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LCA Sensitivity Analysis of Asphalt Modified Nano Silica

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Abstract. Improving long-term resilience of asphalt, various types of modifiers have been investigated to facilitate the development of an advanced asphalt mixture. Nanoparticles with silica layers have gained the interest of pavement researchers because of their contribution to improving the physical, rheological, and mechanical properties of asphalt binders. However, the environmental impact information on using this material is limited. Therefore, further investigation needs to be conducted to assess the environmental burden of incorporating the material into the asphalt mixture. Life Cycle Assessment (LCA) is a key method for evaluating the environmental impacts of new materials such as Nano Silica in asphalt mixtures. Nonetheless, many LCA input parameters are based on estimations or generalisations, such as transport distances and production data. These introduce uncertainty and may significantly affect results. Therefore, a sensitivity analysis was conducted to test how changes in key variables influence total impact category across life cycle stages. The results show that raw material production contributes the highest impact to mineral resource scarcity and global warming, while the asphalt mixing stage dominates freshwater ecotoxicity and energy consumption. Mineral resource scarcity is most sensitive to nano-silica and binder production, freshwater ecotoxicity to electricity use, and both global warming potential and energy demand to thermal energy in the mixing process.

1 Introduction

Asphalt pavement, a vital component of transportation infrastructure, is necessary for facilitating the safe and efficient movement of people and goods. Nonetheless, despite their extensive utilization, conventional asphalt mixtures face numerous challenges, including significant traffic loads, varying environmental conditions, and deterioration from prolonged pavement usage. Cumulative stress frequently leads to surface damage and various structural distress over time [1], [2]. As a result, researchers, engineers, and pavement professionals are endeavoring to enhance both the performance and the durability of asphalt pavement. For the past decades, the use of nanomaterials, with dimensions ranging from 1 to 100 nanometers and high surface area, has offered promising advantages due to their unique properties [3]. One of the nanomaterials introduced for asphalt is Nano Silica (NS). This material has the

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benefit of dissolving effectively in the asphalt binder, exhibits high absorption, a high surface area, and contains pozzolanic content. These properties improve the rheological characteristics, resistance to oxidative aging, and enhance fatigue and rutting resistance [4], [5]. Additionally, NS has been reported to have the ability to increase the viscosity of asphalt binders, as measured by the Brookfield test and the softening point. The increase in these properties prevents the asphalt binder's susceptibility to temperature changes [6]. In terms long long-term implementation, [7] reported that the addition of 4% NS increases the ageing resistance of the modified asphalt binder.

Although its effectiveness in enhancing pavement performance has been demonstrated, the environmental impact of NS as a modification to asphalt binder remains unexplored. Consequently, further investigation is required to assess the viability of this material in asphalt pavement technology. A comprehensive analysis is required. Consequently, Life Cycle Assessment (LCA) is employed to evaluate the environmental sustainability of nano silica-modified asphalt mixtures. However, in the LCA practice, the input parameters were either estimations, such as transit distance, or generalizations, such as NS production. Santero, [8] stated that pavement LCAs routinely fail to adopt any such approach and generally assume a single published value with neither supporting rationale nor a sensitivity analysis. Consequently, the variability related to those characteristics is unavoidable. Changes to the variables in the formulated equation for assessing the impact category can substantially alter its result. A sensitivity analysis is therefore required to evaluate the susceptibility of the results to variations in parameter values at each life cycle stage and to identify the most sensitive parameter for the overall life cycle outcome. Accordingly, this study aims to conduct an LCA and sensitivity analysis to quantify the environmental burden of incorporating NS in asphalt mixtures while determining the key parameters driving the total life cycle impacts.

