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Life Cycle Assessment for the Production Phase of Nano-Silica-Modified Asphalt Mixtures

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Received: 8 March 2019; Accepted: 26 March 2019; Published: 29 March 2019

Featured Application: The application of LCA to NMAM has the potential to guide decision-makers on the selection of pavement modification additives to realize the benefits of using nanomaterials in pavements while avoiding potential environmental risks.

Abstract: To combat the rutting effect and other distresses in asphalt concrete pavement, certain modifiers and additives have been developed to modify the asphalt mixture to improve its performance. Although few additives exist, nanomaterials have recently attracted significant attention from the pavement industry. Several experimental studies have shown that the use of nanomaterials to modify asphalt binder results in an improved oxidative aging property, increased resistance to the rutting effect, and improves the rheological properties of the asphalt mixture. However, despite the numerous benefits of using nanomaterials in asphalt binders and materials, there are various uncertainties regarding the environmental impacts of nano-modified asphalt mixtures (NMAM). Therefore, this study assessed a Nano-Silica-Modified Asphalt Mixtures in terms of materials production emissions through the Life Cycle Assessment methodology (LCA), and the results were compared to a conventional asphalt mixture to understand the impact contribution of nano-silica in asphalt mixtures. To be able to compare the relative significance of each impact category, the normalized score for each impact category was calculated using the impact scores and the normalization factors. The results showed that NMAM had a global warming potential of 7.44563×10^3 kg CO_2-Eq per functional unit (FU) compared to 7.41900×10^3 kg CO_2-Eq per functional unit of the conventional asphalt mixture. The application of LCA to NMAM has the potential to guide decision-makers on the selection of pavement modification additives to realize the benefits of using nanomaterials in pavements while avoiding potential environmental risks.

Keywords: nanomaterials; life cycle assessment; nano-modified asphalt materials; environmental impact

1. Introduction

Asphalt is the most widely used pavement layer in the world. It consists of a binding material called bitumen and crushed or natural aggregates. The mixture of these materials forms asphalt mixtures. Demand for paved roads exceeded the supply of lake asphalts in the late 1800s and led to the use of petroleum asphalts [1]. Asphalt is often used as a shortened form of asphalt concrete which is the material of choice in the pavement sector. In the United Kingdom and the rest of Europe, the term 'bitumen' is used as a synonym for the term 'asphalt binder' while 'asphalt cement' is often used in the United States [2]. Asphalt cement or bitumen is used to bind the aggregates together to provide the required strength and stiffness to transfer vehicular loads. In addition to its strength and stiffness, asphalt pavements offer a damping ability due to the viscous-elastic nature of the bitumen [3]. Consequently, asphalt mixtures are qualified to provide optimal driving comfort as well as flexible maintenance actions. Asphalt pavements are designed to provide maximum performance throughout the design life. Bitumen (asphalt binder) performs two functions: Binding aggregates together and protecting the aggregates from distortions. However, unlike concrete pavements, asphalt pavements experience deformations over short periods of time. This, coupled with increased traffic loads and extreme weather conditions have resulted in asphalt pavement authorities seeking alternative solutions to improve the resistance of the road pavements to the adverse effects of mechanical and environmental loading [4].

Currently, several additives and modifiers produced commercially are used to modify the properties of the asphalt binder. Ref. [3] stated that additives and other modifiers are added in asphalt mixtures to lower mixing and compaction temperatures. This was found to improve adhesion and increase resistance against cracking and rutting. Regarding the viscosity of bitumen, Ref. [5] studied the effects of asphaltene on rheological properties of diluted Athabasca bitumen. Nanotechnology and nanomaterials have recently attracted significant attention from the pavement industry. Nanomaterial application is considered to have the potential to improve asphalt binder properties. As mentioned by Ref. [6], the application of nanomaterials as asphalt modifiers is growing rapidly in popularity due to its unique characteristics that significantly improve the performance of asphalt binder. It has been shown in several studies that the addition of nano-silica in asphalt mixtures improve the oxidative aging property, increases resistance to the rutting effect, improves the rheological properties of asphalt mixture and decreases the interaction between asphalt molecules [7–10]. In addition, Ref. [11] investigated and found that increasing nano-silica content in asphalt mixtures decreases the ductility and temperature sensitivity of the asphalt mixture.

