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"Diseño de pavimento modificado con la adición de plástico reciclado para ciclovías"

Trabajo de titulación previo a la obtención del título de Ingeniera Civil

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Resumen:

En los últimos años, Cuenca - Ecuador mostró aumentos sustanciales en su población y el número de vehículos motorizados, lo que condujo negativamente a incrementos en la contaminación ambiental y las emisiones; por eso, y bajo el propósito de buscar una ciudad sostenible, las agencias de transporte locales están trabajando arduamente con el objetivo de mejorar su planificación y gestión de la movilidad para todos los modos de transporte, incluidas las bicicletas.

En consecuencia, una parte importante de esta estrategia implica el diseño y la implementación de una red importante de carriles para bicicletas en toda la ciudad, sin embargo, la implementación de esta red de carriles para bicicletas puede representar la contaminación ambiental en sí misma si se construye con pavimentos flexibles tradicionales.

Para evitar este problema potencial, el objetivo de este documento es presentar un diseño de pavimento flexible alternativo que sea más sostenible al incorporar plástico reciclado en la mezcla y, al mismo tiempo, mantener el rendimiento requerido. Esta investigación desarrolla el diseño de un asfalto modificado que incorpora en la mezcla de plástico PET triturado que de lo contrario se convertirá en residuo. Esta alternativa de asfalto cumplirá con los códigos de construcción para mezclas de superposición que se colocarán en carriles para bicicletas y espacios públicos definidos en la ciudad de Cuenca.

El proceso de diseño incluye pruebas de Marshall, abrasión, VA, flujo y estabilidad en diferentes mezclas (con ocho porcentajes de plástico PET diferentes) siguiendo los estándares españoles para analizar su rendimiento. Finalmente, la evaluación del ciclo de vida (ACV) también se realiza para definir mejoras desde una perspectiva sostenible.

Palabras claves: Plástico PET. Mezclas asfálticas modificadas. Evaluación del ciclo de vida. Sustentabilidad del reciclaje.

Abstract:

On recent years, Cuenca – Ecuador showed substantial increases in its populations and motor vehicles count, negatively leading towards increments on environmental pollution and emissions; because of that, and under the purpose of seeking for a sustainable city, local transportation agencies are working hard with the aim of improving its mobility planning and management for all transportation modes, including bicycles.
Consequently, an important part of this strategy involves the design and implementation of a significant bikeway network throughout the city, however, the implementation of this bikeway network may represent environmental pollution itself if constructed with traditional flexible pavements.
To avoid this potential problem, the objective of this paper is to present an alternative flexible pavement design that is more sustainable by incorporating recycled plastic in the mixture, and at the same time, maintaining the required performance. This research develops the design of a modified asphalt incorporating in the mixture crushed PET plastic that otherwise will become waste. This alternative asphalt will comply with construction codes for overlay mixes that will be placed on defined cycle paths and public spaces in Cuenca city.
The design process involves Marshall, abrasion, VA, flow and stability tests over different mixes (with eight different PET plastic percentages) following Spanish standards to analyze its performance. Finally, life cycle assessment (LCA) is also performed to define improvements from a sustainable perspective.

Keywords: PET plastic. Modified asphalt mixes. Life cycle assessment. Recycling sustainability.

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1. INTRODUCTION

Plastic is an artificial product obtained via chemical reactions for no-resin matter according to "Aplicaciones del Plástico en la Construcción", plastic products are one of the most used alternative products on flexible pavements in Europe. Polyvinyl chloride (PVC) ranks as the most common material used in flexible pavements (de Cusa, 1977), (Modarres & Hamedi, 2014a).

Another alternative material used as addition in pavement asphalt mixtures is Polyethylene terephthalate (PET); its main used is the elaboration of bottles. (Modarres & Hamedi, 2014b, Widojoko & Purnamasari, 2012) Its principal advantages are:

- Easy fabrication
- Reduced thermal sensibility for the molten material
- High tenacity
- Good flexibility
- Insensitive to cracking
- Chemical products resistance
- High strength
- Low absorption

Several studies about its use as an alternative material has been conducted, comparing performances, not only with this addition, but also with fibers, glass, etcetera; findings are promising, for example there is evidence of increase in adherence between asphalt bitumen and aggregates (Xu et al, 2010).

