sustainability

MDPI

Article

Laboratory Evaluation of Hot Asphalt Concrete Properties with Cuban Recycled Concrete Aggregates

Debora Acosta Alvarez [1], Anadelys Alonso Aenlle [1] and Antonio José Tenza-Abril [2,*]

1 Faculty of Civil Engineering, Technological University of Havana "José Antonio Echeverría", Havana 11500, Cuba; dacostaa@civil.cujae.edu.cu (D.A.A.); anadelys@civil.cujae.edu.cu (A.A.A.)
2 Department of Civil Engineering, University of Alicante, 03080 Alicante, Spain
* Correspondence: ajt.abril@ua.es; Tel.: +34-96-5903-400 (ext. 2729)

Received: 29 June 2018; Accepted: 19 July 2018; Published: 24 July 2018

check for updates

Abstract: Recycled Aggregates (RA) from construction and demolition waste (CDW) are a technically viable alternative to manufacture of asphalt concrete (AC). The main objective of this work is to evaluate the properties of hot asphalt mixtures that have been manufactured with different sources of CDW (material from concrete test specimens, material from the demolition of sidewalks and waste from prefabrication plants) from Cuba. Dense asphalt mixtures were manufactured with a maximum aggregate size of 19 mm, partially replacing (40%) the natural aggregate fraction measured between 5 mm and 10 mm with three types of RA from Cuba. Marshall specimens were manufactured to determine the main properties of the AC in terms of density, voids, stability and deformation. Additionally, the stiffness modulus of the AC was evaluated at 7 °C, 25 °C and 50 °C. The results corroborate the potential for using these sources of CDW from Cuba as a RA in asphalt concrete, thereby contributing an important environmental and economic benefit.

Keywords: recycled aggregates (RA); construction and demolition waste (CDW); hot asphalt mixtures; stiffness modulus; X-ray diffraction

1. Introduction

Natural aggregates are a fundamental part of construction processes and they are essential to ensure the proper function of structural elements. Aggregates used in construction are extracted from quarries or deposits of sedimentary aggregates. However, given the demand for natural resources and the scarcity caused by overexploitation, alternative materials have been analyzed as a potential replacement. The key challenge is to use alternatives that do not alter the quality and functionality of the different structures [1–3]. Recycling and/or reusing construction and demolition waste (CDW) is an important issue to foster sustainable development and has become a focus of research efforts in recent years [4]. Currently, the use of waste generated in construction and demolition activities has become a technically viable alternative for the construction of road pavements [5–7].

In Havana, Cuba, according to the National Office of Statistics and Information (ONEI), more than 1000 m^3 of CDW is generated daily [8]. The accumulation of this waste in landfills results in a significant waste management cost as well as pollution effects on the environment mainly due to the scarce policy provisions and a lack of adequate technology to manage this waste [9]. The Cuban government has set a number of priority goals during the period of 2016 to 2021. These include the promotion of social research to develop the scientific and technological potential of innovation and environmental systems.

The revalorization of the CDW is in line with the Cuban government's priority goals because the reduction of waste landfills is a key problem that requires a solution. The use of recycled aggregates (RA) is limited in the construction sector due to its lower quality as compared to natural aggregates.

However, the use of RA to manufacture asphalt concrete mixtures (AC) has already been addressed by numerous authors internationally [5,6,10–14] due to its economic and environmental benefits. RA can be employed in different fields of civil engineering including the manufacturing of mortars, concretes, asphalt mixtures, fillings of embankments etc. [14–18]. The RA differ from the natural aggregates (NA) in terms of their composition [19] because they are waste concrete and so present a thin layer of mortar adhered to the surface. However, the physical properties of RA depend on both the quality and the amount of adhered mortar. Furthermore, the different techniques used to produce RA can affect its characteristics [20,21]. Replacing NA with RA results in inferior properties of the material due to the attached mortar, which lowers the specific gravity while increasing the water absorption of RA [22]. The RA properties are inferior because the residual mortar is attached to the surface. To improve the RA properties can be achieved either by strengthening or by removing the bonded mortar by different treatments [4].

Several studies report the improvement of the main properties of AC when natural aggregates are replaced with up to 60% recycled concrete aggregate [23]. Al-Baiti et al. [24] found that the incorporation of RCD in asphalt mixtures results in the increase of properties such as stability and stiffness modulus. An analysis carried out by Arabini [10] also found that the incorporation of RA increases the stability of the mixes but also decreases the deformation. Wong [25] demonstrated that the Marshall parameters of the Singapore Land Transport Authority (LTA) are within the specifications asphalt concrete when natural aggregates are replaced by RA. Paranavitthana [18] obtained lower dynamic modulus in asphalt mixtures containing CDW as a coarse aggregate than others produced with natural aggregates.

However, the literature is lacking in information on the use of CDW from the demolition sector in Cuba and the behavior of hot concrete asphalt mixes that incorporate CDW as a coarse aggregate. The main objective of this work is to study hot asphalt concrete by partially replacing (40%) the natural aggregate fraction that is measured between 5 mm and 10 mm with three different Cuban CDW sources: (i) Waste product from the crushing of concrete specimens; (ii) demolition waste from Havana sidewalks; and (iii) concrete from a prefabricated slabs plant (Spiroll). The mineral phases and characteristics of the three sources were analyzed. Volumetric parameters, stability and deformation values were determined for the hot asphalt concrete mixes that were produced. Additionally, the stiffness modulus values and the unitary horizontal deformations of the mixtures with RA at 7 °C, 25 °C and 50 °C were also obtained.

