

Article

Sustainable Pavement Construction in Sensitive Environments: Low-Energy Asphalt with Local Waste Materials and Geomaterials

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Abstract: Low-energy asphalt techniques, such as warm mix asphalt (WMA), combined with the rational consumption of geomaterials and waste recycling would promote more sustainable and energy-efficient asphalt pavements. In volcanic environments, a significant proportion of aggregate production is discarded due to its extreme porosity, and used tires generate a main environmental issue as well. While recycled rubber powder from tire waste can enhance the mechanical behavior of asphalt, it also raises its viscosity. Therefore, joining rubberized asphalt containing local waste geomaterials with WMA technologies is crucial to reduce the manufacturing temperatures and emissions and to produce more eco-efficient pavements. For this purpose, the most relevant technological characteristics of rubberized warm mix asphalt with residual aggregates from highly vesiculated volcanic rocks are tested in the laboratory and contrasted with conventional mixtures. The outcomes demonstrate not only the feasibility of the production of such mixtures in line with the current specifications, but also show a significant improvement in the resistance to moisture and to plastic deformations, and an improvement in the stiffness modulus. The eco-efficiency indicators conclude that the energy consumption and emissions are reduced by 9%, enabling the reuse of waste materials by more than 95%.

Keywords: sustainable asphalt pavement; low-energy asphalt; construction waste; used tire; reclaimed rubber; residual geomaterial; porous volcanic aggregate; eco-efficiency analysis



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1. Introduction

Today's society is challenged by the depletion of natural resources, increase in environmental pollution, and the reduction in biodiversity, and is increasingly aware of the need to protect the environment to achieve social development and economic growth. Sustainability in industrial processes must be based on the fact that innovations in new technologies incorporate sustainability principles, with an adequate analysis of their different dimensions and the creation of methodologies to maximize sustainable development [1].

The production of hot mix asphalt (HMA) for paving is among the most energy- and emission-intensive construction activities [2], with an annual global production of nearly 1.2 billion metric tons. The mixing temperatures are typically between 160 and 170 °C. This implies a yearly fuel consumption of over 9 billion liters (2.4 billion gallons) and CO₂ emissions of approximately 26 million metric tons per year worldwide (based on an average of 7.5 L of fuel consumption and 21.5 kg of CO₂ per metric ton of HMA [3]).

Low-energy asphalt technologies would enable the sustainable long-term use of these fundamental materials for transport infrastructures. In this regard, warm mix asphalt

(WMA) is a technique for manufacturing and compacting asphalt mixes at lower temperatures than conventional hot mixes (HMA), while maintaining their workability and mechanical characteristics. The reduction in temperature during the production of the mixture translates into lower energy requirements (i.e., fuel and electricity consumption) and lower emissions into the atmosphere. It also brings other notable benefits: (a) an improvement in workers' health and safety conditions, by reducing the risk of burns, smoke, and aerosol emissions [4,5]; (b) a reduction in binder aging due to oxidation [6]; and (c) longer transport distances regardless of climatic conditions [7].

WMA techniques can be grouped into diverse types, although all of them try to reduce the binder viscosity to produce the mixture at lower temperature, favoring its workability and compactability. These techniques are the following [7]: (a) binder foaming processes, by injection of sprayed water on the previously heated bitumen, which causes the violent expansion of steam, foaming the bitumen and reducing its viscosity; (b) organic additives of low melting point (i.e., paraffinic resins, waxes with long aliphatic chains) that reduce the viscosity of the mixture; (c) microfoaming inorganic additives (zeolites); and (d) surfactant additives, which promote the coating and adhesion of the binder with the mineral aggregates, decreasing the surface tension of the hot bitumen and the friction between both components, thus enhancing the workability of the mixture during its production and compaction. A comparative life cycle assessment of WMA technologies can be found in some previous research [8]; and the effect of certain chemical additives on the mechanical properties of recycled mixtures has also been assessed [9].

In asphalt mixtures, aggregates account for up to 95% of the total mass, which in general represents an economic and ecological problem for the mining industry [10,11], particularly in volcanic islands, where the impact of quarrying can be rather significant due to the limited territory and the impact of the extractive activities.

Most of the recent previous studies concerning bituminous mixtures containing recycled geomaterials are focused on Reclaimed Asphalt Pavement (RAP) [12,13] or Recycled Concrete Aggregates (RCA) [14,15], but those using residual volcanic aggregates are very limited [16,17]. However, on average, more than 75% of volcanic rocks are scoriaceous and vesicular types which are likely to produce aggregates whose mechanical properties do not satisfy the standard technical requirements due to their extreme heterogeneity, porosity, alveolar structure, and absorption, as well as the non-cubic particle shape [18]. The latter shape property also depends on the crushing method [19].

Consequently, most of the extraction of volcanic geomaterials is discarded because they are considered marginal aggregates and they are not recommended for structural applications. Furthermore, in these volcanic regions, the high degree of environmental protection of the territory prevents the opening of new quarries and landfills. For example, in the Canary Islands (28° N; 15.5° W), the protected natural areas cover the 60% of the territory; there are biosphere reserves (UNESCO) on every island, and five of the seven main islands are biosphere reserve on their own (i.e., the whole territory) [20,21]. Such territories have environmental attributes that need to be protected because of their special natural value, fragility, or vital ecosystem functions and are therefore considered sensitive environments. There are other characteristics commonly associated with these regions: (a) geographical limitations of the territory; (b) isolation and remoteness from the main economic areas; (c) the need to obtain the construction materials from their own local resources; (d) the difficulty of opening new extractive areas due to environmental protection constraints; (e) the fact that waste and residues must be processed and recovered in the same territory, contributing to the development of the local industry and economy.

As a result, the use of residual and marginal aggregates is a key issue to provide eco-friendly solutions to the building industry in these sensitive environments. Some other engineering applications of pyroclastic geomaterials such as volcanic ashes have been previously suggested [22,23] in other volcanic territories.

Another type of waste that generates a major environmental issue in sensitive environments is used tires, since they cannot be incinerated as fuels for clinker production, as

is often carried out elsewhere. However, reclaimed granulated rubber from End-of-Life Tires (ELT) can boost the mechanical behavior of bituminous mixtures if it is incorporated by replacing part of the mineral aggregate (also called rubberized mixtures by the “dry” process [24]) or previously blended with the bitumen to produce a Crumb Rubber-Modified Binder (CRMB), also called rubberized bitumen by the “wet” process [25–27]. In the last decade, a “semi-dry” method using a Reacted and Activated Rubber (RAR) that can be added directly to the asphalt plant has been used in the construction of pavements in certain countries [28], and more recently, some authors have proposed a “semi-dry/semi-wet” process technology [29]. In all cases, the blend of the recycled rubber particles with the bitumen at high temperature promotes the rubber swelling and chemical reactions that modify the elastomeric chains, the devulcanization (breaking of sulfur bonds), the absorption of aromatic fractions of the asphalt bitumen, and thus the modification of the rheological properties [30].