Other research shows improvements in deformation characteristics, and fatigue resistance, their conclusions show that there is a better fatigue resistance performance when crushed glass material is added in the mixture (Arabani M et al, 2010).

Qunshan et al., 2009 made research with polyester, and mineral fibers stablishing optimum percentages of these additions around 3 to 4 % of the total mix weight, improving fatigue resistance.

A. Modarres & H. Hamedi, 2014a compared traditional asphalt mixes with proposed asphalt mixes containing 5.7% of PET obtaining Elastic modulus models and fatigue models. The main tests included indirect tensile testing (ITS), showing an increase in the tensile strength for the proposed mixture for different temperatures (5 and 20°C), but the elastic modulus decreased for the proposed mixture.

Similar studies made by Baghaee Moghadam et al, 2012 incorporating 0.2% of PET in the mixture determined a small increase in the stiffness. However, when increasing PET percentage this stiffness values started to decreased significantly (Modarres & Hamedi, 2014a).

A. Modarres & H. Hamedi, 2014b, in its second study proceeded with the same range for PET and asphalt, but in this case, they followed ASTM: D4123 and EN 12697-24 for the Elastic modulus tests, and fatigue tests, respectively. Their findings show that when increasing PET over 2%, the elastic modulus was reduced for both tested temperatures (5 and 20 ° C) (Modarres & Hamedi, 2014b).

In 2012, Moghaddam et al analyzed stiffness and fatigue with mixtures containing 1% of PET and traditional mixtures, observations concluded that durability was indeed increased twice, but stiffness decreased slightly (Ahmadinia et al, 2011).

According to Widojoko & Purnamasari, 2012, density is negatively affected when PET is introduced. However, for additions between 0 to 4%, cohesion and adherence properties were improved, (Widojoko & Purnamasari, 2012).

For this study, taking into account that bikeways take relatively smaller loads and load configurations, the focus is more on safety and ride quality, therefore, durability and stability testing are proposed. With a strong focus on sustainability.

Even though PET does not improve asphalt pavement performance significantly, it can be used due to its low cost as a sustainable material. Vázquez, 2010 states that PET gives lower viscosity, better flexibility at low temperatures, and better rutting performance.

With this summary and scope defined, the following objectives are drawn.

General Objective

Design a PET-modified asphalt mix to be applied over bikeways that represents a positive alternative, including sustainable approaches by reducing environmental impacts, while maintaining the same or better performance than the base mix.

Specific Objectives

- Determine the optimum PET percentage that the mixture performs with the least abrasion and higher stability.
- Analyze durability, by determining the abrasion reduction percentages for all proposed mixes vs. the traditional standardized mixture
- Verify standards compliance for all analyzed mixtures, especially for the chosen mix built with the optimum PET percentage
- Propose the final modified mix design that complies with standards, while improving sustainability factors like energy consumption, and CO_2e Emissions

2. METODOLOGY

Among various tests defined below, the most representative performance characteristic to be analyzed is abrasion, Cantabrian tests is one of the most common method to do so, where a Marshall-type briquette at a constant temperature (between 15 & 30 ºC) is introduced in the Los Angeles testing machine without the steel spheres, following the NLT-159, Resistance to plastic deformation of bituminous mixtures using Marshall equipment (Vilaplana, 2015).

This study was conducted using crushed PET with particles between 3-5 mm.

A. Mix design

Four aggregate types were used for the mixing process; crushed material passing sieve 3/4, crushed material passing sieve 3/8, crushed material passing sieve 3/16, and river sand. All materials come form Guachapala-Azuay, and Cochancay-Cañar (recognized and approved mines and quarries in Ecuador).

The public agency ASFALTAR EP (one of the approved public agencies for Cuenca City) provided all materials; moreover, the base/traditional mix design complied with the standardized design used by this public agency.

Each and every one of the materials were completely characterized for parameters like granulometry, absorption, specific gravity (Net, SSD, apparent); results are shown in table 1 and table 2.

The ½″ standardized granulometry used for this study is presented in table 1 below and is described on "Especificaciones Generales para la Construcción de Caminos y Puentes". The ASTM C 136 and AASHTO T27 standards were strictly followed.

Table 1. Standardized Granulometry. (MOP, 2002, page IV 95).