It is becoming increasingly important to explore the full benefits of additives and modifiers on the long-term performance of asphalt pavements. With sustainability in mind, and also embracing the global effort to reduce the environmental impacts associated with these newly perforated materials, being able to make decisions and judge the benefits and environmental friendliness linked to the long-term pavement performance has become important. Consequently, having a life-cycle assessment (LCA) tools available to assess modified-asphalt materials on a life-cycle basis becomes necessary. Due to the concern of global warming and resource depletion, LCAs for different materials and products and systems have gained significant popularity with researchers. LCA studies can help to determine and minimize the energy consumption, use of resources, and emissions to the environment by providing a superior understanding of the systems [3]. LCA studies can help to consider different alternatives if the environmental performance of a particular material or product is not favorable. There have been several studies that attempt to assess the environmental impact of asphalt materials and some studies have also been conducted on asphalt binders modified with additives [12–15]. However, to the author’s knowledge, no studies that assess the complete LCA for the production phase of nano-silica-modified asphalt mixtures have previously been published. A new material being used as a modifier, there are uncertainties regarding the environmental impacts associated with nanomaterials. Therefore, it is of paramount importance to investigate the extent to which the use of nano-silica-modified asphalt mixtures for asphalt concrete pavement is beneficial from an environmental perspective.

This study presents the assessment of a Nano-Silica-Modified Asphalt Mixtures in terms of materials production emissions through LCA methodology. The environmental impacts of a conventional asphalt mixture were assessed so that a comparison could be made to understand the impact contribution of nano-silica in the asphalt mixture. In addition, to be able to compare the relative significance of each impact category, the normalized score was computed for each impact category using impact scores and normalization factors. The application of LCA to NMAM has the potential to guide decision-makers on the selection of pavement modification additives to realize the full benefits of the use of nanomaterials in pavements while avoiding potential environmental risks.

2. Literature Review and Definitions

2.1. Life Cycle Assessment

LCA is described by Ref. [16] as a tool for systematically analyzing the environmental performance of products or processes over their entire life cycle, which includes raw material extraction, manufacturing, use, end-of-life disposal, and recycling. LCA is described as a 'cradle to grave' method for the evaluation of environmental impacts [17]. In a similar description, Ref. [18] defines LCA as a methodology that quantifies the environmental impacts of a process or a product. In their study, Ref. [19] stated that most of the environmental impacts do not occur in the use, maintenance, and repair of the product but during the manufacturing, transportation, and disposal stages. Ref. [20] claimed that it would be premature to make any claims on the environmental benefits of a particular product or manufacturing process without first considering its consequences in a life cycle context. LCA methodology includes the establishment of an inventory of all types of emissions and waste products [21,22]. LCA studies are conducted in accordance with the specification and standards of the International Organization for Standardization (ISO). The four major components of an LCA study according to Ref. [23] are illustrated in Figure 1. The inventory analysis part is made up of material extraction phase, manufacturing or production phase, use or operational phase and disposal phase. However, it is quite difficult to effectively assess the environmental impact of a product during its in-service life. Therefore, the analysis of this study does not include the operational phase and/or the disposal phase of the inventory analysis.

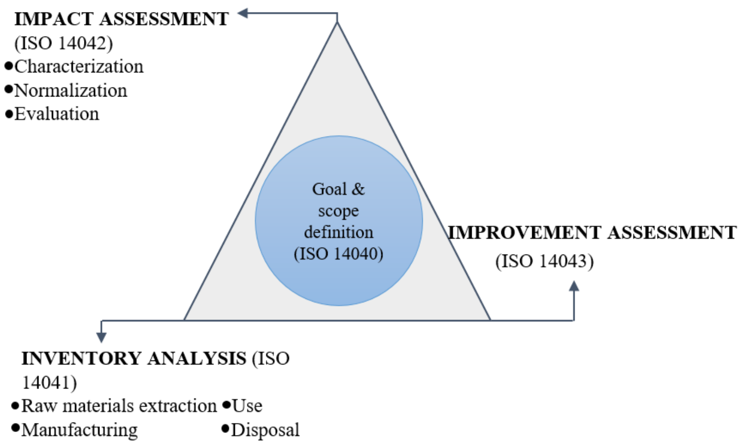

Figure 1. Structure of LCA study.

