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A review of emissions on pavement materials and sustainability rating systems

Revisión de las emisiones y de los sistemas de calificación de la sustentabilidad de materiales de pavimentos

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Abstract
Since 2000 sustainability has become one of the main criteria for assessing and constructing road infrastructure projects. Several methodologies proposed measurements on the pavement's environmental impacts. One of the most relevant is the life cycle assessment (LCA), which estimates emissions generated by each life-cycle stage. A rating system is a tool for decision-making through an environmental rating of a project obtained by applying the best practices in sustainability that could generate impact reductions. This study makes a literature review of methodologies reported in the last years and evaluates the strengths and weaknesses.

***Keywords**: Sustainability; Sustainable Pavements; Life Cycle Impact Assessment; Sustainable Rating System*

Resumen

Desde comienzos del año 2000, la sustentabilidad se ha convertido en un criterio importante en la evaluación y constructibilidad de los proyectos de construcción vial. Diversas metodologías proponen realizar mediciones de los impactos medioambiente provocados en el pavimento. Uno de los métodos más relevantes es el Análisis del Ciclo de Vida (ACV), que estima las emisiones generadas por cada etapa del ciclo de vida. Un sistema de evaluación constituye una herramienta para la toma de decisiones a través de la evaluación medioambiental de un proyecto en el que se aplican las mejores prácticas de sostenibilidad que permitan reducir esos impactos negativos. En este estudio se analiza la literatura existente sobre las metodologías informadas durante los últimos años y evalúa sus fortalezas y debilidades.

Palabras clave: Sostenibilidad; pavimentos sustentables; evaluación del impacto del ciclo de vida; sistema de evaluación sustentable.

1. Concept of sustainability in pavements

The United Nations initially defined sustainability as development that meets present needs without affecting the environmental viability of future generations (Brundtland, 1987). In the last 20 years, sustainable construction, or green construction (Seyfang, 2010), (Bon and Hutchinson, 2000) was adopted to implement environmentally sustainable practices to reduce the impacts generated to the environment throughout the life cycle, from the design stage, through the construction process and end with the use or operation stage.

Measuring the sustainability of pavements includes some steps and methods. Tools have been developed based on the Determinant, Pressure, Condition, Impact, Response (DPSIR) reference framework (EEA, 1999). Under this view, as shown in (Figure 1), economic and social needs are represented as pressures on the environment that generate impacts. It is necessary to provide adequate responses to avoid future effects or reduce impacts. Pavements' construction affects ecosystems' state and causes fragmentation, emissions, and road operation. In addition, it is necessary to avoid future affectations by developing environmental sustainability measurement tools that allow the formulation of actions to reduce or mitigate impacts (Smeets and Others, 1999).

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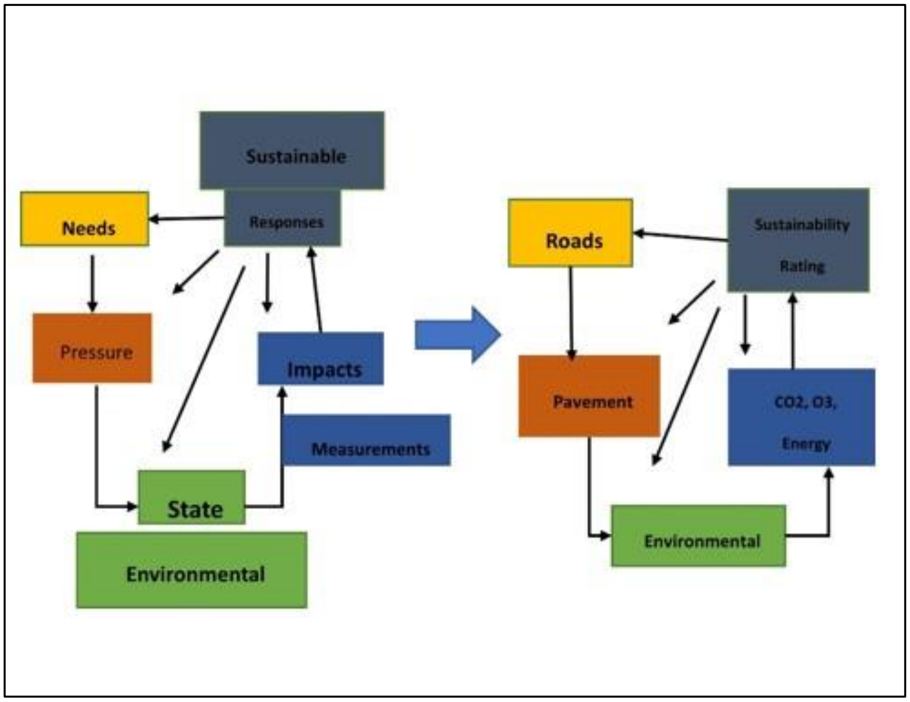


Figure 1. *DPSIR methodology, showing the relationship between socio-economic needs and impacts generated, modified from (EEA, 1999).*

