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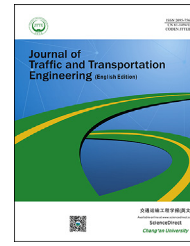

Review Article

Use of recycled concrete aggregates in asphalt mixtures for pavements: A review

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HIGHLIGHTS

- This review presents the studies of asphalt mixtures with the incorporation of RCA.
- The results of the physical characteristics of the RCA found in the literature are analyzed.
- The mechanical behavior of asphalt mixtures with RCA and natural aggregates is compared.
- The treatments carried out on RCA to be used in asphalt mixtures are analyzed.
- Suggestions are presented for future studies of asphalt mixtures with the use of RCA.

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ABSTRACT

Large quantities of natural aggregates (NA) are required in the manufacturing of asphalt mixtures for pavements. The extraction of NA generates high environmental impacts that negatively affect environmental preservation and conservation. Diverse alternative materials obtained in construction and demolition processes in civil construction worked have been studies as possible replacements for NA, with the purpose of reducing these environmental impacts. The foregoing study presents a state of knowledge review referring to the use of recycled concrete aggregates (RCA) when these are used in the manufacturing of asphalt mixtures (mainly hot-mix asphalt HMA type). Environmental aspects are presented, as well as possible benefits and limitations of using RCA as replacements for NA in asphalt mixtures. However, it is not possible to establish a behavior pattern, since the characteristics of the RCA are very heterogeneous and vary from the original source of the concrete. It is highlighted from the literature that RCA has a wide potential for use in the manufacture of asphalt mixtures, since in most studies, the mixtures with these materials comply the quality requirements contemplated by the construction specifications, mainly in low-volume roads. Additionally, based on the literature review, some recommendations and suggestions are presented for future research.

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1. Introduction

The materials used in flexible pavements are comprised (in weight) of more than 95% natural origin aggregates (NA) (Arabani and Azarhoosh, 2012). The manufacturing of hot-mix asphalts (HMA) requires large volumes of NA (aggregates are comprised in weight in 90%–95% or 80%–90% in volume) (Khasawneh and Alsheyab, 2020; Tahmoorian and Samali, 2018). NA can be obtained from natural sources such as alluvial, colluvial fluvial or glacial deposits. The high demand for NA required for the building of civil construction works leads to the search for alternative materials (products of recycled waste from industrial and/or building processes, among others) which allow to reduce exploiting virgin aggregates, reducing negative environmental impacts and contributing to the preservation of ecosystems (Balaguera et al., 2018).

In 2018, the European Union (EU, 2019) (EU-27) reported the production of approximately 2317 million tons of residues corresponding to economical activities (36.0% from the construction sector, 26.3% mining and quarries 10.6% factories 8.2% domestic wastes 3.5% energy sector and 15.4% other activities). The main sources of alternative aggregates from industrial or construction processes, such as steel industry residue (blast furnace slag (BFS), steel slag (SS), fly ash, among others), construction and demolition wastes (CDW), recycled aggregate concretes (RCA), reclaimed asphalt pavement (RAP), among others.