2.2. Nanomaterials and their Application as a Modifier in Asphalt Mixtures

Nanotechnology is an emerging technology and is regarded as a key enabling technology due to its numerous associated benefits to many areas of society. Nanotechnology is defined as the use of very small particles of materials (either by themselves or by their manipulation) to create new large materials [24]. The author added that nanotechnology is not a new science or technology, but an extension of the science and technology that has been in development for many years, and is used to examine nature at an ever-smaller scale. Ref. [25] defines nanomaterials as those physical substances with at least one dimension between 1 and 150 nm (1 nm = 10^{-9} m). With reference to the European Commission's recommended definition of nanomaterials, Ref. [26] defines nanomaterial as a "natural, manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm". The application of nanomaterials in the field of construction is growing rapidly. Ref. [27] mentioned that nanotechnology is a rapidly expanding area of research where novel properties of materials manufactured at the nanoscale can be utilized for the benefits of constructing infrastructure. Although some nanomaterials are already being used in the concrete industry, their application as a modifier in asphalt binder has attracted more interest recently. Several experimental studies have been conducted to determine the effect of nanomaterials, especially nano-silica on the properties of asphalt mixtures. Nano-silica materials are used as additives which are applied in small percentages by weight of the asphalt binder to improve the rheological and other properties of asphalt mixtures. Ref. [7] investigated the characteristics of asphalt binder and mixture containing nano-silica and found that the addition of nano-silica has a positive influence on different properties of the asphalt binder and mixture. Ref. [28] also studied the effect of nano-silica and rock asphalt on rheological properties of modified bitumen. In their study, Ref. [29] found that the inclusion of nano-silica reduces the rutting susceptibility of nano-modified asphalt mixtures. Ref. [30] studied laboratory evaluation of composed modified binder and mixture containing nano-silica/rock asphalt/SBS. In a similar experimental study, Ref. [31] found that increasing the percentage of nano-silica increases the Brookfield Rotational Viscosity (RV). Ref. [32] worked on the application of nano-silica to improve asphalt mixture self-healing. In another study, Ref. [33] investigated the effect of nano-silica on thermal sensitivity of hot-mix asphalt. Nano-silica increases the strength or durability of asphalt mixture [34,35]. Refs. [36–40] also made similar studies on the effect of nano-silica on asphalt binder and mixtures. Table 1 summarizes the review of previous studies on the characterization of asphalt binder modified with nano-silica. Regarding the cost of using nanomaterials, Ref. [41] provides the prices for almost all nanomaterials based on the quantity required. For example: precipitated calcium carbonate Nanopowder, 50 nm (100 g = $45, 1 kg = $85); nano-silica nanopowder, 60–70 nm (100 g = $55, 1 kg = $155); titanium oxide Nanopowder, 20 nm (100 g = $165, 1 kg = $468); zinc oxide Nanopowder, 80–200 nm (100 g = $58, 1 kg = $168). While some nanomaterials may seem costly, others may be cheap. However, on a large scale, an extensive economic analysis is required to determine the optimum cost for each nanomaterial based on the quantity required.

Table 1. Review of previous studies on modification of asphalt binder with nano-silica.

Author	Type of Nanomaterial	Effect on Asphalt Binder and Mixtures
[32]	Nano-silica	Improves the self-healing of HMA
[10]	Nano-silica	Improves marshal stability, resilient modulus, and fatigue life
[29]	Nano-silica	Enhances antiaging property and rutting and fatigue cracking performance
[30]	Nano-silica	Improves temperature stability, decreases temperature cracking resistance and reduces susceptibility to moisture damage
[28]	Nano-silica	Enhances the complex shear modulus and improves the anti-rutting performance of asphalt mixture
[34]	Nanosilica	Reduces the susceptibility to moisture damage and increases the strength of asphalt mixes
[35]	Nano-silica	Improves the performance and durability of asphalt mixtures
[36]	Nano-silica	Improve rutting and fatigue performance of asphalt binder
[37]	Nano-silica	Decreases the interaction between asphalt molecules and increases free volumes in the configuration
[38]	Nano-silica	Decreases the consistency, rate of water absorption and porosity of the roller compacted concrete pavement
[39]	Nano-silica	Improves the rheological characteristics, toughness, and viscosity of bitumen
[40]	Nano-silica	Reduces the creep strain deformation and increases the dynamic shear modulus

3. Methodology

LCA methodology was used (as standardized by the ISO in 2006) to assess the environmental impact of nano-silica-modified asphalt mixtures. There are numerous nanomaterials whose effect on asphalt binder and mixtures have previously been evaluated. However, based on the extensive literature review, the common nanomaterials which have been experimentally shown to have a greater impact on asphalt concrete performance include nanoclay and nano-silica. Consequently, nano-silica was used in this study. However, any other nanomaterial (especially nanoclay) which uses a similar production process could give similar results when modified with asphalt binder and materials. Also, the analysis of this study focused on only material extraction and production phases and does not include the operational or the disposal phase. The inclusion of the operational phase in the LCA analysis could change the inference about the conformity of nano-silica-modified asphalt mixtures.

The structure of LCA studies adopted includes goal and scope definition, inventory analysis, impact assessment, and improvement assessment or interpretation stages.

3.1. Goal and Scope Definition

3.1.1. Goal and System Boundaries

The goal of this study is to assess the potential life-cycle environmental impacts resulting from modifying asphalt materials with nanomaterial (i.e., the environmental impacts of nano-silica-modified asphalt mixtures). Additionally, a comparison is made with the environmental impacts of unmodified asphalt mixture to provide a better understanding of the impact contribution of nanomaterials in asphalt materials to allow for informed decisions to be made. In other words, the extent to which the use of nano-silica-modified asphalt mixtures for asphalt concrete pavement is beneficial from the environmental perspective is evaluated.