Methodologies to measure the environmental sustainability of pavements are responses to the socio-economic needs of road construction. Therefore, this article aims to carry out a literature review of the environmental sustainability evaluation systems applied to pavements and thus identify the different activities that have made it possible to reduce the impacts generated on the environment.According to ISO 14044, life cycle analysis (LCA) is a methodology that allows measuring environmental sustainability through the quantification of the environmental impacts generated from materials exploitation activities to the end of the useful life of a service or product (Jahanshahloo et al., 2006),(Li et al.; 2019a), (Santero et al., 2011). In general, three methodologies are presented in the reported literature to analyze environmental impacts in the life cycle. The first one is the life cycle impacts (LCI), which corresponds to the inventories on the effects throughout the life cycle generated by the inputs of a product or projects delimited to a sector (Li, 2019) and the most widely used. The second is the input-output (IO) methodology, which includes a given process or product's entire production chain and economic sectors (Li, 2019), (Islam et al., 2016). The third is the hybrid LCI (Suh and Huppes, 2005) which combines the LCI and LCI (IO) methodology to measure impacts.

Usually, the pavement life cycle contains five stages: 1) Materials, 2) Construction, 3) Operation, 4) Maintenance, and 5) End of life (Santero et al, 2011), (Harvey et al., 2010), (Thiel at al., 2014). As (Huang et al., 2009), other authors include the design stage as they consider it an essential factor to quantify the impacts since this stage specifies the materials and construction methods. On the other hand, others eliminate the operation stage (Inyim et al., 2016) as they consider it part of the vehicles' life cycle and not of the pavements (Stripple and Uppenberg, 2010). Each phase comprises different activities that allow calculating the impacts of each of them to obtain all the emissions generated over the lifetime of pavement structures. This paper shows the emissions by different pavement materials and the rating systems reported to establish sustainability indicators in pavement projects from a literature review.

2. Research methods

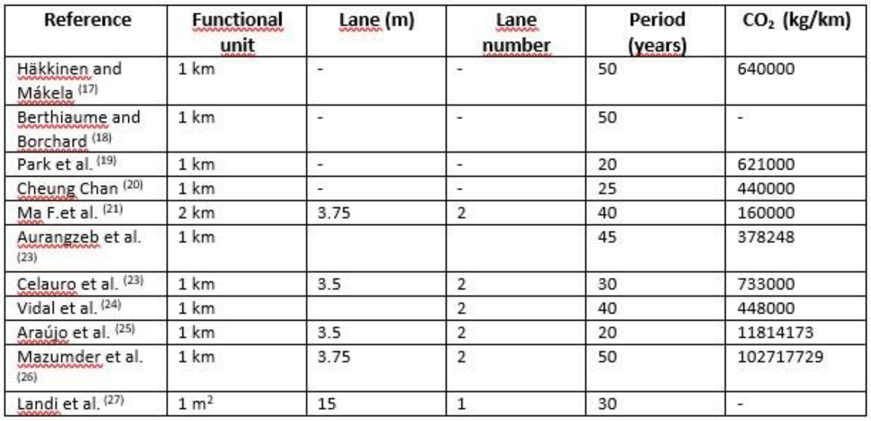
For this study, a comprehensive literature review was conducted. First of all, the authors selected the following words "Sustainability, Sustainable Pavements, Life Cycle Impact Assessment, Sustainable Rating System, Pavement emissions." In addition, an inventory of emissions by materials to build different pavement layers was reviewed as Hot Dense Mixed Aphalts (HDMA), Concrete Pavements, Hot Asphalt Mixtures (HMA) with Reclaimed Asphalt Pavements (RAP), Recycled Concrete Aggregates (RCA), HMA and Crum Rubber from Tires. With these keywords, we did a Boolean equation search in databases as Scholar Google, Scopus, Web of Science, and Springerlink. The correlation between keywords and the number of articles selected was Sustainability 12, Pavement 45, Life cycle Assessment 33, and Rating Systems 11.

3. CO_2 emissions by different pavement structures in the Life Cycle

3.1 Hot dense mixed asphalts.

(Häkkinen & Mäkelä, 1996) reported one of the first life cycle assessments of hot dense mixes. They evaluated CO2 emissions, energy consumption, pollution, and heavy metals generated from the material acquisition stage to the operation stage.; however, the authors did not consider the maintenance stage. (Table 1) shows different life cycle analysis studies carried out for hot dense mixes.