CDW including RCA are the main residues generated throughout the world. CDW are a subproduct of construction and demolition activities as well as enhancements made to civil construction works. These are mainly comprised of the following residues: concrete, brick, wood, ceramic, cast, glass, plastics, excavation soils, among others (Afshar et al., 2017; Arabani and Azarhoosh, 2012; Cong and Cheng, 2021). The lack of management and control of CDW can reduce environmental problems, given that it can cause the production of environmental problems because they produce the useful life of sanitary landfills and places for final disposal (Le and Bui, 2020). Also, an inadequate disposal of CDW May contaminates water sources and modify use of the soil, among others. In Europe, it was estimated that an approximate amount of 322 million tons of CDW were produced in 2016. Germany is the greatest European producer of CDW with an estimated quantity of 86.4 million tons, followed by UK, France, Italy, Netherlands with productions of 63.5, 60.2, 34.9 and 19.3 million tons, respectively. In United States, the Construction Demolition Recycling Association collected about 583 million tons of CDW wastes in 2014 for recycling (CDRA, 2021a,b). In China, the production of 2.36 thousand million tons of CDW wastes were produced during 2003 and 2013 (Zheng et al., 2017). In the case of Colombia (Silva et al., 2016) reported that major cities produce more than 100,000 tons of CDW per day. According to Jin et al. (2017), CDW represents about 40% of the total urban residues of continental China, 26% on solid wastes in USA and 38% of all industrial residues in European countries. For UK and Australia, CDW represents about 50% and 44% of solid waste production, respectively (Rodrigues et al., 2013). In order to face this scenario, the European Union (EU) proposes Directive (EU) 2018/851, where it establishes that residues are to be valued as resources, with the purpose of achieving a sustainable management of the materials, and in order to protect, preserve and improve the quality of the environment, and in consequence, the protection of human and animal health (EU, 2018). For such purpose, it is essential to achieve an adequate sustainable management of resources, promoting reusing and recycling of materials with the purpose of generating circular economy (Giri et al., 2019).

With regards to RCA generation sourced from CDW, there are few studies that show reliable and exact figures of its production. However, concrete is the most used material throughout the world in construction (Bamigboye et al., 2021; Habibi et al., 2021) and when its useful life expires, it produces large amounts of RCA. Faced before the scenario of production and final disposal of RCA, several studies have been conducted in regards to recycling and reusing them as construction materials, mainly in roadway infrastructure construction works (Chen et al., 2018; Oliveira and Correia, 2019). Some of these studies have evaluated their use as total or partial NA replacements in the manufacturing of asphalt mixtures. The results obtained are considered promising from a technical and environmental standpoint given they allow new ways of using said materials. This article presents a state of knowledge review for RCA use in the manufacturing of asphalt mixtures (mainly HMA type), while showing their main advantages and limitations from a technical standpoint. In this review, lifecycle, economical, or environmental impact studies related to the use of RCA were not included for their use in pavement layers. Finely, based on the reviewed literature, the authors share some recommendations and alternatives for continuing with future research on the matter. The most part of the reviewed studies are sourced from high-impact journals (Q1, Q2 and Q3 classifications according to SCOPUS and SCIMAGO bibliographical bases). The information presented in this article could serve as consulting source for researchers developing research projects in relation to the revised matter. Likewise, it helps to continue with the discussion around the possible use of RCA for asphalt mixtures. The manuscript should be original, and has not been published previously. Do not submit material that is currently being considered by another journal.

2. Recycled concrete aggregates

Concrete is the most used material in civil construction throughout the world. RCA are produced mainly through the demolition of concrete structure elements resulting from construction, demolition and repair activities for civil construction works (Tam, 2009). According to Al-Bayati et al. (2018) the amount of NA and cement present in RCA particles varies in 65%–70% and 35%–30%, respectively. Therefore, RCA sourced from CDW may be considered a valuable source of construction material. Some studies indicate that RCA contents produced from construction, demolition, renovation and various civil engineering activities vary between 40% and 75% (Arabani and Azarhoosh, 2012). In this scenario, concrete crushing and size reduction processes produce RCA (Ismail and Ramli, 2013; Jin and Chen, 2015). In Japan, approximately 98% of RCA are processed for generating aggregates such as construction materials (Tam, 2009).