Two alternative case scenarios were examined. In CASE 1A, the environmental impact of nano-modified asphalt material was assessed. The use of nanomaterial (nano-silica), asphalt materials, and the production processes of asphalt mixtures were considered. Modification of bitumen with nanomaterial is depicted in Figure 2.

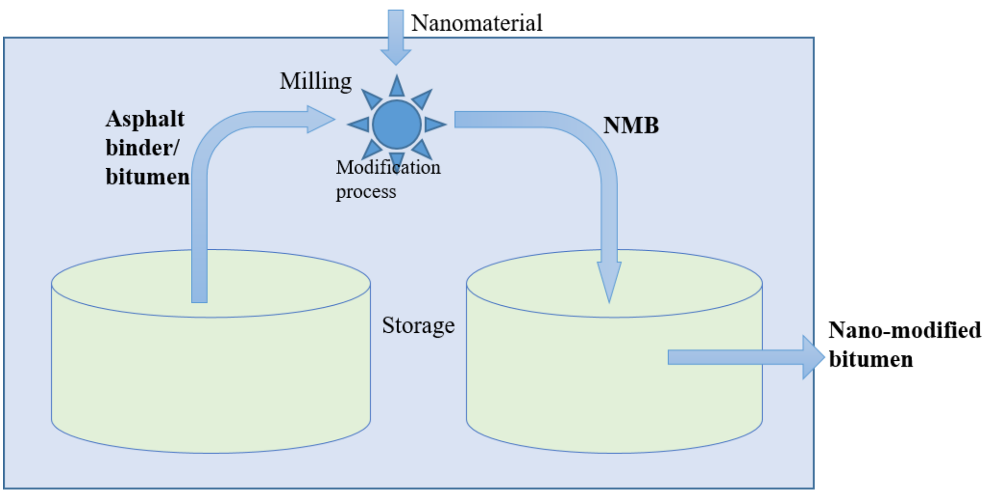

Figure 2. Nano-modified bitumen (NMB) production.

In CASE 2A, the environmental impact of asphalt material production, excluding nanomaterial (conventional asphalt mixture), was assessed. The system boundaries which defines the unit process considered in the LCA studies [4] were limited to cover the following life cycle stages in this study: (1) raw materials extraction; (2) transportation of raw materials for a unit product manufacturing; (3) modification and production of asphalt materials in the plant. Transportation of asphalt materials to the field, use, and the end-of-life were not included. The life cycle stages and key processes of nano-modified asphalt production in the plant are shown in Figure 3. The flow emissions and resource consumption (such as electricity and natural gas) for heating and the production processes were also included in the system boundaries.

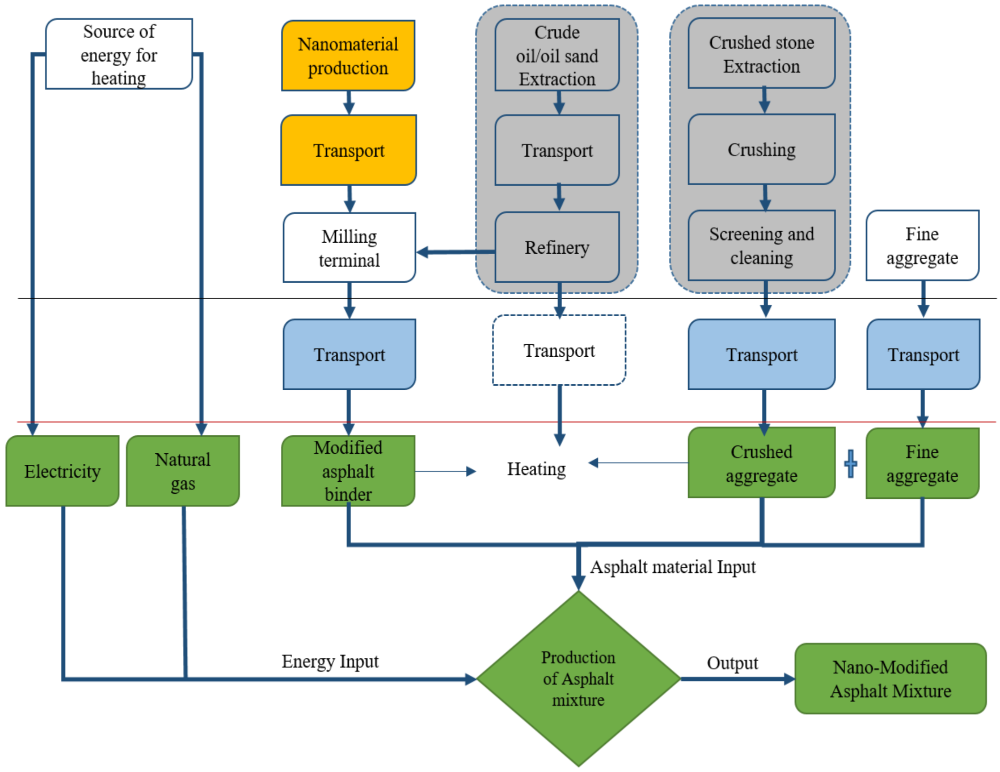

Figure 3. Key processes of nano-modified asphalt materials.