***Table 1**. Emission by Hot dense mix asphalts*



Reference	Functional unit	Lane (m)	Lane number	Period (years)	CO_2 (kg/km)
Häkkinen and Mákela (17)	1 km	-	-	50	640000
Berthiaume and Borchard (18)	1 km	-	-	50	-
Park et al. (19)	1 km	-	-	20	621000
Cheung Chan (20)	1 km	-	-	25	440000
Ma F.et al. (21)	2 km	3.75	2	40	160000
Aurangzeb et al. (23)	1 km			45	378248
Celauro et al. (23)	1 km	3.5	2	30	733000
Vidal et al. (24)	1 km		2	40	448000
Araújo et al. (25)	1 km	3.5	2	20	11814173
Mazumder et al. (26)	1 km	3.75	2	50	102717729
Landi et al. (27)	1 m^2	15	1	30	-

In that sense, (Mazumder et al., 2016) presented a study with an analysis period of 50 years for the traffic of 20.000 vehicles/day as the stages of material extraction, production, construction, transportation, use, final disposal, and reuse of material for hot dense mixes and warm mixes, concluding that the operation stage generates more significant contributions to global warming. Despite the difficulty of reducing emissions in the operation stage, the use of new materials such as warm mixes may have the ability to reduce up to 26% of the impacts of the entire life cycle. On the other hand, (Landi et al., 2020) compared a hot dense mix with other materials and found reductions of up to 25%. Nonetheless, the conclusions and results corresponded to the functional unit establish in their study (m2), which means that the comparison between different studies sometimes cannot be made directly.

3.2 Emissions by Concrete pavement

The first studies of environmental impacts of rigid pavements reported by Roudebush (Roudebush, 2003) and (Häkkinen and Mäkelä, 1996) compared a pavement structure of hot dense mix (HDM) with a rigid pavement. The results showed that concrete requires 90.8% more energy consumption than the pavement structure with a hot dense mix through the LCA (W. Zhang et al., 2008a). An ash inclusion in concrete pavement and permeable pavements (Smith and Durham, 2016b) comparison finding reductions of between 2.7% and 3% in environmental emissions related to traditional pavements (Singh et al., 2020)

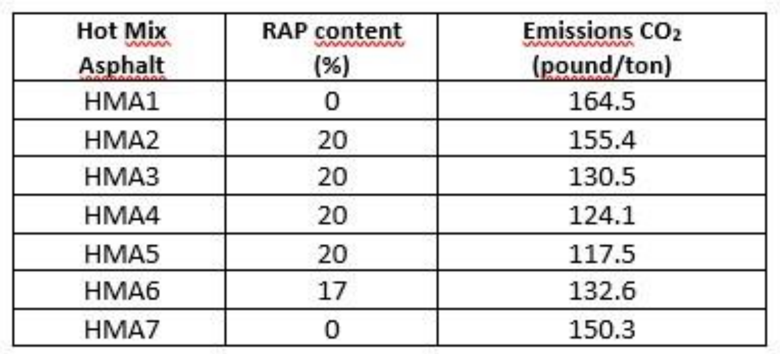
***Table 2**. Emission by concrete pavements*

Reference	Functional unit	Lane (m)	Lane number	Period (years)	CO_2 (kg/km)
Häkkinen and Mäkelä(17)	1 km	-	-	50	896000- 1.024.000
Roudebush(28)	1km	3.60	2	10	
Loijos(32)	1m^2			50	25000
W. Mack et al.(33)	1 Milla			50	3954000
Gregory et al.(34)	1 Km	3.6	6	50	16500000
Santero et al.(8)	1Km	3.6	2	30	6700000
Santos et al.(35)	1KKmm	3.75	6	50	9000000
Xu et al.(36)	1 Km		6	50	15000000
Smith & Durham(30)	18.43 Km	3.65	4	50	3750000
Shi et al.(37)	4.8 Km	3.75	2	20	4000000
Nascimento et al.(38)	1 m^2			20	6070
Mack et al.(33)	1.6 km			50	7200000
Singh et al.(31)	1.0 0km	3.5	2	-	10648000
Heidari et al.(39)	1.0 0 km	3.6	6	-	1.820.316.861
AzariJafari et al.(40)	1m^2			20	6070

3.3 Recycled pavements (RAP)

The primary life cycle studies performed for recycled pavements did run by (Miliutenko et al., 2013). However, the author did not find any emissions reduction compared to traditional hot dense mix asphalt. On the other hand, the United States Environmental Protection Agency (EPA, 2013) compares the greenhouse gases generated by pavements, including RAP, in different proportions to a hot dense mix. These results presented in (Table 3) show that the inclusion of 17% RAP in the asphalt mix generates significant reductions in CO2 emissions compared to a 20% inclusion of RAP.

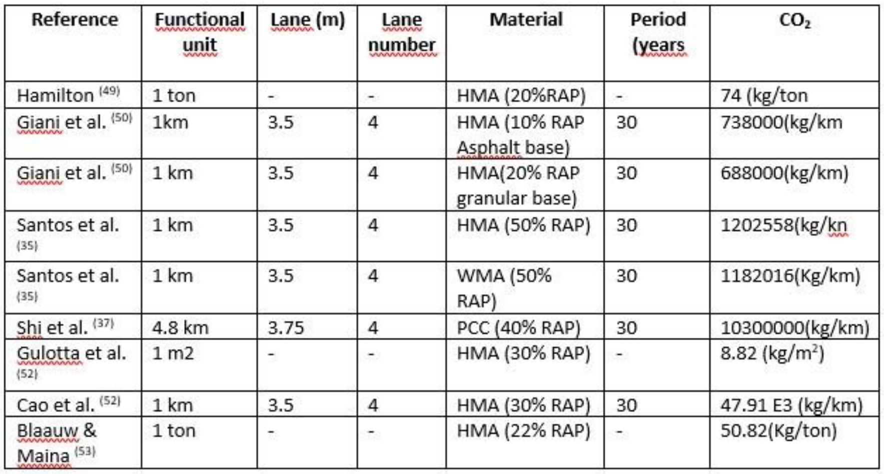
Table 3. *CO2 Emissions due to RAP addition (EPA, 2013)*



