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Life cycle assessment of pavement construction: A case study

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Abstract. Road construction is often associated with carbon emissions from direct and indirect sources, primarily due to construction and maintenance activities. Currently, there is a lack of comprehensive Life Cycle Assessment (LCA) benchmarks to evaluate flexible composite pavement, fully flexible pavement and pavement rehabilitation options under various ground conditions. The objective of this study is to investigate the environmental impact associated with different pavement designs over a 60-year analysis period, comprising a 40-year basic design period with maintenance extended up to 60 years. This research paper encompasses a literature review on pavement LCA and conducts and LCA on various pavement design and construction options, following the ISO 14040 framework and PAS 2080 methodology. The LCA in this study specifically focuses on material production, transportation, construction, maintenance, and end-of-life phases. Using global warming potential as an environmental indicator, the study calculates and compares a range of potential impacts for each component. In terms of carbon emissions, the rehabilitation option was found to be most favourable when compared to other full-depth reconstruction options, while the flexible composite pavement option exhibited the highest carbon emission value compared to other pavement build-ups assessed. Additionally, a sensitivity analysis was conducted to identify 'hotspots' in the study, which increase the confidence level of the results.

1. Introduction

The construction and maintenance of pavement infrastructure requires large quantities of materials, which are often associated with carbon-intensive and high-energy consumption processes [1]. The industry is increasingly adopting Life Cycle Assessment (LCA) methodologies to analyse the environmental impacts of certain processes or products [2]. Various pavement design types are available, with the most commonly utilised including fully flexible (asphalt-based), flexible-composite (asphalt-concrete hybrid), and rigid (concrete-based) options. As each pavement design type has its own unique characteristics, it is crucial to evaluate their unique impacts by applying different methodologies and understanding the conceptual limitations. In this study, a pavement is defined as a smooth riding surface for vehicular traffic and does not include consideration of pedestrian infrastructure.

LCA has been employed to evaluate the environmental impact of infrastructure by researchers such as Stripple [3], Wang et al. [4], Anastasiou et al. [5], and Blaauw and Maina [6]. Santero and Horvath [7] assert that the impacts of pavements extend beyond mere material extraction and production and that the pavement life cycle encompasses five crucial phases: materials, construction, usage, maintenance, and disposal. Each phase offers opportunities for reducing environmental impacts, emphasizing the importance of equal attention to all components. Despite the important role of LCA in pavement design, there is lack of comparative LCA studies on different pavement design options. To address the research gap, the paper aims to compare the carbon emission of three different pavement design and rehabilitation options: flexible composite pavement, fully flexible pavement and pavement rehabilitation in soft and hard ground conditions. It is found that different pavement designs lead to different emission levels. The phases and materials are further compared to identify the option with the least contribution to Global Warming Potential (GWP), which is the rehabilitation option. As global warming will accelerated pavement deterioration, it is important to consider GWP in the LCA study. This study reviewed the past literature on pavement LCA and confirmed the importance of selected components for the analysis. The methodological framework utilised is that specified in ISO 14040 [8] and includes defining of the system boundaries, life cycle phases, impact assessment categories, and validation of the results through sensitivity analyses for the various pavement options considered. The study intends to assist decision-makers in identifying key areas for promoting sustainability in pavement construction.

2. A Review on Pavement LCA

At present, the application of LCA has become a common practice in the construction industry. The current framework of LCA has broadened the scope from mainly environmental impacts to covering three aspects of sustainability: social, economic and environmental [9]. There have been more studies on pavement LCA in the past few decades such as process-based studies, input-output based studies, comparative studies and static versus dynamic studies [10]. Each type of LCA has its limitations and advantages. The definition of goal and scope is important to determine the type of LCA practiced.

Particularly, comparative LCAs require consistency in the definition of functional units, quality of data, impact assessment methods and methodological choices to ensure fairness in the study [11]. It is crucial that comparative LCAs are conducted following the guidelines of ISO 14040 and BS EN 15804 which act as a guidance for disclosing the information about the reported results. Therefore, conducting a comparative LCA study that focuses on different pavement design options and rehabilitation techniques is an innovative research pursuit.

2.1. Pavement LCA Framework

The current framework followed by pavement LCAs is ISO 14040 which introduces four essential steps required in all types of studies and practices: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results from LCIA.

2.1.1. Goal and Scope Definition. This stage is a subjective phase within the LCA methodology which includes system boundaries and functional units. It covers the data necessary to consider in the entire framework. LCA studies of transport infrastructure generally focus on assessing the environmental impact associated with the pavement, comparing different pavement materials or designs, and evaluating choices of material for pavements [12]. Despite the general focus, there remain gaps in LCA studies which consider different pavement designs. These gaps include confining assessments to cradle-to-gate system boundaries, omission of maintenance consideration, lack of sensitivity analyses and exclusion of the impact that underlying ground conditions have on pavement design option selection. When defining the system boundaries, the Society of Environmental Toxicology and Chemistry (SETAC) proposed that the system should cover six phases, namely material extraction and production, transportation process, construction, usage of pavement, maintenance and rehabilitation (M & R) and End of Life (EOL). The usage and EOL stages often get less attention compared to other phases. Babashamsi et al. [13] state that the use phase is often ignored due to uncertainty and insufficient information in terms of environmental impacts affecting pavement such as rolling resistance, albedo, carbonation, and leachate. Table 1 summarises the system boundaries considered by some of the highly cited pavement LCA studies. In LCA studies of roads, various functional units have been used, making it difficult to compare results across studies [14]. For instance, some studies use road length in kilometre [15], while others consider the area of pavement, expressed in square meters [16]. In some cases, LCA may have more than one product or functional unit.