All these techniques aim to ensure that bituminous mixtures incorporating crumb rubber produce paving materials that can offer enhanced performance and durability [31]. They could also contribute to reduce the traffic noise [32–34] as well as the grain size degradation of the extremely porous aggregates during compaction works. However, the elastomeric properties of the rubber particles raise the asphalt viscosity, which also forces an increase in the manufacturing temperature of the asphalt admixture and, consequently, the energy consumption and emissions [35]. Therefore, combining rubberized asphalt with WMA technologies is crucial for the long-term sustainability of this asphalt rubber technique.

The amalgamation of these three technologies (WMA + CRMB + residual geomaterials) could lead to not only eco-friendly bituminous mixtures for paving applications, which would make it possible to achieve the emission reduction targets set by government policies, but also to increase their mechanical properties and durability, by reducing the pavement maintenance. For this purpose, a liquid chemical surfactant additive—composed of renewable components—is used in this study for the mixture manufacture and compaction at lower temperatures. This additive is more economical than granular microcrystalline waxes because it is used in smaller proportions, avoids cracking problems due to crystallization at low temperatures [36], and facilitates the additive dosage. In this study, the main technological characteristics of these rubberized warm asphalt mixtures with residual aggregate from highly vesiculated volcanic rocks are analyzed in the laboratory and confronted with conventional HMA with the same aggregate. Furthermore, their eco-efficiency is assessed.

2. Materials and Methods

2.1. Residual Volcanic Aggregate

All the mixtures were made with an olivine-pyroxene grey basalt of scoriaceous and vesicular structure, obtained from the same quarry (Figure 1). This type of high porosity aggregate is the most common in volcanic regions (approx. 75% of the exploitable resources), but it is considered a marginal or residual aggregate for the production of structural materials, and it is therefore relegated to being used only for embankments and fillings.

Table 1 shows the most relevant properties of the different aggregate fractions. These were determined by laboratory tests that were also carried out within the framework of this research. Ten samples of each of the aggregate fraction were obtained by quartering procedures using riffle sample splitters and the laboratory analysis according to the test methods of the European Standards (EN).

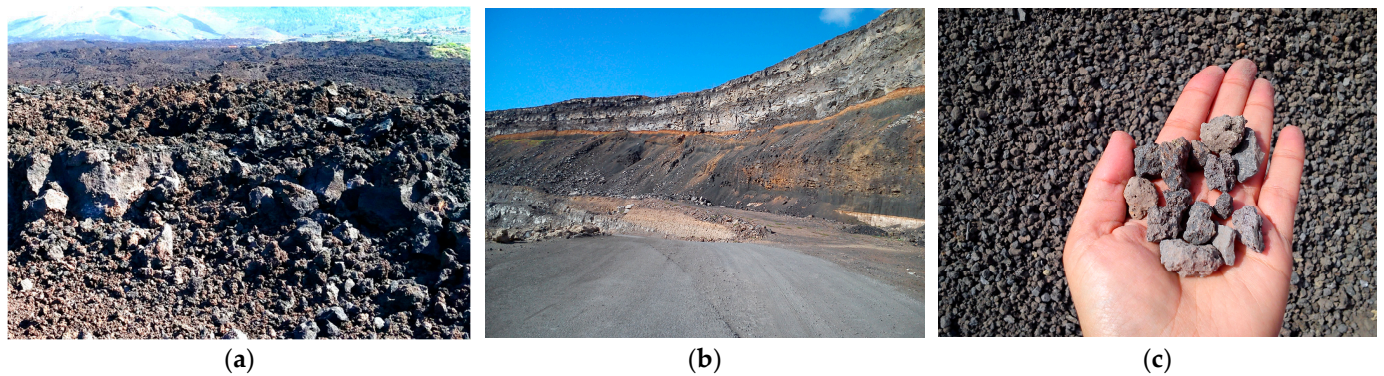


Figure 1. Vesicular volcanic aggregates: (a) rock structure of a lava flow; (b) typical heterogeneity, variability, and discontinuous special distribution of volcanic rocks in a quarry; (c) detail of the fraction 10–20 mm.

Table 1. Main characteristics of the asphalt mixture components.

	Aggregate (Scoriaceous and Vesicular Grey Basalt)			Mineral Filler (CEM II/B-P 32.5 R)	Penetration Grade Binders		
	# 10–20 mm	# 4–10 mm	# 0–4 mm	(# <0.063 mm)	35/50	CRMB 35/50	CRMB 35/50 + 0.5% ⁽³⁾ of Cecabase RT [®]
Proportion (%)	20.93 ⁽¹⁾	36.27 ⁽¹⁾	38.88 ⁽¹⁾	3.92 ⁽¹⁾	6 ⁽²⁾	6 ⁽²⁾	6 ⁽²⁾
ρ_a (g/cm ³)	2.45	2.88	2.89	-	-	-	-
ρ_{SSD} (g/cm ³)	2.36	2.56	2.63	-	-	-	-
ρ_{rd} (g/cm ³)	2.23	2.37	2.35	-	-	-	-
WA ₂₄ (%)	15.5	8.3	5.8	-	-	-	-
FI	-	6	6	-	-	-	-
Cc	56	60	-	-	-	-	-
SE ₄	-	-	73	-	-	-	-
LA	29	28	-	-	-	-	-
PSV	60	60	-	-	-	-	-
Dens. (g/cm ³)	-	-	-	-	1.042	1.028	1.027
Pen. ($\times 10^{-1}$ mm)	-	-	-	-	44	38	30
SP [R&B] (°C)	-	-	-	-	51.6	64.2	67.4
Visc. [at 60 °C] (cP)	-	-	-	-	51,000	215,000	211,000
Visc. [at 150 °C] (cP)	-	-	-	-	250	900	850

(ρ_a) Particle density [apparent]; (ρ_{SSD}) Particle density [saturated surface dry]; (ρ_{rd}) Particle density [dry], according to EN 1097-6; (WA₂₄) Water absorption of particles after 24 h, according to EN 1097-6; (FI) Flakiness index, according to EN 933-3; (Cc) Particles with more than 50% of their surface crushed or broken, according to EN 933-5; (SE₄) Sand equivalent of fraction 0–4 mm, according to EN 933-8; (LA) Los Angeles coefficient (resistance to fragmentation), according to EN 1097-2; (PSV) Polished stone value (resistance to polishing), according to EN 1097-8; (Dens.) Binder density, according to EN 15326; (Pen.) Penetration at 25 °C, 100 g, 5 s, according to EN 1426; (SP) Softening point [Ring and Ball test], according to EN 1427; (Visc.) Dynamic viscosity by Brookfield rotational viscometer, according to EN 13302. ⁽¹⁾ Percentage by weight of total aggregate; ⁽²⁾ Percentage by weight of mixture; ⁽³⁾ Percentage by weight of bitumen.

As aggregate fraction # <0.063 mm (mineral filler), a Portland cement with pozzolanic addition was employed (designated CEN II/B-P 32.5 R, according to the EN 197-1). This type of cement is the most common in volcanic territories due to the presence of pozzolans in certain volcanic rocks.