SIEVE	PERCENTAGE BY WEIGHT PASSING (SQUARE MESH).			
	3/4"	**1/2"**	**3/8"**	**N°4**
1" (25.4 mm)	100	--	--	--
3/4" (19.0 mm)	90-100	100	--	--
1/2" (12.7 mm)	--	90-100	100	--
3/8" (9.50 mm)	56-80	--	90-100	100
N°4 (4.75 mm)	35-65	44-74	55-85	80-100
N°8 (2.36 mm)	23-49	28-58	32-67	65-100
N°16 (1.18 mm)	--	--	--	60-80
N°30 (0.60 mm)	--	--	--	25-65
N°50 (0.30 mm)	5-19	5-21	7-23	7-40
N°100 (0.15 mm)	--	--	--	3-20
N°200 (0.075 mm)	2-8	2-10	2-10	2-10

Specific gravities and absorption determination were performed followed the ASTM C 128 – AASHTO T-84; results are shown in Table 2 below.

Table 2. Specific weight & Aggregate absorption

	Net. Sp. W. (Bulk) $[g/cm^3]$	SSD Sp. W. $[g/cm^3]$	Apparent Sp. W. $[g/cm^3]$	Absorption rate
3/4	2.732	2.751	2.785	0.70
3/8	2.684	2.717	2.777	1.24
3/16	2.683	2.705	2.743	0.80
River sand	2.674	2.717	2.795	1.62

Marshall Test methodology

Marshall Test were used to determine the optimum percentage for asphalt, this percentage was determined after fulfilling the specification range criteria for the aggregates, Table 3 illustrates this standardized specification along with the chosen percentages for each aggregate in order to meet this criterion. Fig 1. Depicts these relationships.

Table 3. *Aggregate combination chosen for the mix design.*

SIEVE OPPENING	PERCENTAGES IN WEIGHT PASSING				MIXTURE 100%	SPECIFICATION RANGE 1/2"		
	10,0%	**22%**	**50,0%**	**18,0%**		**LOWER LIMIT**		**UPPER LIMIT**
	CRUSHED MATERIAL 3/4	**CRUSHED MATERIAL 3/8**	**CRUSHED MATERIAL 3/16**	**RIVER SAND**				
3/4"	99,69	100,00	100,00	100,00	99,97	**100**	-	**100**
1/2"	48,94	100,00	100,00	100,00	94,89	**90**	-	**100**
No. 4	0,34	27,99	98,75	91,36	72,01	**44**	-	**74**
No. 8	0,00	5,46	79,73	71,03	53,85	**28**	-	**58**
No. 50	0,00	0,00	28,47	13,02	16,58	**5**	-	**21**
No. 200	0,00	0,00	13,44	3,86	7,42	**2**	-	**10**

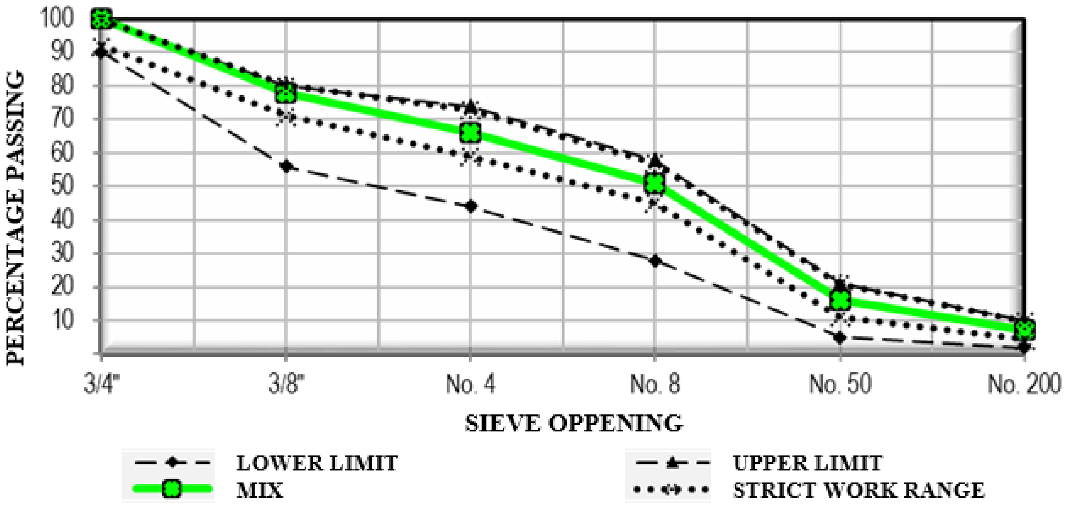


Fig. 1. *Aggregates combined granulometric curve.*

Results for Marshall Test variating percentages from 5.5 to 7.5 % are detailed in Table 4.