RCA are different than NA because of the mortar found adhered to the surface after the recycling process. This mortar is highly porous, increasing water absorption, and contributing in particle density reduction (Martínez et al. 2019; Paranavithana and Mohajerani, 2006). Additionally, it can easily detach and fracture (Pasandín and Pérez, 2013). Despite the aforementioned, RCA present a high utilization potential as alternative aggregates, given their high production (EU, 2019). Several studies have reported the use of CDW and RCA as materials for civil engineering construction works, such as sub base layers and bases for pavements (Arm, 2000; Bassani and Tefa, 2018; Cardoso et al., 2016), structural concretes (Bravo et al., 2015a,b; Correia et al., 2006; Etxeberria et al., 2007; Gómez-Soberón, 2002; Jayasuriya et al., 2021; Kou et al., 2012; Rahal, 2007; Richardson et al., 2011; Sheen et al., 2013; Silva et al., 2014; Sri Ravindrarajah and Tam, 1985), mortars, rigid pavements (Shi et al., 2019; Yaowarat et al., 2019), and asphalt mixtures (Al-Bayati et al., 2018; Aljassar et al., 2005; Alvarez et al., 2020; Arabani, 2011; Arabani and Azarhoosh, 2012; Bastidas-Martínez et al., 2019, 2021; Bhusal et al., 2011; Cho et al., 2011; El-Tahan et al., 2018; Ektas and Karacasu, 2012; Fatemi and Imaninasab, 2016; Galan et al., 2019; Giri et al., 2018a, b; Gopalam et al., 2020; Gul and Guler, 2014; Hou et al., 2014; Kareem et al., 2020; Lee et al., 2012; Mikhailenko et al., 2020; Motter et al., 2015; Nwakaire et al., 2020; Paranavithana and Mohajerani, 2006; Pasandín and Pérez, 2013, 2014, 2017, 2020; Pérez et al., 2012; Pérez and Pasandín 2017; Qasrawi and Asi, 2016; Radević et al., 2020; Rafi et al., 2011; Razzaq, 2016; Sanchez-Cotte et al., 2020; Vega et al., 2020; Zhu et al., 2013), among others.

Main findings indicate that RCA can be used in civil construction (Gedik, 2020). This contributes to the preservation and conservation of the environment in terms of reducing the extraction of NA, minimizing environmental liabilities, cleaning and reduction in abandoned territories and a possible economic growth due to the incorporation of alternative materials in construction activities (Rafi et al., 2011). However, some applications in concretes and mortars manufactured with RCA evidence lower modulus of elasticity, compressive and tension resistance, requiring the use of steel as reinforcement (Shi et al., 2018a,b). For the case of asphalt mixtures, the results reported are ambiguous. They will be presented below, given that they are the main objects of this study.

The physical properties of the aggregates significantly affect the behavior and properties of asphalt mixtures. An adequate internal arrangement of the particles generates greater rigidity of the mixture. In this sense, it is important to analyze the hardness and shape of the aggregate particles. Additionally, it is necessary to analyze the interaction of the aggregate with the asphalt, in order to provide adherence and cohesion between the particles. In this way, the main properties to consider are: hardness of the aggregates, durability, cleanliness, shape of the particles and adhesiveness to the asphalt (Kandhal and Cooley, 2001). With the purpose of using RCA for manufacturing HMA Tables 1 and 2 displays the different physical characteristics of these materials according to the review literature. Table 3 shows the average results found, with their respective standard deviation and variation coefficient.

RCA are highly heterogeneous materials. The high values of variation coefficients (VC) and standard deviation confirm so. This heterogeneousness mainly occurs because of the presence of different extraction sources, quantities and types of aggregates, mortar and coating, among other aspects the source of materials and its design would definitely influence the test results and the VC. Mechanical resistance of RCA is evaluated according to wear tests in the Los Ángeles (LA) machine, Micro-Deval (MD) and aggregate crushing value (ACV), reporting average values of 31.4%, 30.0% and 23.8% with CV of 20.9%, 11.8% and 23.4% respectively. Said results are used to evaluate abrasion or wear resistance through friction of aggregate particles as well as fracture resistance. It is possible to evidence that in many cases, RCA particles present high LA, MD and ACV values, which is mainly attributed to high superficial porosity, detachment of mortar coating, which is fragile and brittle.

