Assessment of a Hot-Mix Asphalt Using Recycled Concrete Aggregate. Case of Study: High Temperature Climate[a]

Evaluación de una mezcla asfáltica utilizando agregados reciclados de concreto. Caso de estudio. Clima de alta temperatura

Received: January 21, 2021 | Accepted: February 27, 2023 | Published: November 28, 2023

Hermes Ariel Vacca-Gamez*
Pontificia Universidad Javeriana, Bogotá, Colombia
ORCID: https://orcid.org/0000-0003-3159-6997

José Elvert Rubio-Tafur
Universidad La Gran Colombia, Bogotá, Colombia
ORCID: https://orcid.org/0000-0003-3395-5922

Hernán Camilo Moreno-Chaparro
Universidad La Gran Colombia, Bogotá, Colombia
ORCID: https://orcid.org/0000-0003-1777-0717

Hugo Alexander Rondon-Quintana
Universidad Distrital Francisco José de Caldas, Bogotá, Colombia
ORCID: https://orcid.org/0000-0003-2946-9411

[a] Research paper (Artículo de investigación)

* Corresponding author. E-mail: vacca@javeriana.edu.co

DOI: https://doi.org/10.11144/Javeriana.iued27.ahau

How to cite this article:

H.A. Vacca-Gamez, J. E. Rubio-Tafur, H.C. Moreno-Chaparro, H.A. Rondon-Quintana, "Assessment of a Hot-Mix Asphalt Using Recycled Concrete Aggregate. Case of Study: High Temperature Climate" Ing. Univ. vol. 27, 2023. https://doi.org/10.11144/Javeriana.iued27.ahau

Abstract

In road infrastructure projects large quantities of naturally occurring aggregates (NA) are exploited and used to form asphalt layers in pavement structures. To reduce the negative environmental impact generated by this practice, these materials could be replaced by recycled concrete aggregates (RCA). In the present research, the change in stiffness under cyclic loading (resilient modulus – RM) and resistance to permanent deformation of an asphalt concrete mixture (HMA) was measured and evaluated when the coarse fraction (gravel and sand) of an NA is replaced by RCA in proportions of 20%, 40% and 80% concerning mass. The RM and permanent deformation were measured because Colombia is a country where high-temperature climate predominates, in one of the main damage mechanisms of HMAs is rutting. The results indicated an increase in the RM and the resistance to rutting of the HMA analyzed for any percentage of substitution. That is, the use of RCA as a substitute for NA could be a sustainable alternative, while at the same time, it could help increase the rutting resistance of HMA.

Keywords: Hot-mix asphalt; HMA; recycled concrete aggregate; RCA; resilient modulus; rutting.

Resumen

En proyectos de infraestructura vial se explotan y utilizan grandes cantidades de agregados de origen natural (NA) para la conformación de capas asfálticas en estructuras de pavimento. Para disminuir el impacto ambiental negativo que genera esta práctica, estos materiales podrían ser sustituidos por agregados de concreto reciclado (RCA). En el presente estudio se midió y evaluó el cambio que experimenta la rigidez bajo carga cíclica (módulo resiliente – RM) y la resistencia a la deformación permanente de una mezcla de concreto asfáltico (HMA) cuando se sustituye la fracción gruesa (gravas y arenas) de un NA por RCA en proporciones de 20%, 40% y 80 % con respecto a la masa. El RM y la deformación permanente fueron medidos debido a que Colombia es un país donde predomina el clima de alta temperatura, en el cual uno de los principales mecanismos de daño de HMAs es el ahuellamiento. En el presente estudio se reporta un aumento del RM y la resistencia a la deformación permanente de la HMA analizada para cualquier porcentaje de sustitución. Es decir, el uso de RCA como sustituto de NAs podría ser una alternativa sostenible, al mismo tiempo que podría ayudar a incrementar la resistencia al ahuellamiento de HMAs.

Palabras clave: Mezcla asfáltica; HMA; agregado reciclado de concreto; RCA; módulo resiliente; ahuellamiento.

Introduction

Large quantities of natural origin aggregates (NA) are extracted from quarries for the building of infrastructure construction works [1]. This negatively impacts the environment, given that extracting these materials generates negative environmental impacts such as soil erosion, destruction of flora and fauna, loss of biodiversity, landscape geomorphological changes, the running out of authorized landfills, soil pollution, underground water bodies and hydrologic basins [2]. With the purpose of contributing to reduce this issue, several research efforts have been conducted in order to evaluate solutions that are economical and environmentally friendly, and sustainable for replacing NAs with alternative materials [3]. RCA (Recycled Concrete Aggregates) comprise a significant part of construction and demolition wastes (C&D), and their recycling is essential for long term sustainability in construction [4][5][6] RCAs are considered inert materials that possess a high susceptibility of being harnessed through transformation and reincorporation as raw material used as aggregates in the manufacturing of new products.