Table 4. *Marshall Test for base mix design*

% ASPHALT	STABILITY	NET SPECIFIC WEIGHT	FLOW	Volume filled with asphalt (VFA)	% VOIDS (VA)	Volume of mineral aggregate (VMA)
5.5	3059.102	2.279	11.333	49.301	9.940	19.605
6.0	3415.865	2.331	10.933	63.494	6.708	18.374
6.5	3021.174	2.337	12.200	69.900	5.513	18.314
7.0	3366.005	2.343	15.100	74.292	4.755	18.495
7.5	3153.588	2.333	15.333	82.312	3.372	19.064

By plotting percentage of asphalt vs stability, net specific weight, flow, VFA, VA, and VMA; the optimum asphalt percentage was determined, being 6.7%. This value will be used for both all upcoming mixes, base mixes, and mixes with PET additions.

B. PET addition on Base mix

For traditional design, materials are warmed up to 160 °C (320 °F), for the mixing process. But, when using PET, this material starts to molten, generating lumps and clots affecting homogeneity.

From several testing during this study, the recommended temperatures for adding PET in the mix is 110°C (230 °F), same recommendations can be found in (Cavanzo & Ortiz, 2002) study, where the recommendation is 110 and 120 °C (230 and 248 °F).

However, for the final stages of this research, the chosen mixing process was to add PET by following the methodology named “proceso en seco” where PET is first mixed with the aggregates, then these initial mix is warmed up to 130 °C (266°F), to finally be joined with the hot asphalt (Modarres & Hamedi, 2014b).

Briquettes were prepared according to Marshall Procedures using the following PET percentages: 2, 3, 4, 5, 6, 8, 10 & 12%. Findings show that flow increases when PET percentage increases; likewise, Stability increases first and then decreases when PET percentage increases (peak stability is around 6% PET); more details are shown and discussed below.

C. Abrasion Test

Following the NLT-352/86 standard, Characterization of the Open Bituminous Mixtures by Means of the Cantabrian Test of Loss by Wear; abrasion was measured for the dry briquettes just after weighting them, with speeds within 3.1 to 3.5 rad/s during 300 revolutions.

After this process, the briquettes were weighted again. A number of four briquettes for each PET percentage were tested. Loss due to abrasion was measured as follows

$$W = \frac{W1 - W2}{W1} * 100 \qquad \text{Eq. 1}$$

Where

W= loss due to abrasion (%)
W1= initial briquette mass (g.)
W2= final briquette mass (g.) (NLT-352/86)

3. RESULTS AND DISCUSSION.

Briquettes with added PET showed more Va in general as shown in a couple of examples in Fig. 2. Briquettes with contents of 0, 6 and 12% PET were compared; each with Va values of 4.79, 13.97 and 21.05% respectively.

For Marshall testing, briquettes with PET additions from 2% to 6% showed a sustained growth in stability, but over 6% showed a sudden decrease in their stability. Fig. 3 shows the peak value for stability and its correspondent PET percentage. NOTE: Since there was a problem with briquettes at 4%, this particular value was not included in the trend.

With respect to Flow, a proportional growth was found when PET percentages increase for all the range chosen for the study (from 2 to 12%), Fig 4 shows this trend below