2. Materials and Methods

2.1. Materials

To design the hot asphalt mixes, three fractions of natural limestone aggregate (0 to 5 mm, 5 to 10 mm, 10 to 19 mm) from the "Alacranes" quarry and RA sources of the 5 to 10 mm fraction were used. These were:

- ARPH; crushing of concrete specimens (Figure 1a)
- ARDA; demolition of Havana sidewalk (Figure 1b)
- ARPP; wastes from the Spiroll slab precast plant (Figure 1c)

The samples from the concrete specimens (ARPH) and the Havana sidewalk waste (ARDA) were reduced in size by using a laboratory crusher. The retained aggregate in the sieves 5 mm to 10 mm was selected for the study. The remaining concrete after the mixture process and the discarded concrete after the fabrication of the slabs from prefabricated plant (ARPP) were selected as the waste. The aggregate from this source was not treated by crushing it but was selected by size using a sieving process.

The samples were oven dried at 70 °C and coated with a conductive film (Au-Pd) to examine the morphology of the three sources of RA (ARPH, ARDA and ARPP) with a scanning electron microscope (SEM). Figure 2 shows a micrograph sequence at 50 and 500 magnifications of the RA used as a coarse aggregate. The main observed cracks correspond to the ITZ between the mortar and the aggregate.

Figure 1. Recycled aggregates (RA) from three sources used as a coarse aggregate in hot asphalt concrete. (**a**) Obtained by crushing concrete specimens; (**b**) from demolition of Havana sidewalk and (**c**) from precast plant waste.

The characteristic compositions of the three RA samples obtained by X-ray fluorescence (XRF) are listed in Table 1. As can be seen, the chemical composition is similar in each different RA.

Table 2 shows the average of three tests that obtained the specific weights and water absorption of the natural aggregates and the RA, according to the Spanish standard UNE EN 13043 [26]. Table 2 shows the properties of the asphalt used and the standards used to obtain the indicated values. The requirements of the asphalt used are also listed in Table 2 to verify the Spanish prescriptions while the specifications given in the Spanish standard UNE EN 12591 [27] are also presented.

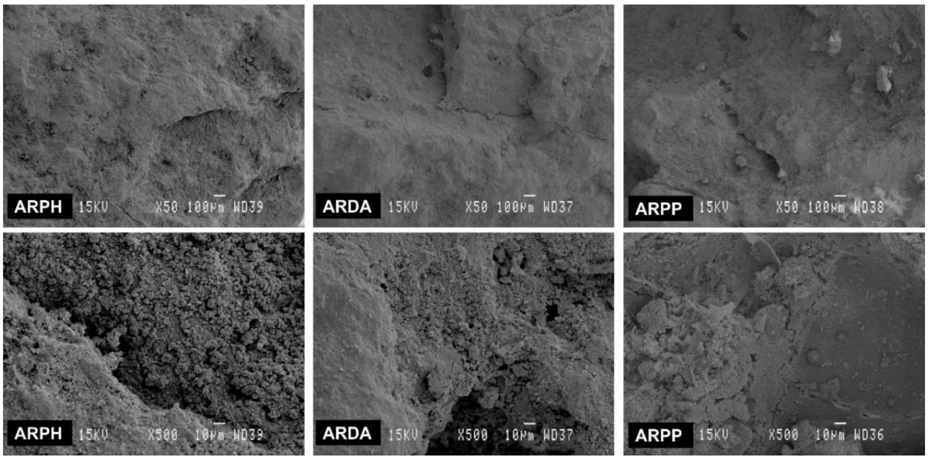

Figure 2. Scanning Electron Microscopy (SEM) micrographs of RA (ARPH, ARDA and ARPP) acquired at 50× and 500×.

Table 1. Chemical composition of the three sources of RA used in hot asphalt concrete.

	Chemical Composition (%)		
	ARPH	**ARDA**	**ARPP**
Na_2O	0.59	0.60	0.26
MgO	2.50	4.00	6.12
Al_2O_3	3.90	3.19	1.38
SiO_2	15.30	13.35	5.98
SO_3	0.47	0.74	0.50
K_2O	0.46	0.39	0.22
CaO	36.64	34.13	39.09
Fe_2O_3	2.10	1.37	0.76
L.O.I. [1]	37.31	41.72	45.37

[1] Loss on ignition.

Table 2 shows that the three sources of RA have lower specific weights and greater absorption than the natural aggregate. This is due to the lower density of the mortar adhered which causes a decrease in the density of the RA [28] and a higher porosity. This higher porosity causes water absorption, according to UNE EN 1097-6 [29] standard. The asphalt used was 50/70. As indicated in Table 3, all the values comply with the requirements.

Table 2. Properties of the aggregates used to produce the hot asphalt concrete.

Properties	Natural Aggregate			Recycled Aggregates		
	(10–19 mm)	(10–5 mm)	(0–5 mm)	ARPH (5–10 mm)	ARDA (5–10 mm)	ARPP (5–10 mm)
Effective Specific Gravity (kg/cm^3)	2654	2597	2672	2373	2422	2200
Apparent specific gravity (kg/cm^3)	2696	2683	2777	2657	2635	2657
Water absorption at 24 h (%)	0.583	1.23	1.4	7.80	5.68	4.95

Table 3. Properties of the asphalt used to produce the hot asphalt concrete.

Properties	Standard	Values	Requirements
Penetration (100 g, 25 °C, 5 seg) (1/10 mm)	UNE EN 1426	58.23	50–70
Softening point (°C)	UNE EN 1427	51	4–54
Flash and fire point (°C) Cleveland cup	UNE EN 22592	290	>230
Specific gravity (g/cm^3)	ISO 3830	1.043	>1.00
Loss-on-Ignition (%)	UNE EN 12607	0.46	<0.5
Percentage of penetration after loss (%)	UNE EN 1427	57.7	>50

Hot Asphalt Concrete Design

Four dense mixtures, which included a maximum size of 19mm were produced following the Marshall Method established in UNE EN 12697-34 [30]. The mixtures were designed by replacing 40% of the weight of 5 to10 mm natural aggregate fraction with RA. The replacement is the 7% of the total weight of the aggregates (Table 4) used to produce the mixture.