2.2. Waste Crumb Rubber from Used Tires

The waste crumb rubber modifier (CRM) was produced by mechanical grinding at ambient temperature and its composition is from car tires (50%) and from trucks (50%). It was supplied by a local company in charge of the treatment of this waste. This company carries out the recovery and separation of the raw material components of discarded tires in the region. Fifty percent of the rubber comes from passenger car tires and the rest from truck tires.

The thermogravimetric analysis revealed the following: 57.41% polymeric rubber, 32.22% carbon black, 6.02% ash, and 4.67% plasticizer and additives. Up to 94% (by weight of CRM) was below 0.5 mm in size. As for its size distribution, the particle size was smaller than 1.0 mm (i.e., 94.1% passed through sieve 0.5 mm, 23.7% through 0.25 mm, 3.7% through 0.125 mm, and 0.4% through 0.063 mm).

2.3. Binders

The bitumen used for the control mixture without rubber—conventional mixture of the type hot mix asphalt (HMA)—was a commercial penetration grade bitumen 35/50. The bitumen for the rubberized hot mixture (RHMA) was a crumb rubber-modified binder of the same penetration grade (CRMB 35/50). This rubberized binder was previously manufactured at the laboratory by blending the CRM with a penetration grade bitumen 50/70. Because the elastomer raises both viscosity and consistency, the resulting binder (CRMB) had a penetration grade 35/50. To achieve this, each sample (600 g) of bitumen 50/70 was heated to 180 ± 1 °C in an oil bath and then 10% (by weight) of CRM was added in the blending unit. It was mixed for 60 min at 4000 rpm with a propeller agitator maintaining the same temperature.

The rubberized warm mixture (RWMA) was produced with a CRMB 35/50 binder previously blended with 0.5% (by wt. of rubberized bitumen) of a surfactant liquid additive (Cecabase RT®) at 180 ± 1 °C for 10 min at 4000 rpm in the same mixer, ensuring that the additive is properly homogenized into the bitumen.

Ten samples of each binder type were obtained to characterize them following the European Standards (EN). The main properties of the binders are also summarized in Table 1.

2.4. Bituminous Mixtures

The type of mixture selected for this study was a Semi-dense Asphalt Concrete (AC16 surf S), following the European Standard EN 13108-1, which is an asphalt mixture typically employed for wearing courses of different roads, traffic types, and climatic conditions because of its adequate macrotexture and its lower susceptibility to plastic deformations, and because its production involves lower costs compared to a dense asphalt concrete. The aggregate gradation is shown in Figure 2a.

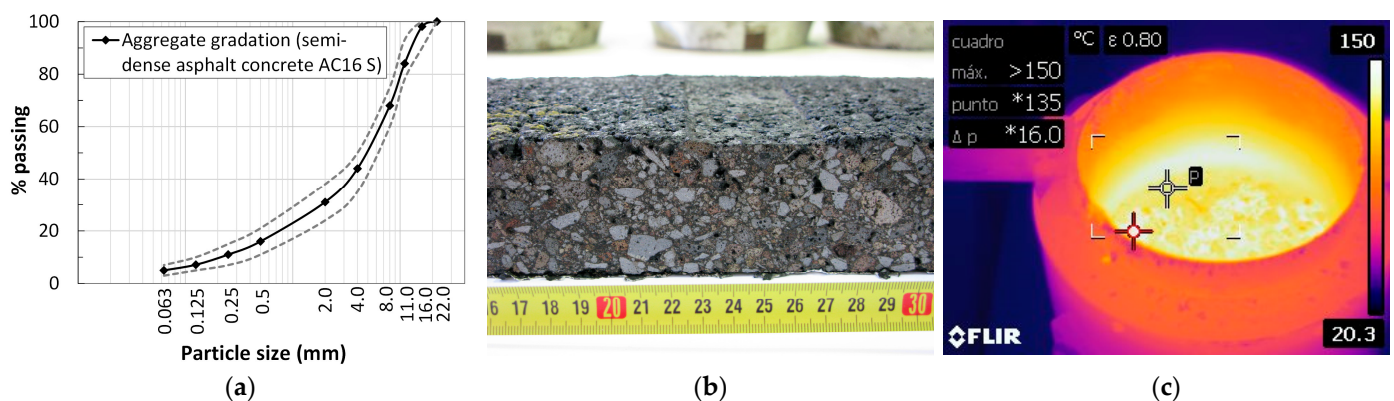


Figure 2. Rubberized warm mix asphalt (RWMA) mixed at 155 °C and compacted at 145 °C: (a) particle size distribution curve; (b) slab specimen after Wheel Tracking Test; (c) infrared photography during the mixing process.

A total of 201 cylindrical specimens, 46 slab specimens (Figure 2b), and 27 non-compacted samples (for theoretical maximum density tests) were prepared in the laboratory following the Spanish technical specifications for roads (PG-3), which are in accordance with the European Standards.

The effect of the CRM binders and the warm mix asphalt (WMA) additive on the physical and mechanical properties of this Semi-dense Asphalt Concrete (AC-S) with

scoriaceous and vesicular basalt was compared by preparing three types of mixtures with a binder content of 6% in reference to the total weight of the mixture. Previous tests showed this was the optimum binder content for this porous mineral aggregate. This percentage is higher compared to conventional aggregates and similar to recycled aggregates (RCA), as highlighted by previous research [14], due to the increased binder absorption. The three types of asphalt mixes used in this research were as follows: (a) the control hot mixture with conventional bitumen (HMA), mixed at 170 ± 1 °C; (b) the rubberized hot mixture with CRM bitumen (RHMA), mixed at 180 ± 1 °C; and (c) the low-energy warm mix asphalt with CRM bitumen (RWMA), mixed at 155 ± 1 °C (Figure 2c). In all cases, the compaction temperatures were 10 °C below the mixing temperatures.

The mixing and compaction temperatures of the RWMA had to be at least 10 °C higher than the control HMA in order to meet the values required by the specifications for road pavements. At lower compaction temperatures, certain properties of the RHMA with this poor-quality aggregate were particularly critical, especially the air void content, the rutting resistance, and the dynamic stiffness modulus, as described in Section 3.

The production temperature of the RWMA was selected based on the results of different mixture properties obtained from previous tests on specimens manufactured between 140 and 180 °C. At mixing temperatures below 140 °C the air void content of the RWMA was above 12% (due to the difficulty of compaction as a result of the higher viscosity of the CRM bitumen and the aggregate roughness), the proportional rut depth at 10,000 cycles by wheel tracking test in air was over 6%, and the indirect tensile strength ratio drop below 70%, therefore failing to comply with most of the specifications for paving mixtures. In contrast, above 150–155 °C (depending on the property being evaluated), the RWMA met these specifications.