Table 1. System boundaries considered by different LCA studies

Literature	**System Boundaries**					
	Material Production	Transportation	Construction	Usage	M & R	EOL
Wang et al. [4]	√	√	χ	√	√	χ
Harvey et al. [17]	√	√	χ	χ	χ	χ
Giani et al. [18]	√	√	√	χ	√	√
Anastasiou et al. [5]	√	√	√	χ	√	√
Santos, et al. [10]	√	√	√	√	√	√
Farina et al. [19]	√	χ	√	χ	√	χ
Blaauw and Maina [6]	√	√	√	χ	√	√
Blaauw et al. [15]	√	√	√	√	√	√

2.1.2. Life Cycle Inventory. LCI data for a pavement may be collected from two different sources: primary and secondary data. Primary data are directly measured or collected data from individual companies which may include on-site surveys and field investigations [20]. However, the collection of primary data in the construction industry is often challenging due to commercial sensitivity [21]. This is where secondary data is introduced, which is often used in combination with primary data in LCA studies. These data are sourced from publications and databases. Additionally, practitioners must rely on their knowledge and experience to assess data quality, which will lead to inherent uncertainties [21].

2.1.3. Life Cycle Impact Assessment. The impact assessment stage includes several impact assessment methodologies that can be applied during this stage based on the defined scope. As there are various impact assessment methods available, it can be challenging to select a suitable approach to align with the scope [21]. It is also possible to choose multiple methods as it can enhance the validity of findings, which is commonly used within pavement LCA studies [22]. One of the methodologies, PAS 2080, has been developed to incorporate carbon management processes with these components: a) Quantification of Green House Gas (GHG) emissions, b) Target setting, baselines and monitoring, c) Reporting, d) Continual improvement [23]. It is also crucial to select the impact categories in line with the goal and scope definition. The LCI results are often needed to provide input and output for this process. However, it is found that there is insufficient standardisation to report these results. Some studies omit the impact assessment step all together and only quantify outputs, which can make decision-making difficult. For example, Cass and Mukherjee [24] only analysed the GHG emissions for the construction of highways by neglecting other impact assessments, which limited the conclusion for the decision-making process due to a lack of information from the simplified analysis of carbon emission [25].

2.1.4. LCIA Interpretation. LCA decisions may be misleading due to different sources of uncertainty including parameter uncertainty, model uncertainty, uncertainty due to methodological choices, spatial variability and variability between sources and objects [26]. Sensitivity analysis is introduced to address various types of uncertainty in the study, investigating how altering one parameter can affect another. A sensitive parameter is a variable that can significantly influence the resulting output or contribute to its variability. Conducting sensitivity analyses aids in identifying these 'sensitive' parameters, often referred to as ‘hotspots’, providing a clearer understanding before drawing conclusions [27].

2.1.5. Environment Related Terms. When introducing the environmental impact category, the environment related terms used for the study are often interchangeable, which is confusing. For example, when analysing carbon emissions of a project, terms like “GWP”, “CO_2”, “CO_2e”, and “carbon” are often used [28]. The GWP represents the amount of warming caused by a gas over a typical period of 100 years. CO_2 is an abundant GHG released by human actions, among others, based on the number and overall impact of global warming. The term CO_2e (carbon dioxide equivalent) is more appropriate to indicate the aggregate of GHGs, known as the Kyoto Protocol gasses, in a common unit, and indicates equivalent CO_2 and the GWP impact for any type of GHG. The whole life carbon is the combination of embodied carbon and operational carbon. Embodied carbon often refers to the CO_2e of each phase that excludes the operational phase.

3. Methodological Framework

The ISO 14040 is applied as the methodological basis for the development of pavement LCA in OneClick LCA. OneClick LCA is a commercial LCA tool that focuses on analysing the carbon emission of building or infrastructure projects, which streamlines the process of identifying the hotspot of the project based on its carbon footprint [29]. A study utilising [30] this software compared the embodied carbon of different building alternatives and validated the reliability of the tool in assessing GWP and guiding decisions toward more sustainable construction practices. The four essential stages for an LCA study of a typical pavement, previously discussed, are defined in subsequent sections.