The results of this study will help practitioners in the asphalt concrete pavement industry to make informed decisions by considering the numerous benefits of nanomaterials (nano-silica) and the environmental impacts resulting from modifying asphalt mixtures with the nano-silica material.

3.1.2. Functional Unit (FU)

The FU is the heart of any LCA studies. The FU is a quantified performance of a product system for use as a reference unit in an LCA study [21] (referring to the Malaysian standards handbook on environmental management). A fixed value must be created and the output results of the environmental impacts of the impact categories depend on this selected FU. In this study, a FU of 1000 kg production of nano-silica-modified asphalt mixtures was assumed.

3.2. Life Cycle Inventory (LCI)

Material Extraction and Production Processes

The life cycle inventory stage is the stage of actual data collection and the modeling of the system product. For the data on material extraction, processing, and production, an openLCA database was used. OpenLCA is an open source LCA tool from GreenDeLTa located in Berlin, Germany. The software uses an Eco-invent 2.2 database and other proprietary databases and produces equally good results compared to other proprietary LCA tools such as SimaPro, Gabi, etc. The software allows the user to import any external database into its platform and it can be used to model any product. For the production process of nano-silica, silica gel and precipitated silica type, the process outlined by Ref. [42] was followed. A 1000 kg production of bitumen and aggregates was assumed. For the input amount of

1kg nano-silica production, the data provided by Ref. [43] were referred to. Additives are often applied in small percentages (1–10%) by weight of asphalt binder. This study used 3% of nano-silica for asphalt binder modification. Therefore, the input amount of 30 kg nano-silica was required to modify the bitumen. Data from Refs. [13,14] were used regarding the energy consumption data per kg of material required for bitumen production, aggregates, and the mixing of asphalt materials at the plant. In other studies, such as the one reported by Ref. [3], the modification of asphalt binder with additives results in an increase in fuel consumption by approximately 15%. Therefore, it was assumed that an increase of 15% in energy for bitumen production was required to modify the bitumen. Hence, to account for the asphalt binder modification with nano-silica in the analysis, an additional 15% increase in energy (fuel) was added to the 0.51 MJ energy for bitumen production. Transportation of nano-silica material to the milling terminal for modification was assumed as 100 km, while the total transportation for bitumen and to the asphalt plant was also assumed to be 100 km and that for aggregates was assumed as 5 km to the mixing plant. In Table 2, the material and energy requirements for the production of nanomaterial (nano-silica) and asphalt materials is summarized.

Table 2. Materials and energy requirements for 1 kg unit production of nano-silica and asphalt materials.

Input	Flow Amount
Nanomaterial (nano-silica)	
Sodium silicate	0.66 kg
Sulfuric acid	3.9 kg
Heat (Natural gas)	15–24 MJ
Water	40 kg
Asphalt material	
Total Energy for bitumen production	0.51 MJ
Energy for aggregates production	0.0354 MJ
Energy for asphalt materials production	0.349 MJ

3.3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) stage involves analyzing the data to evaluate the contribution to each impact category. LCIA consists of characterization, normalization, evaluation, and weighting depending on the LCIA used. In this study, the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) method version 2.1 (provided in openLCA) was used to calculate the impact category indicator scores TRACI is a software from the US Environmental Protection Agency (EPA), Durham, NC, USA. TRACI uses Equation (1) [44] to determine the impact score for each individual environmental impact category.

$$I^i = \sum_{xm} CF^i_{xm} \times M_{xm} \quad (1)$$

where: I^i is the potential impact of all substances (x) for a specific category of concern (i), CF^i_{xm} is the characterization factor for substance (x) emitted to media (m) for each impact category (i), and M_{xm} is the mass of the substance emitted to media (m). OpenLCA version 1.7.4 was then used for modeling the processes in this study.

