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Design of Asphalt Mixtures Integrating Solid Waste from the Automotive Industry (Elastomer) and Roadways (Aged Asphalt Pavement) in Manabí, Ecuador

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Abstract: The purpose of this study is to design asphalt mixtures by integrating solid waste from used tires (elastomer) and aged asphalt pavement in Bolívar Canton, Manabí Province, Ecuador. The factors studied were 4%, 8%, 12% and 16% elastomer, and fine, average and coarse grading, using 52% aged asphalt pavement. A completely randomized two-way factorial arrangement, GxE+1, with thirteen treatments and three replications was used, where G corresponds to grading of aggregates used and E to elastomer. On the basis of the positive outcome of the design of asphalt mixtures with aged asphalt pavement, considering the addition of 4%, 8% and 12% of elastomer in the average and fine grading curves, it was concluded that the design can be used in light and medium traffic roads, such as those in Bolívar Canton, Ecuador.
Key words: elastomer; aged asphalt pavement; industrial waste

1. Introduction

There are approximately 800 million commercial vehicles in use worldwide, with an annual increase of nearly 70 million vehicles (International Bureau of Recycling, 2016). In addition, according to data from Pelaez, Velasquez, and Giraldo (2017), global raw material consumption was estimated to be 28.9 million tons in 2014, an increase of 0.7% in 2015. Among all the global quantities mentioned above, 'Ecuador discards approximately 2.4 million tires annually' (Castro, 2015, p. 2), and due to its design to provide maximum wear resistance during use, it is estimated that natural decomposition will occur over 600 years. The composition of these tires includes hazardous elements such as lead, chromium, cadmium, and other heavy metals, which can pose a threat to health and the environment if not handled properly (Bertalot, 2017). The recycling of asphalt pavement is carried out on deteriorated materials that have severely lost their initial characteristics. It is technically feasible to recycle ground materials and enrich this by adding glass materials (Public Works Research and Experimental Center, 2011).

On the other hand, Sanchez (2012) pointed out that "materials obtained after processing tire residues, once industrially usable residues are separated, may have multiple uses" (page 29). In addition, scholars Sanchez (2012), Martin (2015), Grisenko, Pozdniakova, and Funukova (2015) unanimously believe that one of the applications of rubber is as a component of asphalt layers used in road construction, thereby reducing dry mining in quarries. They also give it special characteristics as it can be used as rubber in rolling layers to help achieve higher average life, greater elasticity, less deformation, higher crack resistance, and higher creep resistance. In addition, it also has the characteristics of a drainage pavement, which obstructs the asphalt mixture when it accumulates water, thereby increasing its adhesion, avoiding water projection, and providing good optical conditions and low noise. In this way, it has both environmental and economic benefits, as with the addition of rubber, the tracks become stronger, more durable, and less fragile, even resisting their breakage, with a lifespan of 10 years (Amorim and Lima, 2018).

On the other hand, Lacamara (2014) provided us with relevant data indicating that "1000 to 7000 tires can be used every two lane highway kilometers. Such high numbers make asphalt pavement one of the main solutions for using waste tires" (paragraph 13). Therefore, road recycling is a more competitive and sustainable alternative to road repair, as it can minimize the use of non renewable resources, natural aggregates, and asphalt; In addition, it also prevents the generation of waste and the occupation of trash cans (Paiva and Ramos, 2014). It also includes a range of constructive technologies aimed at comprehensively utilizing aging materials from both the company and the road surface. Therefore, it is crucial to develop a sustainable recommendation for those who rely on informal recovery of things discarded by others and face health risks. In this informal sector, what is important is how many boys and girls find the only way to survive in an often indifferent society through waste recycling work (Lecitra, 2010, p. 4). Through this approach, Bolivar State in Manabi Province, Ecuador plans to design asphalt mixtures by integrating solid waste from discarded tires (elastomers) and aged asphalt pavements.

2. Methodology

2.1 Experimental design

The research used a completely randomized design (CRD) in a bifactorial arrangement GxE+1 with thirteen treatments and three replicates, where G corresponds to the particle size and E to the elastomer. InfoStad software was used to determine the coefficient of variation (CV%), and in the variables where statistical differences were found, the Tukey test was performed at 5% with probability of error.

2.2 Aggregate dosage

The dosage of the materials and the tolerance were determined according to the values in Table 1, which is recommended by the general specifications for the construction of roads and bridges (Ministry of Transportation and Public Works of Ecuador, 2002).

