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Hot Mix Asphalt Behavior with Recycled PET and Crumb Rubber as Aggregate Substitutions

Ana Ortiz-Viñán[1], Jhonathan Verdesoto[2]
[1]Universidad Técnica Particular de Loja/UTPL
calle París, Loja, Ecuador
aportiz1@utpl.edu.ec; javerdesoto@utpl.edu.ec
Loja, Ecuador

Abstract – This study analyzes the performance of asphalt mixtures incorporating waste particles, specifically polyethylene terephthalate (PET) and crumb rubber from disused tires, as partial substitutes for natural aggregates. The primary objective is to determine their applicability as a wearing course in medium-traffic roads (MAC-2 type), according to the Ecuadorian Road Standard (NEVI 12). A quantitative analysis was conducted through an experimental design that included the characterization of natural aggregates, the determination of the optimum asphalt cement content (AC-20 type), and the design and preparation of asphalt mixtures with the waste materials. Marshall evaluation was applied to determine characteristics such as stability, flow, density, and air voids content in a base mixture and mixtures prepared with 1%, 1.5%, and 2% of PET and crumb rubber as fine aggregate substitutes. The Marshall evaluation results of the mixtures prepared with various percentages of waste in aggregate substitution, when compared to the base asphalt mixture, demonstrate compliance with NEVI 12. It was determined that the low density of PET and crumb rubber is the primary factor causing a significant variation in the volumetric properties of the mixture, with the air voids percentage being the most relevant. The best performance, according to the parameters specified in the standard, was achieved by substituting 1% of fine aggregate with PET and by substituting 1% and 1.5% of fine aggregate with crumb rubber, concluding their suitability as a wearing course. Recycled materials, such as PET and crumb rubber, can be utilized as modifiers in asphalt mixtures, allowing for the preservation of properties. Their use contributes to environmental protection by promoting the development of recycling focused on solid waste management for pavement construction applications.

Keywords: PET, asphalt mixture, marshall method, crumb rubber

1. Introduction

The increasing transportation demands in Ecuador necessitate the annual construction of thousands of kilometers of roads, encompassing both new route development and the restoration of existing pavements. According to [1], hot mix asphalt (HMA) constitutes the most widely used wearing course on Ecuadorian roads. However, the production of this type of mixture requires high temperatures, leading to the emission of toxic gases into the environment and contributing to global warming [2].

In recent years, various waste materials have been investigated for their potential use in asphalt mixtures, yielding promising results that classify them as applicable in major roadways. It has been concluded that certain waste materials can be incorporated into asphalt mixtures to mitigate pothole formation [3].

When asphalt mixtures containing materials such as crumb rubber were analyzed for their Marshall properties, moisture susceptibility, and rutting resistance, they consistently met the specified requirements [4]. Furthermore, the incorporation of crumb rubber (CR) into asphalt mixtures offers the potential for cost-effectiveness while simultaneously conserving valuable landfill space [5]. Consequently, crumb rubber is recognized as one of the most popular asphalt modifiers due to its economic benefits and the desirable physical and rheological properties it imparts to asphalt binders and mixtures [6].

The integration of waste particles like polyethylene terephthalate (PET) in construction presents environmental advantages [7], offering a viable and sustainable option within the industry. This contributes to reducing the environmental footprint and fostering a circular economy in the construction sector [8]. Studies on the application of other waste materials, such as PET, in asphalt mixtures have demonstrated enhanced deformation resistance with increased stability, lower flow, and a higher Marshall quotient compared to control mixtures [9].

Based on the aforementioned research, this study was conceived with the objective of evaluating various percentages of recycled materials, specifically PET and crumb rubber, as aggregate substitutes in the design of hot mix asphalt. These mixtures were analyzed using the Marshall method. For this research, the Municipality of Loja provided natural aggregates and AC-20 asphalt binder.

2. Materials and Methods

The experimental methodology consisted of designing and defining a base asphalt mixture, which was then analyzed with variations of PET and crumb rubber fine aggregate particles. The methodological process is summarized in Figure 1.

