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Life Cycle Assessment of Natural Zeolite-Based Warm Mix Asphalt and Reclaimed Asphalt Pavement

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Abstract: Today, an important part of paved surfaces in the world uses asphalt mixtures. This practice increases the use of aggregates and fossil fuels, the availability of which is limited. Most of the studies referring to asphalt mixtures reported and compared the mechanical performances without detailing the environmental impacts of the different technologies proposed. The objective of this study was to present and compare through a life cycle assessment using a "cradle-to-gate" approach of different types of asphalt mixtures designed for the same performance, hot mix asphalt (HMA) as a control sample, and warm mix asphalt (WMA) using natural zeolite, Evotherm® and reclaimed asphalt material (RAP) in different proportions. The analysis was performed using SimaPro 9 software, using the ReCiPe method version 1.11. For the comparison of the environmental impacts, 1 ton of asphalt mixture was used as a functional unit. The most relevant results show that the use of natural zeolite or Evotherm® helps to reduce environmental impacts. In the global warming impact category, the decrease between the standard HMA and a mix with RAP and natural zeolite was 8%, while in the fossil fuel depletion, the decrease was 13%.

Keywords: life cycle assessment; asphalt production; reclaimed asphalt; Evotherm®; natural zeolites

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1. Introduction

Around the world, the production sectors with the highest indices of fossil fuel consumption are the industrial and construction sectors [1,2]. According to the Global Energy Assessment (GEA), around 80% of the power consumed in the world is produced by fossil fuels [3]. This has generated high emissions of greenhouse gasses and thus a major contribution to climate change [4,5]; it is also leading to the depletion of the resources extracted [6].

In the construction industry, an important activity in terms of energy consumption and use of natural resources is the paving of roads and highways. For example, it is estimated that in the U.S., more than 90% of road surfaces are made of asphalt, and 1.6 trillion tons of this material has been produced for road construction worldwide in the last decade [7]. In this context, there is a need to incorporate sustainability criteria into the design and construction of road surfaces, promoting lasting, low-cost options with low environmental impact.

The asphalt industry has innovated, introducing alternatives that achieve energy savings and a reduction in atmospheric emissions, principally by decreasing the production temperature of traditional hot mix asphalt (HMA) and adding reclaimed asphalt pavement (RAP) to mixtures [8]. Using reclaimed asphalt products is considered a sustainable option since it reduces the carbon footprint of paving, the space needed to store asphalt scrap, the demand for new materials, energy consumption, and associated costs [9].

To lower the production temperature of traditional hot asphalt mixes (HMA), innovative warm mixes (WMA) have been used, manufactured at temperatures between 120 °C and 140 °C [10], i.e., 30 °C or 40 °C cooler than traditional mixes. The temperature reduction of the mix to produce WMA is achieved by the incorporation of organic additives (e.g., Sasobit®, Hamburg, Germany), chemical additives (e.g., Evotherm®, North Charleston, SC, USA), and water-based foaming processes (e.g., Double Barrel Green®, Suffolk, UK) or foaming processes using additives that contain water (e.g., Aspha-Min®, Wächterswach, Germany). In the last case, methods have been tried based on synthetic zeolite that releases the water contained in its structure to create a foam effect in the asphalt cement. This reaction reduces the viscosity and facilitates the integration of the aggregates in traditional mixes [11]. Several studies describe the advantages of this method, e.g., greater manageability, lower mixing temperature than HMA, artificial reduction of the viscosity of the binder, savings in the amount of fuel consumed by the plant, and a decrease in the emissions generated. The levels of compaction and the rutting resistance are also improved, with a marked reduction in bubbles [11].

Oreto et al. (2021) have mentioned that most recent innovations are due to the search for more sustainable infrastructure, and that a key procedure for the study of environmental impacts is the life cycle analysis (LCA) [12]. LCA is the method used to assess the environmental effects of a system or product throughout its whole life [13], and it is accepted and applied to quantify and compare the effects of asphalt products and processes on the environment [14]. Various researchers have studied the effects on the environment in the phases of materials, manufacture of the asphalt mix, maintenance, recycling, use, and end-of-life of asphalt road surfaces in terms of energy and atmospheric emissions [15–17]. Ma et al. (2019), using an LCA, have shown that lower CO_2 and MP2.5 emissions are obtained in WMA compared to HMA, but also that the use of RAP is the most effective way to diminish the environmental impacts [18]. Similar results referring to mixtures made with lower temperature have been reported by [19].