Generally, RCAs have been broadly studied and characterized in order to comprise base, subbase layers and improvements for subgrades [7]. Another way of using them in roadway projects is in the manufacturing of hot-mix asphalts (HMA). This material has a great use potential, given that aggregates comprise more than 75% in volume [8][9]. However, there are some existing aspects that could discourage its use. For example, RCAs are highly heterogenous and present lesser mechanical resistances and hardness in comparison to NAs [10][11][12]. This is mainly because of the fragility of the mortar adhered to RCA surface [13] [14][15] and the presence of other impurites that are difficult to separate from C&D, such as brick, ceramic and clay roof tiles, among others [16].

Due to the lesser specific gravity, high porosity and high absorption of RCA particles, HMAs that use these materials tend to present greater air void contents [13][17][18][19][20][21] [22][23][24][2] and need greater asphalt contents [25][26][27][17][28][29][30]. Despite the above, several studies have demonstrated that these materials can replace NA aggregates and generate HMAs with a good behavior [2][5]. According to [18][25], RCA increases the Marshall stability of some HMAs. [21][25][26][29] report an increase in stiffness under cyclic loading. Others researchers found good behavior in terms of thermal cracking and moisture damage resistance [23][29][30]. Additionally, HMAs using RCAs in many cases comply with national Marshall design specifications for low and medium traffic [31][32][33][22]. On the other hand, due to the high heterogeneousness of RCAs, studies conducted on HMA mixes present results that are contradictory [34] In order to improve some of the undesirable properties of HMAs that use RCAs, some researchers advise to pre-treat RCAs (e.g., bitumen emulsion, Portland cement paste, slag cement paste, liquid silicone resin, abrasive mechanical pre-treatment, among others) before the production of the bituminous mix (e.g., [25][26][35][15][36][10]).

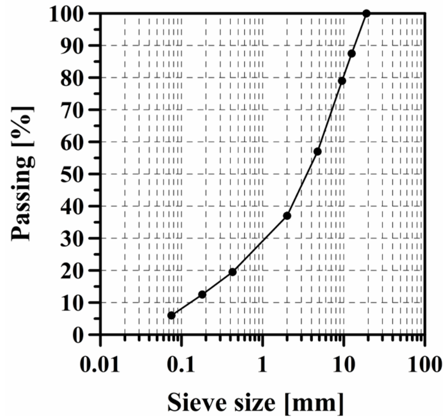
This study replaced an NA for an RCA in the manufacturing of HMA. The properties evaluated on the HMA mixes were stiffness under cyclic load through resilient modulus and permanent deformation resistance. Said properties were evaluated given that Colombia is a tropical country where high temperature climates are predominant, and the main damage mechanism that occurs in HMAs is rutting. Despite the broad number of studies conducted on the topic, there are yet certain discrepancies reported in the referred literature. Given the above, the results of this study are useful for giving continuity and depth to the discussion in relation to this line of research. Finally, we sought to promote the harnessing of RCAs as a means for mitigating the environmental impact generated by the use of natural aggregate materials.

Materials and methods

Materials

The control HMA mix (100% NA as aggregate) is type HMA-19 (see particle size distribution in Figure 1) according to INVIAS (2013) [37]. In order to manufacture the mix, a type AC 60-70 asphalt cement was used (see properties on Table 1). This asphalt has a performance grade PG at high and intermediate service temperatures of 68°C and 20°C, respectively (see Figure 2). The viscosity curve of AC 60-70 is shown in Figure 3. The properties of the NA and RCA used are shown on Table 2. Both AC 60-70 as NA and RCA aggregates comply with the minimum quality requirements established by the INVIAS (2013) specification for manufacturing HMA mixes. Additionally, it is observable that RCA presents greater absorption and lesser specific gravity, abrasion wear resistance and crushing resistance in comparison to NA, such as has broadly been evidenced in the referred literature (e.g., [2]).

