L. Oliveira, B. Bezerra, “Life cycle inventory and impact assessment for an asphalt pavement road construction—a case study in Brazil”, *International Journal of Life Cycle Assessment,* vol. 26, p. 402–416, 2021.

[14] M.A, Feng, W. Dong, Z. Fu, R. Wang, Y. Huang, J. Liu, “Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: A case study in China”, *Journal of Cleaner Production*, vol. 288, p. 125595, 2021.

[15] J.H. Chang Chien, P.C. Chen, “Carbon reduction of plastic’s circular strategies: tracking the effects along supply chains with waste input–output modelling”, *Sustainainable Environmental Research,* vol. 33, no. 18, 2023.

[16] F. Mneimneh, N. Haddad, S. Ramakrishna, “Recycle and Reuse to Reduce Plastic Waste - A Perspective Study Comparing Petro- and Bioplastics”. *Circular Economy amd Sustainability,* vol. 4, p. 1983–2010 2024.

[17] W. Victory, “A review on the utilization of waste material in asphalt pavements”, *Environmental Science and Pollution Research,* vol. 29, p. 27279–27282, 2022.

[18] D. E. Bizarro, Z. Godoi, I. Steinmann, E., K. Nieuwenhuijse, M. Hauck., “Potential Carbon Footprint Reduction for Reclaimed Asphalt Pavement

Innovations: LCA Methodology, Best Available Technology, and Near-Future Reduction Potential" *Sustainability* 13, no. 3, p. 1382, 2021.
[19]M. R. Pouranian, and Shishehbor, M. "Sustainability Assessment of Green Asphalt Mixtures: A Review", *Environments*, vol. 6, no. 6, p. 73, 2019.
[20]A. Azapagic, D. Amienyo, H. Gujba, H. Jeswani, N. Esponiza, A. Morgan, . . . H. Stichnothe. "CCaLC Carbon Calculations over the Life Cycle of Industrial Activities". Retrieved from http://www.ccalc.org.uk/, 2012.
[21]J. Dunn, S. Mueller, Z. Qin, M. Wang. "Carbon Calculator for Land Use Change from Biofuels Production (CCLUB 2016)". Retrieved from: https://greet.es.anl.gov/publications, 2016.
[22]P. Bo, F. Xueyong, W. Xunjie, L. Wenying. "Key steps of carbon emission and low-carbon measures in the construction of bituminous pavement" *International Journal of Pavement Research and Technology,* vol. 10, no. 6, p. 476-487, 2017.
[23]X. Li, L. Chen, X. Ding. "Allocation Methodology of Process-Level Carbon Footprint Calculation in Textile and Apparel Products". *Sustainability*, vol. 11, p. 1-14, 2019.
[24]A. Jexembayeva, M. Konkanov, L. Aruova, A. Kirgizbayev, L. Zhaksylykova. "Performance Optimization Approach of Polymer-Modified Asphalt Mixtures with PET and PE Waste". *Polymers*, vol. 16, no. 23, p. 3308, 2024.
[25]E. A. Fahmy, A. M. Youssef, E. E. Ali, A. Algabry, O. Elbagalati. "Evaluation of asphalt mixtures modified with polyethylene terephthalate (PET)". *Innovative Infrastructure Solutions*, vol. 9, no. 11, p. 1-17, 2024.
[26]S. Baradaran, J. Rahimi, M. Ameri, A. Maleki. "Mechanical performance of asphalt mixture containing eco-friendly additive by recycling PET". *Case studies in construction materials*, vol. 20, p. e02740, 2024.
[27]N. E. Rojas. "Diseño de pavimento modificado con la adición de plástico reciclado para ciclovías". Thesis. University of Cuenca, 2019.

[28]