Various additives (e.g., Cecabase®, Günzburg, Germany, Rediset®, Amsterdam, The Netherlands, or Evotherm®) have been tested to reduce the temperature in the production of asphalt mixtures [11,20]. Vidal et al. (2013), by using artificial zeolite, developed WMA mixes with reclaimed asphalt (RAP) determined by an LCA of the environmental impact of the asphalt mix [8]. The results of the LCA show that artificial zeolite is not decisive in terms of minimizing environmental impact, and that a compensatory effect is derived from the impacts associated with manufacturing. However, to date, the environmental impacts of *natural zeolite*-based asphalt mixtures have not been quantified in an LCA, and this is a niche to address in this study.

Based on the impact categories assessed, the manufacturing and service life phases have been identified as the most important in terms of environmental impact [14,16,18]. The service life of a pavement plays an essential role in the life cycle analysis due to the period of time in which environmental impacts are considered [8]. However, obtaining measured real service life data has technical difficulties. For this reason, only laboratory tests associated with the mechanical resistance of pavements are generally used to model and predict the service life of pavements [15,18]. Furthermore, few assessments focus on the detailed study of environmental impacts at these key stages [17], and it is also common to observe limitations in life cycle assessments due to the scarcity of inventory data related to additive use [21]. In this study, the environmental impacts of different types of asphalt mixes designed for the same performance were compared by using a conventional standard mix and verifying their performance over time using a test section on a real urban highway. It is important to indicate that all the design parameters and the mechanical performance of the asphalt mixtures evaluated in this study are available in the published results of a previous study [22].

2. Materials and Methods

2.1. Goal and Scope

The aim of this study was to evaluate the environmental impacts of different asphalt mixtures, designed for a structural behavior similar to a conventional mixture. For this purpose, the life cycle assessment methodology was applied according to the requirements established by ISO 14040 [23]. The functional unit (FU) was 1 ton of asphalt mix. The scope of the study considers a "cradle-to-gate" approach. Due to the lack of empirical data on the durability of pavements, a similar service life is assumed in this study, even when the results have shown better mechanical performance in the mixture with Zeolite (see Sections 2.4 and 4). In this sense, the environmental impacts associated with the manufacturing stage of 1 ton of HMA, WMA, and recycled WMA asphalt mixtures were comparatively assessed using LCA. Two types of additives were used in WMA and recycled WMA mixes: an additive called Evotherm® (e) and natural zeolite (z). Six types of asphalt mixtures with different percentages of RAP and additives were evaluated: hot mix asphalt (HMA), warm mix asphalt using natural zeolite (WMAz), warm mix asphalt using Evotherm® (WMAe), warm mix asphalt using 20% of RAP and natural zeolite (WMAR20z), warm mix asphalt using 20% of RAP and Evotherm® (WMAR20e), and warm mix asphalt using 30% of RAP and natural zeolite (WMAR30z).

The system boundaries were established from the extraction and production of materials to the production of the asphalt mix. The addition of natural zeolites in the asphalt mixtures does not induce changes in the procedure in the construction phase in relation to the performance and energy expenditure of the equipment used. Thus, the study included an assessment from the reception of the raw materials to the end of production, including the environmental impacts related to transport of the materials to the plant (Figure 1).

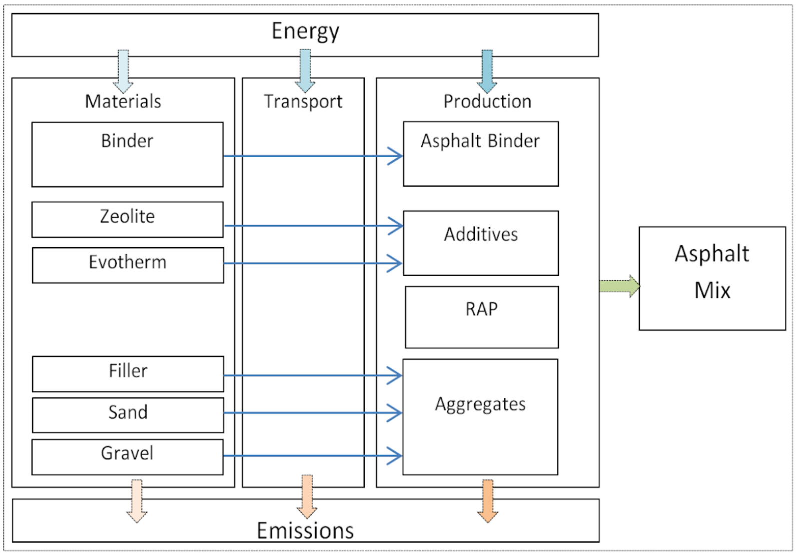

Figure 1. Scope of the LCA model used in this study.