Figure 1. Particle size distribution curve (HMA-19)



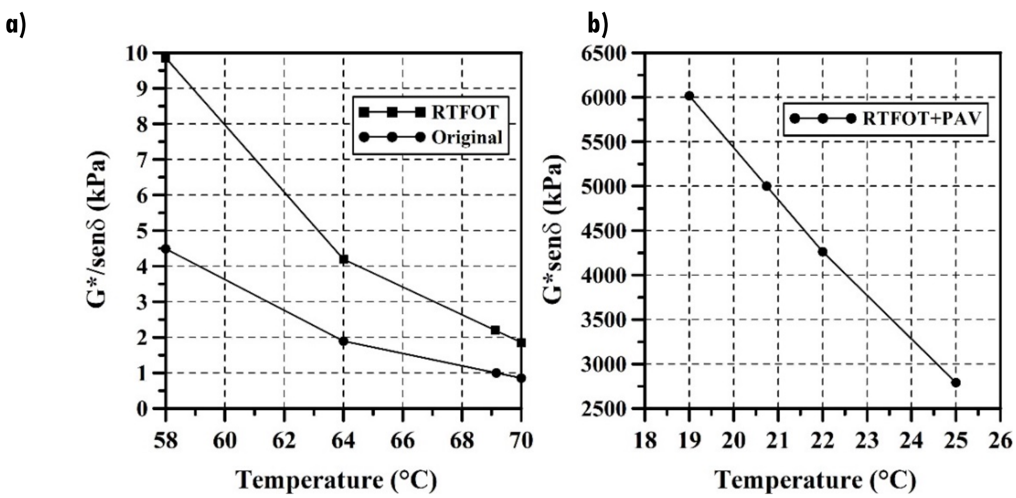
Source: Authors own creation

Table 1. AC 60-70 properties

Test	Method	Unit	Recommended	Result
Tests on the original asphalt				
Penetration (25°C, 100 g, 5 s)	ASTM D-5	0.1 mm	60-70	63
Penetration Index	NLT 181	-	-1.2/+0.6	-0.32
Softening point	ASTM D-36	°C	48-54	51.2
Ductility (25°C, 5cm/min)	ASTM D-113	cm	100 minimum	>100
Flash and fire points	ASTM (2001a)	°C	230 minimum	240.5
Tests on the residue after RTFOT (Rolling Thin Film Oven Test)				
Mass loss	ASTM D-2872	%	0.8 maximum	0.75
Softening point increment	ASTM D-36	°C	9 mximum	7.8
Penetration (25°C, 100 g, 5 s)	ASTM D-5	%	50 minimum	50.4
Viscosity ratio (before/after RTFOT)	AASHTO T-316	-	4 maximum	3.3

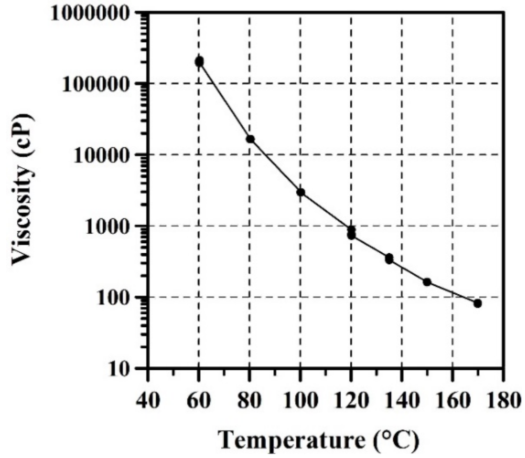
Source: Authors own creation

Figure 2. Determination of PG at a) high and b) intermediate temperature.



Source: Authors own creation

Figure 3. Viscosity curve of AC 60-70.



Source: Authors own creation

Table 2. NA and RCA properties.

Test	Method	RCA	NA
Specific gravity/absorption, coarse fraction	AASHTO T 84	2.707/5.8%	2.795/0.7%
Specific gravity/adsorption, fine fraction	AASHTO T 85	2.734/4.0%	2.771/0.6%
Abrasion in Los Angeles Machine, 500 revolutions (%)	AASHTO T 96	29	17
Micro-Deval (%)	AASHTO T327	15	7
10% of fines (dry resistance) (kN)	DNER-ME 096	156.3	320.3
Fractured particles: 1 face	ASTM D 5821	100	97
Impurities content	UNE 14613	0.0	0.0
Plasticity index	ASTM D 4318	0.0	0.0
Flattening and elongation index	NLT 354	0.0	0.0
Sand equivalent test	AASHTO T 176	79	80