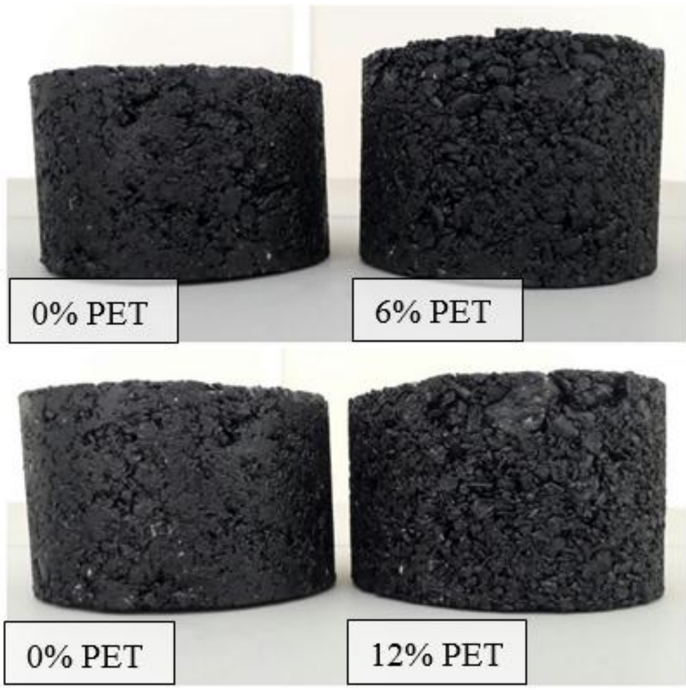


Fig. 2. *Comparative for asphalt briquettes. Upper images: 0% PET (Va=* 4.79%) *vs. 6% PET (Va=* 13.97*).*
Lower images 0%PET (Va= 4.79%) *vs. 12% PET (Va=* 21.05%*).*

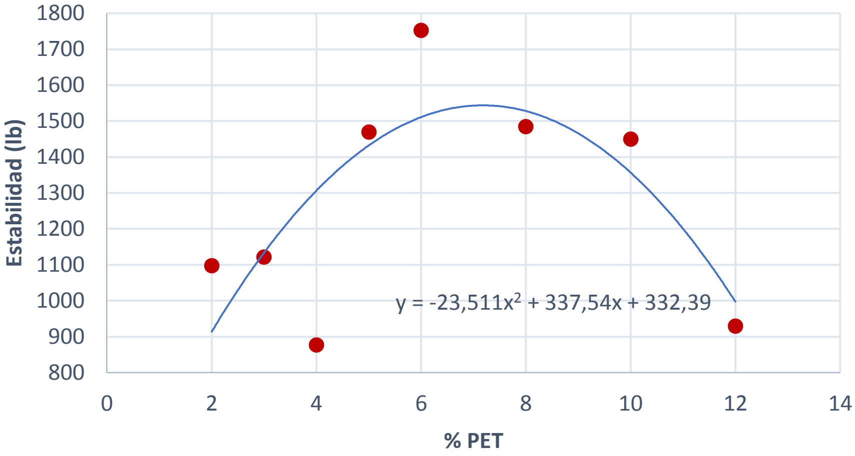


Fig. 3. *Stability - %PET*

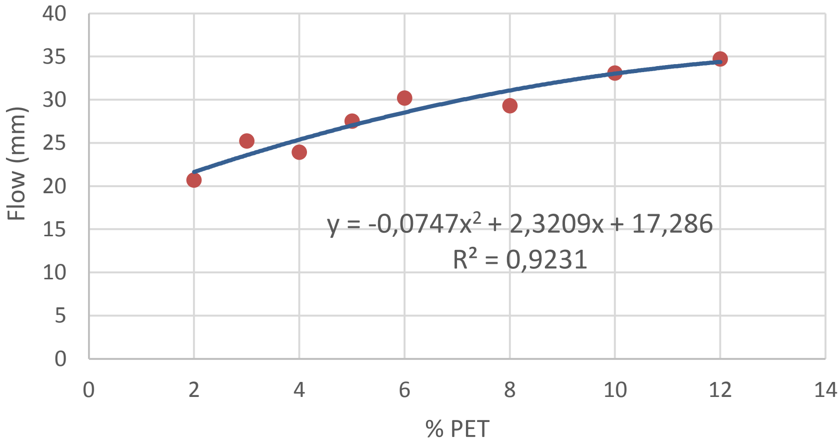


Fig. 4. *Flow -%PET.*

Based on Marshall Results, 6% was the chosen optimum percentage for PET; since this value represents the closest real point to the maximum stability, notice than this value is similar to the recommended by previous literature cited before (5.7% as optimum PET percentage).

Further research made for the base mix and the proposed mix with the chosen optimum PET percentage was developed. RICE testing was made for both in order to find the theoretical maximum specific gravity (Gmm); results showed that for the base mix, Gmm equals 2.451, and for the proposed mix Gmm equals 2.375, with Va = 4.79% and Va = 13.97% respectively, validating the higher porosity for the proposed mix (as shown in fig. 2 above).

Abrasion testing was made over four briquettes with 0% PET and over four briquettes with 6% PET (chosen optimum percentage), using Eq. 1, and results are depicted in table 5.