Finally, to be able to compare the relative significance of each impact category, the normalized score for each impact category was calculated. Normalization is the ratio of the impact score in each category and the estimated impacts from a reference (often called normalization factors). These factors represent the impact produced by an average person in a reference place per year. Equation (2) was used for the computation:

$$NS_i = \frac{EnvI_i}{NF_i} \quad (2)$$

where NS_i is the normalized score of impact category i, $EnvI_i$ is the environmental impact result of impact category i, and NF_i is the normalization factor of impact category i. Regarding the normalization factors, US 2008 reference data was used, the impact per person-year updated in the research by Ref. [40]. Table 3 provides the details of the normalization factors. The units of four categories: ecotoxicity, carcinogenic, non-carcinogenic, and acidification are different from the reference units first converted to the reference units before computing the normalized score.

Table 3. Normalization factors for impact categories based on inventories from the US (2008) and US-Canada [45].

Impact Category	Normalization Factors and Reference Year			
	US 2008		US-CA 2005/2008	
	Impact per Year	Impact per Person Year	Impact per Year	Impact per Person Year
Ecotoxicity-metals (CTUe)	3.30×10^{12}	1.10×10^{4}	3.70×10^{12}	1.10×10^{4}
Ecotoxicity-non-metals (CTUe)	2.30×10^{10}	7.60×10^{1}	2.50×10^{10}	7.40×10^{1}
Carcinogens-metals (CTUcanc.)	1.40×10^{4}	4.50×10^{-5}	1.50×10^{4}	4.30×10^{-5}
Non-carcinogens-metals (CTUcanc.)	3.10×10^{5}	1.00×10^{-3}	3.40×10^{5}	1.00×10^{-3}
Global warming (kg CO_2 eq)	7.40×10^{12}	2.40×10^{4}	8.00×10^{12}	2.40×10^{4}
Ozone depletion (kg CFC-11 eq)	4.90×10^{7}	1.60×10^{-1}	4.90×10^{7}	1.50×10^{-1}
Acidification (kg SO_2 eq)	2.80×10^{10}	9.10×10^{1}	3.20×10^{10}	9.50×10^{1}
Eutrophication (kg N eq)	6.60×10^{9}	2.20×10^{1}	7.00×10^{9}	2.10×10^{1}
Photochemical ozone formation (kg O_3 eq)	4.20×10^{11}	1.40×10^{3}	4.90×10^{11}	1.50×10^{3}
Respiratory effects (kg PM2.5 eq)	7.40×10^{9}	2.40×10^{1}	1.00×10^{10}	3.00×10^{1}

Acidification potential = 1.98×10^{-2} SO_2/kg substance (multiplied its impact result by this value).

Ecotoxicity potential for rural air = 0.064 CTU eco/kg substance (multiplied its impact result by this value).

Human health cancer potential for rural air = 1.2×10^{-7} CTU canc/kg substance (multiplied its impact result by this value).

Human health non-cancer potential for rural air = 3.0×10^{-8} CTU canc/kg substance (multiplied its impact result by this value).

4. Results and Discussion

4.1. CASE 1A: Impact Assessment of Nano-Silica-Modified Asphalt Mixtures Analysis

OpenLCA version 1.7.4 was used to model and analyzed the environmental impacts of nano-modified asphalt materials and the analysis results are shown in Table 4.

Table 4. LCIA results of nano-silica-modified asphalt mixtures per FU.

Impact Category	Reference Unit	Impact Result
Environmental impact ∣ global warming	kg CO_2-Eq	7.44563×10^{3}
Human health ∣ respiratory effects, average	kg PM2.5-Eq	8.86935×10^{2}
Environmental impact ∣ ozone depletion	kg CFC-11-Eq	3.71600×10^{-2}
Environmental impact ∣ eutrophication	kg N-Eq	1.49156×10^{1}
Human health ∣ carcinogenic	kg benzene-Eq	2.18467×10^{3}
Environmental impact ∣ photochemical oxidation	kg NOx-Eq	3.03420×10^{1}
Human health ∣ non-carcinogenics	kg toluene-Eq	6.07040×10^{6}
Environmental impact ∣ ecotoxicity	kg 2,4-D-Eq	1.08917×10^{4}
Environmental impact ∣ acidification	moles of H+-Eq	1.87879×10^{5}

Increase in the production of the raw materials and/or the FU results in an increase in fuel and energy usage and will cause a significant increase in the impact scores in each category. The environmental performance of 7.44563×10^{3} kg CO_2-Eq/FU global warming of nano-silica-modified asphalt mixture is better than the results of (Butt et al.) who found the modification of asphalt materials with a polymer to be 44.9×10^{3} kg CO_2-Eq per FU of 1 km by 3.5 km wide asphalt pavement.

4.2. CASE 2A: Impact Assessment of Unmodified (Conventional) Asphalt Mixture Analysis

The analysis of unmodified (conventional) asphalt materials was needed to better understand the environmental implication of modifying conventional asphalt with nanomaterials. The results of the analysis are shown in Table 5.