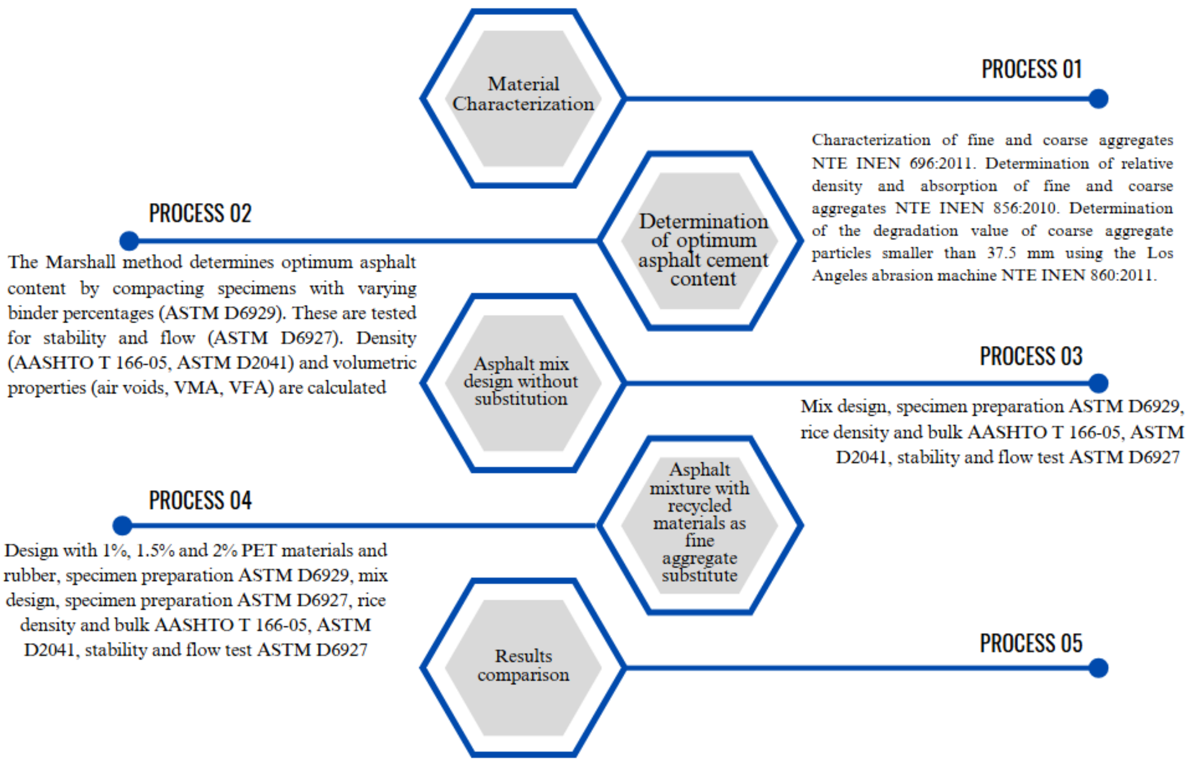

Fig 1. Methodological process

2.1 Materials

The following details the materials employed as natural aggregate substitutes.

Plastic particles with dimensions between 2,5 mm and 4 mm, passing the No. 8 sieve or retained on the No. 50 sieve, were obtained from waste plastic bottles collected at the Integrated Solid Waste Management Center of the Loja Municipal Government. Their processing was carried out at the crushing plant owned located in the city of Ambato, Tungurahua province.

The rubber particles applied in this research were provided by the company ECSADE S. A., located in Durán canton, Guayas province. For their use, the rubber particles were transported to the city of Loja and did not receive any physical or chemical treatment. The rubber particle dimensions range from 2 to 3 mm.

