ENGLISH VERSION.......

A new approach for integrating environmental, social and economic factors to evaluate asphalt mixtures with and without waste tires

Un nuevo enfoque para la integración de factores ambientales, sociales y económicos para evaluar mezclas asfálticas con y sin neumáticos de desecho

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Abstract

In the context of making roads more sustainable, this study compares two asphalt mixes: one conventional, and one with end-of-life tyres (ELT), using a multi-criteria decision-making method focused on the advantages among the different alternatives called "Choosing by Advantages" (CBA). The aim is to answer whether it is appropriate to use ELT in asphalt mixtures in developing countries, and what environmental impacts its use generates in road construction. This research is based on a case study of a road construction project in Chile. The main results are as follows: 1) the use of rubber bitumen (RB) is more advantageous than the use of conventional bitumen, and 2) the cost required for the manufacture and execution of RB is 1.4 times higher than the cost of conventional mixing; however, the cost of maintenance of RB is lower. Finally, research shows that it is convenient to use ELT in asphalt mixes, as it generates social and environmental improvements, such as reducing IRI variability over time, minimizing noise and reducing greenhouse gas emissions.

Keywords*:* *Choose by advantages (CBA), sustainable roads, asphalt mixes, Bitumen Rubber, End-of-life tyres (ELT)*

Resumen

En el contexto de hacer caminos más sostenibles, este estudio compara dos mezclas de asfalto: una convencional, y otra con neumáticos fuera de uso (NFU), utilizando un método de toma de decisiones multicriterio enfocado en las ventajas entre las diferentes alternativas llamado "selección por ventajas" (Choosing by Advantages, CBA). El objetivo es responder si es conveniente utilizar NFU en mezclas asfálticas en los países en desarrollo, y qué impactos ambientales genera su uso en la construcción de carreteras. Esta investigación se basa en un estudio de caso de un proyecto de construcción de carretera en Chile. Los principales resultados son los siguientes: 1) el uso del betún caucho (BC) es más ventajoso que el uso de betún convencional, y 2) el costo requerido para la fabricación y ejecución del BC es de 1.4 veces mezcla más alto que el costo de la convencional; sin embargo, el costo de mantenimiento del BC es menor. Por último, la investigación muestra que es conveniente utilizar NFU en las mezclas del asfalto, ya que genera mejoras sociales y ambientales, tales como la reducción de variabilidad IRI en el tiempo, minimización del ruido y disminución de emisiones de gases de efecto invernadero (GEI).

Palabras clave: Elegir por ventajas (CBA), caminos sostenibles, mezclas asfálticas, Betún Caucho, Neumáticos fuera de uso (NFU)

1. Introduction

Currently several efforts exist to make roads more sustainable, especially since these kinds of projects have an extensive life cycle.(Gosse & Clarens, 2013) For example, Wang et al. (2014) sought to provide a short-term solution to reduce pavement roughness and thereby reduce greenhouse gas emissions, and Li et al. (2007) encouraged the sustainable development of urban construction using a life cycle perspective.

On the other hand, recycling materials in highway construction is a feasible and environmentally wise alternative.(Horvath, 2004; Lee et al., 2010) Moreover, waste tires can be used as additional components of the pavement asphalt mixture.(Feraldi et al., 2013; Fiksel et al., 2011) This application has been used in some countries and offers(Huang et al., 2007), a priori, two relevant benefits: it constitutes a new use for this high environmental impact material and second, and it improves some valuable pavement qualities, such as loudness reduction or long-term behavior improvement.(Centro de Estudios y Experimentación de Obras Públicas, 2007)

The Chilean Producer Extended Responsibility Law (20,920) enacted in May 2016, and the current Clean Production Agreements generate a framework regulation in waste tire management and increase the volume of treated, crushed and "used for others ends" waste products, so it is important to explore new ways to use the material obtained from this treatment.

California, for example, has currently developed a law calling for the use of increasing amounts of recycled rubber in pavement in the coming years. This trend has led to rubber-

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modified products that have reduced reflection of cracks, improved safety in wet conditions and reduced noise. It has also helped to solve the very serious problem of the disposal of waste tires(Santucci, 2009).

Currently, asphalt mixtures are mainly made with a high percentage of aggregates and asphalt; it is possible to add rubber powder from waste tires to these materials without modifying their capabilities and structural strength (Navarro Dupré, 2013; Royano et al., 2010). In this way, the two alternatives to be studied are (1) the traditional asphalt mixture and (2) the asphalt mixture with rubber powder from waste tires.

To be able to decide whether to use waste tires as an additive in asphalt mixtures, this study used a multi-criteria decision-making method that allows us to focus on the advantages of the different alternatives, which is called Choosing by Advantages (CBA). CBA is based on the comparison of each advantage among the alternatives and choosing the most advantageous one, through the seven steps that define the method, which are: (1) identify alternatives, (2) define factors, (3) define criteria, (4) summarize attributes of the alternatives, (5) decide advantages of each alternative, (6) decide the importance of each advantage, and (7) evaluate cost (Arroyo, Fuenzalida et al., 2016; Arroyo et al., 2015b, 2015a; Arroyo et al., 2016)

The authors would like to highlight that in order to account for multiple factors in decision making, a global vision of the whole life cycle of the road must be considered, since several studies have demonstrated that a life cycle analysis (LCA) approach is necessary to provide an in-depth assessment of the environmental impacts of a product or process and to reduce the risk of unwanted negative consequences.(Santero et al., 2011) Additionally, it is necessary to consider the factors that may have global warming potential, differentiating between both alternatives.(Santero & Horvath, 2009) Several studies have applied LCA to pavements and life cycle cost analysis (LCCA), such as Gschösser & Wallbaum, (2013), H. Wang, (2014). Quinn studied specifically the possible environmental impacts of benzothiazoles derived from rubber used in roads, concluding that these components are not harmful.(Quinn, 2000)

However, a more holistic approach to integrate environmental, social, and economic aspects of sustainability is required, which can be achieved using a multi-criteria decision-making method.