3.1. Goal and Scope Definition

The main objective of this study is to analyse and to compare the LCA of different pavement designs and scenarios by evaluating the associated whole life carbon emission. The analysis period of this study is 60 years, incorporating the standard pavement design life of 40 years in the United Kingdom, as proposed by the Design Manual for Roads and Bridges [31]. The design life is extended to 60 years through the implementation of maintenance regimes and is a common approach utilized by the local road authorities. The study considers a 'cradle-to-grave' scenario including a typical maintenance regime and follows the life cycle stages highlighted in Figure 1**,** defined as a partial LCA. The other scenarios in the use stage are omitted as there is currently incomplete supporting information to include environmental impacts of these phases [13]. The functional unit in this study, which represents the reference unit that measures the performance of the indicators, is one square-metre of pavement for the cradle-to-grave approach. The focus indicator is CO_2e emissions with different units as shown in Table 2:

Table 2. Carbon dioxide indicator unit

Components	Unit
Surface	kg CO_2e/kg
Milling off Asphalt Binder Base	kg CO_2e/m^2
Disposal and excavated pavement Foundation	kg CO_2e/m^3

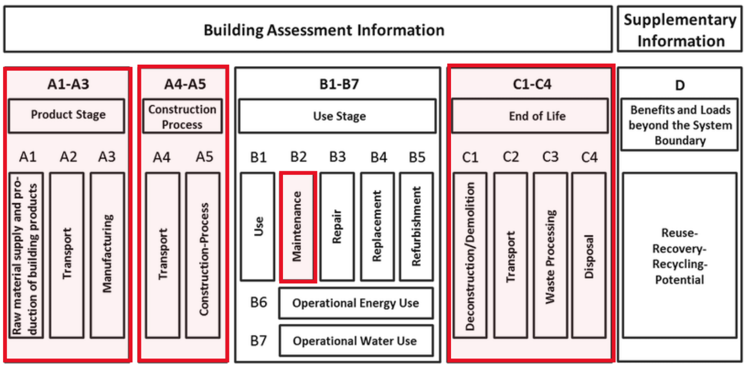

Figure 1. Considerations for pavement life cycle stages (BS EN 15804)

3.2. Life Cycle Inventory Analysis

For the LCI, a quantitative description of the flow of materials across the designated system boundaries is developed, which includes the input and output of the system. The input consists of raw materials, transport, energy and other physical inputs whereas outputs comprise of emissions, wastage and other environmental aspects. More detailed information related to the inventory data utilised in this study can be found in Appendix A. The primary construction data has been provided by Ove Arup and Partners Ltd. from a recent major highway scheme.

3.2.1. Assumptions. The analysis assumed that all materials are sourced 100 km away from the project location. Additionally, common construction activities such as material extraction, production, transportation, construction, maintenance and demolition are considered. For the analysis, the EOL phase is accounted for recycling and reuse of material. Thus, 5% loss is suggested from the OneClick LCA database [29], which means 95% of the materials are recycled and reused in line with standard local industry practice. Machinery and other relevant construction processes are included in the carbon indicator factors utilised in this study. Due to incomplete database in OneClick LCA, certain assumptions are made for the obtained data. It is crucial to understand that these assumptions may cause some degree of uncertainty in the results. Table 3 shows that the original materials are replaced with similar materials which serve with the same function.

Table 3. Alternative materials suggested to replace original materials

Material	Alternative Material
TSCS, 10 to14mm, PMB	TSCS, 11mm, PMB
AC 20 dense bin 40/60	Stone Mastic Asphalt SMA
AC 32 dense base 40/60	AC 31 hot mix
HBM Cat B CBGM - C8/10	Ready Mix Concrete-C8/10
FC3 CBGM - C8/10	Ready Mix Concrete-C8/10

3.3. Life Cycle Impact Assessment

The impact assessment phase aims to evaluate the significance of potential environmental impact categories and category indicators as outlined in ISO 14040. The PAS 2080 impact assessment method is adopted for analysing the whole life carbon in the study. To accommodate the complexities of the impact assessment stage, Table 4 is presented based on the basic principles of ISO 14040 and PAS 2080.

Table 4. Mandatory components for pavement LCA

Component	Example
Impact Category	Climate Change
LCI Result	Amount of GHG per functional unit
Characterization Model	60-years pavement model on carbon emission
Category Indicator	Refer Table 2
Characterization Factor	GWP_{60} for each GHG
Category Indicator Result	$kgCO_2e/m^2$

3.4. Interpretation

The study only considers uncertainty during the material production period due to incomplete data collection from other stages. Thus, the suggested range of uncertainty is based on the manufacturer, facility and product specificity provided by OneClick LCA database [29]. A sensitivity analysis is conducted on the material which contributed the most carbon emissions for each pavement design, generating upper and lower boundaries of the results to analyse its sensitivity toward defined uncertainties.

4. Results and Discussion

An LCA is conducted for five different scenarios, namely, flexible composite pavement (S1) and fully flexible pavement (S2) that are constructed on soft ground, as well as flexible composite pavement (H1) and fully flexible pavement (H2) that are constructed on hard ground, and finally rehabilitation (TR1) which is applied on an existing road. The analysed results are discussed below.