2 Materials

Pavement generally consists of layers that form the road pavement structure, which typically includes an asphalt layer and a base layer. The asphaltic layer includes the surface course, binder course, and base layer, whereas the foundation layer consists of the subbase and subgrade layers. Silica additions are primarily used as modifiers for asphalt in the surface course layer, as this layer is directly subjected to road traffic and requires increased durability. Therefore, the LCA analysis in this study will primarily focus on the application of nano silica in the surface course..The asphalt binder content in the overall asphalt mixture is estimated at 6%, with nano-silica pre-integrated into the binder. Prior research indicates that using 2% nano-silica by weight of binder can significantly improve the performance of asphalt misture [9], [10], [11], [12]. Hence, this work employs a 2% nano-silica concentration for binder modification. It is assumed that nano-silica will be integrated at the refinery or terminal plant phase, when it is combined with conventional asphalt binder to produce a nano-silica rubber-modified binder [13].

3. Methodology

3.1 Goal and Scope

The aims of this research are to examine the environmental impact of nano-silica modified asphalt mixtures by considering the asphalt production life cycle. Such a study is important to provide information to add at the early stages of new mixture development. The results of this study are intended to be utilised by engineering practitioners and experts to assess the benefits and drawbacks of using new material technology regarding road pavement construction. The methodology of this study focused on developing a detailed framework that represents the consideration, assumptions, and outline of the process used in this study.

The study encompasses all the processes and activities that occur throughout the pavement's lifetime. The system boundary considered is the material production stage, which consists of: (1) raw material production, (2) transportation, and (3) the asphalt mixing process. In the material production stage, environmental impact is quantified from raw material extraction activity and the manufacturing process. These materials are then transported to the asphalt mixing plant location, which involves fuel-related distance from all material handling processes. In the asphalt mixing plant, the process encompasses all the plant's mixing operations, resulting in a consequent increase in emissions during this stage. The analysis adheres to the guidelines of the BS EN 17472 standards to provide results in a comprehensive manner. The following life cycle stages are included in the standards to categorise the environmental impacts: production (A1-A3). SimaPro 9.0 software was used to perform LCA calculations. The designated functional unit (FU), which is represented as the reference unit for measuring system performance in this LCA study, is a ton of asphalt mixture production.

3.2 Life Cycle Inventory

The Life Cycle Assessment was conducted in SimaPro 9.3.3 using the Ecoinvent v3.8 database as the background inventory. The modelling covered raw materials, transportation, and mixture production. Raw material inputs were represented by the datasets for bitumen adhesive compound and crushed gravel, while nano-silica production was modelled through dataset from [14], [15]. The transportation stage included the movement of binder, aggregates, nano-silica, and PMB mixture. Land-based transport was represented by the 'Truck 10–20 t EURO4' dataset, and overseas shipping of nano-silica from China to Jakarta was represented by transoceanic freight. Transport activities were expressed in ton-kilometers (tkm), calculated from the mass of each material multiplied by its transport distance.

3.3 Life Cycle Impact Assessment

Mineral resource scarcity, Freshwater ecotoxicity, GWP, and Energy consumption are the key impact categories considered in this analysis. The assessment of Mineral resource scarcity and Freshwater ecotoxicity was carried out using the ReCiPe 2016 Midpoint (H) method, which provides midpoint indicators for resource depletion and ecosystem toxicity based on standardized characterization factors. The GWP Potential (GWP) was evaluated following the Intergovernmental Panel on Climate Change (IPCC) 100-year time horizon approach, which measures the contribution of greenhouse gas emissions to climate change in terms of CO_2-equivalents. Meanwhile, Energy consumption was assessed through the Cumulative Energy Demand (CED) method, which quantifies the total primary GWP throughout the life cycle stages. All impact characterization was performed using background inventory data published in the Ecoinvent database.