Table 5. LCIA results of unmodified (conventional) asphalt materials per FU.

Impact Category	Reference Unit	Impact Result
Environmental impact ∣ global warming	kg CO_2-Eq	7.41900×10^3
Human health ∣ respiratory effects, average	kg PM2.5-Eq	8.79600×10^2
Environmental impact ∣ ozone depletion	kg CFC-11-Eq	3.68100×10^{-2}
Environmental impact ∣ eutrophication	kg N-Eq	1.47700×10^1
Human health ∣ carcinogenic	kg benzene-Eq	2.16300×10^3
Environmental impact ∣ photochemical oxidation	kg NOx-Eq	3.01270×10^1
Human health ∣ non-carcinogenics	kg toluene-Eq	6.01233×10^6
Environmental impact ∣ ecotoxicity	kg 2,4-D-Eq	1.08133×10^4
Environmental impact ∣ acidification	moles of H+-Eq	1.86282×10^5

Any increase in the production of raw materials or a change in the FU will result in an increase in the impact scores in each category and vice versa.

The modification of asphalt materials with nanomaterials results in an increase in environmental impacts, which is clear when comparing the results in Table 5 with that in Table 4. Across all impact categories, there is an increase in the impact scores. This fact is reinforced by Ref. [4] when the authors found that using Ethylene-Vinyl-Acetate (EVA) polymer as a modifier agent leads to a deterioration of the life cycle profile of the pavement compared to unmodified asphalt binder. However, the deterioration of the life cycle environmental profile with nano-modified asphalt materials is insignificant. Specifically, there was only a 0.4% increase in global warming, 0.8% increase in respiratory effects, 0.009% increase in ozone depletion, 0.98% increase in eutrophication, 1.0% increase in human health carcinogenic, 0.7% increase in photochemical oxidation, 0.96% increase in human health non-carcinogenic, 0.72% increase in ecotoxicity, and 0.85% increase in acidification. This means the modification of asphalt materials with nanomaterials (nano-silica) causes more impacts in human health carcinogenic than other impact categories. Apart from ozone depletion, the modification of asphalt materials with nano-silica contributes fewer impacts in global warming per 3% by weight of asphalt binder production of nano-silica.

4.3. Computation of Normalised Score

Table 6 and Figure 4 show the normalized score in each impact category of nano-modified asphalt materials. According to Ref. [46], by inspection, large values of normalized scores as compared to the total are classified as worse performing impact categories, while those with small normalized scores of approximately less than 2% of the total are classified as better performing impact categories. Table 6 shows that nano-modified asphalt materials only perform significantly better in four impact categories: photochemical oxidation (0.0217 pts/FU), ecotoxicity (0.0634 pts/FU), ozone depletion (0.2323 pts/FU), and global warming (0.3102 pts/FU).

However, to fully understand when and how an impact category is classified as either better or worse performing, a logarithmic scale criterion was used. This was especially useful in situations where there existed large variation in the normalization scores. It is argued by Ref. [47] that dimensionless data is more appropriately plotted on an arithmetic scale to clearly understand where the data points lie (better or worse trend). On a logarithmic scale, the center of gravity (where the eye is drawn) lies at the geometric mean, where the line starts at 1 and not 0. Hence, applying the logarithmic scale plot (see Figure 4), all the impact categories below the 1pts line are referred to as ZONE 1 (better performance zone). Hence, it can be said NMAM performs better in five categories: global warming (0.3102 pts/FU), ozone depletion (0.2323 pts/FU), eutrophication (0.6779 pts/FU), photochemical oxidation (0.0217 pts/FU), and ecotoxicity (0.0634 pts/FU).

Table 6. Normalized score per FU of the impact categories for NMAM.

Impact Category	Normalized Score (points, pts)
Environmental impact ǀ global warming	0.3102
Human health ǀ respiratory effects, average	36.9556
Environmental impact ǀ ozone depletion	0.2323
Environmental impact ǀ eutrophication	0.6779
Human health ǀ carcinogenic	5.8258
Environmental impact ǀ photochemical oxidation	0.0217
Human health ǀ non-carcinogenic	182
Environmental impact ǀ ecotoxicity	0.0634
Environmental impact ǀ acidification	41.0101

Small values are better.