The present research goal is to answer two questions: (1) Is it economically efficient to use waste tires in asphalt mixtures in developing countries? (2) What environmental and social impacts are generated in road construction using waste tires? This research uses a case study of a road construction project located in Chile to answer these questions.

2. Methodology

This research is based on a case study of a road construction project located in Chile, building on previous research that uses the same case study by Calahorra et al. (2016), which measured the environmental impacts of an asphalt mixture (with or without rubber from waste tires). Using the case study context, this study presents a novel approach for comparing a conventional asphalt mix (alternative 0) to a rubber asphalt mixture (alternative 1), using CBA as a multi-criteria decision-making method. This method allows for incorporating environmental and social impacts of both alternatives, and for analyzing investment and maintenance costs, which are relevant for contractors and policy makers in highway projects.

In this research, the following activities were carried out:

- *Review of documentation: including papers from indexed scientific journals, technical documentation provided by the contractor of the work, and current legal regulations regarding road construction both in Chile and worldwide.*
- *Case study selection: In this research, a 25 km asphalt road was chosen, located in Valparaiso Region, Chile.*
- *Interviews: Several interviews were conducted with key people in the process: 1) the person in charge of the rubber powder plant, in order to obtain information on the productive capacity and the environmental impacts generated by it; 2) the person in charge of the construction of the highway, to know the technical specifications of the pavement; and 3) the head of the national road laboratory, since she was in charge of the realization of pilot sections of pavements with recycled rubber in Chile and is also responsible for the research of this technology in the Ministry of Public Works.*
- *Direct observation through different site visits to understand the environment and the possible social and environmental impacts generated by its construction.*
- *Life Cycle Assessment (LCA) of asphalt mix with and without rubber, where the environmental, social and economic impacts were evaluated. LCA detail can be reviewed in the paper "Life cycle analysis of asphalt mix with / without rubber: case study" by Calahorra, Giménez, Herrera, Martínez, & Salazar, (2016)*
- *Application of Choosing by advantages (CBA), which is a multi-criteria decision-making method that allows for choosing between two or more alternatives, by determining the importance given to the differences between the advantages of the alternatives (Arroyo et al., 2015a)*
- *Results and conclusions analysis.*

3. Theory/calculation

This section presents the case study background, LCA and CBA theory and pertinent calculations to evaluate the decision.

3.1 Case Study

The present case study is the analysis of the pavement designed to build and operate a 25 km road, located in the Region of Valparaíso, Chile. This road starts in the commune of San Felipe and ends on Route 60 CH.

The road section has two 3.5 m lines, one for each direction, and a section of pavement with a 5 cm thick upper asphalt layer, a 6 cm thick intermediate asphalt layer and a 7 cm thick base asphalt layer. The study focuses on the use of rubber from waste tires in the upper asphalt layer. The asphalt *layer can be made with different types of bituminous mixtures depending on the granulometry of the aggregates and the typology of bitumen (asphalt). For the determination of the mixture, this study used the Spanish legislation, namely Article 542 Bituminous mixtures of bituminous concrete of PG-3 BOE(BOE Gobierno de España, 2014) and the user manual for rubber from waste tires in bituminous mixtures, prepared by the Center for Studies and Experimentation of Public Works, the Ministry of Public Works of Spain.(Centro de Estudios y Experimentación de Obras Públicas, 2007)*

This study considers the introduction of rubber when the asphalt still "wet", this means that the introduction of the rubber is made directly into the bitumen, and subsequently this bitumen is mixed with the aggregates to generate the asphalt mixture. Depending on the percentage of rubber that is introduced, three types of bitumen are generated: Rubber Bitumen (RB), which has between 8% and 12% rubber, Modified Bitumen with Rubber (MBR) content between 12% and 15%, and bitumen modified with high density rubber, which has between 15% to 22% rubber.(Centro de Estudios y Experimentación de Obras Públicas, 2007) For this case study, an RB with 10% rubber was used.

This study compares a conventional asphalt mixture (alternative 0) with a rubber asphalt mixture (RB) (alternative 1). Alternative 0 is an asphalt mixture composed of aggregates and conventional bitumen. According to the recommendations of Article 542 on bituminous mixtures of bituminous concrete of Spanish PG-3 BOE (BOE Gobierno de España, 2014), the bituminous concrete is 4.5% of the weight of the mixture. Are used in for tread layers.

On the other hand, in alternative 1, the conventional bitumen is replaced by the rubber bitumen, with the introduction of the rubber by a "wet way" with a percentage of 10% of the bitumen weight. In addition, following the recommendations of the Rubber from Waste Tires Use Manual in bituminous mixes from Spain (Centro de Estudios y Experimentación de Obras Públicas, 2007), when using rubber bitumen, it is appropriate to increase the percentage of bitumen in the bituminous mixture and decrease the density of the mixture by 5%. Therefore, in this alternative the amount of bitumen is increased from 4.5% to 5.2%.