The asphalt cement used for the binder is derived from crude oil. Two types of additives were used indistinctly to reduce the temperature of the mix. One was Evotherm®, calculated at 0.5% in relation to the weight of the asphalt binder [24], to give a comparative pattern of products existing in the market; the other was natural zeolite since the properties of this additive have been investigated recently [25]. The aggregates considered were gravels of different grain sizes (1.27 mm and 1.91 mm), sand, and filler. In some types of mixes, RAP was also included to replace a portion of the virgin materials (aggregates and asphalt cement). The RAP used in this study comes from the residual stockpiles of the asphalt mix production plant. RAP is the material milled from urban highways located in Santiago de Chile. This material is collected, homogenized, and classified by the production plant for use in asphalt mixtures [22].

In the production phase of the asphalt mix, the aggregates were conditioned by a heating and drying process. For this phase, the energy consumption of the plant was quantified, which uses fuel oil and electricity for this process. In parallel, the energy from natural gas used to heat the asphalt binder was also quantified.

2.2. Life Cycle Inventory

The inventory analysis was adjusted to the production of 1 ton quantity of asphalt mix. It considered each of the input raw materials (coarse and fine aggregates, filler, asphalt binder, and additives proposed in this study) and the energy consumption associated with the production.

The amount of raw material and the heating temperatures of the aggregates used were specified for each of the mixes considered in this study (Table 1). In warm mixes with reclaimed material (WMA R20 and WMAR30 at 134 °C and 144 °C), the percentage of RAP used varies (20% and 30%), so do the quantity of additive, either natural zeolite (z) or Evotherm® (e), and the quantities of asphalt binder, natural aggregates, and mineral aggregates, as a function of the percentage of RAP added. The selection of the RAP percentages was made based on the maximum allowed by Chilean specification (20%). Due to the administration's regulatory restrictions, only one section could be included with a mixture with a higher percentage of RAP, in this case, the WMA with natural zeolite WMA-R30-Z. The mentioned temperatures correspond to the optimum mixture temperature according to the Marshall design method (154 °C), and the reduced temperatures (144 and 134 °C) are those according to the design protocol for mixtures with greater energy efficiency and low environmental impact, determined from the technology of using natural zeolite as the additive to produce WMA. Details can be found in [22]. It may be noted here that the inputs and outputs related to direct and indirect transport for the manufacture of the asphalt mix were also quantified.

Table 1. Dosing of materials in kilogram (kg) for the manufacture of 1 ton of asphalt mix.

Mix	Gravel 1.91 mm (kg)	Gravel 1.27 mm (kg)	Sand (kg)	Filler (kg)	RAP (kg)	Zeolite (kg)	Binder (kg)
HMA (154 °C)	170	380	440	10	0	0	50
WMAz (134 °C)	170	380	440	10	0	6	50
WMAe (134 °C)	170	380	440	10	0	0	50 **
WMA R20z (134 °C)	170	310	310	10	200 *	6	45
WMA R20e (134 °C)	170	310	310	10	200 *	0	45 **
WMA R30z (144 °C)	150	290	250	10	300 *	6	43

* The RAP corresponds to material with a maximum particle size of 12.5 mm with an asphalt content of 5.2%.
** The asphalt used in these mixes contains 0.5% (o/w) of Evotherm®.

In the asphalt mix production stage, the energy sources associated with each technique used were quantified (HMA and WMA). For the production of HMA, the sub-processes of classification/dosing of raw materials, drying, and mixing were included. In the plant, the processes of aggregates dried and heated to a temperature of 154 °C in a rotating drying drum heated by a boiler fired principally with fuel oil were considered. To produce the WMA, the same process was used as in the HMA, but the aggregates were heated to 134 °C. Furthermore, in mixes of this type (WMA), natural zeolite and Evotherm® were used, both of which allowed lower production temperatures to be used without reducing their mechanical properties [15,25]. They were also combined with RAP. It is important to note that the addition of natural zeolite or Evotherm® does not increase the mixing time and therefore there is no additional associated energy consumption in the production stage.

The energy consumption for the different mixes was calculated using the following thermodynamic equilibrium equation, also used in other studies for the same purpose [18].

$$M \cdot q \cdot \lambda \cdot \eta = \sum_{i}^{n} c_i m_i \cdot \left(T_f - T_i\right) + c_w m_w \cdot (T_w - T_i) + L_w m_w \tag{1}$$

In Equation (1), M is the weight of fuel used in kg, q is the calorific power of the fuel (J/kg), λ is the consumption efficiency (-), η is the heat exchange rate of the equipment (-), c_i is the specific heat of the i-th aggregate used in the mix (J/kg °C), m_i is the weight of the i-th aggregate used in the mix (kg), T_f is the final temperature of the aggregate after heating (°C), T_i is the initial temperature of the aggregate (°C), c_w is the specific heat of the water (4190 J/kg °C), m_w is the mass of water used (kg), T_w is the boiling temperature of the water (100 °C), and L_w is the latent heat of the water for evaporation (2256 kJ/kg).