4.1. Life Cycle Impact Assessment

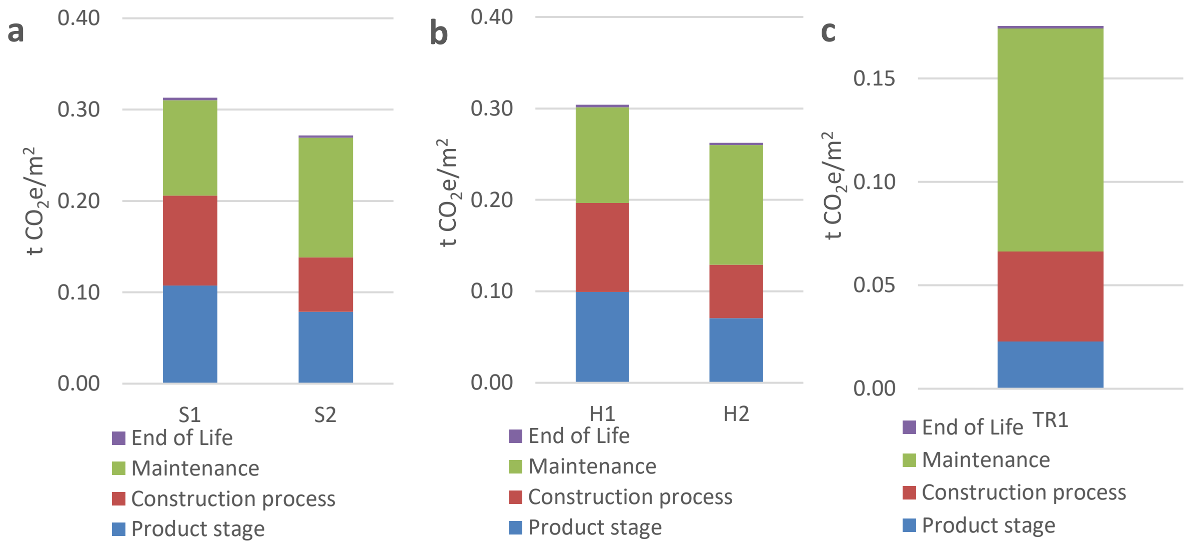

Figure 2. Carbon emission per functional unit for life cycle phase of (a) S1 & S2 at soft ground (b) H1 & H2 at hard ground (c) TR1

Figure 2 illustrates the simplified life cycle impact assessment, which considers the four life cycle stages of different pavement designs, expressed in tonne CO_2e/m^2. It was found that flexible composite designs (S1 and H1) would have higher carbon emissions than fully flexible pavements (S2 and H2) at both soft ground and hard ground conditions. These findings align with those of Zhang et al. [32]. However, Zhang et al. additionally found that despite the higher carbon footprint associated with flexible-composite design options, they tend to outperform fully flexible alternatives economically. This underscores the importance of comprehensive evaluations that take into account all three pillars of sustainability. It is also identified that the carbon emission of the rehabilitation option is significantly lower than other design options as the emissions generated during the production stage of rehabilitation is considered very small when compared to the others. It is seen that rehabilitation provides a better option for the lowest carbon emission. However, it is still difficult to conclude it as the preferred option due to lack of consideration of social and economic impacts, which are key to achieving holistic sustainability [6]. It can also be seen from Figure 2 that the EOL phase is the lowest for each of the design options. This phase is contributed by two major components in pavement design: concrete and asphalt. Both materials are set to follow the market scenario of the United Kingdom, which considers the conditions of waste management regulations in the locale of the study. Due to the increase landfill tax imposed in the construction sector, waste sent to landfills has decreased in recent years [33], resulting in improvements of recycling systems in the United Kingdom. Thus, the study considers that concrete is crushed into aggregate for reuse purposes in pavements whereas asphalt is reused via reprocessing it in asphalt plants. These innovative approaches are further supported by relaxed regulations imposed by local government.

Figure 2(a) shows that the flexible composite (S1) option has the highest emission in the production stage followed by the maintenance stage, which has quite similar value. For the fully flexible option (S2), it is clearly seen that maintenance dominates the overall emissions, followed by the production of the material. The fully flexible option has lower emissions in the production and construction stage but higher emissions in maintenance stage when compared to the flexible composite option. Figure 2(b) presents an identical pattern as shown in Figure 2(a). However, it can be seen from the graphs that both the production and construction stages have lower emission levels when compared to the soft ground options. This is due to a thicker pavement layer required for soft soil to account for weaker subgrade strength [34] and thus, requires more material consumption. Figure 2(c) shows that rehabilitation (TR1) has the lowest emissions for each phase of the life cycle when compared to others. The emissions are mostly contributed by maintenance as it does not focus on building a new pavement, but instead on preserving the existing pavement quality, which is crucial to reservice over a period. The disposal of excavated pavement is also a contributing factor to the emissions.