Table 5. *Abrasion results.*

			ABRASION			
% PET	**W1 (g)**	**W2 (g)**	**% ABRASION**		**VARIANCE σ^2**	**STANDARD DEVIATIONσ**
0%	1170.34	1104.79	5.60	**7.74**	3.54	**1.88**
	1108.24	1001.89	9.60			
	1194.43	1113.84	6.75			
	1171.27	1065.68	9.02			
6%	1082.84	922.2	14.84	**15.36**	61.65	**7.85**
	1160.67	1072.69	7.58			
	1173.78	1023.22	12.83			
	1048.25	773.5	26.21			

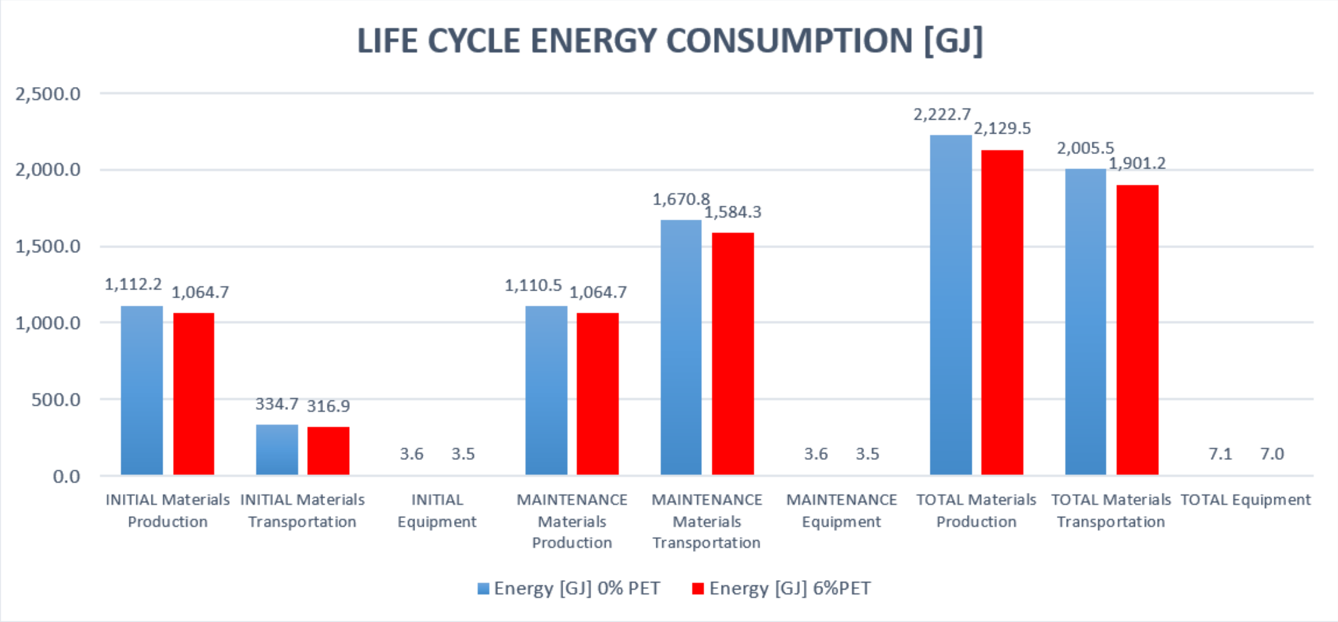
This outcome highlights that the proposed mix design doubles the abrasion percentage, however, the abrasion percentage for the proposed mix complies with the standard (abrasion must be lower than 25% according to the NLT-352/86 standard), fig. 5 shows a comparison of the abrasion rate for this test.

Fig. 5. *Abrasion results comparison, for 6% PET (left) vs. 0% PET (right)*

Finally, with the help of a sustainable calculator software like PaLATE, and considering maintenance every 5 years, the environmental impact for both design mixes (base and proposed) was determined, in terms of energy consumption, and CO2-e emissions.

For this determination, several factors were considered, like equipment, extraction, material transport, etc. Fig. 6 and Table 6 shows this final comparison.

The exercise was made for 1 km of bikeway, with 0.2 m thickness, and two ways of 1.8 m width in total. Considering the same volume of pavement mix for both designs (base mix and proposed 6% PET mix).