2.5. Laboratory Tests

The cylindrical specimens ($D = 101.6$ mm; $h = 63.5$ mm) were compacted by the Marshall method (EN 12697-30) with either 50 or 75 blows per side, based on the lab test. The slab specimens of $300 \times 300 \times 60$ mm were compacted by the rolling method (EN 12697-33). Three series of characterization tests for each type of mixture were carried out on the compacted specimens and non-compacted samples, with a total number of 552 tests for the entire investigation:

- (a) Volumetric properties: theoretical maximum density (EN 12697-5, Procedure A: volumetric) of non-compacted samples, bulk density (EN 12697-6, Procedure B: saturated surface dry, SSD), and void characteristics (EN 12697-8) of cylindrical specimens compacted by impact with 75 blows per side;
- (b) Moisture resistance (EN 12697-12, by Indirect Tensile Test, ITT [EN 12697-23]) of cylindrical specimens compacted by impact with 50 blows per side;
- (c) Resistance to permanent deformation: Wheel Tracking Test, WTT (EN 12697-22, Procedure B: in air, small device, at 60 °C and 10,000 cycles), on slab specimens compacted by metallic roller, and Marshall Test (EN 12697-34) of cylindrical specimens compacted by impact with 75 blows/side;
- (d) Dynamic stiffness modulus (EN 12697-26) by Indirect Tensile Test on cylindrical specimens [IT-CY] compacted by impact with 75 blows per side, $k = 0.6$, $T = 20$ °C, $f = 2.2$ Hz;
- (e) Resistance to fatigue (EN 12697-24) by Four-Point Bending Test on prismatic specimens [4PB-PR] with 1 million load cycles, at 20 °C, 10 Hz).

3. Results and Discussion

3.1. Physical Properties

Figure 3 shows the average values of the main volumetric properties of the rubberized mixtures, allowing comparison of results with respect to the control hot mixture with conventional bitumen (HMA), all of them manufactured following the same procedure and the same type of residual volcanic aggregate. The bulk density of the rubberized mixtures

(RHMA and RWMA) was superior to the HMA; for the RWMA, it was 3.4% higher and the results were more homogenous (lower statistical deviation). Both the air void content and voids in mineral aggregate of the RWMA comply with the standard specifications for this type of asphalt concrete for wearing courses, and proved to be inferior to the RHMA, whose air void contents are superior to the HMA because of the higher theoretical maximum density of the rubberized mixtures.

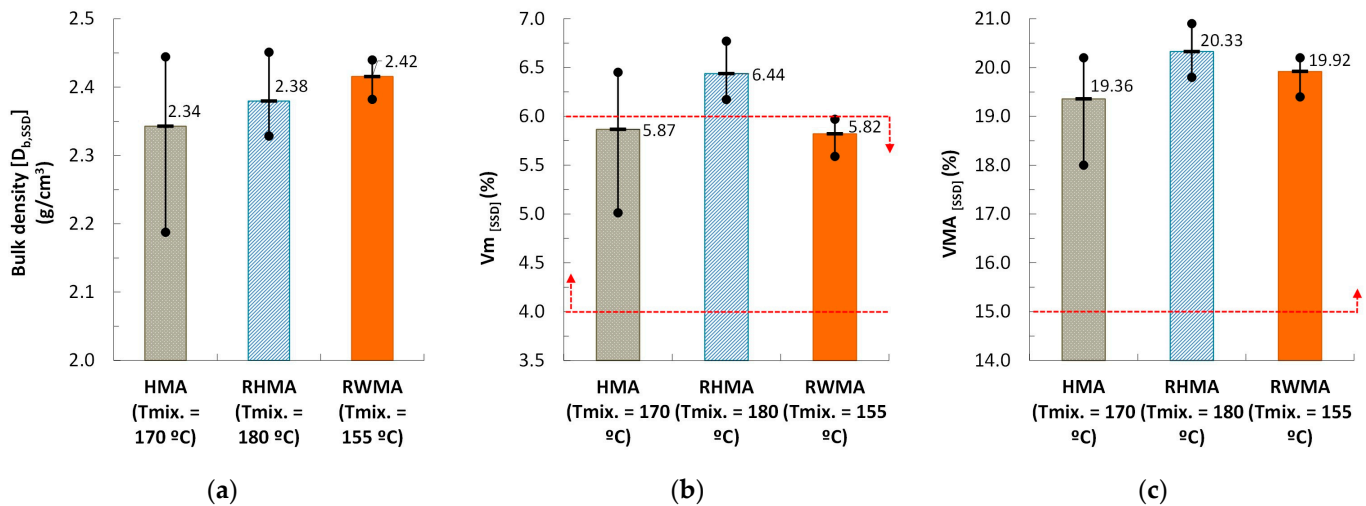


Figure 3. Volumetric characteristics of the asphalt mixtures: (a) bulk density by procedure B: saturated surface dry, SSD; (b) air voids in the mixture; (c) voids in mineral aggregate.

3.2. Strength Properties

Figure 4a clearly shows the improvement of the resistance to moisture action of the rubberized mixtures with respect to the hot mixture with conventional bitumen (HMA) in terms of the indirect tensile strength ratio (ITSR). The ITSR of the RWMA increased by 36.6%, thus complying with pavement technical specifications. Although the indirect tensile resistance of dry specimens (ITS_d) decreased with respect to the HMA (Figure 4c), with the saturated specimens (ITS_w) it was similar (Figure 4b), showing the favorable effect on the adhesion under wet conditions of the combined action of the surfactant additive and the rubber on these mixtures with highly porous aggregates.

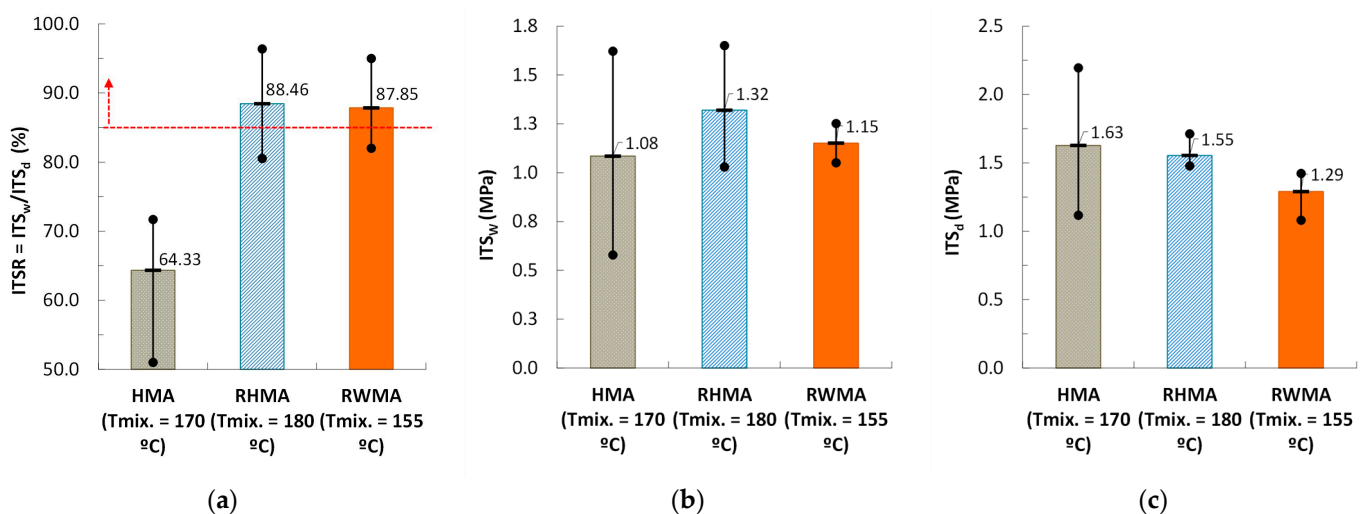


Figure 4. Resistance to water action of the asphalt mixtures: (a) indirect tensile strength ratio; (b) indirect tensile strength of saturated specimens (72 h at 40 °C); (c) indirect tensile strength of dry specimens.