3.2 Life Cycle Assessment (LCA)

To perform the Life Cycle Assessment of the different alternatives, according to the ISO 14040, first it was necessary to define the goal and scope of the study. A kilometer of road was considered as the functional unit, which corresponds to one kilometer that is 7 meters wide. This study considered the extraction, transportation, mixing, and construction of the asphalt mix.

For the inventory analysis, this study considered the amount of energy used, from the extraction of material to the construction of the road (Table 1 & 2).

***Table 1.** Alternative 0. Energy consumed during life cycle (Inventory Analysis)*

			Alternative 0		
			Extraction		
	Tons		*Energy (J/t)*		*Total in J.*
Arid	*44,164.44*		*3,080,000,000*		*1.36026E+14*
Bitumen	*1,987.4*		*32,000,000*		*63,596,800,000*
			Transportation		
	Tons	*Km*	*Energy (J/t-km)*	*journeys*	*Total in J.*
Arid	*44,164.44*	*85*	*2.90E+07*	*6,309*	*1.56E+13*
Bitumen	*1,987.4*	*90*	*2.90E+07*	*284*	*7.41E+11*
			Mix		
	Tons		*Energy (J/t)*		*Total in J.*
Mix	*46,151.84*		*39,213,000,000*		*1.80975E+15*
			Construction		
	m^2		*Energy (J/m^2)*		*Total in J.*
	175,000		*1.30E+06*		*2.275E+11*
				Total	*1.96E+15*
			Total per functional unit		*7.84945E+13*

Table 2. *Alternative 1: Energy consumed during life cycle*

Alternative 1					
Extraction					
	Tons	*kWh*	*Energy (J/t)*		*Total in J.*
Arid	*41,956.22*		*3,080,000,000*		*1.29225E+14*
Bitumen	*1,963.5*		*32,000,000*		*62,832,000,000*
Rubber	*217.17*	*95011.8*			*3.42042E+11*
Transportation					
	Tons	*Km*	*Energy (J/t-km)*	*Journeys*	*Total in J.*
Arid	*41,956.22*	*85*	*2.90E+07*	*5,994*	*1.48E+13*
Bitumen	*1,963.5*	*90*	*2.90E+07*	*281*	*7.32E+11*
Rubber	*217.17*	*98.3*	*2.90E+07*	*31*	*8.84E+10*
Mix					
	Tons		*Energy (J/t)*		*Total in J.*
	44,136.89		*39,213,000,000*		*1.73074E+15*
Construction					
	m^2		*Energy (J/m^2)*		*Total in J.*
	175,000		*1.30E+06*		*2.275E+11*
				Total	*1.88E+15*
			Total per functional unit		*7.50477E+13*

For the impact assessment, the environmental effects on global warming caused during each of the stages, in CO2 eq. (for 100 years) were calculated. The following results were obtained in each of the alternatives:

Alternative 0

The CO2, N2O and CH4 emissions for this option were calculated from the information contained in the "Final Engineering Project Report Route 60 CH. Sector 1. The Andes Route 5 North, section 2: San Felipe – Panquehue detour", supplied by the road design company. For this alternative, the composition of the mixture was not changed, that is, no rubber powder was added. The materials used for this alternative were arid (44,164.44 tons) and bitumen (1,987.40 tons).

During the extraction and processing phase of the building materials, 0.137 t CO2 / t, 1.06E-07 tN2O / t and 3.50E-08 t CH4 / t were generated for each of the aggregates and 0, 001537 t CO2 / t, 5.80E-08 t N2O / t and 5.29E-07 t CH4 / t for bitumen (Azhar Butt, 2014). Therefore, the emissions generated by the total materials used for this alternative were 411.70 t CO2, 0.0028 t N2O and 0.023 t CH4.

In the transportation phase, the construction materials were moved in 14 tons. trucks, which took them from their production places, where the suppliers were located, to the work site. The distance between aggregates suppliers and the work site was 85 km and from bitumen suppliers to the work site was 90 km. The number of trips required to transport the materials was 3.155 for the aggregates and 142 for the bitumen. Therefore, the emissions generated by this activity using the information above were 34,665.20 T CO2, 0.76 t N2O and 0.024 t CH4.

During the asphalt mixture preparation phase, this study considered that this activity would be carried out at the work site, through an asphalt plant (Six Pack Portable, Astec), considering an emission per ton of processed asphalt material of 0.019 t CO2 / T 4.30E-07 t N2O / t 7.57E-07 tCH4 / t (Azhar Butt, 2014).

The total emissions, considering the total amount of materials required in alternative 0 (46,151.84 t) was: 894.97 t CO2, 0.0198 t N2O and 0.0349 t CH4.

During the road construction, the emissions depended on the total road square meters constructed. Given that the road has a 25 km length and 3.5 m width, the square meters of total construction were 175,000 m2. The emissions generated during this activity in kg / m2 are considered as 9.59E-02 kg CO2 / m2, 8.66E-04 kg N2O / m2 and 6.06E-08 kg CH4 / m2;(H. Wang, 2014) Therefore, for the established *area, 16.78 t CO2, 0.15 t N2O and 0.000011 t CH4 were obtained.*

Alternative 1

With the use of bitumen rubber, the percentage of aggregates is reduced and the percentage of bitumen and rubber are increased. The composition of the asphalt mixture is given by: aggregates: 41,956.22 t, bitumen: 1,963.50 t and rubber: 217.17 t.