Hot Mix Asphalt	RAP content (%)	Emissions CO_2 (pound/ton)
HMA1	0	164.5
HMA2	20	155.4
HMA3	20	130.5
HMA4	20	124.1
HMA5	20	117.5
HMA6	17	132.6
HMA7	0	150.3

(Jullien et al., 2006) conducted LCA studies for mixes with the inclusion of 30% RAP in asphalt mixes and found reductions of up to 30% of greenhouse gas emissions. (Aurangzeb et al. 2014) evaluated the environmental impacts of including 30% - 40% and 50% RAP in asphalt mixes, finding reductions of up to 25% of greenhouse gas emissions (Aurangzeb et al. 2014) (Araújo et al., 2014a).

Table 4. *Emission by Reclaimed Asphalt Pavements (RAP)*

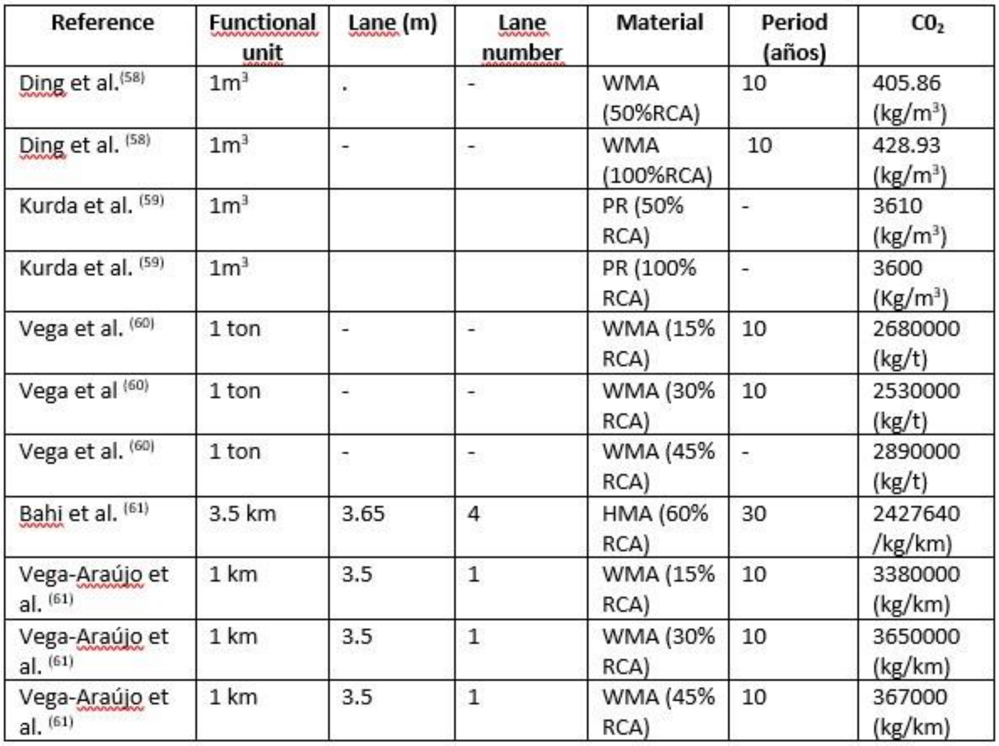


Reference	Functional unit	Lane (m)	Lane number	Material	Period (years	CO_2
Hamilton (49)	1 ton	-	-	HMA (20%RAP)	-	74 (kg/ton
Giani et al. (50)	1km	3.5	4	HMA (10% RAP Asphalt base)	30	738000(kg/km
Giani et al. (50)	1 km	3.5	4	HMA(20% RAP granular base)	30	688000(kg/km)
Santos et al. (35)	1 km	3.5	4	HMA (50% RAP)	30	1202558(kg/kn
Santos et al. (35)	1 km	3.5	4	WMA (50% RAP)	30	1182016(Kg/km)
Shi et al. (37)	4.8 km	3.75	4	PCC (40% RAP)	30	10300000(kg/km)
Gulotta et al. (52)	1 m2	-	-	HMA (30% RAP)	-	8.82 (kg/m^2)
Cao et al. (52)	1 km	3.5	4	HMA (30% RAP)	30	47.91 E3 (kg/km)
Blaauw & Maina (53)	1 ton	-	-	HMA (22% RAP)	-	50.82(Kg/ton)