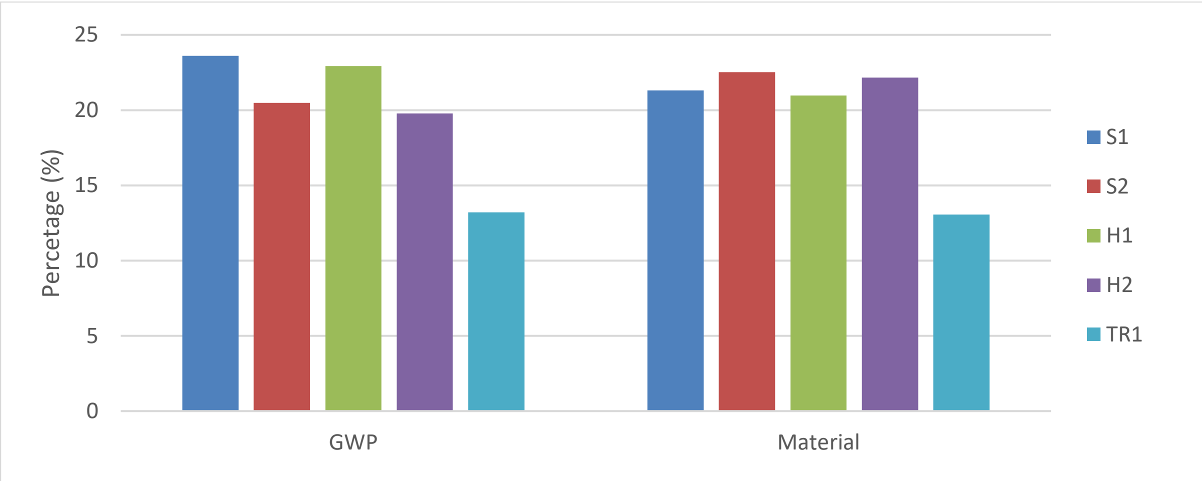

Figure 3. Percentage of Global Warming Potential and material consumption per functional unit of design S1, S2, H1, H2 & TR1

Figure 3 presents the percentage GWP and material for each case. It is observed that both flexible composite options, S1 and H1, have lower consumption of material when compared to the fully flexible options, S2 and H2, but with a higher GWP. This contrasts with fully flexible options because fully flexible designs require more material by weight due to the higher density of asphalt concrete than ready mix concrete. Another notable point for the fully flexible pavement is that it has a lower GWP in comparison as the carbon emission of asphalt concrete are significantly lower than concrete or other cementitious materials. Rehabilitation (TR1) has the lowest percentage contribution of GWP and material consumption as it only involves the act of repairing portions of existing pavement, in which the material consumption is relatively lower than the demand of constructing a new pavement.

Figure 4(a) shows that the highest material percentage consumption for flexible composite is ready-mix concrete, and for the fully flexible option asphalt concrete is dominant. Asphalt concrete has a higher density which results in more consumption of material in terms of tonnage in comparison, and this explains why a fully flexible option requires more material consumption than flexible composite. Fully flexible pavement does not rely much on cementitious bound material as it only contributes to the foundation part, which is different from a flexible composite that consists of an additional base constructed by concrete. Figure 4(b) shows the same pattern as Figure 3(a), where the percentage consumption of material is identical to the soft ground option. The results are in line with Liu et al. [35], stating that cement that is used to produce pavement layers are major contributors to carbon emissions.

Figure 4(c) shows that asphalt for paving roads has the highest consumption of material followed by stone mastic asphalt. Those components function to replace the deteriorated parts of the road and provide for maintenance over a 60-year analysis period.

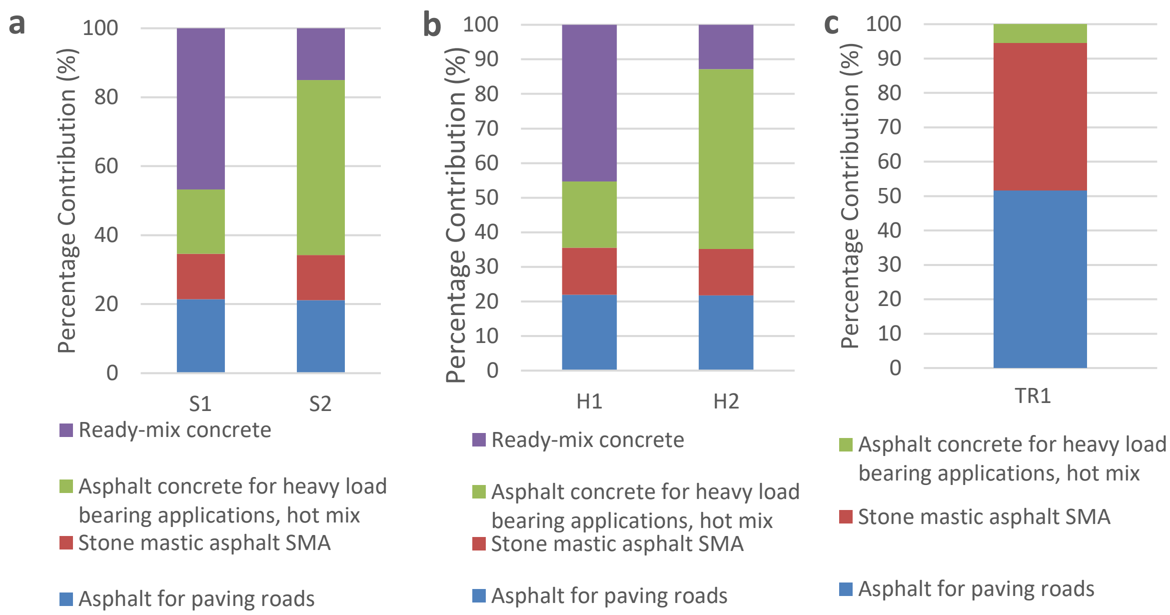

Figure 4. Percentage contribution of material breakdown for (a) S1 & S2 at soft ground (b) H1 & H2 at hard ground (c) TR1

4.2. Sensitivity Analysis

PAS 2080 suggests excluding activities that do not significantly change the result of the quantification, such as minor sources of emissions from the material used. From the case study, three significant aspects have been identified: asphalt for paving road in TR1, concrete in S1 and H1, plus asphalt concrete in S2 and H2. The sensitivity checks on data uncertainty are calculated as suggested in ISO 14044.