4. Results and Discussion

4.1 Environmental Impact Analysis

The result of environmental impact generated from each LCA stage and the total amount of those stages is presented in Table 1. The results show that raw material production has the highest percentage impact on mineral resource scarcity, with 0.0052 kg Cu eq, followed by Asphalt Mixing and the transportation process. As for freshwater ecotoxicity, the highest impact is produced from asphalt mixing, raw material production, and transportation. In GWP, raw material production contributes the highest CO2, with 35,837.1 kg CO2 eq, slightly larger than the mixing process with 34,901.4 kg CO2 eq, while transportation is the least contributing process, producing only 3,580.6 kg CO2 eq. Lastly, Asphalt Mixing generated the highest energy to produce the asphalt mixture amounted to 517,5016 GJ, compared with other phases with only 53,8795 GJ and 3,3206 GJ subsequently for transport and raw production stages.

Table 1. Impact analysis of NS modified asphalt mixture

Impact Category	Unit	Raw material production	Transport	Asphalt Mixing	Total
Mineral Resource Scarcity	kg Cu eq	0.0052	0.0001	0.0002	0.0055
Freshwater Ecotoxicity	kg 1.4-DCB	0.2027	0.0038	0.2273	0.4338
GWP	kg CO2 eq	35.8371	3.5806	34.9014	74.3191
EC	GJ	3.3206	53.8795	517.5016	574.7017

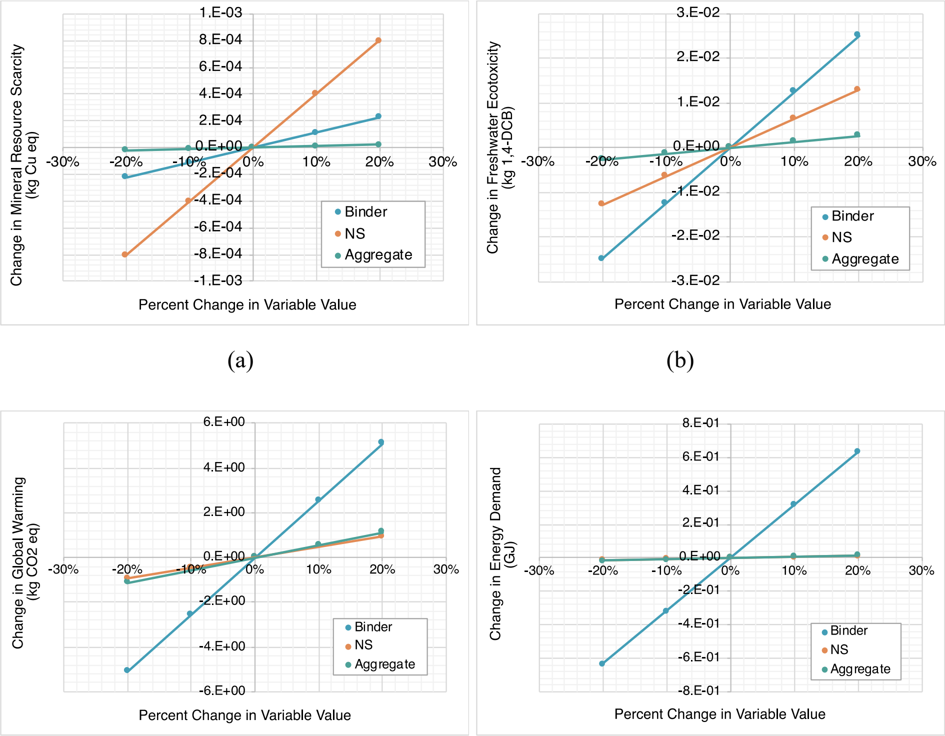
4.2 Sensitivity Analysis

In the previous section, the input parameters were either an estimation, e.g., transportation distance, or generalisation, e.g., NS production. As a result, variability that is inherent in those parameters is unavoidable. And changes to variables in the developed formula for calculating the impact category can significantly change its outcome. Accordingly, a sensitivity analysis was carried out to assess the sensitivity of the results to changes in the values of parameters in each life cycle stage, and to compare the most sensitive parameter in each stage for the whole life cycle outcome.