3.4 Recycled Concrete Aggregate (RCA) emissions

In 2000, (Mroueh et al., 2021) studied how industrial products and mixtures in pavement structures generated higher environmental emissions and looked mainly at materials' mining and production stages. As of 2006, the Athena Institute compares the energy and greenhouse gas emissions produced by six case studies in Canada and concluded that the inclusion of recycled concrete as aggregate for asphalt mix generates higher impacts when compared to the use of natural aggregates (Chowdhury et al., 2010) and that this could be related to the hauling distances of the material (Marinkovi et al., 2013). In contrast, it was a reduction in environmental emissions with the inclusion of recycled concrete as aggregate for asphalt mix composition but without transportation to road (Mroueh et al., 2021), (AzariJafari et al., 2016). (Table 5) presents the different studies conducted with pavements with RCA inclusions for different functional units and the impacts obtained in each of these studies.

***Table 5**. Emission by Recycled Concrete Aggregate (RCA)*

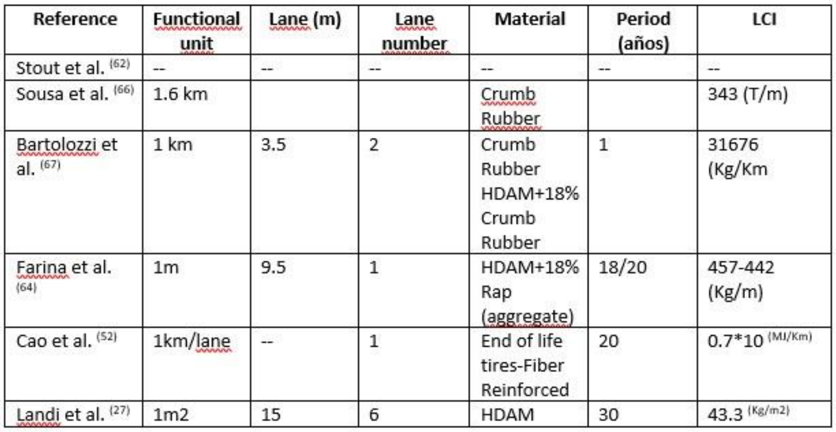


Reference	Functional unit	Lane (m)	Lane number	Material	Period (años)	CO_2
Ding et al.(58)	1m^3	.	-	WMA (50%RCA)	10	405.86 (kg/m^3)
Ding et al. (58)	1m^3	-	-	WMA (100%RCA)	10	428.93 (kg/m^3)
Kurda et al. (59)	1m^3			PR (50% RCA)	-	3610 (kg/m^3)
Kurda et al. (59)	1m^3			PR (100% RCA)	-	3600 (Kg/m^3)
Vega et al. (60)	1 ton	-	-	WMA (15% RCA)	10	2680000 (kg/t)
Vega et al (60)	1 ton	-	-	WMA (30% RCA)	10	2530000 (kg/t)
Vega et al. (60)	1 ton	-	-	WMA (45% RCA)	-	2890000 (kg/t)
Bahi et al. (61)	3.5 km	3.65	4	HMA (60% RCA)	30	2427640 /kg/km)
Vega-Araújo et al. (61)	1 km	3.5	1	WMA (15% RCA)	10	3380000 (kg/km)
Vega-Araújo et al. (61)	1 km	3.5	1	WMA (30% RCA)	10	3650000 (kg/km)
Vega-Araújo et al. (61)	1 km	3.5	1	WMA (45% RCA)	10	367000 (kg/km)

3.5 Crumb rubber from tires emissions

(Stout et al., 2003) compare d emission studies between unmodified asphalt mixtures and others with rubber granules, obtaining that the emissions derived from the manufacturing process do not present significant differences in terms of CO2 emissions. In 2008 (Chiu et al., 2008) compared pavement structures containing recycled asphalt (RAP), rubber, and ground glass in traditional hot dense mixes estimated with Eco-indicator 99® software. The results showed that the mixes modified with RAP and ground rubber had lower impacts than the hot dense mix structures. The mix with the addition of ground glass increased in terms of energy consumption and impacts generated. The results showed that ground rubber to asphalt mixes generates a 23% reduction in environmental impacts, but (Farina et al.,2017) establish that the high temperatures required for its construction result in high energy consumption; while other authors such as (Heidari et al., 2020) propose warm mixes to reduce energy consumption by improving the efficiency of the recycled rubber grain and its use in pavements. (Table 6) shows the different studies carried out with the inclusion of ground rubber. Although in Colombia, there is scarce evidence on estimating the environmental burdens of materials used for the construction and maintenance of pavement structures. (Martinez-Arguelles et al., 2013) analyzed environmental impacts for different maintenance cases using Eco-indicator99 as a calculation tool in Bogotá.