To calculate the energy balance, it was considered that the efficiency of the combustion and the plant was 0.7, based on a measurement in an asphalt plant in Chile [26]. The quantities of aggregates used in each mix were varied using the data shown in Table 1. It is important to mention here that warm mixes with RAP (WMAR) require greater heating of the aggregates than standard hot mixes, but the amount of material heated is smaller. For example, in WMA R20 mixes (134 °C), 80% of the aggregates are heated to 179 °C, while the other 20% (the RAP) enters the system at ambient temperature. For WMA R20 mixes (144 °C), 70% of the aggregates were heated to 203 °C, while the other 30% (the RAP) entered the system at ambient temperature (Table 2). The ambient temperature used in this study was the annual mean temperature in Santiago, Chile (14.6 °C) [27], where the plant was located. To complete the data in Equation (1), it was considered that the rock aggregates contained 2% moisture and the RAP 0.3% (both data obtained by measurements taken during the production phase in the plant), representing that part of the total mass of water that must be extracted to complete the mix manufacturing process. Using Equation (1), the energy needed to heat the binder was quantified, which was heated to 154 °C using gas as the energy source, considering the different proportions used according to the type of mix (Table 1).

Table 2. Temperatures used to quantify the energy demand of the different asphalt mixes.

Mix	Final Mix Temperature (°C)	Heating Temperature of Natural Aggregates (°C)
HMA	154	154
WMAz	134	134
WMAe	134	134
WMAR20z	134	179
WMAR20e	134	179
WMAR30z	144	203

The energy consumption considered in this study for each technique (HMA and WMA) is shown in Table 3.

Table 3. Energy consumption calculated by using Equation (1) in the production of 1 ton of asphalt mix.

Type of Consumption/Emission	HMA	WMA	WMA R20	WMA R30
Fuel oil (MJ)	207	188	184	176
Gas (MJ)	0.19	0.19	0.17	0.16
Electricity (kWh)	7.9	7.3	7.1	6.8

Real data for comparing the results of the energy demand using Equation (1) could not be obtained from the plant where the mixes were produced. For this reason, Equation (1) was used to quantify the fuel oil, and the data published by Ma et al. 2019 [18] were used to quantify the electricity. Table 3 shows energy consumption results (by using Equation (1)) for the different mixes; the electricity consumption was adjusted in the same proportion as the variation in the consumption of fuel oil energy.

2.3. Environmental Impact Assessment

The impact was carried out using SimaPro 9 software. The ReCiPe midpoint (H) impact assessment method 1.11 [28] was selected. SimaPro is a specialized software to carry out LCA with an extensive database of products and processes. Additionally, it is possible to select more than one methodology for the evaluation of environmental impacts (e.g., Impact 2002+, EF Method, ReCiPe, Greenhouse Gas Protocol) in various categories (e.g., global warming, human toxicity, ozone depletion, agricultural land occupation). The ReCiPe method was developed by the Radboud University Nijmegen, Leiden University and Pré

Consultants. The method (in the version used in this work) addresses 18 impact categories at the midpoint level and then aggregates the midpoints into a set of three endpoint categories (i.e., on human health, ecosystems, and resources). The dataset extracted from SimaPro considered in this study for the asphalt binder was "Bitumen adhesive compound, hot {GLO}| market for | Cut-off, S", for sand and gravel was "Sand {RoW}| gravel and quarry operation | Cut-off, S", for oil was "Heavy fuel oil {RoW}| market for | Cut-off, S", for transport was "Transport, freight, lorry, unspecified {RoW}| transport, freight, lorry, all sizes, EURO5 to generic market for | Cut-off, S", for gas was "Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, S", and for electricity was "Electricity, high voltage {CL}| production mix | Cut-off, U | 2021".

In this work, the impact categories analyzed were global warming (kg CO_2 eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), marine ecotoxicity (kg 1,4-DB eq), human toxicity (kg 1,4-DB eq), agricultural land occupation (m^2a), and ozone depletion (kg CFC-11 eq) to assess each impact in detail. Standardized results are shown in the impact category related to global warming and fossil fuel depletion to assess in detail which parts of the production of asphalt mixes have the greatest impact on the environment.