Table 1. General specifications for road and bridge construction

Sieve	Weight percentage passing through the sieve			
	N.° 3/4	N.° 1/2	N.° 3/8	N.° 4
N.° 1 (25.4 mm)	100			
N.° 3/4 (19.0 mm)	90-100	100		
N.° 1/2 (12.7 mm)		90-100	100	
N.° 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)				40-80
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

Ministry of Transportation and Public Works of Ecuador (2002).

2.3 Material particle size

The abrasion test was performed on the 1/2 material, which was carried out with gradation B, which consists of obtaining material extracted from the granulometry, using 2500 g ± 2 passing the 19 mm or No. 3/4 sieve, retained in the 12.5 mm or No. 1/2 and 2500 g ± 2, passing the 12.5 mm or No. 1/2 sieve, retained in the 9.5 mm or No. 3/8, and placed in the Los Angeles machine, where 500 turns are made. Once finished, the material is removed and sieved by the 1.70 mm or No. 12, washed and dried at 110 °C. After drying, it is weighed to calculate the wear coefficient.

The unit mass or volumetric weight test consisted of having the materials (1/2, 3/8, aggregate and sand) completely dry, metal moulds with known weights and volumes to carry out the test, which consists of adding material in a constant manner until the container is full, levelling and weighing. Thus, the procedure is repeated 3 times to know the loose unit mass. On the other hand, for the compacted unit mass, the container is filled in three equal layers and 25 rod strokes are given per layer. Once the tests have been carried out on the 1/2 (aggregate 1), 3/8 (aggregate 2), aggregate (aggregate 3) and sand (aggregate 4) materials, the results are entered and calculated, as shown in Table 2.

Table 2. Aggregate mix (Own elaboration)

Joint particle size distribution of the mixture							
Material type	Percentage	Percentages passing through sieves					
		N.° 3/4	N.° 1/2	N.° 4	N.° 8	N.° 50	N.° 200
Aggregate N.° 1	12%	12.0	6.2	0.3	0.3	0.2	0.2
Aggregate N.° 2	28%	28.0	28.0	4.9	1.1	0.9	0.7
Aggregate N.° 3	45%	45.0	45.0	42.5	27.5	12.4	5.7
Aggregate N.° 4	15%	15.0	15.0	14.9	14.5	4.4	0.2
Obtained granularity		100.0	94.2	62.5	43.3	18.0	6.8
Specifications		100	90-100	44-77	28-58	5-21	2-10
Expected granularity		100.0	95.0	60.5	43.0	13.0	6.0

2.4 Determination of the optimum percentage of asphalt

This is obtained with the optimum percentage of asphalt defined from the voids curve, with which 6.2% was obtained, as shown in Table 3. In addition, the other results of the curves were obtained, such as unit weights (density), voids, stability, mineral aggregate voids, flow and VFA.

Table 3. Marshall's design to obtain the optimum percentage of asphalt (Own elaboration)

Properties	% asphalt-design	Value obtained	Requirements
Stability	6.20	2546	> 1800 lb
Flow	6.20	12.0	8-16 in/100
Unit weight	6.20	2281	< 2000
Voids in mix	6.20	4.0	3.0-5.0%
Voids in aggregates	6.20	15.20	> 13%
Voids filled with asphalt	6.20	71	65-75%

2.5 Integration of the aged asphalt pavement and the elastomer

The molding and testing of the briquettes in the research were carried out in a similar way, only with the inclusion of tire dust, passing the No. 10 sieve and retained on the No. 40 sieve and aged asphalt pavement. The stone aggregates were mixed individually without the addition of solid residues, maintaining temperatures with maximum and minimum (160 ºC - 80 ºC). According to Figueroa, Fonseca, Amaya and Prieto (2008), at this temperature there is a better mixing process, achieving greater homogenization in the modified asphalt binder. Table 4 shows the average values of the Marshall design requirements, where 52% of aged asphalt pavement was used and it was determined that the asphalt pavement does not meet the requirements proposed by the Ministry of Transportation and Public Works of Ecuador (2002) and Garnica, Delgado, Gómez, Alonso and Alarcón (2004), so stone aggregates were included.

Table 4. Marshall's design of aged asphalt pavement (Own elaboration)

Properties	% asphalt-design	Value obtained	Requirements
Stability	5.70	3381	> 1800 lb
Flow	5.70	15.5	8-16 in/100
Unit weight	5.70	2174	> 2000
Voids in mix	5.70	6.37	3.0-5.0%
Voids in aggregates	5.70	19.62	> 13%
Voids filled with asphalt	5.70	67.37	65-75%

Tables 5, 6, and 7 show the particle size of 52% aged asphalt pavement rich in stone aggregates.