The asphalt cement employed in the canton's wearing courses was provided by the Municipality. Table 1 presents a summary of the AC-20 type asphalt cement's characteristics

Table 1: Summary of AC-20 asphalt cement characteristics

Test Name	AASHTO & ASTM Standard	NEVI Requirement	Asphalt Cement (Experimental Value)
Kinematic Viscosity at 135°C	ASTM D2170	210 Pa·s min	364 Pa·s
Determination of flash point in open cup	AASHTO T79-96	232°C	298°C
Determination of fire point in open cup	AASHTO T79-96	--	316°C
Penetration at 25°C	ASTM D5	40 ths m/m	64.3 ths m/m
Density at 25°C	ASTM D70	1600 to 2400	2300 Poise
Softening point of bituminous material	AASHTO T53	--	57°C
Stripping of nituminous material on aggregate sample	ASTM D1559	10%	5%

Percentages of PET and crumb rubber were incorporated into the asphalt mixture relative to the 5,4% optimum asphalt content.

3. Results

Table 2 and Table 3 summarize the proportions for the base asphalt mixture (containing 0% of substitutes), as well as the material weights when including 1%, 1,5%, and 2% of PET and crumb rubber particles, respectively, as substitutes for natural aggregate

Table 2. Asphalt mix design with PET substitution percentages

% PET adición	briquette No.	weight					
		Fine aggregate (g)	aggregates (g)	PET (g)	Aggregates + PET (g)	asphalt (g)	total mix (g)
0	1	660,00	1200,19	0,00	1200,19	64,81	1265,00
	2	660,00	1200,28	0,00	1200,28	64,82	1265,10
	3	660,00	1200,09	0,00	1200,09	64,81	1264,90
1	1	653,40	1193,50	6,53	1200,03	64,80	1264,83
	2	653,40	1193,40	6,53	1199,93	64,80	1264,73
	3	653,40	1193,40	6,53	1199,93	64,80	1264,73
1,5	1	650,10	1190,10	9,75	1199,85	64,80	1264,65
	2	650,10	1190,10	9,75	1199,85	64,80	1264,65
	3	650,10	1190,10	9,75	1199,85	64,80	1264,65
2	1	646,80	1186,80	13,20	1200,00	64,80	1264,80
	2	646,80	1186,80	13,20	1200,00	64,80	1264,80
	3	646,80	1186,80	13,20	1200,00	64,80	1264,80

Table 3. Asphalt mix design with crumb rubber substitution percentages

% crumb rubber adición	briquette No.	weight					
		Fine aggregate (g)	aggregates (g)	crumb rubber (g)	aggregates + crumb rubber (g)	asphalt (g)	total mix (g)
0	1	660	1200,19	0	1200,19	64,81	1265
	2	660	1200,28	0	1200,28	64,82	1265,1
	3	660	1200,09	0	1200,09	64,81	1264,9
1	1	654,5	1193,5	6,5	1200,05	64,8	1264,9
	2	655,1	1193,4	6,6	1199,95	64,8	1264,8
	3	654	1193,4	6,5	1199,94	64,8	1264,8
1,5	1	660	191	9,90	1200,00	64,8	1265,7
	2	659,8	1190,1	9,90	1200,90	64,8	1264,8
	3	657,3	1190,1	9,86	1199,99	64,8	1264,7
2	1	659,7	1186,8	13,19	1199,99	64,8	1264,8
	2	659,4	1186,8	13,19	1199,99	64,8	1264,8
	3	660	1186,8	13,20	1200,00	64,8	1264,8

The temperature of the mixture (aggregates and asphalt cement) was maintained between 140 °C and 150°C.

The Marshall evaluation test results for medium traffic design, MAC-2 type according to NEVI 12, applied to asphalt mixture briquettes containing varying percentages of PET and crumb rubber are summarized in Table 4 and Table 5.