Table 5. Sensitivity Check on S1, S2, H1, H2 & TR1

Design Option	Material Uncertainty (%)	Resulting Sensitivity (%)
S1	20.20	± 6.94
S2	28.35	± 3.18
H1	20.20	± 6.73
H2	28.35	± 3.18
TR1	35.64	± 2.84

Based on ISO 14044, if the resulting sensitivity, known as the upper and lower boundary, is larger than 10%, it is considered a significant change [36]. The uncertainty of inventory is achieved based on the value suggested in OneClick LCA, where the uncertainty is subject to material production which is obtained from the database of OneClick LCA. As seen from Table 5, the sensitivity is most significant in S1 and H1, which is related to concrete. It is estimated that the uncertainty for ready mix concrete, which is crucial in flexible composite design for both soft and hard ground, has little impact on the results of both design's GWP. Thus, it is found that the results are not sensitive to the uncertainty ranges calculated for Ready Mix Concrete. In S2 and H2 cases, the estimated uncertainty for Asphalt Concrete in fully flexible pavement in both soft and hard ground has no significant impact on the carbon emission.

Therefore, it is not sensitive to the uncertainty ranges estimated for asphalt concrete. Lastly, TR1 has shown that it has the lowest resulting sensitivity, which also has no significant impact on the emission results. It is concluded that treating the uncertainties for each data is insignificant individually, however when uncertainties in the inventory analysis are compounded, it could increase the variation.

5. Limitations

5.1. Limitation in Goal and Scope Definition
As this is a comparative LCA, it is important to understand that every road construction project varies and is affected by its geographic and meteorological location. As not all these differences are able to be expressed in the functional unit, comparing the environmental impacts of various pavement projects becomes challenging. To adequately assess any variations of the impact of various pavement projects, further background information is needed.

5.2. Limitation in Inventory Analysis
The units of the materials used did not match the units used within the LCA database. Some of the data required conversion that will increase the uncertainty within the data. Besides, the absence of material within the database of the LCA tools has led to the selection of similar materials or materials from different regions, resulting in differing environmental loads [10]. Thus, sensitivity analysis is essential to address these.

5.3. Limitation in Impact Analysis
Due to the lack of standardisation of the LCIA procedure, it is difficult to conduct a comparison across existing work due to the inconsistencies in selecting environment impact categories. According to Inyim et al. [25], limited comparable studies result in difficulties to confirm and validate the claimed environmental impacts. Additionally, a single impact assessment method is unable to draw a conclusion on the size of carbon emission in the LCA of pavement.

5.4. Limitation in Interpretation
This study only considers the uncertainties at the production stage due to data collection limitations and time constraints. It is also found that there are numerous factors contributing to the uncertainties, which result in difficulties in choosing which uncertainties to be accounted for in the study. Thus, it is impossible to definitively announce generalised findings on the environmental performance of various pavement types due to these uncertainties [25]. It is important to note that this study has considered an analysis period of 60 years. It is possible that radical changes may occur in the future, such as changes in fuel or energy type and traffic volumes [11]. These wider assumptions need to be taken into consideration to fully understand the potential implications of the study's findings.

6. Conclusion
The GWP per functional unit is highest for flexible composite pavement on soft ground, followed by flexible composite pavement on hard ground. Fully flexible pavement generally has lower GWP per functional unit than flexible composite pavement, which ranks third for soft ground condition whereas hard ground condition ranks fourth. Pavement rehabilitation has the lowest GWP per functional unit.

The result is analysed and compared by simplified life cycle phases and material comparison. Based on the comparison of life cycle phases, the maintenance phase is the most significant contributor to carbon emission for every design option except the case of flexible composite pavement in soft ground, where the production phase has the highest carbon emissions. This is due to thicker pavement layers needed in soft ground conditions, resulting in higher concrete usage for the foundation and hydraulic bound material base. In addition, ready mix concrete has the largest contribution of material in the flexible composite pavement, particularly contributed by the base and foundation layers whereas asphalt concrete, which is used as the base, has the highest consumption of material among flexible composite pavement options. In pavement rehabilitation, asphalt for paving road is used the most as resurfacing work is a major part for this option. The paper evaluates the different pavement options from a real project adopting an LCA approach for a highly trafficked pavement with varying design types (fully flexible and flexible composite) as well as underlying ground conditions (soft ground and hard ground) over the entire life cycle of the infrastructure. Similar research is limited, and when conducted often does not include a whole life cycle approach and omits consideration of holistic life cycle assessments for pavement infrastructure. Additionally, most papers do not include sensitivity analyses, underscoring the contribution made in this study. The analyses and conclusions presented in this research, which are based on data obtained from the aforementioned organisations, are solely those of the authors and do not necessarily reflect the views or findings of the mentioned entities.