4.2.1Raw material production impact analysis

The formula for calculating the four environmental impact categories was tested for sensitivity to changes in the values for each raw material input. Figure 1 illustrates the influence of changes in the quantity of asphalt binder, aggregate, and nano-silica on the four impact categories. For mineral resource scarcity (Fig. 1a), nano-silica demonstrated the highest sensitivity among the other materials. This outcome reflects the dependence of nano-silica on non-renewable mineral resources, in contrast to aggregates and binders, which are not classified as mineral-based resources.

On the other hand, for freshwater ecotoxicity (Figure 1b), asphalt binder dominated the sensitivity effect with an increase in material amount and followed by NS. This occurrence reflects that the upstream production of asphalt binder involves a process with higher ecotoxic emissions, whereas aggregate had minimal influence on this impact category. In addition, Figures 1c and 1d show that the amount of asphalt binder was most sensitive to the increase in GWP and GWP. At the same time, aggregate and NS resulted in less sensitive increases, although NS still showed noticeable sensitivity for GWP. This may happen due to reduced energy requirements in the aggregate production process in the quarry. Meanwhile, NS is present in a very small amount in the asphalt mixture, which is why this material is not sensitive to GWP. This result signifies that Binder impact values have a greater sensitivity because it creates much more energy and CO2 equiv. emissions per ton of asphalt mixture than other materials.



(a) (b)

(c) (d)

Fig. 1. Raw material sensitivity analysis for: (a) Mineral resource scarcity, (b) Freshwater ecotoxicity, (c) GWP, and (d) Energy consumption

Overall, these results suggest that in raw material production, NS is the key driver of non-renewable mineral resources' sensitivity, while binder is the most critical factor for GWP and GWP. Hence, a strategy focusing on optimizing the binder content and strategies aimed at improving the production process of nano-silica could significantly reduce environmental variability in asphalt mixtures.

4.2.2 *Transport stages impact analysis*

Figure 2 presents the sensitivity analysis of transport distance to the asphalt mixing plant by varying travel distances for each raw material. The results show that transport distance influences the system's environmental impacts, with varying degrees across materials.

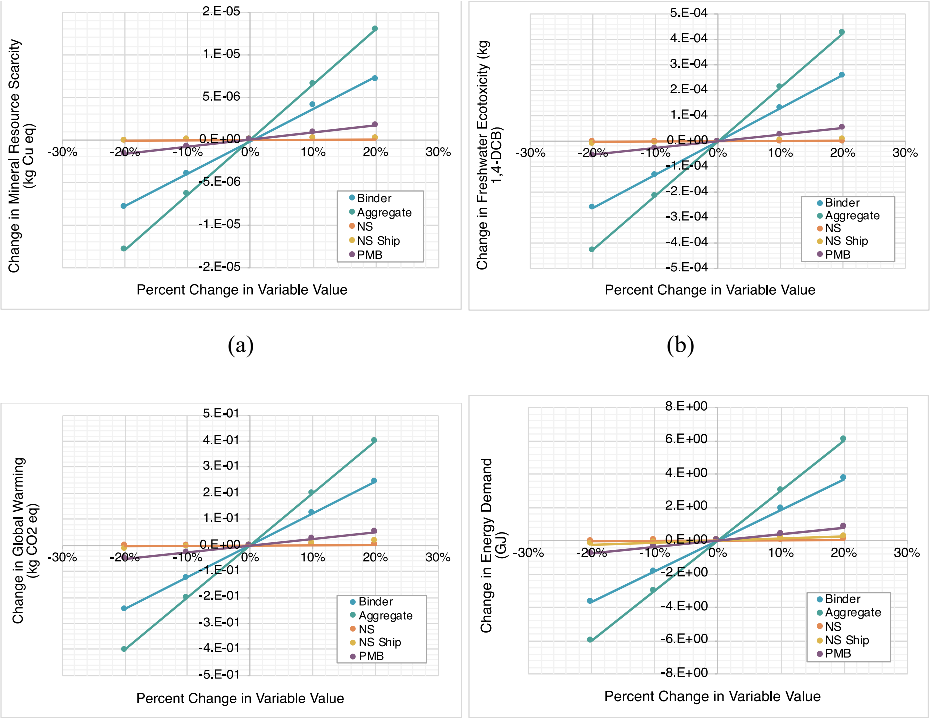


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Fig. 2. Transport distance sensitivity analysis for: (a) Mineral resource scarcity, (b) Freshwater ecotoxicity, (c) GWP, and (d) Energy consumption