***Table 6.** Emission by Crumb rubber from tires*



Reference	Functional unit	Lane (m)	Lane number	Material	Period (años)	LCI
Stout et al. (62)	--	--	--	--	--	--
Sousa et al. (66)	1.6 km			Crumb Rubber		343 (T/m)
Bartolozzi et al. (67)	1 km	3.5	2	Crumb Rubber HDAM+18% Crumb Rubber	1	31676 (Kg/Km
Farina et al. (64)	1m	9.5	1	HDAM+18% Rap (aggregate)	18/20	457-442 (Kg/m)
Cao et al. (52)	1km/lane	--	1	End of life tires-Fiber Reinforced	20	0.7*10 (MJ/Km)
Landi et al. (27)	1m2	15	6	HDAM	30	43.3 (Kg/m2)

As a summary, (Figure 2) shows CO2 emissions reported by several authors. There is a significant variance of the results because the functional geometry is not the same. However, as shown in (Figure 2) the mean CO2 emissions for one kilometer of road construction would be between 1500 to 2000 Ton, as (Castro and Sabogal, 2021) reported. This study reported emission for a highway with two lanes in 1 Km as a functional unit of analysis.

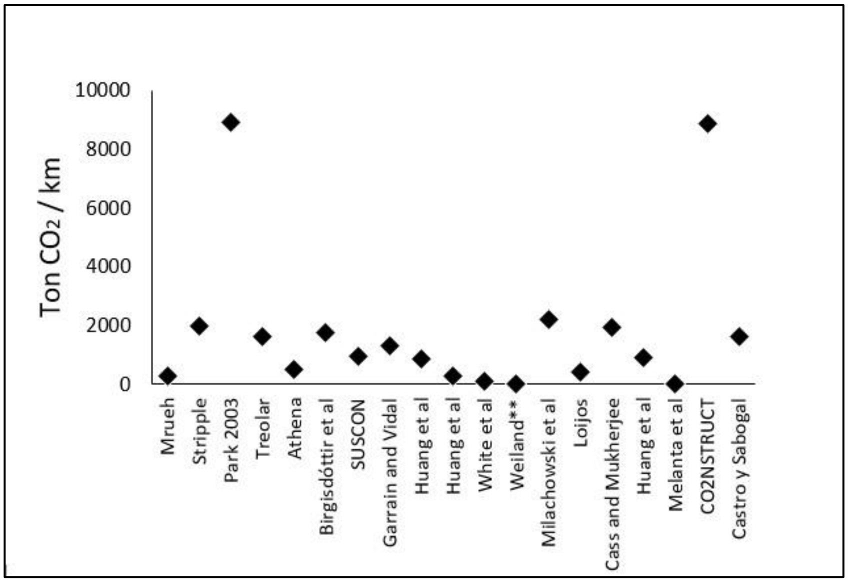


Figure 2. *CO2 Emissions reported in one kilometer of road construction*

3.6 Current pavement sustainability rating systems

Rating systems are an essential tool to measure the sustainability of pavement structures (Mattinzioli et al., 2020). Those are, in essence, a list of best practices that comply with two fundamental principles: (Brundtland, 1987) go beyond those of the required regulatory minimums or commonly performed practices and (Seyfang, 2010) show innovation in of these required regulatory minimums (Dam et al., 2011). Good practices refer to the inclusion of activities in the different stages of the life cycle that generate reductions in environmental impacts and can be applied to a project to evaluate the project's sustainability performance (Zhang and Mohsen, 2018).

Since 2004, in the case of road infrastructure, some research groups and institutions have focused their studies towards measuring sustainability (Amaral and Abraham, 2020), e.g., the Federal Highway Administration, The University of Washington, The Institute for Sustainable Infrastructure of Washington, and the Zofnass Sustainable Infrastructure Program of Harvard University, and the European Union Road Federation (Melizza et al, 2015), and most cases applied to new road infrastructure construction projects (Clevenger et al., 2013). Until 2021, different rating systems related to road infrastructure sustainability have been reported (Bryce et al., 2017), (Díaz-Sarachaga et al., 2016b) (Díaz-Sarachaga et al., 2017), (Szpotowicz and Tóth, 2020), (Griffiths et al, 2017) e.g., (CEEQUAL, 2010), Green LITES Green Leadership in Transportation Environmental Sustainability (McVoy et al., 2010), Greenroads (Muench et al, 2010), BE2ST-in-highways systems (Lee et al., 2013), STARS Sustainable Transportation Analysis and Rating System (Sarsam, 2015), INVEST Infrastructure Voluntary Evaluation Sustainability Tool (Clevenger et al, 2013), I-LAST Livable And Sustainable Transportation (Knuth and Fortmann, 2010), Envision (Shivakumar et al., 2014), GreenPave (Chan et al., 2013) Goldset (Maher et al., 2015), Pavement Sustainability Index for Maintenance (PSIM) (Zhang and Mohsen, 2018), Sustainable transportation environmental engineering and Design (STEED)(Demich, 2020). (Table 7) presents the rating systems reported up to date, with their objectives and corresponding evaluation criteria.