2.4. Evaluation of the Mixes in the Test Track

The test track was built on the right roadway, south side (west to east), center lane, between 32,780 km and 33,320 km of the Vespucio Norte Highway in Santiago, Chile. The daily average traffic load in the test section is 25.500, with a yearly average of 430.000 ESALs. The original pavement structure was composed of 28.9 cm of asphalt layer, 20 cm of granular base, and a subgrade with a resilient modulus of 103 MPa. A 15 cm surface milling was performed throughout the original section, and then, using the evaluated mixes, two layers were constructed: (1) an 8 cm binder layer, and (2) a 7 cm thick wearing course. The experimental part included 6 pavement sections on a continuous (Figure 2), straight highway section with no slopes, with an approximate length of 90 m each (one of them served as the control section, SE (6). All the mixes underwent the same compaction cycle to achieve the design density: 1 smooth roller cycle with vibration, 2 pneumatic roller cycles, and 1 smooth roller cycle without vibration.

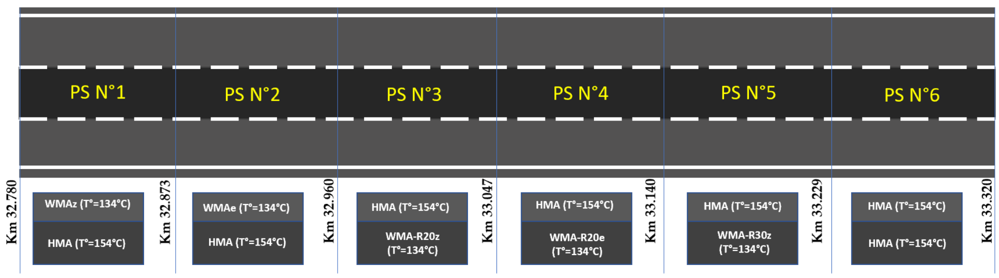

Figure 2. Cross-section of the test tracks.

To evaluate the behavior of the mixes, the effective structural number (ESN) was determined from the retro analysis carried out using the AASHTO method. These measurements were carried out on the test tracks in two monitoring campaigns, in Month 1 and Month 12. The ambient temperatures were 16.3 °C and 25.2 °C, respectively. The annual average temperature is 16.6 °C.

3. Results

First, the impacts associated with the seven categories (global warming, terrestrial acidification, freshwater eutrophication, marine ecotoxicity, human toxicity, agricultural land occupation, and ozone depletion) were calculated to analyze the production of the six asphalt mixtures described in Table 1. Figure 3 shows the impact of each category in percentage terms.

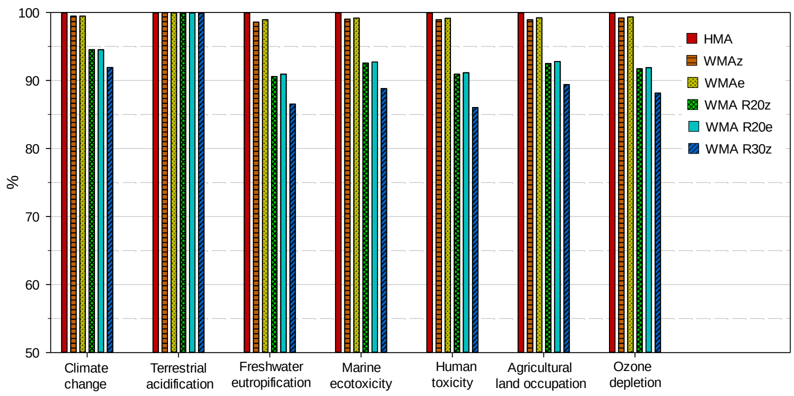

Figure 3. Contribution to environmental impact of the main processes of pavement production.

This established the mix with the highest environmental impact as 100%, and the remaining mixes were compared in relative percentages. In other words, the percentage reductions of environmental impact mainly refer to the standard mix, which presents the greatest impacts in almost all the indicators used.

The results showed that the reference mix (HMA) was the most damaging to the environment based on the impact categories considered. Figure 3 also shows the percentage reduction of environmental impact in almost all the impact categories using warm mixes (WMA). However, these conclusions must be broken down into the warm mixes that only use additives (WMAe and WMAz) compared with the warm mixes with added RAP. In some indicators, such as terrestrial acidification, agricultural land, occupation, and ozone depletion, the environmental impacts of using warm mixes that only use additives (WMAe and WMAz) were very similar. This is because basically the difference in these indicators was due to the use of both additives, and in this case, both additives had similar effects on these impact categories. By contrast, the mixes that combined RAP with a reduction of the temperature to which aggregates and binder were heated presented lower environmental impacts in all the indicators. We observed that the WMA mix with RAP and zeolite produced a reduction of up to 8% in the global warming impact indicator as compared with the HMA mix. This is because there was a decrease in carbon dioxide emissions due to the lower use of fossil fuels thanks to the lower temperature requirement in WMA production. In the other categories, we also observed a decline in environmental impacts by up to 14%.