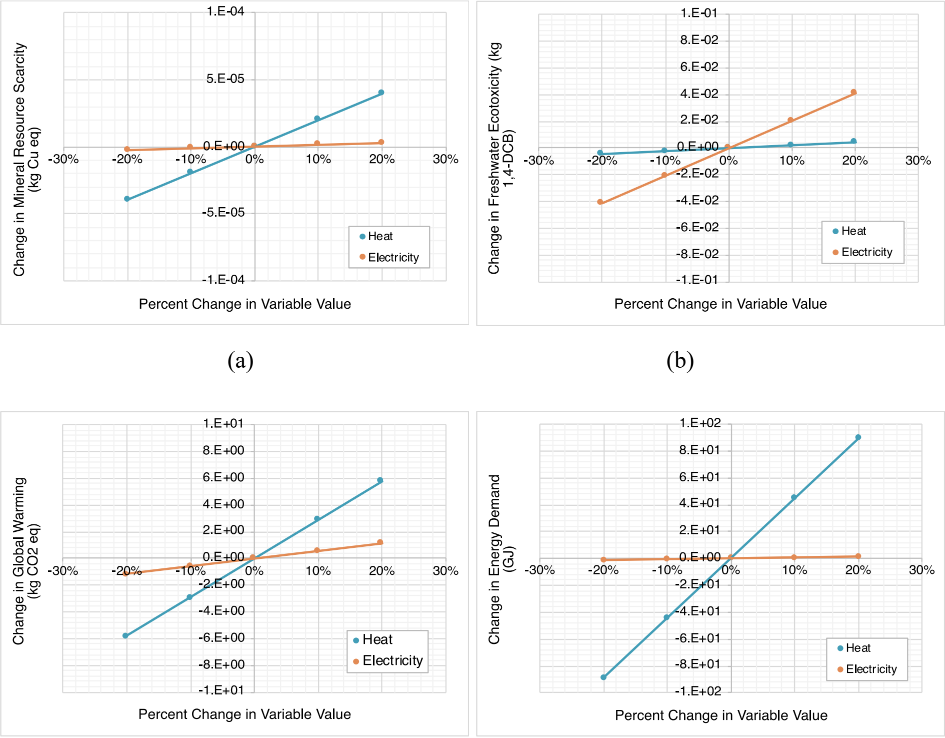
Aggregate transportation is the most sensitive parameter for all impact categories, reflecting asphalt's composition of nearly 95% aggregate by weight, making its transport one of the most energy-intensive processes despite relatively short distances. In contrast, binder, PMB, and nano-silica display minimal sensitivity across categories due to their lower transported mass. It is worth noting that the sensitivity ranking follows a consistent pattern: aggregate road transport, binder road transport, PMB road transport, nano-silica shipping, and nano-silica road transport. This pattern arises from the assumption that all road transport uses the same mode, making distance and transported mass (ton-km) the main influencing factors.

These results highlight that in the transportation stage, the quantity of material transported is the main driver of impact variation. Thus, sourcing aggregate from quarries closer to the asphalt mixing plant could significantly reduce transportation-related environmental impacts. Conversely, for low-volume materials such as nano-silica, longer transport distances have negligible influence on overall impacts and therefore should not be a barrier to its use, even if sourced from farther locations such as overseas shipping.