The shape and geometry of particles bears an influence in the mechanical stability of the asphalt mixtures. In this regard, it is desirable to have angled particles (rounded, with fractured faces) and rough. The presence of long and flat particles is undesirable for the mix, given it tends to fracture during manufacturing, construction and useful life of said pavement (Tahmoorian and Samali, 2018) and generate porous granular skeletons (Rondón and Reyes, 2015). Through results drawn from the revised literature, average values are reported for elongation and flattening indexes, as well as percentage of fractured particles 17.1%, 15.8% and 96.2% with CV of 50.0%, 52.2% and 3.2% respectively. These high CV values impede drawing clear conclusions in regards to the predominant shape of RCA particles. However, in several studies, values for flattening and elongation indexes can be considered to be relatively low, allowing to deduce that there is a cube shape particle predominance. This can be a result of the RCA crushing and size reduction process during its recycling process. Additionally, the percentage of fractured faces also broadly varies in the reviewed studies. This percentage greatly depends in the original shape of aggregate particles, as well as the crushing and size reduction process of RCA particles.

Aggregate particle cleanliness is essential to facilitate adherence to asphalt binder within the mix. According to data reported in the literature, Schutzbach (1992) determined 0.1% of contemptible material. Additionally, Radević et al. (2020) reports a value of 3.7 g/ml of methylene blue. According to Motter et al. (2015) the content of fine material is approximately 4% of the total RCA mass. Said values can be considered to be low, however, for RCA particle used in asphalt mixtures, it is advisable to carry out a washing and drying process for the material with the purpose of withdrawing fine particles that can affect adherence to asphalt (Mikhailenko et al., 2020).

Table 1 – RCA physical property.

Study	Los Ángeles (LA) abrasión machine (%)	Micro-Deval (%)	10% fine value (kN)	Aggregate crushing value (ACV) (%)	Elongation index (%)	Frankness index (%)	Flat or elongated (%)	Fractured particle (%)	Fine aggregate angularity (%)	Sand equivalent (%)	Methylene blue	Sodium sulfate soundness (%)
Schutzbach (1992)	33.0											33.0
Schutzbach (1992)	30.0											30.7
Mills-Beale and You (2010)	43.0						3.8	93.8				15.2
Bhusal et al. (2011)	22.0						1.0	100.0				
Cho et al. (2011)							16.8					
Rafi et al. (2011)	36.9	31.5		22.0								
Arabani et al. (2012)	25.5						9.3		70.1			
Pasandín and Pérez (2013)	32.0									67.0		
Zhu et al. (2013)			140.0									
Gul and Guler (2014)												
Hou et al. (2014)				26.7					45.0	90.5		
Pasandín and Pérez (2014)	32.0									67.0		
Motter et al. (2015)	27.0											
Qasrawi and Asi (2016)	31.0			28.3			3.1					
Razzaq (2016)	48.0							98.0				
Radevic et al. (2017)	31.5											
Pasandín and Pérez (2017, 2020)	32.0									67.0		
Tahmoorian and Samali (2018)			163.0	29.2		6.9						
El-Tahan et al. (2018)	19.0											
El-Tahan et al. (2018)	31.8											
Giri et al. (2018a,b)	29.0			23.0	24.0	21.0				67.0		
Giri et al. (2019)	29.0				21.0	24.0						
Bastidas-Martínez et al. (2019)	32.0				13.0	12.0		91.4		62.0		45.9
Alvarez et al. (2020)	30.0				3.2							
Gopalam et al. (2020)	31.0			26.0	24.0	22.0						
Kareem et al. (2020)	40.7			32.4								
Mikhailenko et al. (2020)										89.0		
Martinho et al. (2018)	43.0				6.0					30.0		
Nwakaire et al. (2020)	18.7			13.6	21.6	3.4						
Redevic et al. (2020)	31.5										3.7	
Sanchez-cotte et al. (2020)	31.6	32.6	115.0	20.7				97.0		49.0	3.8	
Sanchez-cotte et al. (2020)	27.3	26.0	120.0	16.4				97.0		65.0	1.8	

Table 2 – RCA specific gravity's and absorption.