During the extraction and processing phase of building materials, the building materials for this alternative are aggregates, bitumen and rubber (waste tires). Rubber emissions were calculated from the tire crusher processing plant, as follows, for aggregate and bitumen, the following values of emissions generated were considered: 0.173 t CO2 / t, 1.06E-07 t N2O / t and 3.50E-08 t CH4 / t, for the case of the aggregate and 0.001537 t CO2 / t, 5.80E-08 t N2O / t and 5,29E-07 t CH4 / t for bitumen (Azhar Butt, 2014). Therefore, the total emissions generated in this phase were 404.64 t CO2, 0.00264 t N2O and 0.022 t CH4.

The crushed rubber was supplied by Polambiente, which is a pioneer in the grinding and granulation processes of waste tires in Chile. This plant processes 2,000 kg / h of tires. The estimated annual value is approximately 8,000 tons. The amount of rubber obtained is 70% to 80% of the total weight of material of the processed tires (with traces of special fibers). The required kWh for the rubber processing required for this alternative is 95,010.85. Emissions in kg CO2 for each kWh produced by the main electrical grid in Chile is 0.35 kg / kWh. Based on the information above, the emissions generated by the production of the 217.17 tons of rubber for the pavement are in the order of 44 t CO2, 0.00170 t N2O and 0.01 t CH4.

The transport of raw materials is considered in the same way as in alternative 0. They will be transported in 14 tons trucks from their origin places to the work site. The distance between the supplier location and the work site was 85 km, 90 km and 98.3 km for the aggregated bitumen and rubber, respectively. The number of trips required to transport the total materials are 2.997 for the aggregates, 141 for the bitumen and 16 for the rubber. Therefore, the emissions generated by this activity are in the order of 33,179.98 t CO2, 0.731 t N2O and 0.023 t CH4.

During the asphalt mixture preparation phase, it is assumed that the preparation of this mixture will be realized in the work site, through an Asphalt Plant, (Six Pack Portable, Astec), considering an emission per ton of processed asphaltic material of 0, 01939 t CO2 / t, 4.30E-07 t N2O / t and 7.57E-07 t CH4 / t (Azhar Butt, 2014). The total emissions, based on the total volume of materials required in alternative 1 (44,136.89 t) are: 855.90 t CO2, 0.019 t N2O and 0.033 t CH4.

The emissions generated during the construction stage are considered to be the same as those used in alternative 0: t / m2 of 9.59E-02 kg CO2 / m2, 8.66E-04 kg N2O / m2 and 6.06E -08 kg CH4 / m2;(H. Wang, 2014) Therefore, the emissions generated in the construction stage from the considered road surface are 16.78 t CO2, 0.11515 t N2O and 0.000011 t CH4.

The comparison of the results obtained in the two alternatives is shown in Table 3:

Table 3. *Comparison Emissions for Both Alternatives (Impact Assessment)*

	ALTERNATIVE 0			***ALTERNATIVE 1***		
PHASES	***CO2***	***N2O***	***CH4***	***CO2***	***N2O***	***CH4***
Extraction	*411.70*	*0.0028*	*0.0234*	*448.64*	*0.004*	*0.032*
Transportation	*34,665.21*	*0.76*	*0.0241*	*33,179.98*	*0.731*	*0.023*
Mix	*894.98*	*0.0198*	*0.0349*	*855.90*	*0.019*	*0.033*
Construction	*16.78*	*0.152*	*0.000011*	*16.78*	*0.152*	*1.06E-05*
TOTAL	***35,988.67***	***0.94***	***0.082***	***34,501.30***	***0.906***	***0.089***
CO_2 equivalents	***35,988.67***	***280.12***	***2.05***	***34,501.30***	***269.988***	***2.225***
Total CO_2 eq.	***36,270.84***			***34,773.51***		
CO_2 eq./Km	***1450.8***			***1390.9***		

For the interpretation, this study can state that based on the data presented in Table 3, the CO2 generation percentage reduction is 4.13% of alternative 1 compared to alternative 0; for N2O the reduction is 3.41% of alternative 1 compared to alternative 1; and for CH4 it is 3.91% of alternative 1 compared to alternative 0. This is considering the extraction, transportation, mixing, and construction of each of the asphalt alternatives.

In conclusion, the emissions of alternative 1 show a reduction of 4% compared to alternative 0. On the other hand, the emissions ratios per kilometer obtained for each of the alternatives are as follows: alternative 0: 1,450.83 t CO2eq / km, and alternative 1: 1,390.94 t CO2eq / km. Figure 1 shows the CO2 eq. emissions per alternative. The difference is not very big, due to transportation emissions are similar in both alternatives in the context of this study.