Table 5. Center particle size distribution of aged asphalt pavement rich in stone aggregates (Own elaboration)

Combined graduation for mixing							
Type of material	Percentages for mixing	Percentages passing through sieves					
		N.° 3/4	N.° 1/2	N.° 4	N.° 8	N.° 50	N.° 200
Aggregate N.° 1	10%	10.0	4.8	0.2	0.2	0.1	0.1
Aggregate N.° 2	16%	16.0	16.0	2.3	0.7	0.5	0.4
Aggregate N.° 3	16%	16.0	16.0	15.3	10.2	4.8	2.0
Aggregate N.° 4	6%	6.0	6.0	5.9	5.8	1.7	0.1
Recycled	52%	52.0	50.4	37.7	25.8	10.5	2.0
Obtained granulometry		100.0	93.2	61.4	42.7	17.6	4.6
Specification		100	90-100	44-77	28-58	5-21	2-10
Expected granulometry		100.0	95.0	60.5	43.0	13.0	6.0

Table 6. Fine particle size grading of aged asphalt pavement enriched with stone aggregates (Own elaboration)

Combined graduation for mixing							
Type of material	Percentages for mixing	Percentages passing through sieves					
		N.° 3/4	N.° 1/2	N.° 4	N.° 8	N.° 50	N.° 200
Aggregate N.° 1	8%	8.0	3.8	0.1	0.1	0.1	0.1
Aggregate N.° 2	8%	8.0	8.0	1.2	0.3	0.3	0.2
Aggregate N.° 3	26%	26.0	26.0	24.9	16.6	7.8	3.3
Aggregate N.° 4	6%	6.0	6.0	5.9	5.8	1.7	0.1
Recycled	52%	52.0	50.4	37.7	25.8	10.5	2.0
Obtained granulometry		100.0	94.2	69.8	48.8	20.3	5.6
Specification		100	90-100	44-77	28-58	5-21	2-10
Expected granulometry		100.0	95.0	60.5	43.0	13.0	6.0

Table 7. Coarse particle size grading of aged asphalt pavement enriched with stone aggregates (Own elaboration)

Combined graduation for mixing							
Type of material	Percentages for mixing	Percentages passing through sieves					
		N.° 3/4	N.° 1/2	N.° 4	N.° 8	N.° 50	N.° 200
Aggregate N.° 1	12%	12.0	5.7	0.2	0.2	0.2	0.1
Aggregate N.° 2	22%	20.0	22.0	3.2	0.9	0.7	0.5
Aggregate N.° 3	14%	14.0	14.0	13.4	9.0	4.2	1.8
Aggregate N.° 4	2%	2.0	2.0	2.0	1.9	0.6	0.0
Recycled	52%	52.0	50.4	37.7	25.8	10.5	2.0
Obtained granulometry		100.0	94.1	56.5	37.8	16.1	4.5
Specification		100	90-100	44-77	28-58	5-21	2-10
Expected granulometry		100.0	95.0	60.5	43.0	13.0	6.0

Once the optimum percentage of asphalt in the mix was established, which turned out to be 6.2%, the tire powder was added in different percentages, from 4% to 16%, by means of the dry process.

3. Results and Discussion

3.1 Bulk density

Table 8 shows the average values of the variable "Bulk density". The analysis of variance (ADEVA) did not determine statistical differences for factor G, nor for factor E, neither in the GxE interaction nor in the factorial comparison versus control.

Table 8. Bulk density, percentage of voids in the mix and stability. Design of asphalt mixtures integrating solid wastes from the automotive (elastomer) and road (aged asphalt pavement) industries (Own elaboration)