Source: Authors own creation

Control Mix Design

HMA-19 control mix was designed based on the Superpave methodology. As compaction parameters, a number of initial (Ni), design (Ndes) and maximum (Nmax) gyrations of 7, 86 and 134, respectively. 15 samples were compacted, using asphalt percentages of 4.0, 4.5, 5.0, 5.5 and 6.0% (three samples per percentage). Based on the results presented on Figure 3, mix and compaction temperatures were 150°C and 135°C, respectively. The optimal asphalt content (OAC) was determined considering as a main criterion, reaching a mix air void content of 4.0%. Additionally, the theoretical maximum specific gravity (Gmm) was evaluated. We also considered that the TSR (Tensile Strength Ratio) should comply with the minimum value recommended by the INVIAS (2013) specification, namely 80%. This parameter, used especially for evaluating moisture damage resistance, was measured by following the procedure established by the AASHTO T 283 specification. TSR = 82% for HMA-19 control mix.

Substitution of NA with RCA

Using the control mix OAC, HMA-19 mixes were manufactured substituting by mass, part of the NA aggregate with RCA. The fractions that were replaced were in the sizes of gravels and sands (material retained in sieve No. 200 up to the one retained in ½" but passing through sieve ¾"). The percentage of material that passed through sieve No. 200 was not replaced. Substitution for gravel and sand sizes was carried out proportionally in 20, 40 and 80%. Mixes that used these substitutions were named HMA-RCA20%, HMA-RCA40% and HMA-RCA80%. Traditionally, mixes that use aggregates with greater absorption and surface porosity require greater asphalt contents. However, in this study, the OAC was maintained as equal to the one of the control mix with the purpose of evaluating if it was possible to use mixes with RCA without increasing their cost, which occurs when greater asphalt contents are used.

Resilient Modulus and Permanent Deformation

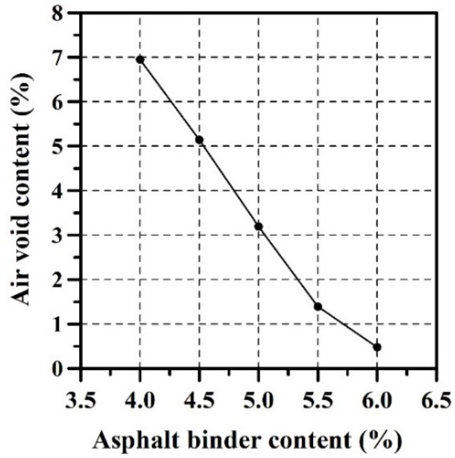
The following mixes (control, HMA-RCA20%, HMA-RCA40% and HMA-RCA80%) were subjected to resilient modulus test RM in indirect tension, using a Nottinghan Asphalt Tester (NAT) and following the guidelines established in the ASTM D 4123 specification. Each RM was determined under three temperatures (10 °C, 20 °C and 30 °C) and three load application frequencies (2.5 Hz, 5 Hz and 10 Hz). Each test was conducted on three samples per each type of mix and temperature. Permanent deformation tests were carried out under the action of a repetitive load that was axially applied, following the guidelines established by UNE – EN 12697-25, and using the NAT. Said load was applied in the form of a square wave with a frequency of 0.5 Hz (1 s of load application and 1 s of rest per cycle). Samples for the test were previously conditioned at a temperature of 40º C during 4 hours. When samples reached the temperature of 40°C, 600 cycles of preload (10 kPa) were applied during 20 minutes and then 3600 load cycles of (100 kPa) were applied under which the vertical displacement experienced by the sample was measured. For this purpose, Linear Variable Differential Transformer (LVDT) type systems were used. These tests were carried out on RM samples, given that this last one is non-destructive.

Results

Control Mix Design

The evolution of air voids content with the asphalt percentage shown on Figure 4. The OAC obtained from said Figure is 4.8%. The volumetric composition of control HMA-19 is shown on Table 3. It is observable that the OAC obtained complies with the criteria established by the Superpave method for manufacturing HMA mixes.

Figure 4. Air void content vs. asphalt binder content.



Source: Authors own creation

Table 3. Volumetric composition of control HMA-19

Property	Requirement	Result
OAC (%)	-	4.8
Air void (%)	4.0 %	4.3
Voids in Mineral Aggregate – VMA (%)	Min. 14	15.3
Voids Filled with Asphalt – VFA (%)	65 – 75	73.0
% Gmm @ N_i	<89	87.8
% Gmm @ N_{max}	<98	97.1
Filler ratio (%)	0.6 – 1.6	1.39

Source: Authors own creation

Using the same OAC in the control mix (4.8%) mixes were manufactured in which NA was replaced with RCA. Some volumetric composition parameters of the mixes are presented on Table 4. Gmb corresponds to bulk specific gravity. It is possible to observe in an obvious manner, that based on the consulted reference literature, an increase in air voids in mixes and decrease of Gmm and Gmb as the content of NA substitution for RCA increases [2][10]. This mainly occurs because of: i) RCA present particles with greater absorption; ii) RCA present lesser specific gravity, and upon replacing by mass, a greater quantity of particles to be coated with asphalt are being introduced by volume [38][2][12], iii) during the process of kneading inside the gyratory compactor, the mortar adhered to RCA could detach, increasing the quantity of fine particles in mixes [2].