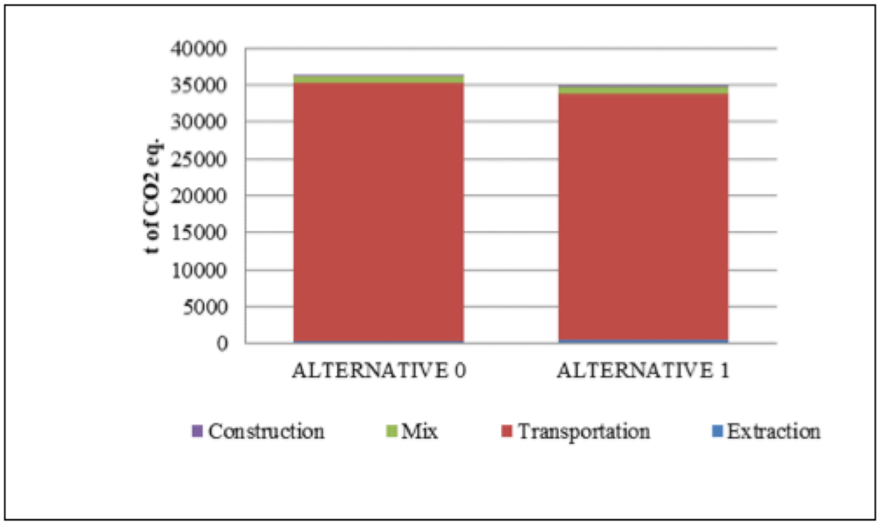

Figure 1. *GWP of the alternatives*

3.3. Choosing by Advantages (CBA)

When deciding which alternative is more sustainable than others (material selection, considering environmental, social and economic results) in the AEC industry, stakeholders should select a method for their decision-making process.(Arroyo et al., 2015a)

CBA is a system for making decisions using well-defined vocabulary to ensure clarity and transparency in the decision-making process. According to this system, it is important to identify which factors reveal significant differences between alternatives, not what factor will be important in the decision. To describe how to use the CBA to select a sustainable alternative within the AEC Industry, the terms of this book are used (Suhr 1999)(Table 4).

Table 4. *CBA Method. Definitions. Source: (Suhr, 1990)*

Term	***Definition***
Alternatives	*Two or more construction methods, material, building design, or construction systems, from which one must be chosen.*
Attribute	*A characteristic, quality, or consequence of one alternative (construction methods, materials, etc.).*
Advantage	*A benefit, gain, improvement, or betterment. Specifically, an advantage is a beneficial difference between the attributes of two alternatives.*
Factor	*An element, part or component of a decision. For assessing sustainability factors should represent economic, social and environmental aspects. It is important to notice that CBA considers money separately from other factors.*
Criterion	*A decision rule, or guideline-usually. A "must" criterion representing conditions each alternative must satisfy, or a "want" criterion, representing preferences of one or multiple decision makers.*

The CBA method has been proven to be more transparent and consistent than other methods, such as the Analytical Hierarchy Process, or AHP.(Arroyo et al., 2015a) In addition, CBA is simple and practical to use in group decisions, allowing for a faster consensus and less frustration among team members than weighting rating and calculating or the weighted sum method.(Arroyo et al., 2015b; Arroyo, Tommelein, et al., 2016)

In CBA, the weighting process is based only on the advantages, not on criteria, attributes or other types of data. In addition, the CBA postpones the value judgment on the alternatives as much as possible. The application of the CBA method is described as follows:

3.3.1 Identify Alternatives

Alternative 0 alternative: Asphalt mix with traditional bitumen (TB)

Alternative 1 alternative: Asphalt mix with rubber bitumen (RB)

3.3.2 Identify Factors

The authors identified the factors that caused differences between the two alternatives, classifying them in the following areas:

Technical

- *Need for maintenance: Regarding the determination or prediction of the damage that the pavement could suffer during the time and the durability of the material (fissures, cracks, etc.). Reger, Madanat, & Horvath, (2014) presented a framework for including GHG emissions minimization into pavement resurfacing policy. It is measured in % of deterioration at the end of 10 years of service. The quantitative factor was obtained from the study "Where the rubber meets the rubber: 12 years of durable success".(Way, 2003)*
- *Knowledge and experience of the production process: This refers to the knowledge based on experience with the production process (mix suitable design, advantages, handling of the disadvantages of the alternative, stability of the mixture, behavior of the mixture, waiting times, if it requires training, adequate transportation, etc.). The qualitative factor was obtained through interviews with the National Road Laboratory and the company Polambiente.*
- *Thermal susceptibility: This refers to the behavior of the pavement regarding to the temperature. The temperature is considered to be one of the environmental agents that influence directly the behavior of the pavements, modifying its stiffness, due to the thermoplastic characteristics of the material that constitutes the asphaltic layers of the flexible pavements. As the temperature increases, the layers of the asphalt pavement become less rigid, and when it decreases the stiffness of these layers increases.(Roberts, Offler, & Fanning, 2004) In this case, the softening point value was used, which represents the temperature at which the asphalt starts to become unstable (soft, liquid). The quantitative factor was obtained from a compilation document made by CEPSA & Universidad Politécnica de Cataluña.(CEPSA & Universidad Politécnica de Cataluña, 2013)*

Social

- *IRI (international regularity index) variability is defined as a single scale of values for the measurement of the surface regularity of the roads, which can be used by the vast majority of the auscultation machines that exist today. This index simulates the response of a vehicle when driving on a highway at 80 km / h and thus it allows us to consider factors such as safety, comfort and cost of use.(Sánchez & de Solminihac, 1989) It is measured in mm / M during a given period of time. The quantitative factor was evaluated in the life cycle analysis.*
- *Noise: This refers to the noise (measured in decibels) of the vehicles that transit on the pavements. This measurement includes the vehicle's own noise. It is considered social, since it can affect the people living in houses located near the road. The quantitative factor was evaluated in the life cycle analysis with information collected in the Rubber from Waste Tires Employment Manual in bituminous mixtures.(Centro de Estudios y Experimentación de Obras Públicas, 2007)*
- *Workers' health risk: During the production of the asphalt mixture, in both alternatives, emission of particulate material and toxic components occurs; The quantitative factor does not indicate significant differences between the measurements made in the production of conventional asphalt mix and the measurement of mixtures with the addition of rubber.(Department of Transportation, 2011)*
- *Flammability: This refers to the temperature point at which the mixture may catch fire. It is measured in degrees Celsius or degrees Fahrenheit. The quantitative factor was obtained from a compilation document made by CEPSA & Universidad Politécnica de Cataluña.(CEPSA & Universidad Politécnica de Cataluña, 2013)*