Figure 5a–c highlight the enhanced rut resistance of the rubberized mixtures (lower wheel tracking slope by 47.12%, rut depth by 51.3%, and proportional rut depth by 54.1%) with respect to the control mixture. Similar results are shown by the Marshall tests, in which the stability (Figure 6a), deformation (Figure 6b), and Marshall Quotient (Figure 6c) of the RWMA were significantly higher than the average values of the HMA (by 99.3%, 12.8% and 45.7%, respectively). This improvement suggests a noteworthy finding for the practical reuse of waste vesicular aggregates from volcanic islands in pavement construction.

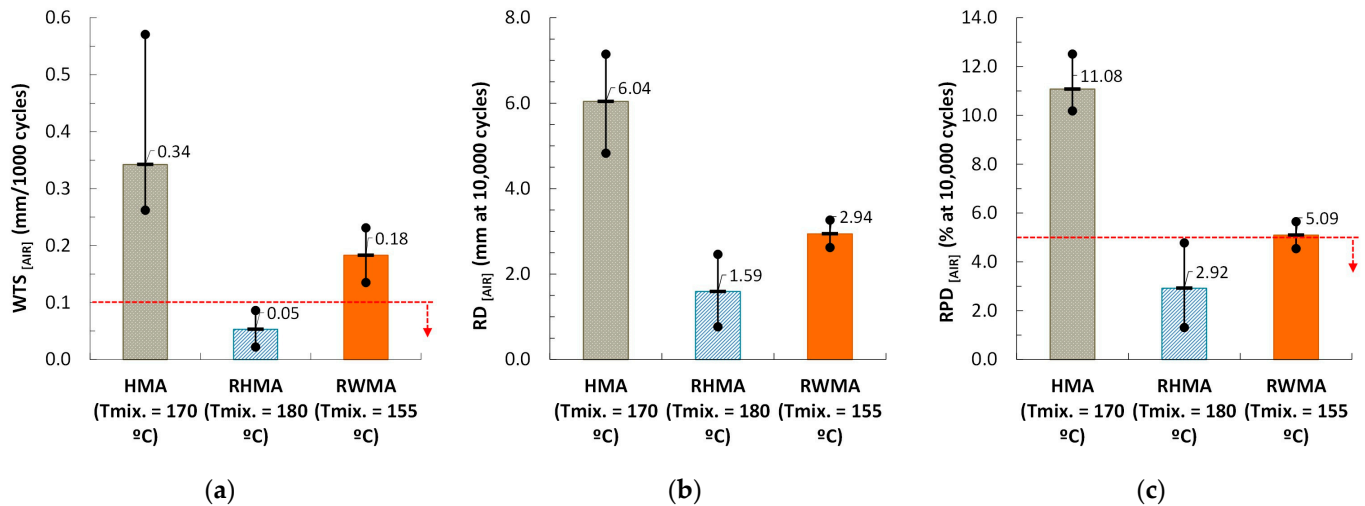


Figure 5. Resistance to plastic deformations by Wheel Tracking Test (WTT) in air at 60 °C and 10,000 cycles: (a) wheel tracking slope between 5000 and 10,000 rolling cycles; (b) rut depth at 10,000 cycles; (c) proportional rut depth at 10,000 cycles.

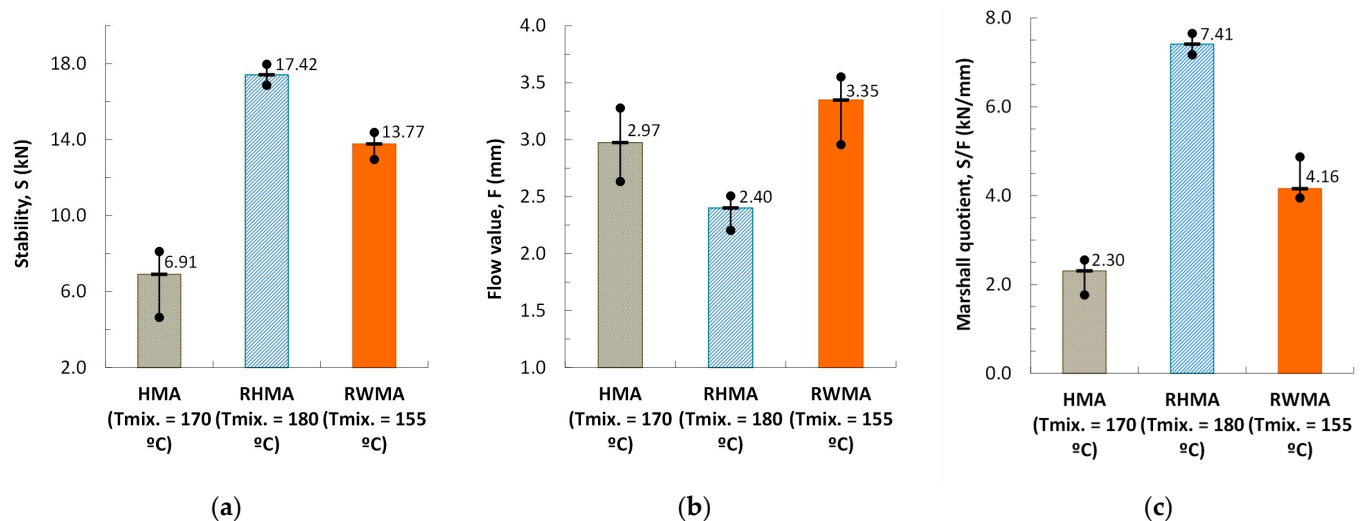


Figure 6. Resistance to plastic deformations by Marshall Test: (a) stability; (b) flow value; (c) Marshall Quotient.

These results are consistent with those reported by other previous studies using recycled aggregates (RCA), which showed better performance in terms of moisture sensitivity and rutting resistance [14].

3.3. Mechanical Properties under Dynamic Loading

The dynamic stiffness modulus by Indirect Tensile Test on cylindrical specimens of the RWMA was 34.5% higher than the hot mixture with conventional binder (HMA) and up to 51.9% superior to the RHMA (Figure 7a). These results prove that the stiffness increment is

not due to the rubberized binder as expected, but the favorable effect on the adhesion and coating between aggregates and bitumen promoted by the surfactant additive.