Treatments	Bulk density	% of voids in the mixture	Stability
Factor G	NS	**	**
G1 fine granulometry	2282.17	4.26% (a)	2849.09 lb (a)
G2 medium granulometry	2274.67	4.58% (ab)	2880.86 lb (a)
G3 coarse granulometry	2272.50	5.00% (b)	2640.34 lb (b)
E factor	NS	NS	**
E1 4% elastomer	2270.11	4.73%	2785.78 lb (b)
E2 8% elastomer	2274.89	4.60%	2883.15 lb (b)
E3 12% elastomer	2276.56	4.46%	3018.59 lb (a)
E4 16% elastomer	2284.22	4.64%	2472.87 lb (c)
Interaction	NS	NS	**
G1E1	2282	4.15%	2890.00 lb (ab)
G1E2	2284.67	4.27%	2953.57 lb (ab)
G1E3	2279.33	4.49%	2042.36 lb (a)
G1E4	2282.67	4.13%	2510.42 lb (de)
G2E1	2267.33	5.00%	2870.94 lb (abc)
G2E2	2275.67	4.42%	2935.18 lb (ab)
G2E3	2281.67	4.18%	3119.73 lb (a)
G2E4	2274	4.72%	2597.57 lb (cd)
G3E1	2261	5.05%	2596.39 lb (cd)

Treatments	Bulk density	% of voids in the mixture	Stability
G3E2	2264.33	5.12%	2760.70 lb (bcd)
G3E3	2268.67	4.72%	2893.68 lb (ab)
G3E4	2296	5.07%	2310.61 lb (e)
Factorial versus control	NS	NS	**
Absolute control	2286.67	4.21%	2605.67 lb (c)
Granulometry	2278.11	4.61%	2790.10 lb (a)
Elastomer	2290.30	4.60%	2640.10 lb (b)
Coefficient of variation	0.87	9.75	3.38
P	0.6711	0.044	<0.0001

(*) Significant difference between treatments.
(**) Highly significant difference between treatments. Letters in common are not statistically different.

3.2 Percentage of voids in the mixture

Table 8 shows the average values of the variable "% voids in the mix"; the ADEVA did not determine statistical differences for factor E, neither in the GxE interaction, nor in the factorial comparison versus control, with the exception of factor G. The significance test determined two ranges of statistical similarity in factor G, where the best "% voids in the mix" corresponded to G1 with 4.26%, followed by G2. In this regard, the Ministry of Transport and Public Works of Ecuador (2002) states that 5% is the maximum value required in the percentage of voids, therefore the coarse grain size with 5% does not meet the requirements; in addition, it is worth adding that the permitted percentage of voids in laboratory samples for base and surface layers is between 3% and 5%.

3.3 Stability

Table 8 shows the average values of the variable "Stability"; the ADEVA determined significant statistical differences for factor G, factor E, the GxE interaction and for the factorial comparison versus control. In the significance test performed on factor G, two ranges of statistical similarity were established, of which G2 obtained the greatest stability with 2880.86 lb; on the other hand, G3, with 2640.34 lb, obtained the lowest stability. Likewise, in the significance test performed on factor E, three ranges of statistical similarity were determined, where E3 stood out with the greatest stability with 3018.59 lb; and E4, with 2472.87 lb, obtained the lowest stability. In the significance test performed on the GxE interaction, four statistical similarity ranges were established, where G2E3 (medium G-12% elastomer) and G1E3 (fine G-12% elastomer) had 3119.73 lb and 3042.36 lb, respectively. In addition, G2E3 and G1E3 stood out with the highest stability, while G3E4 (G thick-16% elastomer) had the lowest stability at 2310.61 lb. In the factorial comparison versus control, three ranges of statistical similarity were established, where the G factor stood out with 2790.10 lb, followed by the E factor with 2640.10 lb and, in last place, the control with 2605.67 lb of stability.

A stable pavement is capable of maintaining its shape and smoothness under repetitive loads [...]. Stability specifications should be high enough to adequately accommodate the expected traffic, but not higher than the traffic conditions demand [sic] (Carrasco, 2004, p. 65).

Likewise, the Ministry of Transportation and Public Works of Ecuador (2002) requires stabilities greater than 1800 lb, for all treatments to comply with Marshall's design requirements.

3.4 Flow

Table 9 shows the average values of the variable "Flow"; the ADEVA did not determine statistical differences for the GxE interaction; on the contrary, statistical differences were found for the G factor, the E factor and the factorial comparison versus control. The significance test performed on factor G established two ranges of statistical similarity, where G2 and G1 resulted with 14.42 in/100 and 14.83 in/100, respectively, and stood out on the coarse grain size with 15.17 in/100. In the statistical test performed on factor E, two ranges of statistical similarity were established, resulting in E1, E2 and E3, with 14.44 in/100, 14.56 in/100 and 14.89 in/100, respectively, which showed good flow values compared to the 15.33 in/100 of E4. The significance test performed on the comparison of the factorial versus the control established two ranges of statistical similarity, of which the control obtained the best flow value with 13 in/100, followed by factors G and E with 14.81 in/100 in both cases.