Table 4. Volumetric composition of control HMA-19

HMA type	Air voids (%)	Gmm	Gmb
Control	4.3	2.48	2.37
HMA-RCA20%	6.0	2.44	2.30
HMA-RCA40%	7.6	2.40	2.22
HMA-RCA80%	11.1	2.35	2.09

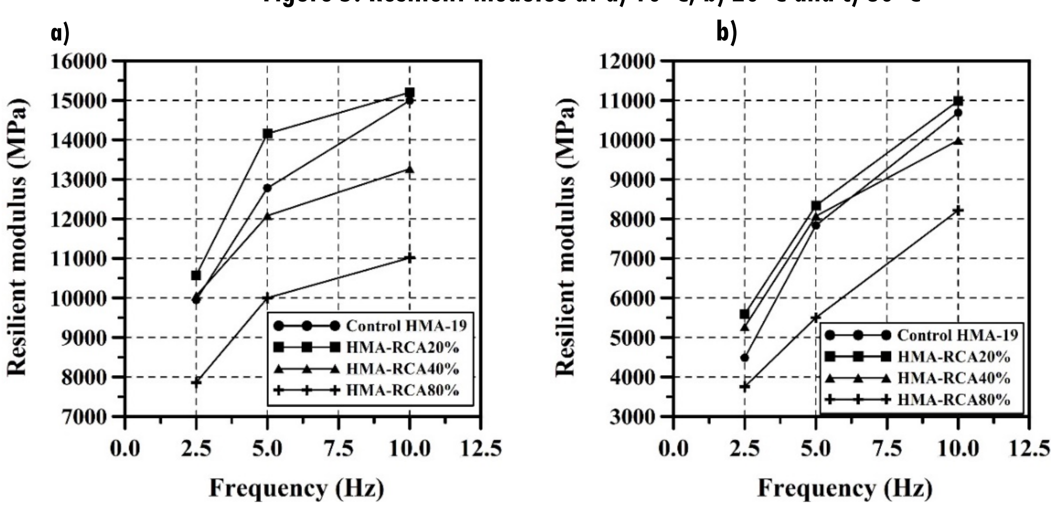
Source: Authors own creation

Resilient Modulus and Permanent Deformation

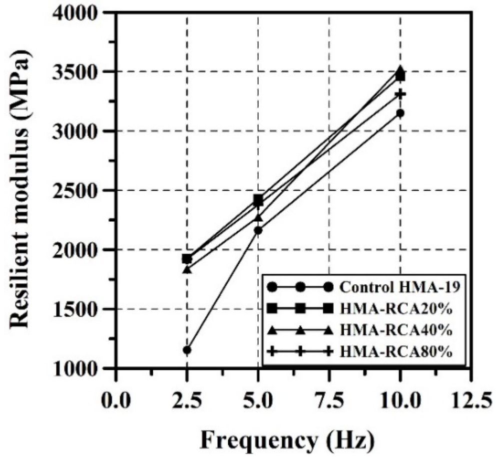
Results of RM tests are presented in Figure 5. There is no clearly identified trend that can be observed. However, it is possible to observe that the HMA-RCA20% mix presents a greater RM in relation to the control mix for any test temperature. The above, occurs despite the fact that the air void content of HMA-RCA20% is higher (see Table 4.) The increase of RM in HMA-RCA20% varies between 3 and 67% depending on the temperature and frequency in the test. Another important aspect that can be observed in Figure 5, is that mixes with RCA tend to undergo a greater RM than the control mix as temperature increases. At 30°C, all RCA mixes present a greater RM with relation to the control mix. This phenomenon is observable, despite the fact that air void content is much greater in mixes with RCA. This increase in RM in RCA mixes could explain the greater permanent deformation resistance that can be observed in Figure 6 when samples were subjected to a test temperature of (40°C). The greatest resistance to rutting was observed in HMA-RCA40% mix.