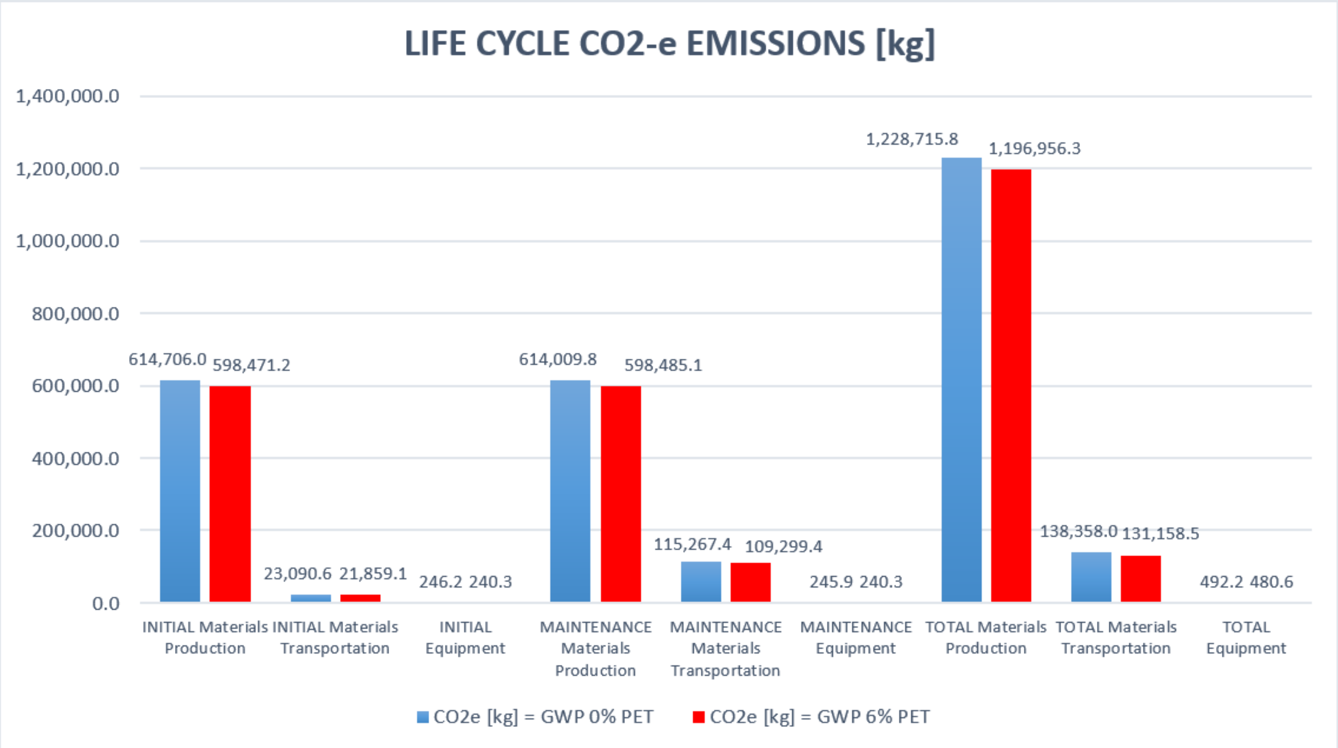


Fig 6. *Graphic sustainability comparison for 0%PET (Blue columns) vs 6% PET (Red Columns)*

Notice than, for both, energy consumption and CO2-e emissions, there is a considerable improvement in terms of sustainability, a very significant factor when proposing alternative materials for future design. As mentioned before, these results are also presented as matrix format in table 6 below for better numerical comparisons.

Table 6. *Sustainability results matrix*

Parameters		Base mix		Proposed 6% PET mix	
		Energy [GJ] 0% PET	**CO2e [kg]=GWP 0% PET**	**Energy [GJ] 6%PET**	**CO2e [kg]=GWP 6% PET**
Initial Construction	INITIAL Materials Production	1,112.2	614,706.0	1,064.7	598,471.2
	INITIAL Materials Transportation	334.7	23,090.6	316.9	21,859.1
	INITIAL Equipment	3.6	246.2	3.5	240.3
Maintenance	MAINTENANCE Materials Production	1,110.5	614,009.8	1,064.7	598,485.1
	MAINTENANCE Materials Transportation	1,670.8	115,267.4	1,584.3	109,299.4
	MAINTENANCE Equipment	3.6	245.9	3.5	240.3
Total	TOTAL Materials Production	2,222.7	1,228,715.8	2,129.5	1,196,956.3
	TOTAL Materials Transportation	2,005.5	138,358.0	1,901.2	131,158.5
	TOTAL Equipment	7.1	492.2	7.0	480.6
	Total	4,235.4	1,367,566	4,037.6	1,328,595