References

[1] Santos J, Ferreira A and Flintsch G 2015 A life cycle assessment model for pavement management: road pavement construction and management in Portugal, *International Journal of Pavement Engineering* ***16*:4** 315-336 doi: 10.1080/10298436.2014.942862

[2] Santero N J, Masanet E and Horvath A 2011 Life-cycle assessment of pavements. Part I: Critical review *Resources, Conservation and Recycling* **55(9-10)** 801–809 doi: 10.1016/j.resconrec.2011.03.010

[3] Stripple H 2001 *Life Cycle Assessment of Road- A Pilot Study for Inventory Analysis*. Gothenburg; Swedish Environmental Research Institute (IVL)

[4] Wang T, Lee I S, Kendall A, Harvey J, Lee E B. and Kim C 2012 Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance *Journal of Cleaner Production* **33** 86–96 doi: 10.1016/j.jclepro.2012.05.001

[5] Anastasiou E K., Liapis A and Papayianni I 2015 Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials *Resources, Conservation and Recycling* **101** 1–8 doi: 10.1016/j.resconrec.2015.05.009

[6] Blaauw S A and Maina J W 2021 Life Cycle Inventory for Pavements - A Case Study of South Africa *Transportation Engineering* **3** 100049 doi: 10.1016/j.treng.2021.100049

[7] Santero N J and Horvath A 2009 Global warming potential of pavements *Environmental Research Letters* **4(3)** 034011 doi: 10.1088/1748-9326/4/3/034011

[8] BSI 2006a Environmental management, Life cycle assessment, Principles and framework *ISO EN BSI 14040* British Standard Institution

[9] Guinée J B, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T and Rydberg T 2011 Life Cycle Assessment: Past, Present, and *Future Environmental Science & Technology* **45(1)** 90–96 doi: 10.1021/es101316v

[10] dos Santos J M O, Thyagarajan S, Keijzer E, Flores R F and Flintsch G 2017 Comparison of Life-Cycle Assessment Tools for Road Pavement Infrastructure *Transportation Research Record* **2646(1)** 28-38 doi: 10.3141/2646-04

[11] Huang Y and Parry T 2014 Pavement Life Cycle Assessment *Climate Change, Energy, Sustainability and Pavements* 1–40 doi: 10.1007/978-3-662-44719-2_1

[12] Jiang R and Wu P 2019 Estimation of environmental impacts of roads through life cycle assessment: A critical review and future directions *Transportation Research Part D: Transport and Environment* **77** 148–163 doi: 10.1016/j.trd.2019.10.010

[13] Babashamsi P, Md Yusoff N I, Ceylan H and Md Nor N C 2015 Life Cycle Assessment for Pavement Sustainable Development: Critical *Review Applied Mechanics and Materials* **802** 333-338 doi: 10.4028/www.scientific.net/AMM.802.333

[14] Anand C K and Amor B 2017 Recent developments, future challenges and new research directions in LCA of buildings: A critical review *Renewable and Sustainable Energy Reviews* **67** 408–416 doi: 10.1016/j.rser.2016.09.058

[15] Blaauw S A, Maina J W, Mturi G A J. and Visser A T 2022 Flexible pavement performance and

life cycle assessment incorporating climate change impacts *Transportation Research Part D: Transport and Environment* **104** 103203 doi: 10.1016/j.trd.2022.103203

[16] Gschösser F, Wallbaum H and Boesch M E 2012 Hidden Ecological Potentials in the Production of Materials for Swiss Road Pavements *Journal of Management in Engineering* **28(1)** 13–21 doi: 10.1061/(asce)me.1943-5479.0000077

[17] Harvey J, Saboori A, Dauvergne M, Steyn W, Jullien A and Li H 2014 Comparison of New Pavement Construction GHG and Energy Impacts in Different Regions *Papers from the International Symposium on Pavement Life Cycle Assessment 2014 – Harve y, Jullien and Jones (Eds)* 133

[18] Giani M I, Dotelli G, Brandini N and Zampori L 2015 Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling *Resources, Conservation and Recycling* **104** 224–238 doi: 10.1016/j.resconrec.2015.08.006

[19] Farina A, Zanetti M C, Santagata E and Blengini G A 2017 Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement *Resources, Conservation and Recycling* **117** 204–212 doi: 10.1016/j.resconrec.2016.10.015

[20] Miah J H, Griffiths A, McNeill R, Halvorson S, Schenker U, Espinoza-Orias N, Morse S, Yang A and Sadhukhan J 2017 A framework for increasing the availability of life cycle inventory data based on the role of multinational companies *The International Journal of Life Cycle Assessment* **23(9)** 1744–1760 doi: 10.1007/s11367-017-1391-y

[21] Smith S 2003 *Life cycle assessment of civil engineering projects* University of Bath: Department of Architecture and Civil Engineering

[22] Kim S, Hwang T Y and Overcash M 2001 Life cycle assessment study of color computer monitor *The International Journal of Life Cycle Assessment* **6(1)** 35–43 doi: 10.1007/bf02977594

[23] BSI 2016 Carbon management in infrastructure *PAS 2080;2016* British Standard Instituion

[24] Cass D and Mukherjee A 2011 Calculation of Greenhouse Gas Emissions for Highway Construction Operations by Using a Hybrid Life-Cycle Assessment Approach: Case Study for Pavement Operations *Journal of Construction Engineering and Management* **137(11)** 1015–1025 doi: 10.1061/(asce)co.1943-7862.0000349