(a) Mixture 1 (0% RA): Conventional mixture with natural aggregates.
(b) Mixture 2 (40% ARPH): Mixture with 40% natural aggregate replacement by CDW of concrete specimens, in 5 to 10 mm fraction.
(c) Mixture 3 (40% ARDA): Mixture with 40% natural aggregate replacement by the Havana sidewalk waste, in 5 to 10 mm fraction.
(d) Mixture 4 (40% ARPP): Mixture with a 40% natural aggregate replacement by waste from Spiroll slab precast plant, in the 5 to 10 mm fraction.

Table 4. Mix proportions (percentages by weight) to produce the mixtures.

Proportions	0% RA	40% ARPH	40% ARDA	40% ARPP
0–5 mm	45	45	45	45
5–10 mm	17	10	10	10
10–20 mm	38	38	38	38
ARPH (5–10 mm)	-	7	-	-
ARDA (5–10 mm)	-	-	7	-
ARPP (5–10 mm)	-	-	-	7

To determine the optimum asphalt content, Mixture 1 was manufactured with 4.5%, 5.0% and 5.5% of asphalt content. The optimum asphalt content (OAC) obtained was 5%. All the mixtures, with CDW as a coarse aggregate, were produced with 5% of asphalt content. Table 4 shows the proportions used to manufacture each mixture. Figure 3 shows the size distribution of the mixtures designed. As can be seen, the curves in the three mixtures were continuously represented by a dense asphalt mixture, which meets the minimum and maximum requirements established by the Cuban standard NC 253 [31].

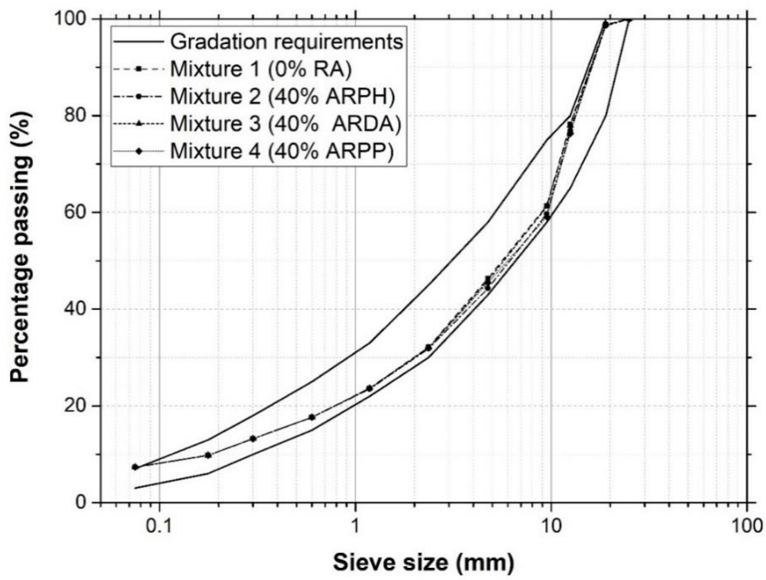

Figure 3. Size distribution of the three mixtures with RA and the control mix. The continuous lines represent the maximum and minimum gradation required.

2.2. *Experimental Methodology*

2.2.1. X-ray Diffraction

To identify the mineralogical phases of the recycled aggregate used in the mixtures, the samples were reduced in size (<63 mm) using a Retsch PM 100 ball mill. The mineralogical phases were determined by X-ray diffraction (XRD) using a Bruker D8 Diffractometer. During the analysis, a voltage acceleration of 40 kV, a current of 40 mA and an angular sweep of 4° to 60° were used. The mineralogical phases of the samples were quantified by using a Rietveld analysis with the software PANalytical Highscore Plus, version 4.6. (Malvern Panalytical Ltd., Malvern, UK).

2.2.2. Marshall Method

To analyze the properties of the mixtures, the Marshall method established in UNE EN 12697-34 was used. The specimens were reduced to 75 strokes per side. Six specimens were manufactured. Three specimens for the stability and deformation tests and three specimens to determine the density and the percentage of voids. The values of the stability, deformation, voids in the mixtures (VA) and voids in the mineral aggregate (VMA) were determined. Then, the optimum asphalt content was established [32]. After this, the mixtures were designed with a partial replacement of natural aggregate by CDW in the fraction (5 to 10 mm). The stiffness of the Marshall modulus was determined according to the relationship between the stability and the deformation of each specimen.

2.2.3. Stiffness Modulus

The stiffness modulus of each mixture at different temperatures (7 °C, 25 °C and 50 °C) was obtained by observing the behavior of the mixtures at those temperatures. This was done to guarantee the bearing capacity of the mixtures throughout all seasonal temperature changes. The test was carried out following the UNE-EN 12697-26 (Annex C) [33] standard which requires an indirect tensile test on cylindrical specimens. To determine the stiffness modulus, the specimens were placed in the conditioning chamber for 24 h before the test was performed at the different test temperatures.

As for Marshall specimens, the samples were compacted to 75 strokes per side. Five test pulses were applied along the vertical diameter of each Marshall cylindrical specimen. The load had a rise time of 124 ms and a repetition period of 3 s which was equivalent to a frequency of 0.33 Hz. The maximum load applied was selected to produce a maximum horizontal deformation of 0.005% of the diameter of the sample. The test procedure was repeated for a perpendicular diameter. A Poisson coefficient of 0.35 was used. The average stiffness of the five test pulses of the two diameters tested was recorded as the stiffness modulus of the AC sample.

2.2.4. Statistical Analysis

The one-way analysis of variance (ANOVA) was used to determine whether there were any statistically significant differences between the means of the hot asphalt mixtures parameters. The independent variables were: Density, VA, VMA, stability, deformation, stiffness modulus and horizontal deformation. The study was carried out with a 5% significance level. Moreover, the statistically different subsets were determined using Tukey's HSD test ($p < 95\%$).