3.1. Category of Standardized Impact on Global Warming Potential (GWP)

Global warming refers to the mean temperature increase on the earth's surface. It is estimated that global warming is caused principally by increasing concentrations of greenhouse gasses (GHGs) in the atmosphere due to human activities. GHGs are represented by equivalent units of carbon dioxide, since this is the compound that makes up the highest percentage of GHGs. For this reason, the global warming potential (GWP) is calculated in terms of CO_2, and the GWP unit is administered as CO_2-equivalent (CO_2-eq.). m.

In this work, we showed the contribution of the six types of mixes to the global warming impact. The analysis was broken down into each phase of the manufacturing of the raw materials, with their transport and the GHG emissions associated with production in the plant (Figure 4).

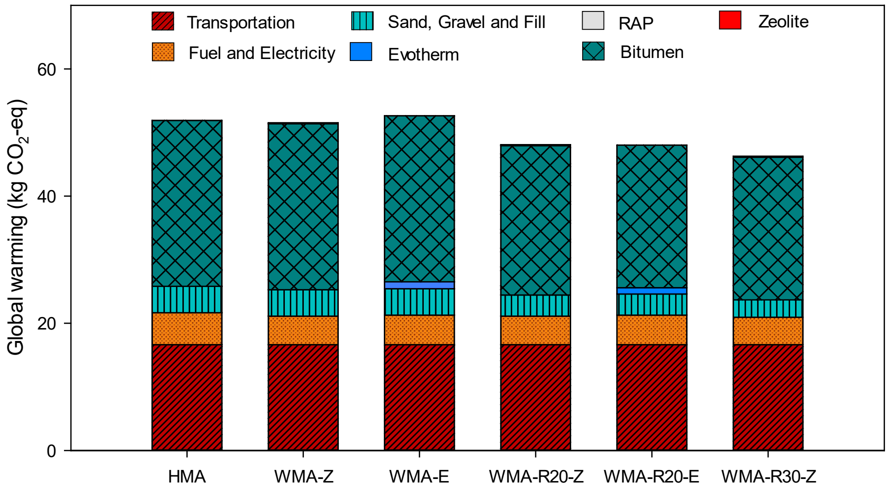

Figure 4. Impacts on global warming from asphalt mix production using the midpoint impact assessment by the ReCiPe midpoint (H) method (V1.11/Europe ReCiPe H). Fuel and Electricity is considered for the asphalt mixing.

The results of the LCA using the global warming impact category and the CO_2-eq. unit indicated that both the use of RAP and the use of natural zeolite had a positive effect on the reduction of greenhouse gasses. This is because the processes of extraction and crushing of the raw material were included for natural zeolite, whereas in the case of Evotherm® additional thermochemical processes had to be added as required by the Environmental Product Declaration (EPD) of the product [29]. Other authors (Vidal et al. 2013) who have used synthetic zeolite have indicated that from the point of view of sustainability the use of artificial zeolite is not decisive. In this study, by contrast, we showed that the use of natural zeolite generated a decrease in CO_2-eq. units ranging between 0.7% and 8% (Figure 4). It should be noted here that the use of natural zeolite produces greater effects than the increased use of RAP in combination.

In addition, in this category, we observed that it was the manufacturing of asphalt binder (bitumen) that had the greatest environmental impact on the production of all the warm mixes (WMA). Here we note that bitumen represents on average 49% of the global warming environmental impacts. This suggests in the first instance that the use of asphalt cement needs to be decreased in order to reduce global warming impacts. It can similarly be deduced that lowering the quantity of bitumen in warm mixes, replacing it with 20% RAP (−5 kg) or 30% RAP (−7 Kg), will have a positive effect on the environment in comparison with HMA (Table 1). In the global warming impact category, we observed a decrease in CO_2-eq. emissions by 4% and 5% due to the reduced use of bitumen in the WMA-R20 and WMA-R30 mixes.

An improvement was also observed in the transportation phase, which represents 34% of the environmental impacts. In this study, we considered a distance of 120 km between the plant and the extraction sites of the aggregates and the RAP. This value was based on a maximum radius calculated from the mean width of the country. It should be noted here that this distance can have a significant effect on the results, and that conducting a larger number of studies to determine this parameter more precisely would represent an advance in this field.