The results for modulus and permanent deformation do not have a clear explanation, given that the asphalt mixtures tend to present a lesser RM as air void content increases. Additionally, RCA is a material that presents particles with lesser abrasion wear resistance and crushing resistance in comparison to those of the NA used in this study. A possible explanation to what was observed is that perhaps, since NA was substituted for RCA by mass, a greater number of RCA particles were added (due to its lesser specific gravity), generating a granular skeleton with a greater number of contacts that tend to increase permanent deformation resistance under cyclic load. Additionally, the mixture of a low absorption and low surface roughness aggregate (NA) and an aggregate with high absorption and high surface roughness (RCA) could have contributed to the generating of a granular skeleton with a good behavior, such as has been reported in studies with similar materials [38].

Figure 5. Resilient modulus at a) 10°C, b) 20°C and c) 30°C

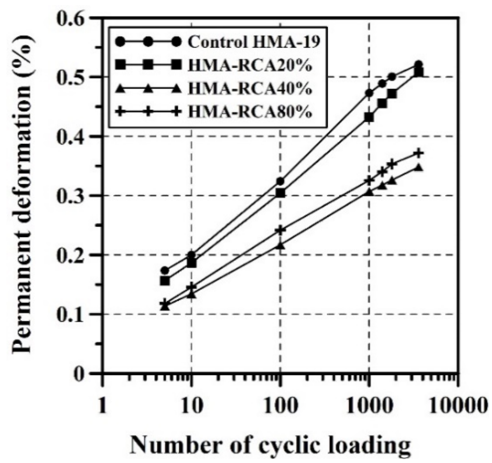


c)



Source: Authors own creation

Figure 6. Permanent deformation evolution.



Source: Authors own creation

Conclusions

This study analyzed the response that an HMA mix could undergo in a high temperature climate when the fraction of gravels and sands of an NA is substituted with RCA. Based on the results obtained, conclusions are the following:

- The RCA used complies with criteria established for the Colombian specification for manufacturing HMA mixes. However, this material presents a greater absorption and a lesser specific gravity, abrasion wear resistance and crushing resistance in comparison to the NA used.

- Mixes with RCA present a greater resilient modulus at high temperatures in comparison to the control mix. This caused said mixes to be more resistant to the phenomenon of rutting. This occurred despite the fact that RCA mixes were more porous. The mix that used a substitution of 40% of the fraction of natural gravels and sands for RCA undergo the greatest resistance to said phenomenon.

- The results obtained do not possess a clearly identified explanation. Apparently, the response of mixes with RCA to evaluated parameters (RM and permanent deformation resistance) must be studied considering other variables such as the number of particle contacts (recommended in future studies to carry out substitution by volume) and in porosity and surface roughness of the aggregate. Additionally, future studies must evaluate aspects associated to the quantity mortar adhered to RCA, and the chemical-mineralogic composition of RCA and NA particles.

References

[1] R. L. Al-Mufti y A. N. Fried, «Improving the strength properties of recycled asphalt aggregate concrete», Constr. Build. Mater., vol. 149, pp. 45-52, 2017.

[2] E. H. Sanchez-Cotte, L. Fuentes, G. Martinez-Arguelles, H. A. R. Quintana, L. F. Walubita, y J. M. Cantero-Durango, «Influence of recycled concrete aggregates from different sources in hot mix asphalt design», Constr. Build. Mater., vol. 259, p. 120427, 2020.

[3] A. Albayati, Y. Wang, Y. Wang, y J. Haynes, «A sustainable pavement concrete using warm mix asphalt and hydrated lime treated recycled concrete aggregates», Sustain. Mater. Technol., vol. 18, p. e00081, 2018.

[4] P. Mikhailenko, M. Rafiq Kakar, Z. Piao, M. Bueno, y L. Poulikakos, «Incorporation of recycled concrete aggregate (RCA) fractions in semi-dense asphalt (SDA) pavements: Volumetrics, durability and mechanical properties», Constr. Build. Mater., vol. 264, p. 120166, dic. 2020, doi: 10.1016/j.conbuildmat.2020.120166.

[5] C. M. Nwakaire, S. P. Yap, C. W. Yuen, C. C. Onn, S. Koting, y A. M. Babalghaith, «Laboratory study on recycled concrete aggregate based asphalt mixtures for sustainable flexible pavement surfacing», J. Clean. Prod., vol. 262, p. 121462, jul. 2020, doi: 10.1016/j.jclepro.2020.121462.