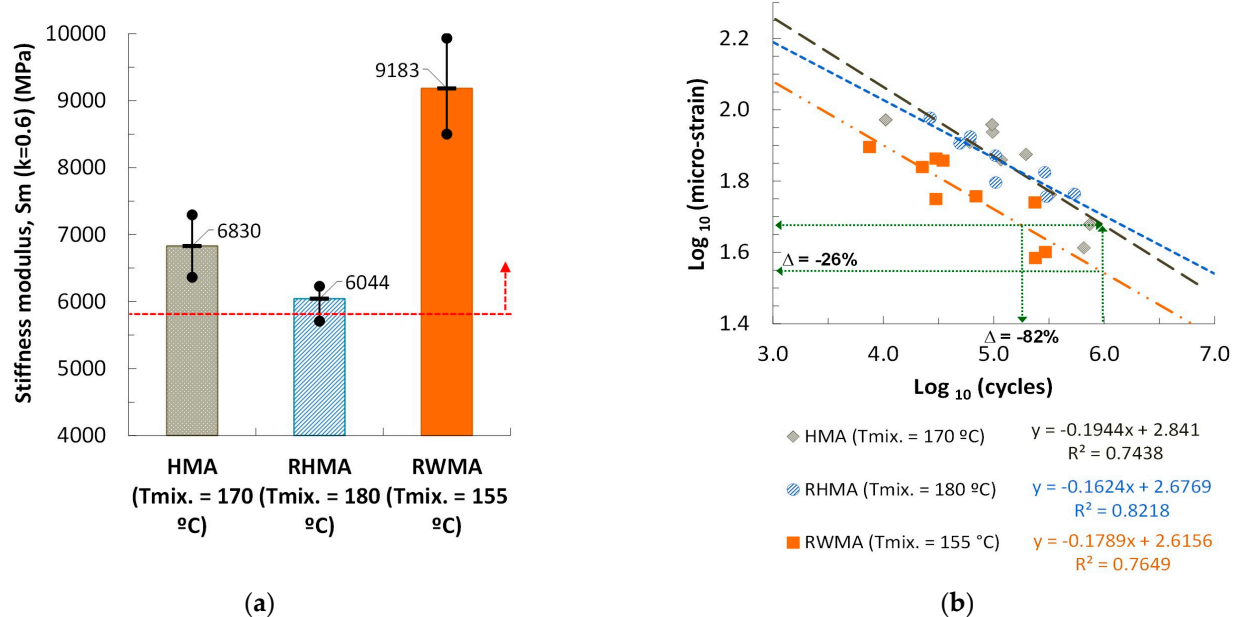


Figure 7. Dynamic performance characteristics: (a) stiffness modulus by Indirect Tensile Test (ITT) at 20 °C; (b) fatigue laws by four-point bending test at 20 °C, 1 million cycles, 10 Hz.

Fatigue resistance of RWMA mixtures is reduced compared to the HMA, even though the fatigue law of the RHMA slightly improved with respect to the mixture with conventional bitumen (HMA). The initial micro-strain for an expected service life of 1 million load cycles until fatigue failure decreased by 26%, which supposes a reduction in the expected number of fatigue cycles by 82% (Figure 7b). This result is in accordance with previous research, which stated the reduced cracking resistance of WMA by bending tests on semi-circular specimens, albeit produced with a foam-based additive [37]. However, this apparent reduction in the durability of these asphalt mixes can be counterbalanced at the design stage by using thicker asphalt layers for the pavement structure or by the disposition of the constituent materials in the pavement layers, and it is justified by the sustainability improvement with the use of natural materials and waste products that this technology offers for highly sensitive environments such as volcanic islands.

3.4. Statistical Analysis of the Experimental Results

The data collected from the laboratory tests were analyzed following the next steps:

- (1) An Exploratory Data Analysis (EDA) was performed to evaluate the quality of the data by using descriptive statistics tools (i.e., relevant statistics about the deviation and error of the laboratory results, basic plots, normality tests). The main statistics related with deviation are summarized in Table 2.
- (2) Based on the results of the normality test and the dependency of the samples, a non-parametric statistical approach was used to assess the effect of the mixture type on the different properties evaluated. In this case, the Kruskal–Wallis test was chosen (non-parametric analogue of the one-way ANOVA).
- (3) A Dunn's post hoc test was also performed along with Kruskal–Wallis to answer two main questions, namely, whether at least one type of mixture is different from the other two, and between which types exactly this difference is. The p -values are shown in Table 3.

Table 2. Statistics of dispersion of the laboratory results for each property and type of mixture, and Shapiro–Wilk normality test.

		N	Mean	SD	CoV (%)	Std. Error	MAD	Shapiro–Wilk	Shapiro–Wilk <i>p</i> -Value
$D_{b,SSD}$ (g/cm ³)	HMA	18	2.34	0.09	3.73	0.021	0.061	0.891	0.0414
	RHMA	18	2.38	0.04	1.64	0.009	0.028	0.924	0.155
	RWMA	18	2.42	0.02	0.90	0.005	0.018	0.842	0.006
$D_{m,V}$ (g/cm ³)	HMA	16	2.49	0.18	7.21	0.045	0.045	0.696	<0.001
	RHMA	16	2.54	0.02	0.64	0.004	0.001	0.566	<0.001
	RWMA	15	2.54	0.01	0.52	0.003	0.008	0.750	<0.001
ITS _W (MPa)	HMA	16	1.08	0.41	37.56	0.102	0.366	0.846	0.012
	RHMA	16	1.32	0.25	19.31	0.064	0.213	0.827	0.006
	RWMA	16	1.15	0.10	9.03	0.026	0.101	0.644	<0.001
ITS _d (MPa)	HMA	14	1.63	0.41	25.28	0.110	0.371	0.855	0.026
	RHMA	12	1.55	0.10	6.31	0.028	0.030	0.715	0.001
	RWMA	12	1.29	0.16	12.15	0.045	0.054	0.701	<0.001
ITSR (%)	HMA	14	64.33	9.78	15.20	2.524	1.383	0.644	<0.001
	RHMA	12	88.46	8.29	9.37	2.392	7.934	0.650	<0.001
	RWMA	12	87.85	5.85	6.65	1.688	5.597	0.650	<0.001
WTS _[air] (mm/1000 cycles)	HMA	12	0.34	0.14	40.22	0.040	0.007	0.579	<0.001
	RHMA	12	0.05	0.03	51.20	0.008	0.024	0.819	0.016
	RWMA	12	0.18	0.05	27.40	0.014	0.048	0.650	<0.001
RD _[air] (mm at 10 ⁴ cycles)	HMA	12	6.04	0.86	14.27	0.249	0.578	0.856	0.043
	RHMA	12	1.59	0.63	39.34	0.181	0.415	0.840	0.027
	RWMA	12	2.94	0.33	11.38	0.097	0.321	0.650	<0.001
PRD _[air] (%at 10 ⁴ cycles)	HMA	12	11.08	1.07	9.64	0.308	0.357	0.699	<0.001
	RHMA	12	2.92	1.49	51.04	0.430	1.373	0.799	0.009
	RWMA	12	5.09	0.58	11.29	0.166	0.551	0.650	<0.001
S (kN)	HMA	16	6.91	1.41	20.41	0.352	0.529	0.739	<0.001
	RHMA	16	17.42	0.57	3.29	0.143	0.555	0.644	<0.001
	RWMA	15	13.77	0.62	4.49	0.159	0.410	0.759	0.001
F (mm)	HMA	16	2.97	0.29	9.69	0.072	0.255	0.758	<0.001
	RHMA	15	2.40	0.14	5.989	0.037	0.016	0.635	<0.001
	RWMA	15	3.35	0.29	8.52	0.074	0.010	0.614	<0.001
Marshall Quotient [S/F] (kN/mm)	HMA	16	2.30	0.31	13.30	0.082	0.081	0.678	<0.001
	RHMA	15	7.41	0.25	3.33	0.062	0.239	0.644	<0.001
	RWMA	15	4.16	0.54	12.93	0.139	0.300	0.741	<0.001
$S_{m[IT-CY]}$ (k = 0.6) (MPa)	HMA	20	6829.97	510.51	7.47	114.153	523.000	0.864	0.009
	RHMA	30	6043.72	312.51	5.17	57.057	313.600	0.909	0.014
	RWMA	30	9182.84	633.28	6.90	115.620	509.005	0.896	0.007