4.2.3 *Asphalt mixing stage impact analysis*

The variation of energy for both thermal and electrical was plotted to see how sensitive the energy input during asphalt mixing affects the environmental impact value. According to the analysis, energy consumption will have a large impact on Mineral Resource Scarcity, GWP Potential, and Energy Consumption results (Figure 3). Thermal power or heat is used for drying and heating aggregates in the dryer drum, while electricity is used to power all other machinery (i.e., drum turning, conveyor belts). It is noticeable that energy consumption for thermal power is a more sensitive variable than electricity used for all three impact categories, except for freshwater toxicity. This is plausible since energy consumption in the form of light fuel oil used for heating and drying aggregates is the dominant energy input that makes it the most critical contributor to total energy consumption. In addition, the fuel used to produce thermal energy is non-renewable and thus drives mineral resource depletion, while the combustion results in the release of substantial greenhouse gas.

On the other hand, electricity has a higher sensitivity only in freshwater ecotoxicity. This result is likely associated with the upstream process in electricity production, which includes the power plant. The production processes in the power plant include the production and discharge of heavy metals, wastewater effluents, and chemical residues in electricity production that contribute to freshwater ecotoxicity. Therefore, although electricity shares a small contribution in total GWP compared to thermal power, its contribution to toxic release to the aquatic system is more significant and thus more sensitive to the freshwater ecotoxicity impact.



(a) (b)

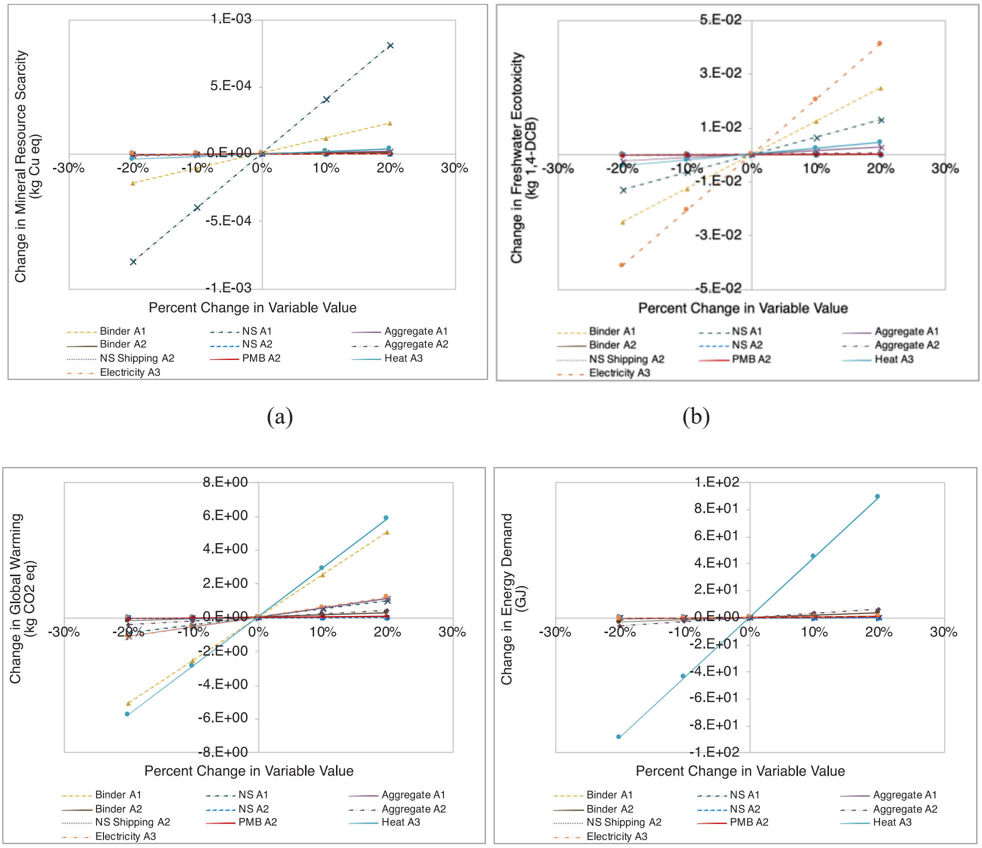
(c) (d)