Table 4. Results of asphalt mixtures with PET aggregate substitution

Criterion	NEVI 12 Standard	BASE	PET		
			1%	1,50%	2%
Air Voids (Va), %	3 to 5	4,38	3,35	3,99	6,07
Voids in Mineral Aggregate (VMA), %	14 minimun	14,33	14,52	15,36	19,43
Voids Filled with Asphalt (VFA), %	65 to 78	69,45	76,95	74,04	68,73
Stability (kN)	5,34 minimum	12,39	13,14	11,9	7,91
Flow (mm)	8 to 16	12	8	7	8

Mixtures incorporating 1% PET as an aggregate substitute successfully meet all specifications of the NEVI 12 standard. However, when 1,5% PET is substituted, the flow value is lower than specified. This reduction in flow, as stated by, indicates an increase in the overall mixture stiffness[6]. Furthermore, substituting 2% PET for aggregate results in a non-compliant air voids percentage, which is higher than required. According to [10], excessive air voids act as channels for oxygen and moisture ingress into the mixture, accelerating the oxidation process of the asphalt binder and consequently causing its premature hardening and embrittlement. As noted by [11], increasing PET content in asphalt generally leads to increased brittleness and reduced flexibility; in this study, the addition of 2% PET resulted in the asphalt mixture failing to meet the required air voids percentage. The mixture's properties are also influenced by volumetric substitutions, selected based on specific gravity differences between PET granules and pure mineral aggregates, aiming for a consistent mixture [12]. The stability of a mixture is closely related to its resistance to deformation under traffic loads. Conversely, the stability value increases with increasing levels of PET plastic in the mixture.

Table 5. Results of asphalt mixtures with crumb rubber aggregate substitution

Criterion	NEVI 12 Standard	BASE	crumb rubber		
			1%	**1,50%**	**2%**
Air Voids (Va), %	3 to 5	4,38	6,84	3,21	3,63
Voids in Mineral Aggregate (VMA), %	14 minimun	14,33	17,71	15,87	16,79
Voids Filled with Asphalt (VFA), %	65 to 78	69,45	61,37	78,39	79,76
Stability (kN)	5,34 minimum	12,39	7,59	11,52	9,57
Flow (mm)	8 to 16	12	9	8	8

Regarding crumb rubber, the addition of 1% and 1,5% of this waste material resulted in mixtures that meet all established normative requirements. However, substituting 2% crumb rubber for aggregate led to a non-compliant VMA (Voids in Mineral Aggregate) value, as it exceeded the specified limit. According to [13], VMA is a critical volumetric parameter that ensures the durability of asphalt mixtures by providing an adequate asphalt film thickness on the aggregates. Consequently, it has been observed that adding fibers to asphalt mixtures increases VMA content at the optimum bitumen content, particularly in mixtures incorporating a high content of lightweight fibers [14]. [15] determined that Marshall stability in rubber-modified mixtures is an indicator of the mixture's high-temperature performance.

When 2% crumb rubber is substituted for aggregate, the mixture's non-compliance may lead to increased susceptibility to permanent deformation (rutting) under high-temperature and traffic conditions [6]. The percentage of voids in the mineral aggregate (VMA) represents the volume of voids between the ¾ inch aggregate particles in the compacted mixture. The Asphalt Institute recommends a minimum VMA of 14% for mineral aggregate with a nominal maximum size of 19 mm. [17]

A higher quantity of plastic additives typically generates larger voids in the aggregate, as they may not be capable of homogeneously bonding with the asphalt binder or the aggregate [18]. This phenomenon can also be attributed to the potential for rubber particles to swell 3 to 5 times their original size due to the absorption of the maltene component of the bitumen [19].

4. Conclusion

The low specific gravity of both PET and crumb rubber constitutes the primary factor inducing significant variations in the volumetric properties of the asphalt mixture, with the air voids percentage being the most prominently affected. In this context, the optimal performance, as per the parameters specified in NEVI 12, was achieved by substituting 1% of PET and by substituting 1% and 1,5% of crumb rubber as fine aggregate replacements.

Recycled materials, including PET, crumb rubber, and slag, demonstrate viable potential for employment as modifiers in asphalt mixtures. Beyond enhancing the intrinsic properties of these mixtures, their utilization contributes significantly to environmental stewardship by fostering the development of a recycling economy centered on solid waste management for pavement construction applications.

The obtained results indicate a general trend of decreasing stability and flow in asphalt mixtures as the substitution percentage of fine aggregate with recycled PET and crumb rubber increases.

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