(N) Number of valid results; (Mean) Averaged result; (SD) Standard Deviation; (CoV) Coefficient of Variation; (Std. Error) Standard Error of the Mean; (MAD) Median Absolute Deviation; ($D_{m,V}$) Theoretical maximum density: Volumetric procedure, according to EN 12697-5.

The statistical tests have proven that the differences in the properties of the mixtures manufactured with CRM binders with respect to the control mix without rubber (HMA) are statistically significant, except for a limited number of them (i.e., density properties and ITS_W). However, it is known that the dispersion of these laboratory tests is usually higher due to the heterogeneous nature of these materials. These differences are evident when comparing RWMA mixtures not only with the HMA control mixture but also with respect to the RHMA mixture, according to the *p*-values.

Table 3. Statistical test results about the effect of the mixture type on the different properties.

Property of the Mixture	Kruskal–Wallis Test	Dunn’s Post Hoc Test	
	<i>p</i> -Value	Mixtures to Compare	Holm’s <i>p</i> -Value
$D_{b,SSD}$ (g/cm ³)	0.020	HMA-RHMA	0.596
		HMA-RWMA	0.024 ⁽¹⁾
		RHMA-WMA	0.068
$D_{m,V}$ (g/cm ³)	0.061	HMA-RHMA	0.088
		HMA-RWMA	0.123
		RHMA-WMA	0.785
ITS _W (MPa)	0.272	HMA-RHMA	0.445
		HMA-RWMA	0.760
		RHMA-WMA	0.382
ITS _d (MPa)	0.003	HMA-RHMA	0.718
		HMA-RWMA	0.009 ⁽²⁾
		RHMA-WMA	0.006 ⁽²⁾
ITSR (%)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	<0.001 ⁽³⁾
		RHMA-WMA	1.000
WTS _[air] (mm/1000 cycles)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	0.010 ⁽²⁾
		RHMA-WMA	0.010 ⁽²⁾
RD _[air] (mm at 10 ⁴ cycles)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	0.010 ⁽²⁾
		RHMA-WMA	0.010 ⁽²⁾
PRD _[air] (%at 10 ⁴ cycles)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	0.002 ⁽²⁾
		RHMA-WMA	0.061
S (kN)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	0.003 ⁽²⁾
		RHMA-WMA	0.003 ⁽²⁾
F (mm)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	0.031 ⁽¹⁾
		RHMA-WMA	<0.001 ⁽³⁾
Marshall Quotient [S/F] (kN/mm)	<0.001	HMA-RHMA	<0.001 ⁽³⁾
		HMA-RWMA	0.003 ⁽²⁾
		RHMA-WMA	0.003 ⁽²⁾
S _{m[IT-CY]} (k = 0.6) (MPa)	<0.001	HMA-RHMA	0.004 ⁽²⁾
		HMA-RWMA	<0.001 ⁽³⁾
		RHMA-WMA	<0.001 ⁽³⁾

A *p*-value less than 0.05 indicates that there is a significant statistical difference: ⁽¹⁾ *p* < 0.05; ⁽²⁾ *p* < 0.01 (strong difference); ⁽³⁾ *p* < 0.001 (very strong difference).

3.5. Eco-Efficiency Analysis

A preliminary eco-efficiency assessment was carried out using the main indicators in the manufacture of asphalt mixes: energy consumption, atmospheric emissions, and waste generation. Only the mixing, laying, and compaction processes of the three types of mixtures were compared, considering the following: (1) heating of the aggregates, including the mineral filler; (2) heating of the binder; (3) mixing temperature; and (4) compaction temperature.

Energy consumption and emissions are directly related to the temperature required to manufacture the asphalt mix, and the latter depends on the content of rubber powder incorporated, the quality, adhesion and porosity of the aggregate used, as well as the type

and bitumen content. With the “wet” method used in this research incorporating the waste rubber powder to obtain a rubber-modified bitumen (10% of rubber by bitumen weight), and with the extremely porous aggregates (water absorption up to 16%, see Table 1), the required manufacturing temperature for the RHMA (with a binder content of 6%) increased 10 °C with respect the control mixture. It is precisely this drawback that justifies this research, and aims to reduce the manufacturing temperature using a chemical surfactant.

3.5.1. Energy Consumption

Vesicular volcanic aggregates, due to their high porosity, require longer heating time to completely dry out their moisture, which means an additional 0.7 L of fuel per metric ton for each increase by 1% in moisture, consuming 5.1 L of additional fuel per metric ton compared to mixtures with conventional low-porosity aggregates. A conventional asphalt concrete mixture with neat bitumen 35/50 and limestone aggregate involves approximately 271.1 MJ/metric ton of fuel (natural gas) [38]. Assuming the linear relationship between energy consumption and manufacturing temperature above the water vaporization temperature (Figure 8a), the RHMA mixture accounts for an increase in fuel consumption of 7.1% over the HMA. However, the RWMA allows a reduction in fuel consumption of 8.4% (14.5% compared to the RHMA) (Figure 8b). These results have been calculated from statistical analysis of data provided by local asphalt mix manufacturers using dense volcanic aggregates (mainly dense basalt and phonolite). For conversion to mixtures with highly porous aggregates, a proportional calculation has been applied (proportionally to their porosity, according to Table 1), since more energy is needed to evaporate the moisture from their pores and the required binder content is also increased proportionally.