3. Results and Discussion

3.1. X-Ray Diffraction

In Figure 4, the XRD diagrams of the three RA sources and the percentages of each mineral phase determined by Rietveld are shown. The main component of the CDW was calcite ($CaCO_3$) followed by dolomite. These are common mineral phases in concretes manufactured with limestone natural aggregates. In ARPH, 1.2% of Portlandite indicated that Portland cement had been used in the RA, which is typical in non-carbonated concretes. The presence of 3.7% of aragonite in the RA coming from the demolition of the sidewalk (ARDA) shows that it was one of the polymorphic forms of $CaCO_3$, which indicates that it was a carbonated concrete [34]. Furthermore, it was also noted that the samples of the analyzed CDW had a homogeneous chemical composition and that they did not contain any type of contaminant (Table 1).

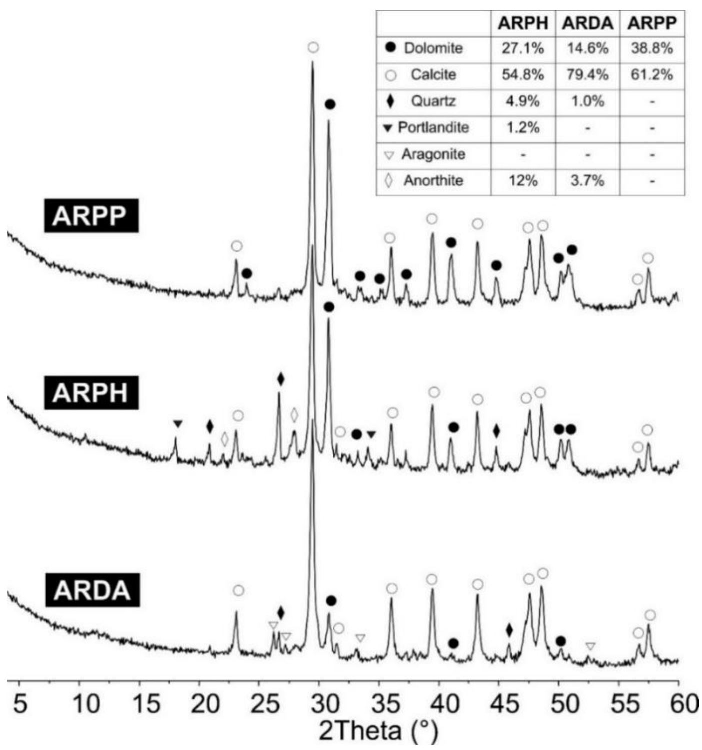

Figure 4. XRD of RA aggregates used to manufacture AC.

3.2. Marshall Analysis

As shown in Figure 5, the density of the40% ARPP mixture is lower than the reference mixture (0% RA) due to the lower density of the RA compared to the natural aggregates (Table 2). Contrarily, for the 40% ARPH and 40% ARDA mixtures, their densities are higher than the reference. During the compaction of those mixtures, the crushing process changed the particle size distribution of the fractured RA particles which caused a higher amount of fine particles in the mixtures. Those fine particles occupied the voids and resulted in a higher density in the mixtures.

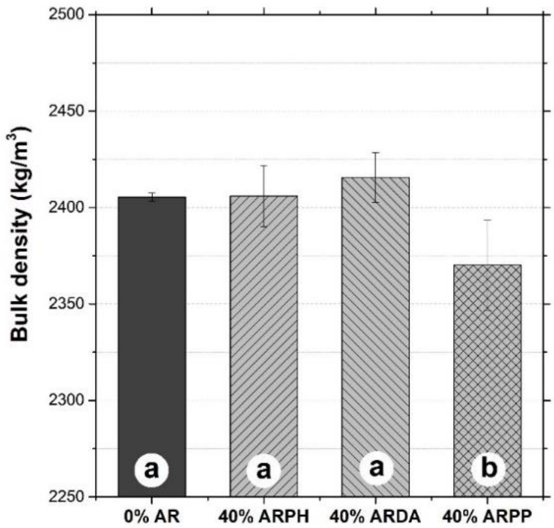

Figure 5. Mixture density with 5% of asphalt content. The error bars represent ±SD. Letters inside each bar indicate statistical differences among groups recovered by one-way ANOVA followed by post-hoc HSD Tukey's multiple comparison test (significant differences are shown by different letters at $p < 0.05$).

VA and VMA in AC are related to its density. As the density of the mixture increases, the number of voids decrease and vice versa. As is observed in Figure 6a,b, the VA of the 40% ARPP mixture increased due to the high porosity of the RA [18,35]. Despite the low density of the RA, the40% ARPH and 40% ARDA mixtures had equal or lower amounts of voids than the reference mixture without RA due to the aforementioned compaction process. The VA (Figure 6a) and VMA (Figure 6b) are in line with the densities of all the mixtures (Figure 4) and meet the requirements proposed by Spanish standard PG-3 [36]. PG-3 proposes a range of 4% to 6% of VA for dense surface mixtures. All of the mixtures met the requirement. This increase in the mixture voids influences the durability of the mixtures. The greater the void content, the faster the aging process [16].

As Figure 7 shows, the stabilities are lower than the that of reference mixture but they comply with the minimum specification established by PG-3 [36]. A reduction of up to 6% in Marshall stability compared to the reference mixture was observed (Figure 7). The reduction of the stability is due to the to the cement paste that adhered to the RA. The stiffness of the mixtures has the same behavior as the stability as the stiffness for RA mixtures was lower than the reference, as reported by Pérez et al. [5].