[6] A. Alnedawi y M. A. Rahman, «Recycled Concrete Aggregate as Alternative Pavement Materials: Experimental and Parametric Study», J. Transp. Eng. Part B Pavements, vol. 147, n.o 1, p. 04020076, mar. 2021, doi: 10.1061/JPEODX.0000231.

[7] C. Maduabuchukwu Nwakaire, S. Poh Yap, C. Chuen Onn, C. Wah Yuen, y H. Adebayo Ibrahim, «Utilisation of recycled concrete aggregates for sustainable highway pavement applications; a review», Constr. Build. Mater., vol. 235, p. 117444, feb. 2020, doi: 10.1016/j.conbuildmat.2019.117444.

[8] F. R. Lizcano y H. R. Quintana, Pavimentos: Materiales, construcción y diseño. Ecoe Ediciones, 2015.

[9] A. Abedalqader, N. Shatarat, A. Ashteyat, y H. Katkhuda, «Influence of temperature on mechanical properties of recycled asphalt pavement aggregate and recycled coarse aggregate concrete», Constr. Build. Mater., vol. 269, p. 121285, feb. 2021, doi: 10.1016/j.conbuildmat.2020.121285.

[10] J. G. Bastidas-Martínez, H. A. Rondón-Quintana, y C. A. Zafra-Mejía, «Study of hot mix asphalt containing recycled concrete aggregates that were mechanically treated with a Los Angeles machine», vol. 10, pp. 226-243, 2019.

[11] M. Upshaw y C. S. Cai, «Critical Review of Recycled Aggregate Concrete Properties, Improvements, and Numerical Models», J. Mater. Civ. Eng., vol. 32, n.o 11, p. 03120005, 2020.

[12] H. A. Rondón-Quintana, C. A. Zafra-Mejía, y J. C. Ruge-Cárdenas, «Substitution by Mass and Volume of a Natural Aggregate with Recycled Concrete Aggregate in an Asphalt Mixture», Int. J. Adv. Sci. Technol., vol. 29, n.o 04, Art. n.o 04, oct. 2020.

[13] S. Paranavithana y A. Mohajerani, «Effects of recycled concrete aggregates on properties of asphalt concrete», Resour. Conserv. Recycl., vol. 48, n.o 1, pp. 1-12, 2006.

[14] M. Arabani y A. R. Azarhoosh, «The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures», Constr. Build. Mater., vol. 35, pp. 1-7, 2012.

[15] A. R. Pasandín y I. Pérez, «Laboratory evaluation of hot-mix asphalt containing construction and demolition waste», Constr. Build. Mater., vol. 43, pp. 497-505, 2013.

[16] A. I. Kareem, H. Nikraz, y H. Asadi, «Characterization of Asphalt Mixtures Containing Double-Coated Recycled Concrete Aggregates», J. Mater. Civ. Eng., vol. 32, n.o 2, p. 04019359, feb. 2020, doi: 10.1061/(ASCE)MT.1943-5533.0003028.

[17] M. M. Rafi, A. Qadir, y S. H. Siddiqui, «Experimental testing of hot mix asphalt mixture made of recycled aggregates», Waste Manag. Res., vol. 29, n.o 12, pp. 1316-1326, 2011.

[18] I. Pérez, A. R. Pasandín, y J. Gallego, «Stripping in hot mix asphalt produced by aggregates from construction and demolition waste», Waste Manag. Res., vol. 30, n.o 1, pp. 3-11, 2012.

[19] A. R. Pasandín y I. Pérez, «Effect of ageing time on properties of hot-mix asphalt containing recycled concrete aggregates», Constr. Build. Mater., vol. 52, pp. 284-293, 2014.

[20] M. S. Pourtahmasb y M. R. Karim, «Performance Evaluation of Stone Mastic Asphalt and Hot Mix Asphalt Mixtures Containing Recycled Concrete Aggregate», Adv. Mater. Sci. Eng., vol. 2014, p. 863148, sep. 2014, doi: 10.1155/2014/863148.

[21] S. Fatemi y R. Imaninasab, «Performance evaluation of recycled asphalt mixtures by construction and demolition waste materials», Constr. Build. Mater., vol. 120, pp. 450-456, sep. 2016, doi: 10.1016/j.conbuildmat.2016.05.117.

[22] H. Qasrawi y I. Asi, «Effect of bitumen grade on hot asphalt mixes properties prepared using recycled coarse concrete aggregate», Constr. Build. Mater., vol. 121, pp. 18-24, sep. 2016, doi: 10.1016/j.conbuildmat.2016.05.101.