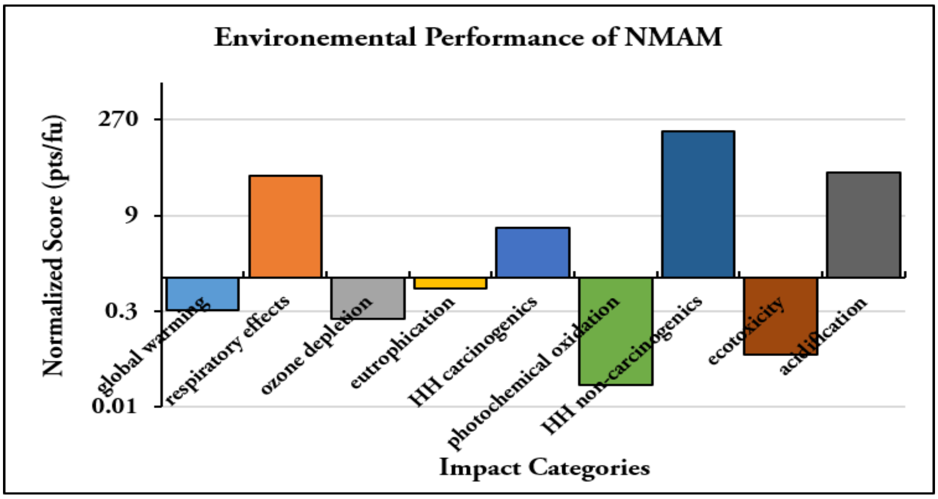

Figure 4. Environmental performance (normalized score) of NMAM.

All the impact categories above the 1 pts line are referred to as ZONE 2 (worse performance zone). NMAM performs worse in this zone in 4 categories: respiratory effects (36.9556 pts/FU), human health carcinogenic (5.8258 pts/FU), human health non-carcinogenic (182 pts/FU), and acidification (41.0101 pts/FU).

The worst performance in acidification, which is the increase in hydrogen ions (H+) concentration within the environment as a result of the presence of acids, can be attributed to the sulfuric acid used in the production of nano-silica and the cause of sulphur dioxide and nitrogen oxides released during transportation of the materials and including asphalt materials. As mentioned previously, the modification of asphalt materials with nanomaterial causes only 0.4% per unit increase in global warming. This is because carbon dioxide (the main cause of global warming) is released during the production of bitumen, aggregates, asphalt mixing, and also during transportation. In short, the fact that the modification of asphalt materials with nanomaterial causes just less than or equal to 1% increase in impact score across all impact categories suggests that modifying asphalt materials with nanomaterials does not cause an unreasonable risk to the environment. However, the results of this study using nano-silica does not conclude that all other nanomaterials may have very low impact. The impact on the environment and the combined impact when modified with asphalt materials depend on the production process of the nanomaterial. Therefore, it is expected that some nanomaterials may have a more negative environmental impact.

5. Conclusions

LCA is a tool that helps to assess the environmental impacts of materials and products so that decisions can be made not just on the benefits of using these materials but also considering their environmental contributions (especially to climate change and human health). This study assessed a Nano-Silica-Modified Asphalt Mixtures in terms of materials production emissions through the Life Cycle Assessment methodology (LCA), and the results were compared to a conventional asphalt mixture to understand the impact contribution of nano-silica in asphalt mixtures. The results showed that NMAM had a global warming potential of 7.44563×10^3 kg CO_2-Eq per FU as compared to 7.41900×10^3 kg CO_2-Eq per FU of unmodified asphalt mixture. The study also computed the normalized score for each impact category and the results showed NMAM performs better in five categories: global warming (0.3102 pts/FU), ozone depletion (0.2323 pts/FU), eutrophication (0.6779 pts/FU), photochemical oxidation (0.0217 pts/FU), and ecotoxicity (0.0634 pts/FU). NMAM performs worse in four categories: respiratory effects (36.9556 pts/FU), human health carcinogenic (5.8258 pts/FU), human health non-carcinogenic (182 pts/FU), and acidification (41.0101 pts/FU). The modification of asphalt materials with nano-silica causes less than or equal to 1% per unit increase in impact score across all impact categories. The application of LCA to NMAM has the potential to guide decision-makers on the selection of pavement modification additives to realize the benefits of nanomaterials in the pavement while avoiding potential environmental risks. Additionally, this study has shown that even though the modification of asphalt mixtures with nano-silica results in an increase in fuel consumption, it does not cause an unreasonable risk to the environment nor does its application as a modifier results in significant deterioration of the life cycle environmental profile. However, future research is required by considering the analysis of the whole life cycle for nano-modified asphalt materials using different nanomaterials as a modifier to confirm that nanomaterials are sustainable materials.

Author Contributions: Conceptualization, S.S.; Methodology, S.S.; Software, S.S.; Validation, S.S.; Formal Analysis, S.S.; Writing–Original Draft Preparation, S.S., D.E.L., B.S.K.; Writing–Review & Editing, B.S.K.; Funding Acquisition, D.E.L., B.S.K.

Funding: This work was supported by the National Research Foundation (NRF) of Korea grant funded by the Korea government (MSIT) (No.NRF-2018R1A5A1025137).

Conflicts of Interest: The authors declare no conflict of interest.

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