3.2. *Fossil Resource Scarcity (FRS) Impact Category*

It is known that fossil fuels are a limited resource, and that due to the sustained increase in demand, they will be unavailable to future generations [30]. For this reason, the ReCIPE method proposes the use of this category to assess environmental impacts, and it has also been used in this study because the production of asphalt cement is closely linked to the use of fossil fuels.

Figure 5 shows that in terms of fossil resource scarcity, the results did not vary much with the different types of mixes. However, it is again clear that the production of asphalt cement has the greatest influence in terms of environmental impact. For all types of mixes, bitumen production represents on average 80% of the fossil resource scarcity. This again suggests the need to reduce the use of this raw material in the manufacturing of asphalt mixes. Furthermore, we observed that there were no significant differences between the mixtures with the addition of zeolite (WMAz) or Evotherm® (WMAz). This is because these additives do not represent the main environmental loads compared to, for example, bitumen or transportation. However, the use of these additives in conjunction with RAP implies a reduction in fossil fuel use, and this does make a positive contribution to this indicator. Here we can observe that lowering the temperature of the mix, combined with the use of an additive and RAP, helps to reduce fossil fuel depletion by up to 13%.

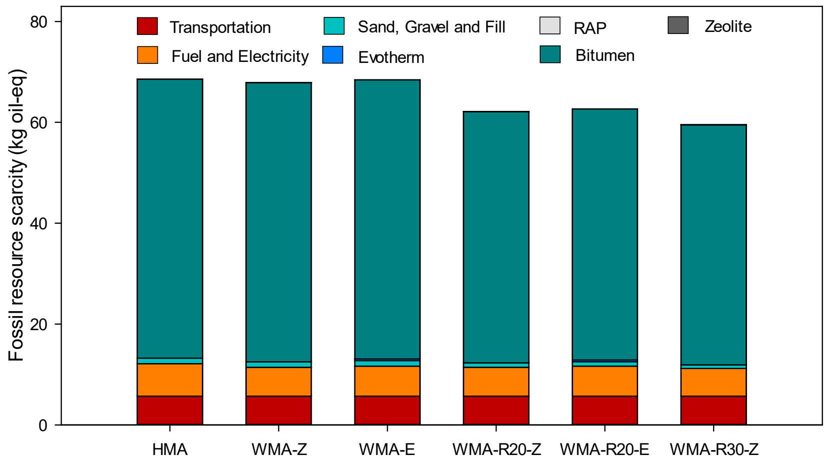

Figure 5. Impacts on fossil resource scarcity from asphalt mix production using the midpoint impact assessment by the ReCiPe midpoint (H) method (V1.11/Europe ReCiPe H). Fuel and Electricity is considered for the asphalt mixing.

4. Discussion

In general terms, the results show that the environmental impacts of an HMA are higher than the WMA. For both impact categories considered here (fossil resource scarcity, global warming potential) it is observed that the environmental loads decrease between 4% and 13% if an HMA mixture is compared with a WMA. The same results have been reported by other authors [8,18,31,32], so on the one hand, some certainty in the results is expected, and on the other hand, it would confirm that in terms of sustainable pavement development it is essential to reduce the mixing temperature of the asphalt mix.

To make a fair comparison between asphalt mixes, it is suggested to consider in the LCA the "service life" [17,21,33]. Due to the temporal difficulty of having empirical data on the durability of pavements, several authors use scenarios assuming a theoretical service life [12,19,34], or in some cases, a declared unit are used instead of a functional unit in order to avoid the uncertainty related to the use of the product and its functional requirements [35]. In this study, the declared unit of 1 ton asphalt mix is considered in order to address stages with fewer uncertainties. In any case, previous results show that the use of zeolite would improve the mechanical performance and durability of the pavements. For example, in the study of Valdés-Vidal et al. (2020) [22] and also in this study (Figure 6), it was shown that the different asphalt mixtures evaluated give the pavement a similar structural capacity (modulus of rigidity and resistance to cracking), which indicates that they have equivalent service life.