[23] Z. Zhang, K. Wang, H. Liu, y Z. Deng, «Key performance properties of asphalt mixtures with recycled concrete aggregate from low strength concrete», Constr. Build. Mater., vol. 126, pp. 711-719, nov. 2016, doi: 10.1016/j.conbuildmat.2016.07.009.

[24] I. Pérez y A. R. Pasandín, «Moisture damage resistance of hot-mix asphalt made with recycled concrete aggregates and crumb rubber», J. Clean. Prod., vol. 165, pp. 405-414, nov. 2017, doi: 10.1016/j.jclepro.2017.07.140.

[25] Y. D. Wong, D. D. Sun, y D. Lai, «Value-added utilisation of recycled concrete in hot-mix asphalt», Waste Manag., vol. 27, n.o 2, pp. 294-301, ene. 2007, doi: 10.1016/j.wasman.2006.02.001.

[26] C.-H. Lee, J.-C. Du, y D.-H. Shen, «Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt», Constr. Build. Mater., vol. 28, n.o 1, pp. 66-71, mar. 2012, doi: 10.1016/j.conbuildmat.2011.08.025.

[27] S. Bhusal, X. Li, y H. Wen, «Evaluation of Effects of Recycled Concrete Aggregate on Volumetrics of Hot-Mix Asphalt», Transp. Res. Rec., vol. 2205, n.o 1, pp. 36-39, ene. 2011, doi: 10.3141/2205-05.

[28] I. S. Bessa, V. T. F. Castelo Branco, y J. B. Soares, «Evaluation of different digital image processing software for aggregates and hot mix asphalt characterizations», Constr. Build. Mater., vol. 37, pp. 370-378, dic. 2012, doi: 10.1016/j.conbuildmat.2012.07.051.

[29] B. Gómez-Meijide, I. Pérez, G. Airey, y N. Thom, «Stiffness of cold asphalt mixtures with recycled aggregates from construction and demolition waste», Constr. Build. Mater., vol. 77, pp. 168-178, feb. 2015, doi: 10.1016/j.conbuildmat.2014.12.045.

[30] B. Gómez-Meijide y I. Pérez, «Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures», Constr. Build. Mater., vol. 51, pp. 267-277, ene. 2014, doi: 10.1016/j.conbuildmat.2013.10.096.

[31] J. Mills-Beale y Z. You, «The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates», Constr. Build. Mater., vol. 24, n.o 3, pp. 230-235, mar. 2010, doi: 10.1016/j.conbuildmat.2009.08.046.

[32] I. Pérez, M. Toledano, J. Gallego, y J. Taibo, «Mechanical properties of hot mix asphalt made with recycled aggregates from reclaimed construction and demolition debris», Mater. Constr., vol. 57, n.o 285, Art. n.o 285, mar. 2007, doi: 10.3989/mc.2007.v57.i285.36.

[33] I. Pérez, A. R. Pasandín, y L. Medina, «Hot mix asphalt using C&D waste as coarse aggregates», Mater. Des. 1980-2015, vol. 36, pp. 840-846, abr. 2012, doi: 10.1016/j.matdes.2010.12.058.

[34] M. M. de Farias, F. Q. Sinisterra, y H. A. R. Quintana, «Behavior of a hot mix asphalt made with recycled concrete aggregate and crumb rubber», Can. J. Civ. Eng., dic. 2018, doi: 10.1139/cjce-2018-0443.

[35] J. Zhu, S. Wu, J. Zhong, y D. Wang, «Investigation of asphalt mixture containing demolition waste obtained from earthquake-damaged buildings», Constr. Build. Mater., vol. 29, pp. 466-475, abr. 2012, doi: 10.1016/j.conbuildmat.2011.09.023.

[36] A. R. Pasandín y I. Pérez, «Mechanical properties of hot-mix asphalt made with recycled concrete aggregates coated with bitumen emulsion», Constr. Build. Mater., vol. 55, pp. 350-358, mar. 2014, doi: 10.1016/j.conbuildmat.2014.01.053.

[37] «Especificaciones Generales de Construcción de Carreteras». INVIAS. (Instituto Nacional de Vías), Bogotá Col., 2013.

[38] H. A. Rondón-Quintana, J. C. Ruge-Cárdenas, y M. M. de Farias, «Behavior of Hot-Mix Asphalt Containing Blast Furnace Slag as Aggregate: Evaluation by Mass and Volume Substitution», J. Mater. Civ. Eng., vol. 31, n.o 2, p. 04018364, feb. 2019, doi: 10.1061/(ASCE)MT.1943-5533.0002574.