***Table 7**. Pavement rating systems*

System	Release	Author	Objetive	Categories
CEEQUAL	2003	Institute of Civil Engineers and the Government of the United Kingdom.	Evaluate environmental performance and sustainability in landscaping and civil engineering projects during the design, construction, and maintenance stages .	Project Strategy. Projects management. Population and communities. Land Use and Landscape. Environment. Ecology and Biodiversity. Aquatic environment. Physical resources. Transport
GreenLITES.	2008	Nueva York Department of Transportation.	Promote sustainable transport and carts as an alternative to reduce negative impacts	Sustainable Sites. Water quality. Materials and Resources. Energy and Environment. Innovation.
Green roads	2010	University of Washington (UW) and CH2M Hill	Recognize the application of positive, sustainable practices in the design and construction of roads.	Highway Project Requirements. Environment and Water. Access and Equity. Construction Activities. Materials and Resources. Pavement Technology.
BE^{2}ST-in- Highways	2013	Recycled Materials Resource Center-University of Wisconsin / Madison (Lee et al., 2013)	Quantify the impact of the use of recycled materials in construction	Energy consumption Material recycled on-site / Total material recycled Water consumption Traffic noise The social cost of carbon. (Lee et al., 2013)
STARS	2011	Oregon Department of Transportation (W. Zhang et al., 2008a)	Measure the environmental sustainability of transport systems.	Access and mobility. Security and health. Equity Economy (North American Sustainable Transportation Council, 2012)
Infrastructure Sustainability	2012	Infrastructure Sustainability Council of Australia. AGIC	Evaluate the sustainability in the design, construction, and operation of the transport infrastructure.	Management and Governance. Use of Resources. Emissions, Pollution, and Waste. Ecology. Community. Innovation.
INVEST	2012	Federal Highway Administration (FHWA) United States (Reid et al., 2010)	Guide professionals to assess the sustainability of their transportation projects and programs.	System planning. Project development. Operations and maintenance., (FHWA 2020)
Envision	2012	Washington Institute for Sustainable Infrastructure and Harvard University's Zofnass Program for Sustainable Infrastructure.	Qualify and evaluate the social, environmental, and economic aspects by analyzing the life cycle of any type and size of a civil infrastructure project.	Quality of life. Leadership. Resource allocation. Natural world. Climate and risk. Highway Planning and Design. Highway Construction, Operation, and Maintenance.
Green Pave	2013	Ontario Infrastructure Institute Canada.	Improve the sustainability of transport infrastructure through the design and selection of sustainable alternatives.	Pavement technology. Materials and resources. Energy and Atmosphere Innovation and design process
Goldset	2015	Golder Associates Ltd	Integration of Sustainability Rating Tools in Contemporary Pavement Management Systems	Environmental, social, and economic
Pavement Sustainability Index for Maintenance (PSIM)	2018	Zhang & Moshen	Provide a bridge between the concept and practice of sustainable pavement maintenance	Technique, Material, Energy and water, environment, safety, community, and innovation
STEED (Sustainable transportation environmental engineering and Design	2012	Eisenman. Georgia Department of Transportation.	By evaluating a project in each stage of project completion, the overall project intentions can be tracked to determine if the objectives were met, "and, if not, during which stage things either improved or deteriorated."	Sustainable sites, water quality and quantity, materials and resources, energy and atmosphere, and innovation

(Figure 3) shows the pavement relevance of rating systems presented in (Table 7). The rating systems shown below evaluate pavement structures and overall road infrastructure; for that reason, it was necessary to evaluate the relevance of the pavements on the total weight of the rating granted. (Figure 3) shows the percentage of the rating awarded to the pavement structures for each of these systems.