Environmental

- *CO2, N2O and CH4 emissions refers to CO2, N2O and CH4 estimates from the extraction of raw materials (aggregates, bitumen), the processing of the waste tires and the production of rubber, transportation of the raw materials to the mixing plant for asphalt, and the manufacture of asphalt mix. The quantitative factor was evaluated in the life cycle assessment and measured in equivalent CO2 emissions.*
- *Deconstruction (material recycling potential) (qualitative): As recorded in the document Asphalt-Rubber Standard Guide, rubber mixtures can be recycled following the same methods and procedures as conventional mixtures.(Kaloush & Biligiri, 2011) Due to the above, the mixtures of both alternatives have a high recycling potential.*
- *Percentage of recycled material inclusion (quantitative): Refers to the amount of material reused in the original blend design. The milling and reuse of the asphalt conglomerate or incorporation*

of rubber from waste tires comprises a smaller use of bitumen or aggregates, and therefore a lower extraction of resources.

3. Criteria definition

Next, the authors defined the criteria that help to differentiate each factor among the alternatives. As specified above, some attributes are quantitative and others qualitative. Factor / Criterion / Argument:

- *Maintenance requirement / Lower percentage is better / Minimization of road maintenance is required, since it is a process that involves time and costs and should be considered to avoid deterioration of the road.*
- *Knowledge and experience of the production process / Greater experience and knowledge is better / Knowledge and experience is sought in the process of production of the road, to avoid errors during its development.*
- *Thermal susceptibility (softening point) / Higher temperature is better / Alternatives are required to allow more temperature before the asphalt begins to become unstable in its operation and to avoid early failure in this operation.*
- *IRI variability / Less variation is better / Alternatives should have less variation in IRI during the operation of the roadway, to have greater safety and comfort for road users.*
- *Noise / Less decibels is better / It is required that the alternatives in their operation phase minimize noise from vehicular traffic, in order to minimize the impact on the people located near the road.*
- *Workers' health risk / Less risk is better /This seeks to minimize the risks to the health of workers, as they are exposed to particulate material during the manufacturing process, which can cause respiratory problems and occupational diseases.*
- *Flammability / Higher temperature is better / Alternatives should have a higher temperature in the manufacturing process of the mixture, to minimize the risk of fire.*
- *CO2 emissions / Less emission is better / Alternatives throughout their life cycle are urged to emit the least amount of equivalent CO2 emissions to minimize the effect of this activity on global warming.*
- *Deconstruction / Greater potential for recycling is better / It is required that the alternatives, at the end of their useful life, can be recycled to avoid waste.*
- *Percentage of recycled material / Higher percentage of recycled materials is better / This refers to the amount of recycled material in the initial blend.*
-

3.3.4 Each alternative attribute summarized

Table 5 presents a summary of the attributes for each alternative, according to the definition of criteria made in the previous point and the analysis performed by the researchers.

Table 5. *Summary of attributes by alternative*

Factor	***Asphalt mix with traditional bitumen***	***Asphalt mix with bitumen-rubber***
Need for maintenance	*Att: 9%*	*Att: 4%*
Knowledge and experience of production process	*Att: higher Knowledge and experience*	*Att: lower Knowledge and experience*
Thermal susceptibility	*Att: 46-54° C*	*Att: ≥ 53° C*
IRI Variability	*Att: 0.9 mm/km*	*Att: 0.2 mm/km*
Noise	*Att: 51.14 decibels at day y 40.28 decibels at night.*	*Att: 47.64 decibels at day y 36.78 decibels at night.*
Occupational health risk (toxicity)	*Att: High risk to health*	*Att: High risk to health*
Inflammability	*Att: ≥ 235 ° C*	*Att: ≥ 235 ° C*
CO_2 equivalents emissions (t / Km)	*Att: 1450.83*	*Att:1390.94*
Demolition	*Att: High recycling potential*	*Att: High recycling potential*
Percentage of inclusion of recycled material	*Att: 0%*	*Att: 0.5%*

3.3. 5 Advantages of each alternative decision

The advantages of both alternatives for each factor are shown in table 6. It is important to note that for each factor, there will be at least one alternative that has no advantage, that is, the one with the least preferred attribute, with respect to that criterion (cells with line). In the case that in both alternatives have no advantages, the category will be eliminated from the subsequent analysis, since it does not help to identify differences between both alternatives.

Table 6. *Advantages by alternative*

Factor	Asphalt mix with traditional bitumen	Asphalt mix with bitumen-rubber
Need for maintenance	--	5% Less percentage of deterioration
Knowledge and experience of production process	Knowledge and experience	--
Thermal susceptibility	--	7 ° C more resistant to temperature
IRI Variability	--	0.7 mm/km less variability
Noise	--	3.5 db less both day and night
Occupational health risk (toxicity)	--	--
Inflammability	--	--
CO_2 equivalents emissions (t / Km)	--	59.89 t less than CO_2 eq. for each Km.
Demolition	--	--
Percentage of inclusion of recycled material	--	0.5% more recycled material

The decision is not based on which factor is most important but is based on the advantages that occur with the two alternatives.