As Figure 8 shows, the deformation was greater for the mixtures with RA compared to the reference mixture. This was attributed to the mortar adhered to the RA, which reduced the adhesion of the RA to the asphalt. The mixtures with RA exhibited higher deformations than the limited values proposed by PG-3, which established a deformation range from 2.0 mm to 3.5 mm. However, the mixtures with RA presented greater stabilities than those established by PG-3. Therefore, it was concluded that the mixtures displayed good behavior. By incorporating 40% of RA in the 5 to 10 mm fraction, the deformation increased by up to 13%.

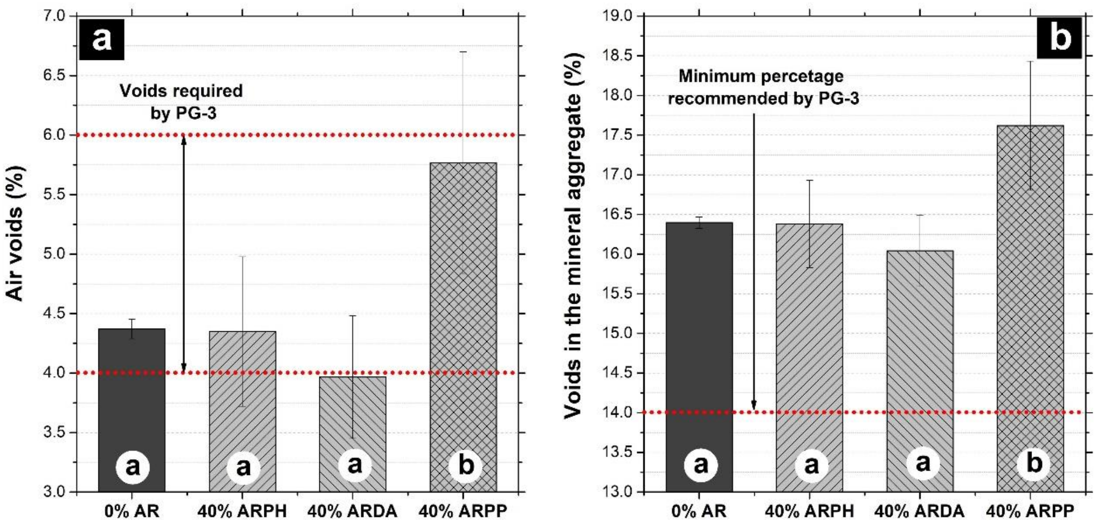

Figure 6. (**a**) Air voids (VA, mean ± SD) with 5% asphalt content. Red lines (4 to 6%) indicate the limit values established by PG-3. (**b**) Voids in the mineral aggregate (VMA, mean ± SD) for the studied mixtures with 5% of asphalt content. Red lines indicate the limit values (≥14%) according to PG-3. The letters inside each bar indicate the statistical differences among groups recovered by one-way ANOVA followed by post-hoc HSD Tukey's multiple comparison test (significant differences are shown by different letters at $p < 0.05$).

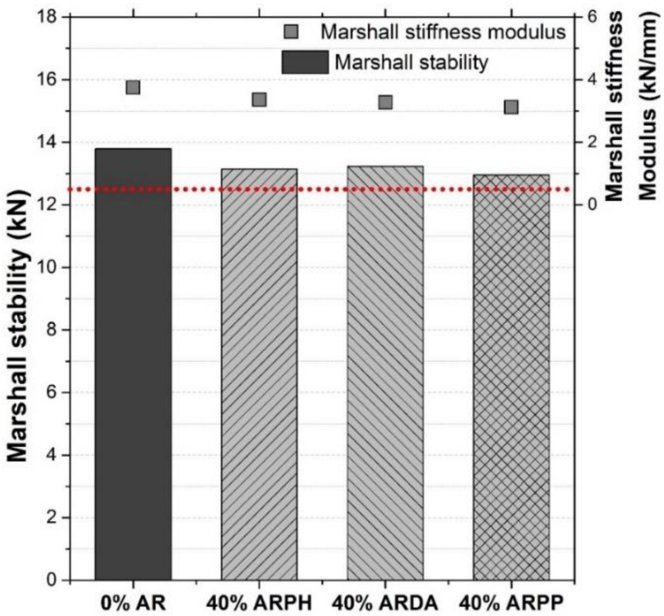

Figure 7. Marshall Stability with 5% of asphalt content. Red line indicates the limit value (≥12.5 kN) according to PG-3.

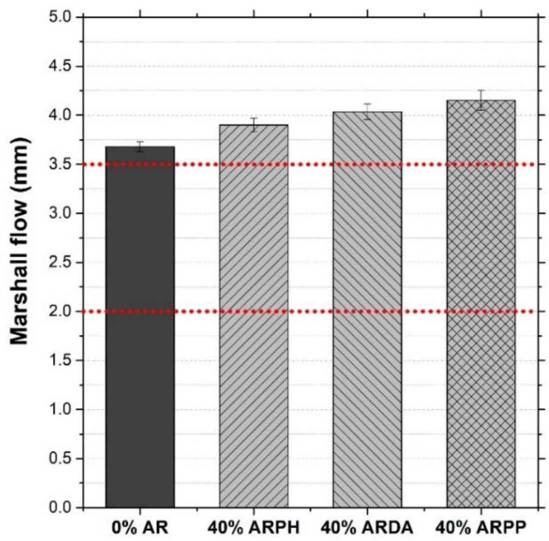

Figure 8. Deformations for mixtures with 5% asphalt content. Red lines indicate the limit values (2 to 3.5 mm) according to PG-3.

3.3. Stiffness Modulus

Figure 9 shows the decrease in the stiffness moduli of the mixtures when the temperature increased. This is due to the thermal susceptibility of the asphalt binder. At 7 °C, the stiffness modulus was between 21,500 and 24,000 MPa; at 25 °C, it was between 5000 and 7500 MPa; and at 50 °C, it was between 650 and 1000 MPa. For temperatures higher than 40 °C, the deformations were greater and even specimen breakage may have occurred.