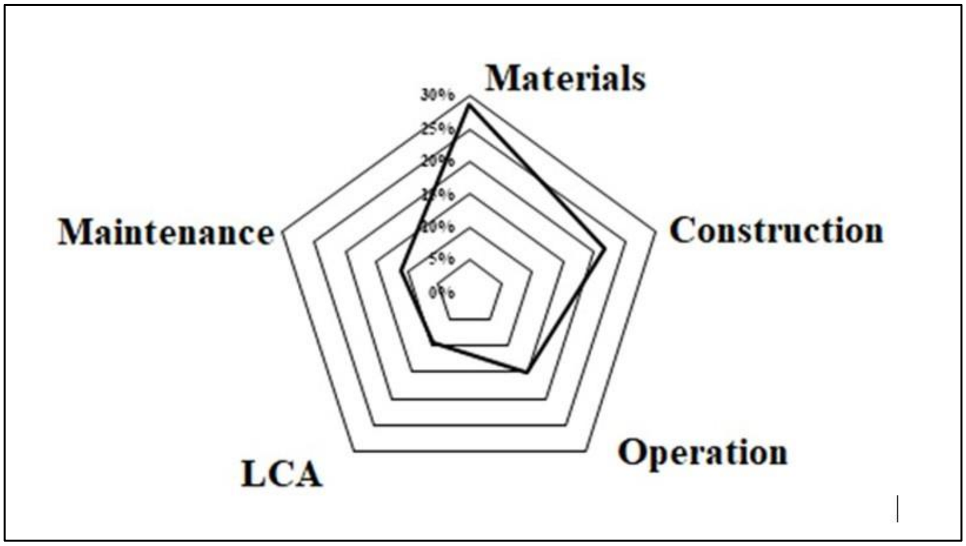


***Figure 3**. Relevance of pavements in the rating systems*

Due to each system was developed by an independent institution, the evaluation methods are dissimilar. The scientific rigor of the study depends on each system and the relative weight of each category. (Figure 4) presents an evaluation of the strengths and weaknesses of the rating systems applied to highway infrastructure projects. It shows that the rating systems, on average, focus on materials, construction, and operation but LCA and maintenance are low studied. The scale represents the depth of the rating systems for each of the categories evaluated.

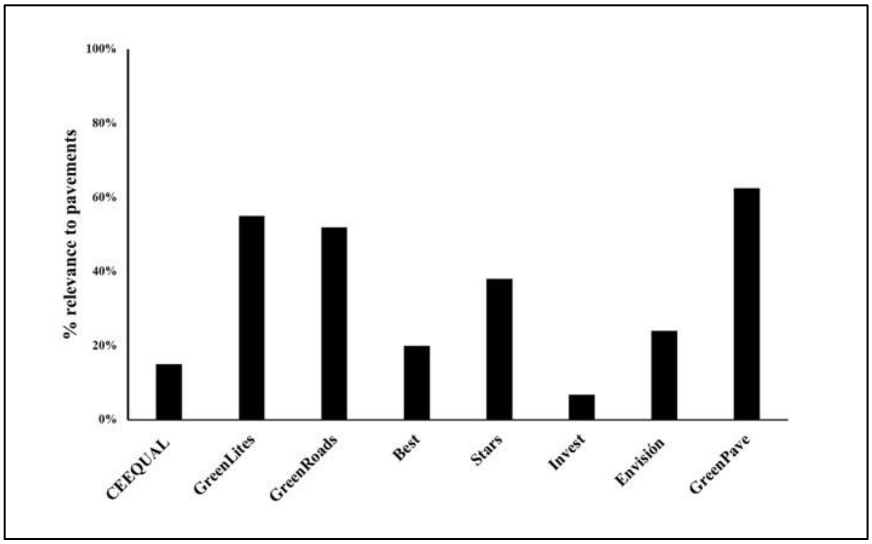


***Figure 4**. Deepening of the qualification systems by category*

4. Discussion and conclusions

The main components in rating systems studied are materials, construction, operation, maintenance, and Life Cycle Assessment components to evaluate in the rating systems (Zhang and Mohsen, 2018), (Clevenger et al., 2013), (CEEQUAL, 2010), (McVoy et al., 2010), (Muench et al, 2010), (Lee et al., 2013), (Sarsam, 2015), (Knuth and Fortmann, 2010),(Shivakumar et al., 2014), (Chan et al., 2013), (Maher et al., 2015), (Demich, 2010) 2010). Those components present unbalanced weights concerning the others. Hence, materials and construction have significant development instead of operation, maintenance, and LCA. The study of materials refers to the inclusion of recycled materials for the conformation of pavement structures and construction activities. However, there is no considerable relevance in realizing the life cycle analysis (LCA) to know how implementing new practices or activities can reduce environmental impacts. Therefore, it is necessary to include the Life Cycle Assessment methodology in the rating systems. With the results obtained from the environmental emissions, it is possible to measure the impact reductions generated by implementing new environmentally sustainable practices.

This paper reviewed emissions from different pavement layer materials and rating systems oriented toward pavement sustainability. The literature reports the different amounts of emission depending on the functional unit of analysis. Life cycle impact analysis (LCI) is widely used to evaluate the environmental benefits of including recycled (Jahanshahloo (6-and Lotfi, 2006), (Li et al., (2019a), (Santero et al., 2011). However, to better understand the interaction of pavements with the environment, more studies should be conducted on the different stages of the life cycle, not only in the construction stages but also in operation and maintenance and its relationship with environmental impacts. In addition, it is essential to provide the functional unit with a constant geometry of 1 Km and two lanes to obtain the emissions and compare the results.

Although different rating systems have been developed, their application is not exclusively for pavement structures; this requires efforts to implement a system exclusively for pavements; in this sense, literature report methodologies on environmental sustainability measurements. Projects like CEEQUAL 2003, GreenLITES 2008, Green Roads 2010, Best in Highways 2011, STARS 2011, Infrastructure Sustainability 2012, INVEST 2012, Envision 2012, GreePave 2014 come mainly from North America, Europe, and Asia that do not reflect the situation in Latin America. Due to either the machinery involved in construction and maintenance stages, and vehicles are different in technology as those regions and emissions depend on geography, altitude, aging of equipment, and other variables, these particularities motivate to develop studies on the impacts of regional pavements in Latin America.

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