3.3.6 Importance of each advantage decision.

To determine the importance of each advantage, it is essential to have the collaboration of a team, in this case the authors of the document, who through a discussion group analyzed the advantages and decided the importance of each advantage, selecting the importance of the advantages by writing them on sticky notes and the use of a whiteboard, to allow the modification of their order of importance on a scale of 0 to 100. During the process, the most important advantage was estimated to be "5% less deterioration", associated with the need for maintenance, since this implies time and costs, a crucial factor when deciding between alternatives. For this reason, it was assigned 100 points. Then, the alternative with "more experience and knowledge" in the manufacturing process of the mixture was evaluated with 95 points, since it seeks to minimize errors in the process.

Then, the alternative with the advantage "7°C more resistant to the thermal susceptibility", was evaluated with 70 points because it is desirable to avoid early faults in the road, due to the instability of the asphalt in its operation. We gave 55 points to the alternative with the advantage "0.7 mm / km less variation of IRI", to ensure greater safety and comfort for the users of the road.

We rated with 40 points the alternative that had "3.5 dB less in both day and night", so that during the phase of operation of the road, people located in the surroundings would have fewer negative effects due to the excessive emission of noise. Finally, the advantage associated with the difference in the amount of recycled material, was assessed with 15 points, since it is only 0.5%, and with 10 points, the alternative of emitting 59.89 t less CO2 eq./km.

In Figure 2, the summary of the importance scale of each advantage is shown. This scale represents a subjective assessment of the relevance of the advantages relative to the most important advantage, which is "5% less deterioration" of alternative 1 vs. alternative 0.

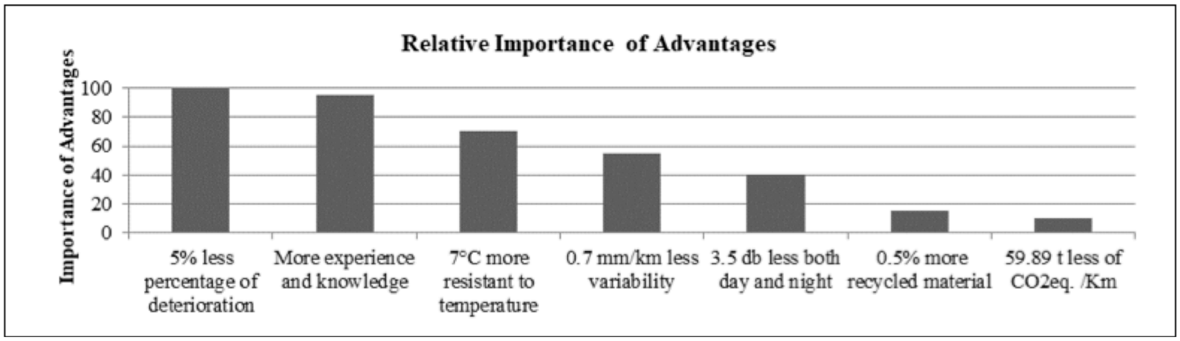

Figure 2. *Advantages. Scale of importance*

The summary of the CBA method can be seen in Table 7 bellow:

Table 7. *CBA Method. Summary*

Factor *(Criterion)*	*Asphalt mix with traditional bitumen*	*Imp*	*Asphalt mix with bitumen-rubber*	*Imp*
Need for maintenance *(lower percentage is better*	*Att: 9%*		*Att: 4%*	
	--	*0*	***Adv: 5% less percentage***	*100*
Knowledge and experience with production process *(higher is better)*	*Att: higher experience and knowledge*		*Att: lower experience and knowledge*	
	Adv: more experience and knowledge	*95*	**--**	*0*
Thermal susceptibility *(higher temperature is better)*	*Att: 46-54°C*		*Att: ≥ 53°C*	
	--	*0*	***Adv: 7°C more resistant to temperature***	*70*
IRI Variability *(Lower is better)*	*Att: 0.9 mm/km*		*Att: 0.2 mm/km*	
	--	*0*	***Adv: 0.7 mm/km less variability***	*55*
Noise *(less decibels are better)*	*Att: 51.14 db during day and 40.28 db at night*		*Att: 47.64 db during day and 36.78 db at night*	
	--	*0*	***Adv: 3.5 db less both day and night***	*40*
CO_2 equivalents emissions *(less is better)*	*Att: 1450.83 t CO_2/km*		*Att: 1390.94 t CO_2/km*	
	--	*0*	***Adv: 59.89 t less CO_2/km.***	*10*
Percentage of inclusion of recycled material *(more is better)*	*0%*		*0.5% (Rubber)*	
	--	*0*	***Adv: 0.5%***	*15*
Total importance		***95***		***290***

3.3.7 Cost evaluation

After determining the advantages of the alternatives, the researchers proceeded to calculate the costs of each one for the decision. Both initial and maintenance costs were estimated for this case.

For the initial costs, the data of measured in USD were used.(Caltrans. State of California Department of Transportation, 2003) Table 8 shows the cost per ton of the conventional mixture, in our case, alternative 0; and the cost per ton of the RAC-G, (Rubber Asphalt Concrete) mixture corresponding to the rubber bitumen or alternative 1, in the present study.

Table 8. *First Cost Ratio. Asphalt mix traditional and bitumen-rubber. Source: Caltrans. State of California Department of Transportation Services (2003)*

	Hot Mix ***$/ton***	***Chip Seal*** ***$/m***^{2}
Conventional	*33-38*	*1.20-1.50*
Polymer modified	*38-44*	*1.50-1.80*
RAC-G	*49-55*	*3.00-3.60*

Generally, RAC-G hot blends cost about $ 16 / t more than conventional blends, although this may vary with the size of the work, the mobilization and execution of the asphalt rubber and the costs of the binder production equipment. Large projects can be allowed some unit cost reduction because mobilization costs can be distributed over higher RAC tonnage. Table 9 shows the initial cost for both alternatives.