Table 9. Flow, voids in mineral aggregates and voids in asphalt fillers. Design of asphalt mixtures integrating solid wastes from the automotive (elastomer) and road (aged asphalt pavement) industries (Own elaboration)

Treatments	Flow in/100	% of voids in mineral aggregates	% of voids in asphalt fills
Factor G	*	**	**
G1 fine granulometry	14.83 (ab)	15.12% (b)	71.80% (a)
G2 medium granulometry	14.42 (a)	15.40% (b)	70.36% (ab)
G3 coarse granulometry	15.17 (b)	15.82% (a)	68.47% (b)
E factor	*	NS	NS
E1 4% elastomer	14.44 (a)	15.57%	69.66%
E2 8% elastomer	14.56 (ab)	15.39%	70.17%
E3 12% elastomer	14.89 (ab)	15.33%	70.96%
E4 16% elastomer	15.33 (b)	15.49%	70.14%
Interaction	NS	NS	NS
G1E1	14.67	15.12%	72.57%
G1E2	14.33	15.03%	71.67%
G1E3	15.00	15.22%	70.59%
G1E4	15.33	15.10%	72.67%
G2E1	14.00	15.67%	68.13%
G2E2	14.00	15.36%	71.27%
G2E3	14.67	15.15%	72.47%
G2E4	15.00	15.43%	69.55%
G3E1	14.67	15.92%	68.29%
G3E2	15.33	15.78%	67.57%
G3E3	15.00	15.63%	69.83%
G3E4	15.67	15.94%	68.18%
Factorial versus control	**	NS	NS
Absolute control	13.00 a	14.96%	71.92%
Granulometry	14.81 b	15.45%	70.21%
Elastomer	14.81 b	15.59%	70.23%
Coefficient of variation	4.42	2.57	3.04
P	0.0001	0.041	0.038

(*) Significant difference between treatments.
(**) Highly significant difference between treatments. Letters in common are not statistically different.

In this way, asphalt mixes with reusable material only meet the requirements for medium and heavy traffic, which coincides with the Ministry of Transport and Public Works of Ecuador (2002), which establishes that the minimum should be 8 in/100 for all types of traffic, such as very heavy, heavy, medium and light. The maximum flow value required for very heavy and heavy traffic will be 14 in/100; on the other hand, for medium and light traffic it can be extended to a maximum of 16 in/100.

3.5 Pores in mineral aggregates

Table 9 shows the values of the variable 'percentage of voids in mineral aggregates'; ADEVA did not identify significant statistical differences in the interaction between factor E, GxE, and the comparison between factors and witnesses; However, it determined the statistical differences of factor G. In the significance test of factor G, two statistical similarity ranges were established, where factor G3 emphasized a porosity of 15.82% in mineral aggregates, while G1 and G2 were 15.40% and 15.12%, respectively, and parameter values were obtained in the "porosity in mineral aggregates". The requirements of the Ecuadorian Ministry of Public Transport (2002) do not specify the maximum value to be considered, therefore, it is incorrect to claim that the larger the voids in mineral aggregates, the larger the space for asphalt film. Therefore, according to Carrasco (2004):

VMA [oVAM] has a minimum value, it is recommended to specify it as a function of aggregate size. These values are based on the fact that the thicker the asphalt particles covering the aggregate particles, the more durable the mixture is (pages 62-63).

3.6 Vacuums in asphalt fillers

Table 9 shows the mean values of the variable "% of voids in asphalt fillings"; the variance analysis determined statistical differences for factor E, GxE interaction and factor versus control comparison; however, statistical differences were evidenced for factor G. In the significance test performed for factor G, two ranges of statistical similarity were established, in which G3 stood out with 68.47%, followed by G2 with 70.36% and, finally, G1 with 71.80%. In this way, the results coincide with the requirements of the Marshall design, which establishes a minimum value of 65% and a maximum of 75% (Ministry of Transport and Public Works of Ecuador, 2002).

4. Conclusions

The addition of 4%, 8% and 12% elastomer in the design of asphalt mixtures with aged asphalt pavement resulted in a good practice, which serves to be used at the field level in modified asphalt mixtures. Medium and fine grain sizes, in the design of asphalt mixtures with aged asphalt pavement, contributed to obtaining good behavior with the reuse of elastomer and asphalt pavement, therefore, it can be used at the field level in modified asphalt mixtures.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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