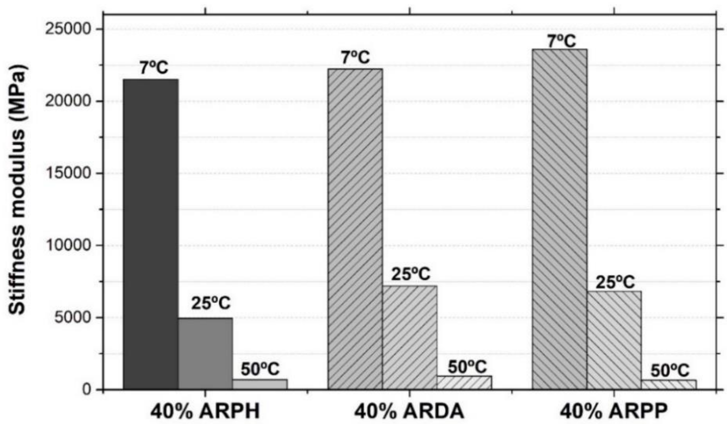

Figure 9. Stiffness modulus of mixtures with RA at different temperatures.

At 7 °C, a stiffness modulus of 18,360 MPa was obtained in the work carried out by Alonso [37] for a standard mixture that was similar to the reference mixture for this study. This value at 7 °C is higher in all the mixtures with RA in this study (Figure 8), which shows the potential use of RA in asphalt mixtures at low temperatures.

AC stiffness modulus between 2500 and 8000 MPa at 25 °C has been recommended [36]. In addition, the standard in Spain [38] proposed that these moduli should be between 3500 and 9500 MPa. Both of these recommendations are met for the mixtures analyzed.

According to Figure 9, the highest values of the stiffness modulus are obtained for the ARDA and ARPP mixtures at 25 and 50 °C (the same results were observed in the stability values). At 7 °C, the highest value is observed in the ARPP mixture. At 50 °C, Alonso et al. [39] obtained a stiffness modulus of 924 MPa for a conventional mixture which has characteristics that are similar to the mixtures of this research. It is observed that the ARDA mixture behaved similarly to that analyzed by Alonso et al. [39]. It is important to point out that at 50 °C, the resulting deformations observed during the stiffness modulus test were not excessive or caused by the breakage of the analyzed specimens (Figure 10).

3.4. Horizontal Deformation

Figure 10 shows the increase in deformation at higher temperatures. It can be noted that both the horizontal deformations and the Marshall deformations had similar behaviors for each of the different RA sources. However, the ARPP mixture at 50 °C showed a greater degree of horizontal deformation.

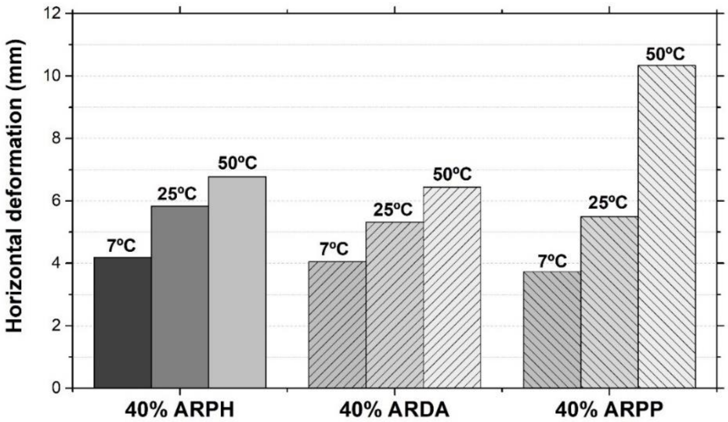

Figure 10. Horizontal deformation in the mixtures with RA.

3.5. Statistical Analysis

Table 5 shows the results of the ANOVA. The type of asphalt mixture had a significant influence ($p < 0.05$) on the density (Figure 4), the VA (Figure 5a) and in the VMA (Figure 5b). The ANOVA classified the mixtures in different groups or subsets performed according to the Tukey's HSD test at 95% level. As observed in Figures 4 and 5, the mixtures were grouped into two homogeneous subsets (a and b).

Table 5. Results of ANOVA.

Parameter		DF [1]	Sum of Squares	Mean Square	*F* Value	*p* Value [2]
Bulk density	Model	3	0.00594	0.00198	10.35732	0.0005
	Error	16	0.00306	1.9112×10^{-4}		
	Total	19	0.009			
Stability	Model	3	0.48675	0.16225	1.15271	0.455
	Error	3	0.4226	0.14075		
	Total	6	0.90901			
Marshall flow	Model	3	0.16664	0.05555	3.23879	0.180
	Error	3	0.05145	0.01715		
	Total	6	0.21809			
Stiffness	Model	2	2.86591×10^{6}	1.43296×10^{6}	0.01126	0.989
	Error	6	7.63358×10^{8}	1.27226×10^{8}		
	Total	8	7.66224×10^{8}			
Horizontal deformation	Model	2	4.7538	2.3769	0.50604	0.626
	Error	6	28.1826	4.6971		
	Total	8	32.9364			

[1] DF: Degree of freedom. [2] At the 0.05 level the population means are not significantly different.

The ANOVA also shows that there is no significant influence from the mixture type on: (i) The Marshall stability (p value = 0.455); (ii) the Marshall flow (p value = 0.18); (iii) the stiffness (p value = 0.989); and (iv) the horizontal deformation (p value = 0.626).