Table 9. *Initial Costs. Asphalt mix traditional and bitumen-rubber*

Alternative 0			***Alternative 1***	
	Tons			*tons*
Arid	*44.164.44*		***Arid***	*41.956.22*
Bitumen	*1.987.4*		***Bitumen***	*1.963.5*
			Rubber	*217.17*
Total	*46151.84*		***Total***	*44136.89*
Average cost in USD	*1,638,390.32*		***Average cost in USD***	*2,295,118.28*

In Figure 3, the ratio of the advantages and the initial cost are shown in the abscissa and ordinate axis, respectively. It is illustrated that the use of rubber bitumen presents greater advantages than the traditional one, but it also has also higher *initial costs.*

Figure 3. *Initial cost and importance of advantages, both alternatives*

Maintenance costs were assumed as a percentage, according to Jung et al.(2002) The total life cycle cost, which includes initial cost and maintenance cost, for the bitumen-rubber alternative were approximately 58% of the cost of the traditional bitumen alternative in a 25-year period.

Finally, in Figure 4, it is possible to observe, in the abscissa axis, the total score of the importance of the advantages for each alternative and in the ordinate axis the percentage of lifecycle cost. It is noted that the most convenient alternative is the Rubber Bitumen (alternative 1), because it presents higher scores and lower lifecycle costs. Therefore, alternative 1 should be chosen. This analysis does not consider user cost and difference between services provided by the two alternatives. However, according to Jung et al., alternative 1 should have a lower user cost than alternative 0.

Figure 4. *Life cycle cost vs. importance of advantages*

4. Results and Discussion

The development of the steps that constitute the method of choosing by advantages has allowed us to obtain the following results regarding with the decision on which bitumen to use in an asphalt mixture to be placed in a pavement upper layer:

1) *The use of Bitumen Rubber (alternative 1) is more advantageous than the use of Conventional Bitumen (alternative 0).*
2) *The cost required for the manufacturing and execution of the Rubber Bitumen mixture (alternative 1) is 1.4 times higher than the cost to invest in the conventional blend. The lifecycle cost, including maintenance during the road operation in 25 years, in the case of pavement constructed with rubber bitumen (alternative 1), supposes a reduction of 58% with respect to the lifecycle cost of a pavement made with traditional mixture (alternative 0). These costs are not generalizable, and should be studied on a case by case basis.*

It should be noted that obtaining the most advantageous alternative is based on:

A series of technical, social and environmental factors, selected by the authors as the most relevant to establish the comparison. The use of these factors in the present study does not imply that they should always be the same for this type of analysis; their definition must be established, in each case, by the decision-makers according to the final objective for which the alternatives are being selected.

Attributes associated with these factors. These attributes, for the present case, have been calculated on the basis of actual data and data obtained from related studies. To repeat this analysis, the authors recommend obtaining quantitative and qualitative attributes of the greatest for each of the alternatives analyzed.

The score associated with the advantage of each alternative should be obtained from the comparison of attributes based on established criteria. Both the criterion to compare attributes and the score given to the advantages obtained is determined in the opinion of the team responsible for the selection of alternatives. A greater knowledge of team members about the attributes of the alternatives and the final objectives of the selection will result in a better selection. On the other hand, and having determined which alternative is most advantageous, the difference in cost, both in the initial (cost required for manufacturing and executing) and maintenance costs, will allow the final decision maker to take the alternative that best adapts to the available resources. (It must be always remembered what features make better alternatives compared with others regardless of cost.

5. Conclusions

At the beginning of the study the following questions were raised:

(1) Is it efficient economically to use waste tires in asphalt mixtures in developing countries? and (2) What environmental and social impacts are generated in road construction using waste tires?

In relation to the first question and in light of the results, we recommend the use of waste tires in asphalt mixtures for three fundamental reasons. First, the use of rubber from waste tires in asphalt mixtures allows an outlet for a high-impact and continuously growing residue in developed countries.

Second, the use of rubber in asphaltic mixtures improves, among other factors, road maintenance, that is, the serviceability characteristics will be maintained for a longer time, minimizing the investment of resources in repairs. This makes the road, a product that is perceived by users as a high quality and value product, contribute to the trend of generating value that is an increasing tendency in the developed countries.

Third, considering that the manufacture and execution of asphalt mixtures are more costly than conventional mixtures, developing countries with the greatest resources must take the initiative in these processes and achieve over time an optimization of them so that they can be applied by any administration.

In relation to the second question and as a result of our analysis, the mixture with rubber bitumen generates substantial improvements in the social and environmental areas.

In the social area, the improvement is reflected in 1) the IRI variability decreasing over time, which results in greater comfort and safety for drivers; And 2) a minimization of the noise generated by vehicles when driving along the route that can be a source of inconvenience to people whose location is near the road.

Environmentally, during the life cycle of the asphalt mixture made with rubber bitumen, a slightly reduction in the emission of greenhouse gases is achieved; due mainly to the decrease in the volumes of raw materials used.

Finally, CBA is an easy to use multi-criteria decision-making method that allows for integrating social, environmental and economic perspectives in highway construction. The methodology can be expanded to choosing materials, constructive methods, and other applications in the AEC industry.

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