[25] Inyim P, Pereyra J, Bienvenu M and Mostafavi A 2016 Environmental assessment of pavement infrastructure: A systematic review *Journal of Environmental Management* **176** 128–138 doi: 10.1016/j.jenvman.2016.03.042

[26] Huijbregts M A J 1998 Application of uncertainty and variability in LCA *The International Journal of Life Cycle Assessment* **3(5)** 273-280 doi: 10.1007/bf02979835

[27] Groen E A, Heijungs R, Bokkers E A M and de Boer I J M 2014 Methods for uncertainty propagation in life cycle assessment *Environmental Modelling & Software* **62** 316–325 doi: 10.1016/j.envsoft.2014.10.006

[28] Brander M 2012 GHGs CO2 CO2e and Carbon What Do These Mean?

[29] One Click LCA® software 2023 LCA Database of Building products: local and global data for your LCA.

[30] Apellániz D, Pasanen P and Gengnage C 2021 A Holistic and Parametric Approach for Life Cycle Assessment in the Early Design Stages Symposium on *Simulation for Architecture + Urban Design*

[31] Design Manual for Roads and Bridges Pavement Design *CD 226 Design for new pavement construction* 2021 National Highway

[32] Zhang R, Tang N, Zhu H, Zeng J, Bi Y and Xi Y 2022 Environmental and economic comparison of semi-rigid and flexible base asphalt pavement during construction period *Journal of Cleaner Production* **340** 130791. doi: 10.1016/j.jclepro.2022.130791

[33] Environment Food & Rural Affair D 2022 *UK statistics on waste* GOV.UK

[34] Design Manual Chapter 6 -Geotechnical 6E -subgrade Design and Construction Iowa Statewide Urban Design and Specifications

[35] Liu N, Wang Y, Bai Q, Liu Y, Wang P, Xue S, Yu Q and Li Q 2022 Road life-cycle carbon dioxide emissions and emission reduction technologies: A review *Journal of Traffic and Transportation Engineering (English Edition)* **9(4)** 532–555 doi: 10.1016/j.jtte.2022.06.001
[36] BSI 2006b Environmental management, Life cycle assessment, Requirements and guidelines *ISO EN BSI 14044 British* Standard Institution

Appendix A: Inventory List

Option S1		
Surface – Thin Surface Course System (TSCS), 10-14mm, Polymer Modified Bitumen (PMB)	94,700	m^2
Binder – Asphalt Concrete (AC) 20 dense bin 40/60	94,700	m^2
Base 1 – Asphalt Concrete (AC) 32 dense base 40/60	94,700	m^2
Base 2 – Hydraulic Bound Mixture (HBM) Cat B CBGM - C8/10	94,700	m^2
Foundation – Foundation Class 3 Cement Bound Granular Mixture (CBGM) - C8/10	94,700	m^2

Option S2		
Surface – Thin Surface Course System (TSCS), 10-14mm, Polymer Modified Bitumen (PMB)	94,700	m^2
Binder – Asphalt Concrete (AC) 20 dense bin 40/60	94,700	m^2
Base – Asphalt Concrete (AC) 32 dense base 40/60	94,700	m^2
Foundation – Foundation Class 3 Cement Bound Granular Mixture (CBGM) - C8/10	94,700	m^2

Option H1		
Surface – Thin Surface Course System (TSCS), 10-14mm, Polymer Modified Bitumen (PMB)	28,000	m^2
Binder – Asphalt Concrete (AC) 20 dense bin 40/60	28,000	m^2
Base 1 – Asphalt Concrete (AC) 32 dense base 40/60	28,000	m^2
Base 2 – Hydraulic Bound Mixture (HBM) Cat B CBGM - C8/10	28,000	m^2
Foundation – Foundation Class 3 Cement Bound Granular Mixture (CBGM) - C8/10	28,000	m^2

Option H2		
Surface – Thin Surface Course System (TSCS), 10-14mm, Polymer Modified Bitumen (PMB)	28,000	m^2
Binder – Asphalt Concrete (AC) 20 dense bin 40/60	28,000	m^2
Base – Asphalt Concrete (AC) 32 dense base 40/60	28,000	m^2
Foundation – Foundation Class 3 Cement Bound Granular Mixture (CBGM) - C8/10	28,000	m^2

Option TR1		
Milling off asphalt; 150mm thick	1,000	m^2
Disposal of Excavated pavement	150	m^2
Surface – TSCS, 10-14mm, PMB	1,000	m^2
Binder – AC 20 dense bin 40/60	1,000	m^2

Typical Maintenance	
Treatment	**Year**
40 mm resurface (50mm Thin Surface Course System (TSCS) + milling)	10
100mm inlay (40mm Thin Surface Course System (TSCS) + 60mm Binder + milling)	20
40 mm resurface (50mm Thin Surface Course System (TSCS) + milling)	30
200mm inlay (40mm Thin Surface Course System (TSCS), 60mm binder, 100mm base + milling)	40
40 mm resurface (50mm Thin Surface Course System (TSCS) + milling)	50
100mm inlay (40mm Thin Surface Course System (TSCS) + 60mm Binder + milling)	60