Fig. 3. Asphalt mixing stage sensitivity analysis for: (a) Mineral resource scarcity, (b) Freshwater ecotoxicity, (c) GWP, and (d) Energy consumption

4.2.4 *Total impact analysis*

The result of total impact analysis, which totalling the three stages of raw material production, material transport, and asphalt mixing, is shown in Figure 4. In mineral resource sensitivity, mineral resource scarcity is most sensitive to NS and binder production (NS A1 and Binder A1). Meanwhile, the other process is less sensitive and is comparable. This outcome reflects the high dependence of these non-renewable materials (NS and asphalt binder). NS, as a mineral category, contributes directly to resource depletion. In addition, the dependence of asphalt binder manufacturing on the petroleum extraction process, which is also classified as a non-renewable resource, has also become a contributing factor.

In freshwater ecotoxicity, the change in the electricity value during asphalt mixing (Electricity A3) has the highest impact value change. This is followed by binder and NS production (Binder A1 and NS A1). The dominance of electricity is attributed to the upstream processes, which include the release of heavy metals, pollution, and chemical by-products, which have a harmful effect on the freshwater environment. The production of asphalt binder and NS also has a high impact on this impact due to the presence of chemical refining and mineral processing, which release toxic compounds.



(a) (b)

(c) (d)

Fig. 4. Cradle to gate sensitivity analysis for: (a) Mineral resource scarcity, (b) Freshwater ecotoxicity, (c) GWP, and (d) Energy consumption

For Binder GWP, the Heat value (Heat A3) from the asphalt mixing process has the highest sensitivity level, followed by binder production (binder A1). In contrast, other processes are less sensitive to changes in GWP. This result signifies that Heat and Binder's

GWP values have a greater sensitivity because it creates much more CO2 equiv. emissions per ton of NS asphalt mixture than other processes. Likewise, in the GWP impact category, the sensitivity analysis results show that the impact values are substantially sensitive to the change of heat input in the asphalt mixing stage (Heat A3). This is due to the drying and heating of the aggregate and asphalt mixture accounts for the largest share in the asphalt mixture production process.

5. Conclusion and recommendation

This research investigates the environmental effect of incorporation NS into the asphalt mixture. It assesses the sensitivity analysis of each process stage to the total impact of Mineral resource scarcity, Freshwater ecotoxicity, GWP, and Energy consumption. The following conclusions can be drawn.

1. Raw material production contributes the highest impact to mineral resource scarcity and GWP, while asphalt mixing dominates freshwater ecotoxicity and energy use. Transportation has only a minor share in all categories.
2. Sensitivity analysis in raw material production shows aggregate extraction as most sensitive to freshwater ecotoxicity, GWP, and energy use due to its large share in the mixture, while mineral resource scarcity is most sensitive to nano-silica production.
3. In transportation, aggregate hauling is the most sensitive process across categories, reflecting its 94% weight share. In contrast, nano-silica transport remains negligible even over long distances.
4. In asphalt mixing, thermal energy for aggregating and binder heating is most sensitive to mineral resource scarcity, GWP, and energy use, while electricity use is most sensitive to freshwater ecotoxicity due to pollutant emissions.
5. Overall, cradle-to-gate LCA highlights nano-silica and binder production, electricity in mixing, and thermal energy input as the most sensitive parameters across categories.

Based on the conclusions drawn from this study, several recommendations can be made to advance the environmental performance of asphalt mixtures.

1. Improved NS and binder production process efficiency to reduce resource depletion.
2. Developed low-temperature asphalt mixing strategy to cut heat and thermal power to mitigate global warming potential and cut energy demand.
3. Optimize aggregate quarry location and transport logistics to lower energy demand and emissions.

This study relies on secondary datasets in SimaPro and assumptions (eg; in transport modeling and source of raw material) and suggest directions for future experimental or field validation which may introduce uncertainty. Future research should emprise more in experimental testing and field validation to confirm reliability.

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