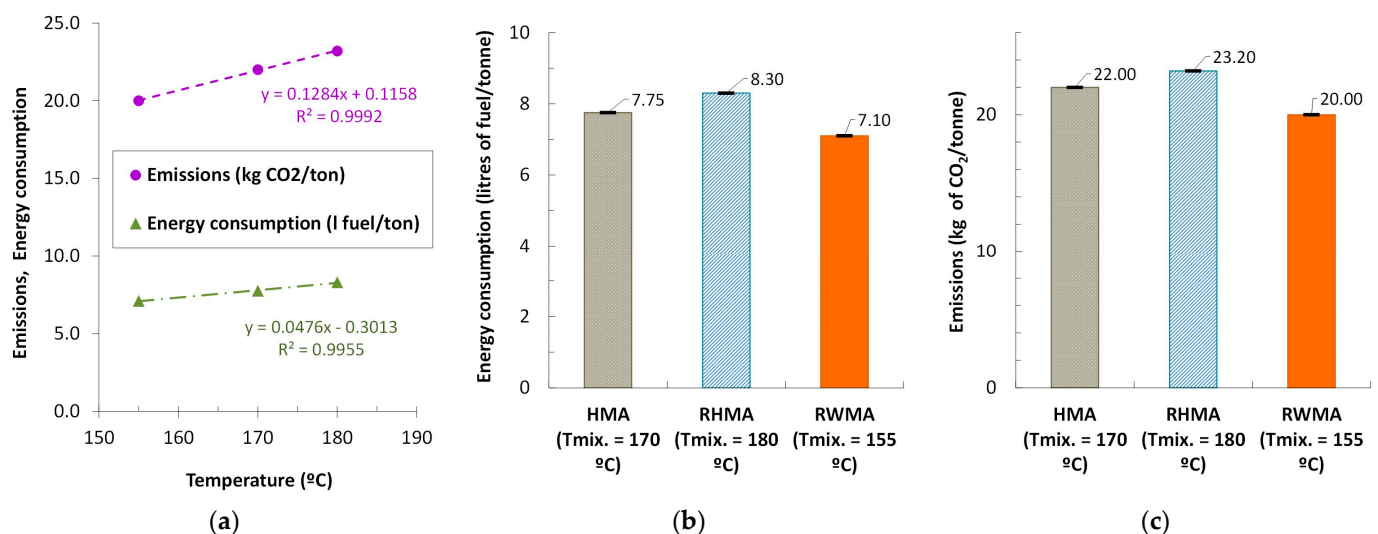


Figure 8. Eco-efficiency indicators: (a) influence of the manufacturing temperature; (b) fuel consumption; (c) CO₂ emissions.

To evaluate the consumptions involved in the manufacture of each component material of asphalt rubber mixtures, the following results of Refs. [39,40] can be used: (a) production of crushed aggregate: 57.6–78.6 MJ/metric ton; (b) obtaining the raw materials for the binder: 40,200 MJ/metric ton; (c) binder manufacture: 2890–5320 MJ/metric ton.

3.5.2. Emissions

CO₂ emissions for the RHMA mixture are increased by 5.5% compared to the HMA, considering that they also depend linearly on fuel consumption and, thus, on temperature (Figure 8a). However, the RWMA leads to a reduction of 9.1% (13.8% compared to the RHMA) (Figure 8c). Emissions were obtained from in situ measurements in local asphalt plants using dense volcanic aggregates. As indicated above, the appropriate conversion

was made to take into account the higher porosity of the aggregates used in this study based on the proportional relationship of the emissions with the higher energy consumption.

According to Ref. [41], for an asphalt concrete of type WMA with conventional aggregates, the following reductions in gases to the atmosphere are achieved: NO_x : 73.5%; CO: 12.2%; SO_2 : 74.6%.

3.5.3. Waste Recycling

The use of rubber from used tires in these bituminous mixtures allows a proportion of 10% of the bitumen weight, which means 6 kg of rubber per metric ton of mixture. Although this may seem a small percentage of this waste, this would mean recovering 25 metric tons of rubber for each kilometer of conventional road (i.e., 10 m wide roadway) that would be taken to landfill sites otherwise. This figure would increase to more than 50 metric tons per kilometer in the case of dual carriageways.

4. Conclusions

The results presented in this experimental study lead to the following conclusions:

- The bulk density of the rubberized warm mixture (RWMA) was 3.4% higher than the hot mixture with conventional binder (HMA). The volumetric properties of the RWMA meet the standard specifications for this type of asphalt concrete, even the most stringent requirements for wearing courses.
- The resistance to water action of the RWMA is increased by 37%, complying with pavement technical specifications. This shows the favorable effect on the adhesion under wet conditions of the combined action of the surfactant additive and the rubber on these mixtures with highly porous aggregates.
- It is important to highlight the enhanced rut resistance of the rubberized mixtures by approximately 50%. Similar results show the increased stability (by 99%), and reduced permanent (plastic) deformation (by 13%). This improvement supposes a noteworthy finding for the practical reuse of waste vesicular aggregates from volcanic rocks in pavement construction, especially for infrastructures under heavy traffic and at high weather temperatures.
- The dynamic stiffness modulus of the RWMA was 35% superior to the HMA, due to the favorable effect on the adhesion and coating between aggregates and bitumen promoted by the surfactant additive. This increase in the modulus of the asphalt mixture would allow a reduction in the thickness of the asphalt layers estimated at 13% (for an equivalent heavy-vehicle traffic of 300 trucks/day).
- The enhancements in the properties above mentioned lead to asphalt mixtures for paving that require less maintenance due to rutting damages and degradation promoted by the moisture action.
- The fatigue resistance of the RWMA mixtures is reduced compared to the HMA. However, this apparent worsening in the durability of these asphalt mixes can be addressed at the design stage of the pavement structure, and it is justified by the sustainability improvement with the use of raw materials and the waste recycling that this technology offers for extremely sensitive environments such as volcanic islands.
- The eco-efficiency analysis revealed that the RWMA mixture reduce fuel consumption and thus, CO_2 emissions to the atmosphere by about 9% if compared to the HMA, and 15% if compared to RHMA. The use of rubber from used tires in these bituminous mixtures facilitates the recovery of between 25 and 50 metric tons of waste per roadway kilometer (in single roadways and dual carriageways, respectively). Additionally, this mixture enables the reuse of more than 95% of residual materials (ELT) and geomaterials (marginal aggregates).
- Experimentally, it has been shown that it is technically possible to produce asphalt mixtures with a lower energy consumption, certain improved properties, and a reduced environmental impact by recycling two large volume residues, while meeting specifications for paving.

- The amalgamation of these three technologies (WMA + CRMB + residual geomaterials) promotes cleaner and more sustainable pavements, contributing to a zero waste society, and enhances their performance by reducing the maintenance.

Although this research has been carried out with residual materials and geomaterials from volcanic islands, the proposed technique, method, and conclusions are applicable elsewhere, since residual poor-quality aggregates are common, and the accumulation of used tires together with the need to limit emissions are global challenges. On the other hand, high porosity volcanic rocks can also be found in large extensions of continental areas in East and Southeast Asia, America and Africa.

For future research, it would be of interest to compare the performance properties and the eco-efficiency of these warm mixtures with high porosity marginal volcanic aggregates manufactured by the “wet” process and the “dry” or “semi-dry” process in order to optimize the production method. A life cycle assessment (LCA) would also make it possible to determine the sustainability over several life cycles after recycling.

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