4. Conclusions

In this work, hot asphalt concrete mixtures manufactured with recycled aggregate from three different sources were evaluated. The recycled aggregate was used to partially replace (40%) the natural aggregate fraction measured between 5 and 10 mm. From the results obtained, the following conclusions can be drawn:

(1) The main mineral phases observed in the RA were $CaCO_3$ and dolomite. This was due to the origin of the aggregates used to manufacture the original Cuban concrete.
(2) For the same percentage of asphalt, the density and voids of the mixture varied depending on the source of RA origin.
(3) The stability obtained in the RA mixtures is less than the reference stability. However, all the RA mixtures comply with the limits established in PG-3.
(4) The deformation of the mixtures was slightly higher than the deformation of reference mixture.
(5) RA mixtures had a stiffness modulus, even at high temperatures, that was in line with recommendations.
(6) The statistical analysis performed shows that the percentage of RA influenced the physical properties. However, there was no significant influence in the Marshall stability, flow, stiffness and horizontal deformation.

In conclusion, the results of this research show the possibility of using RA from different sources of Cuban RA for partial replacement in the production of good quality hot asphalt mixes.

Author Contributions: D.A.A. wrote the paper. D.A.A., A.A.A., A.J.T.-A. performed the experiments. A.A.A. and A.J.T.-A. supervised the research work and revised the paper. All the authors contributed to conceive and design the experiments, and to analyze and discuss the results.

Funding: This research was funded by Pavasal Empresa Constructora SA and the University of Alicante (Spain) through projects GRE13-03 and VIGROB-256.

Acknowledgments: Pavasal Empresa Constructora SA.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Huang, W.L.; Lin, D.H.; Chang, N.B.; Lin, K.S. Recycling of Construction and Demolition Waste via a Mechanical Sorting Process. *Resour. Conserv. Recycl.* **2002**, *37*, 23–37. [CrossRef]
2. Robinson, G.R.; Menzie, W.D.; Hyun, H. Recycling of Construction Debris as Aggregate in the Mid-Atlantic Region, USA. *Resour. Conserv. Recycl.* **2004**, *42*, 275–294. [CrossRef]
3. Tenza-Abril, A.J.; Saval, J.M.; Cuenca, A. Using Sewage-Sludge Ash as Filler in Bituminous Mixes. *J. Mater. Civ. Eng.* **2015**, *27*. [CrossRef]
4. Shi, C.; Li, Y.; Zhang, J.; Li, W.; Chong, L.; Xie, Z. Performance Enhancement of Recycled Concrete Aggregate—A Review. *J. Clean. Prod.* **2016**, *112*, 466–472. [CrossRef]
5. Pérez, I.; Pasandín, A.R.; Medina, L. Hot Mix Asphalt Using C&D Waste as Coarse Aggregates. *Mater. Des.* **2012**, *36*, 840–846. [CrossRef]
6. Zhu, J.; Wu, S.; Zhong, J.; Wang, D. Investigation of Asphalt Mixture Containing Demolition Waste Obtained from Earthquake-Damaged Buildings. *Constr. Build. Mater.* **2012**, *29*, 466–475. [CrossRef]
7. Huang, Y.; Bird, R.N.; Heidrich, O. A Review of the Use of Recycled Solid Waste Materials in Asphalt Pavements. *Resour. Conserv. Recycl.* **2007**, *52*, 58–73. [CrossRef]
8. Pavón, E.; Martínez, I.; Etxeberria, M. The Production of Construction and Demolition Waste Material and the Use of Recycled Aggregates in Havana, Cuba. *Rev. Fac. Ing. Univ. Antioq.* **2014**, *71*, 167–178.