4. CONCLUSIONS

It was possible to propose a more sustainable pavement mix design for bikeways that complies even with current normative and standards for high volume traffic, current standards that are stablished by the “Ministerio de Transporte y Obras Públicas Ecuador (MTOP),

The optimum PET percentage was determined to be 6%, considering as the percentage related with the maximum stability value, complying as well with Flow parameters.

Even though, the traditional base mix presents significantly better abrasion resistance (almost twice the proposed value), both mix designs comply with the standards comfortably.

The 6% PET mix stability value of 1752 lb. complies even with the motor vehicles traffic standards, for the “low traffic” category (category that has significantly higher traffic, and significantly heavier traffic than the expected traffic for bikeways)

From the sustainability analysis, it is important to conclude that, besides proposing a more economic mix design that complies with current standards, it is also a more sustainable mix design in terms of environmental impact. The proposed mix design uses less energy during its construction and maintenance and produces less CO2-e emissions than the traditional base mix design used nowadays.

Finally, it is important to mention that all municipal, public and private agencies in Ecuador can use this mix design not only for bikeways, but also for all their walkway projects in parks, trails, recreational areas, etcetera. Given that the proposed mix design complies with strict standards satisfactorily, with the additional benefits of being a cheaper and more sustainable pavement mix design

REFERENCES.

De Cusa, Juan (1977): *Aplicaciones del plástico en la construcción.* España: CEAC.

Modarres, A., & Hamedi, H. (2014a). Developing laboratory fatigue and resilient modulus models for modified asphalt mixes with waste plastic bottles (PET). *Construction and Building Materials*, *68*, 259–267.

Modarres, A., & Hamedi, H. (2014b). Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. *Materials and Design*, *61*, 8–15.

Widojoko, L., & Purnamasari, P. E. (2012). Study the Use of Cement and Plastic bottle Waste as Ingredient Added to the Asphaltic Concrete Wearing Course. *Procedia - Social and Behavioral Sciences*, *43*, 832–841.

Xu Q, Chen H & Prozzi JA. (2010). Performance of fiber reinforced asphalt concrete under environmental temperature and water effects. *J Constr Build Mater*, 24(10):2003–10

Arabani M, Mirabdolazimi SM & Sasani AR. (2010). The effect of waste tire thread mesh on the dynamic behaviour of asphalt mixtures. *Construction Build Mater,* 24:1060–8.

Ye Qunshan, Wi Shaopeng, Le Ning. (2009). Investigation of the dynamic and fatigue properties of fiber-modified asphalt mixtures. *Int J Fatigue*; 31:1598-602.

Baghaee Moghaddam T, Rehan Karim M & Symmaun T. (2012). Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. *Constr Buil Mater*, 34:236–42.

Ahmadinia E, Zargar M, Karim MR, Mahrez A & Shafigh P. (2011). Using waste plastic bottles as additive for stone mastic asphalt. *Mater Des,* 32:4844–9.

Vázquez, I. (2010). Ventajas y Desventajas del Uso de Polímeros en los Asfaltos.

NLT-159 «Resistencia a la deformación plástica de mezclas bituminosas empleando el aparato Marshall».

Vilaplana, J. (2015). Development of a ravelling test for bituminous mixes for wearing surfaces.

ASTM C136-01, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM International, West Conshohocken, PA, 2001, DOI: 10.1520/C0136-01.

Especificaciones generales para la construcción de caminos y puentes. (2002). *Ministerio de Obras Públicas y Comunicaciones (República del Ecuador)*

ASTM C128-07, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate, ASTM International, West Conshohocken, PA, 2007, DOI: 10.1520/C0128-07.

Cavanzo, J., & Ortiz, M. Mejoramiento de la capa asfáltica mediante la inclusión de desechos plásticos. Pontificia Universidad Javeriana (Bogotá, Colombia). 2002.

NLT-352/86 «Caracterización de las mezclas bituminosas abiertas por medio del ensayo cántabro de pérdida por desgaste».