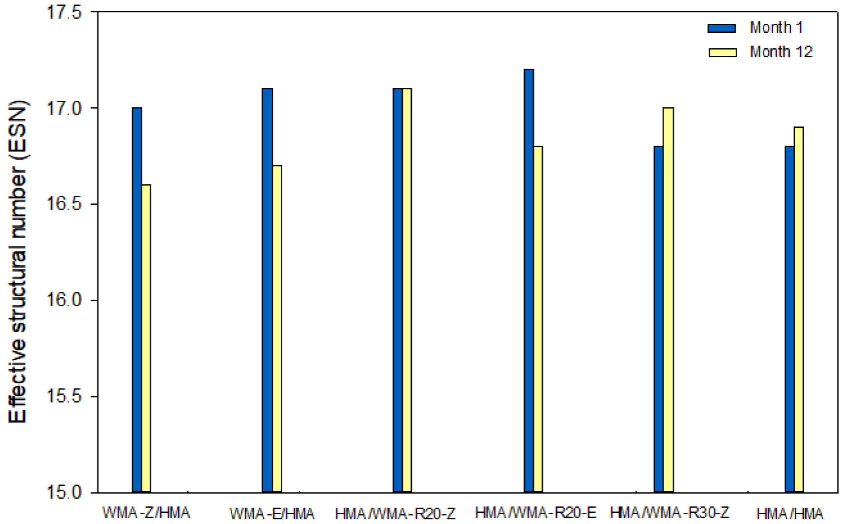

Figure 6. Comparison of effective structural number determined between month 1 (T°Pav = 16.3 °C) and month 12 (T°Pav = 25.2 °C).

From the results obtained for ESN, it can be indicated that for Section 1 (WMAz-HMA) and Section 2 (WMAe-HMA), both sections with WMA mixtures (both technologies, zeolite and Evotherm®) showed slightly lower average values (~2.3%) than the reference Section 6 (HMA-HMA). For Section 3 (HMA-WMA R20z), Section 4 (HMA-WMA R20e), and Section 5 (HMA-WMA R30z), values similar to the reference section (Section 6) were obtained. These values were similar to those obtained in 2019, and the variations may be due to the difference in pavement temperature at which they were measured. In addition, it can be observed that one year after the construction of the test section, the mixes under study with zeolite and Evotherm® behaved with a similar structural contribution to the reference asphalt mix. Figure 6 shows the comparative values and their deviations between the two measurements (Month 1, Year 2019 and Month 12, Year 2020).

The structural number was obtained using a falling weight deflectometer (FWD). The procedure consisted of subjecting the pavement structure to a load pulse of duration and magnitude similar to that of a heavy vehicle. The FWD measured the deflection caused by this load pulse in the pavement structure. Through retrocalculation, it was possible to obtain the structural capacity of the soil and of the different layers of the pavement structure. This information was used to calculate the structural number of each section through the AASHTO retro analysis.

Both the procedure used (based on) and the database provided by SimaPro are aspects of standardized use and with the possibility of being replicated anywhere in the world. In this sense, it is expected that the results presented in this work may also be transferable to contexts other than the case modeled in the Chilean context.

5. Conclusions

In this study, through an LCA, the environmental impacts of the use of hot mix asphalt (HMA) and warm mix asphalt (WMA) using natural zeolite, Evotherm®, and RAP by using seven categories (global warming, terrestrial acidification, freshwater eutrophication, marine ecotoxicity, human toxicity, agricultural land occupation, and ozone depletion) were calculated and compared. The results showed that the use of any product that lowers the production temperature has an effect on reducing the greenhouse gasses produced by energy consumption. A comparison between HMA and WMA asphalt mixes showed that in all categories of environmental impacts, a mean reduction of 5% was observed, and that the greatest difference was produced in the human toxicity category, where the difference was up to 14%.

In addition, it is concluded that the component of the asphalt mixtures that contributes the greatest environmental impact is the use of bitumen. For example, in the global warming category, the use of bitumen represented on average 49% of the environmental impacts, and this percentage increased to 80% if the category of fossil resource scarcity was taken into consideration. From this, it follows that any technique that contributes to reducing the use of bitumen in asphalt mixtures also contributes to diminishing environmental impacts. Based on the results of this study, the use of RAP and natural zeolite is recommended. On the one hand, with the use of RAP, the demand for bitumen is reduced by up to 5 kg per ton of mixture, and on the other, the use of zeolite (by reacting with water) improves the ability of the gravel to be covered with the bitumen.

Furthermore, due to technical limitations and the diversity of variables that influence the use life of a pavement (e.g., weather, traffic, loads), the scope of the LCA carried out in this study was limited to the manufacture of one ton of asphalt mix. This approach has the limitation that possible results and conclusions obtained in the manufacturing phase of the mixture could change if the service life is very different for each of the considered mixtures. Nevertheless, it was observed that one year after the construction of the test track, the mixes under study with zeolite and Evotherm® behaved with a structural contribution similar to the reference asphalt mix. These preliminary results suggest that there will be no significant differences in the service life of the various mixtures analyzed here.

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