9. Martínez, I.; Etxeberria, M.; Pavón, E.; Díaz, N. A Comparative Analysis of the Properties of Recycled and Natural Aggregate in Masonry Mortars. *Constr. Build. Mater.* **2013**, *49*, 384–392. [CrossRef]
10. Arabani, M.; Azarhoosh, A.R. The Effect of Recycled Concrete Aggregate and Steel Slag on the Dynamic Properties of Asphalt Mixtures. *Constr. Build. Mater.* **2012**, *35*, 1–7. [CrossRef]
11. Pasandín, A.R.; Pérez, I. Laboratory Evaluation of Hot-Mix Asphalt Containing Construction and Demolition Waste. *Constr. Build. Mater.* **2013**, *43*, 497–505. [CrossRef]
12. Mills-Beale, J.; You, Z. The Mechanical Properties of Asphalt Mixtures with Recycled Concrete Aggregates. *Constr. Build. Mater.* **2010**, *24*, 230–235. [CrossRef]
13. Pasandín, A.R.; Pérez, I. Mechanical Properties of Hot-Mix Asphalt made with Recycled Concrete Aggregates Coated with Bitumen Emulsion. *Constr. Build. Mater.* **2014**, *55*, 350–358. [CrossRef]
14. Ossa, A.; García, J.L.; Botero, E. Use of Recycled Construction and Demolition Waste (CDW) Aggregates: A Sustainable Alternative for the Pavement Construction Industry. *J. Clean. Prod.* **2016**, *135*, 379–386. [CrossRef]
15. Evangelista, L.; De Brito, J. Concrete with Fine Recycled Aggregates: A Review. *Eur. J. Environ. Civ. Eng.* **2014**, *18*, 129–172. [CrossRef]
16. Pasandín, A.R. *Sensibilidad al Agua y Propiedades Mecánicas de Mezclas Bituminosas en Caliente Fabricadas con áridos Reciclados de Residuos de Construcción y Demolición, Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos*; Universidade da Coruña: A Coruña, Spain, 2013.
17. Alexandridou, C.; Angelopoulos, G.N.; Coutelieris, F.A. Mechanical and Durability Performance of Concrete Produced with Recycled Aggregates from Greek Construction and Demolition Waste Plants. *J. Clean. Prod.* **2018**, *176*, 745–757. [CrossRef]
18. Paranavithana, S.; Mohajerani, A. Effects of Recycled Concrete Aggregates on Properties of Asphalt Concrete. *Resour. Conserv. Recycl.* **2006**, *48*, 1–12. [CrossRef]
19. Tam, V.W.Y.; Gao, X.F.; Tam, C.M. Microstructural Analysis of Recycled Aggregate Concrete Produced from Two-Stage Mixing Approach. *Cem. Concr. Res.* **2005**, *35*, 1195–1203. [CrossRef]
20. Colangelo, F.; Cioffi, R. Mechanical Properties and Durability of Mortar Containing Fine Fraction of Demolition Wastes Produced by Selective Demolition in South Italy. *Compos. Part B Eng.* **2017**, *115*, 43–50. [CrossRef]
21. Colangelo, F.; Petrillo, A.; Cioffi, R.; Borrelli, C.; Forcina, A. Life Cycle Assessment of Recycled Concretes: A Case Study in Southern Italy. *Sci. Total Environ.* **2018**, *615*, 1506–1517. [CrossRef] [PubMed]
22. Kim, Y.; Hanif, A.; Kazmi, S.M.S.; Munir, M.J.; Park, C. Properties Enhancement of Recycled Aggregate Concrete through Pretreatment of Coarse Aggregates—Comparative Assessment of Assorted Techniques. *J. Clean. Prod.* **2018**, *191*, 339–349. [CrossRef]
23. Vazquez Ramonich, E.; Barra, M.; Moreno Lasalle, L.; Sopena Canals, F.J.; Valero López, I.; Rebollo Pericot, J.; Andreu, T.; Balmaceda, A. Aportación de árido reciclado mixto con predominio de hormigón para la sustitución de parte del árido fino en la fabricación de mezclas bituminosas. In *VII Jornada Nacional de ASEFMA*; ASEFMA: Madrid, Spain, 2012; p. 8.
24. Al-Baiti, H.K.; Al-Sarrag, N.I.; Saleh Al-maliky, S.E. Use of Recycling Building Demolition waste As Coarse Aggregate in Hot Mix Asphalt. *Tikrit J. Eng. Sci.* **2014**, *21*, 63–76.
25. Wong, Y.D.; Sun, D.D.; Lai, D. Value-added Utilisation of Recycled Concrete in Hot-Mix Asphalt. *Waste Manag.* **2007**, *27*, 294–301. [CrossRef] [PubMed]
26. Asociación Española de Normalización y Certificación. *UNE-EN 13043: Áridos para Mezclas Bituminosas y Tratamientos Superficiales de Carreteras, Aeropuertos y Otras Zonas Pavimentadas*; AENOR: Madrid, Spain, 2003.
27. Asociación Española de Normalización y Certificación. *UNE-EN 12591: Betunes y Ligantes Bituminosos. Especificaciones de Betunes Para Pavimentación*; AENOR: Madrid, Spain, 2009.
28. De Juan, M.S.; Gutiérrez, P.A. Study on the Influence of Attached Mortar Content on the Properties of Recycled Concrete Aggregate. *Constr. Build. Mater.* **2009**, *23*, 872–877. [CrossRef]
29. Asociación Española de Normalización y Certificación. *UNE-EN 1097-6: Ensayos para Determinación las Propiedades Mecánicas y fíSicas de los áridos. Parte 6: Determinación de la Densidad de Partículas y la Absorción de Agua*; AENOR: Madrid, Spain, 2001.
30. Asociación Española de Normalización y Certificación. *UNE-EN 12697-34: Mezclas Bituminosas. Métodos de Ensayo para Mezcla Bituminosa en Caliente. Parte 34: Ensayo Marshall*; AENOR: Madrid, Spain, 2006.

31. Oficina Nacional de Normalización. *NC 253 Carreteras. Materiales Bituminosos. Hormigón Asfáltico Caliente. Especificaciones*; Oficina Nacional de Normalización: La Habana, Cuba, 2005.
32. Christopher, W.J.; Crawford, F.J.; Edward, T.H.; Adock, M.; Delaney, E.P.; Freer, H. *A Manual for Design of Hot Mix Asphalt with Commentary. NCHRP Report No. 673*; National Academies Press: Washington, DC, USA, 2011; ISBN 9780309155649.
33. Asociación Española de Normalización y Certificación. *UNE-EN 12697-26: Métodos de Ensayo para Mezcla Bituminosa en Caliente. Parte 26: Rigidez*; AENOR: Madrid, Spain, 2005.
34. Blanco, M.T.; Puertas, F.; Vázquez, T.; de la Fuente, A. The Most Suitable Techiniques and Methods to Identify High Alumina Cement and Based Portland Cement in Concretes. *Mater. Constr.* **1992**, *42*, 51–64. [CrossRef]
35. Pérez, I.; Toledano, M.; Gallego, J.; Taibo, J. Mechanical Properties of Hot Mix Asphalt Made with Recycled Aggregates from Reclaimed Construction and Demolition Debris. *Mater. Constr.* **2007**, *57*, 17–29. [CrossRef]
36. Ministerio de Fomento. *Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3)*; Dirección General de Carreteras, Ministerio de Fomento, Ed.; Ministerio de Fomento: Madrid, Spain, 2015.
37. Alonso Aenlle, A. *Obtención a Nivel de Laboratorio de Una Mezcla Asfáltica Semicaliente a Partir de la Utilización de Zeolita Natural Cubana del Yacimiento de Tasajeras*; CUJAE, Instituto Superior Politécnico José Antonio Echeverría, Facultad de Ingeniería Civil: Havana, Cuba, 2012.
38. Generalitat Valenciana. *Norma de Secciones de Firmes de la Comunidad Valenciana*; Conselleria d'Infraestructures i Transport; Generalitat Valenciana: Valencia, Spain, 2009.
39. Alonso, A.; Tejeda, E.; Moreno, F.; Rubio, M.C.; Medel, E. A Comparative Study of Natural Zeolite and Synthetic Zeolite as an Additive in Warm Asphalt Mixes. *Mater. Constr.* **2013**, *63*, 195–217. [CrossRef]