Study	Apparent specific gravity coarse	Bulk specific gravity coarse	Specific gravity saturate surface dry coarse	Absorption coarse (%)	Specific gravity fine	Apparent specific gravity fine	Bulk specific gravity fine	Specific gravity saturate surface dry fine	Absorption fine (%)	Specific gravity of filler
Schutzbach (1992)			2.450	4.1						
Schutzbach (1992)			2.420	5.0						
Schutzbach (1992)								2.370	7.3	
Paranavithana and Mohajerani (2006)	2.706	2.333	2.471	5.9						
Mills-Beale and You (2010)	2.692	2.433	2.586	2.3						
Bhusal et al. (2011)		2.412					2.092			
Cho et al. (2011)	2.658			2.8						
Rafi et al. (2011)		2.230		4.6						
Arabani et al. (2012)	2.484	2.457	2.471			2.496	2.463	2.477		2.461
Pasandín and Pérez (2013)	2.630			5.1						
Zhu et al. (2013)	2.378			7.6						
Gul and Guler (2014)	2.654	2.302		5.6		2.657	2.280		5.9	
Hou et al. (2014)	2.684			5.3						
Pasandín and Pérez (2014)	2.630			5.1						
Motter et al. (2015)		2.419		4.3			2.562		1.1	
Qasrawi and Asi (2016)	2.280			5.8						
Razzaq (2016)	2.298									
Radevic et al. (2017)	2.667	2.450	2.532	3.2		2.645	2.430	2.512	3.4	
Tahmoorian and Samali (2018)	2.570	2.212	2.351	6.3						
El-Tahan et al. (2018)	2.708	2.237	2.411	7.7		2.456	1.787	2.098	17.0	
El-Tahan et al. (2018)	2.698	2.282	2.436	6.8		2.214	1.666	1.913	14.9	
Giri et al. (2018a,b)	2.370			5.6						
Giri et al. (2019)	2.370			5.6						
Bastidas-Martínez et al. (2019)		2.400		6.5	2.79					
Alvarez et al. (2020)	2.372			4.5						
Gopalam et al. (2020)		2.480		4.8						
Kareem et al. (2020)				5.6		2.679			7.0	
Mikhailenko et al. (2020)						2.654	2.439		5.2	
Martinho et al. (2018)	2.549			6.1						
Nwakaire et al. (2020)	2.480	2.520	2.410	4.8		2.600	2.490	2.420	7.4	
Redević et al. (2020)	2.670	2.450	2.530	3.2		2.650	2.430	2.510	3.4	
Sanchez-cotte et al. (2020)		2.240		7.1	2.41					
Sanchez-cotte et al. (2020)		2.320		6.6	2.41					

Table 3 – Average test results of RCA physical characterization.

Physical property	Average value	Coefficient of variation CV (%)
Los Ángeles (LA) abrasión machine	31.4%	20.9
Micro-Deval	30.0%	11.8
10% fine value	134.5 kN	16.3
Aggregate crushing value (ACV)	23.8%	23.4
Elongation index	17.1%	50.0
Frakiness index	15.8%	52.3
Flat or elongated	6.8%	93.9
Fractured particles	96.2%	3.2
Fine aggregate angularity	57.6	30.8
Sand equivalent	65.4%	26.7
Methylene blue	2.8	50.5
Sodium sulfate soundness	31.2%	40.4
Apparent specific gravity coarse	2.5	5.9
Bulk specific gravity coarse	2.4	4.2
Specific gravity saturate surface dry coarse	2.5	2.7
Absorption coarse	5.3%	25.4
Specific gravity fine	2.5	8.6
Apparent specific gravity fine	2.6	5.9
Bulk specific gravity fine	2.3	13.8
Specific gravity saturate surface dry fine	2.3	10.0
Absorption fine	7.3%	69.2
Specific gravity of filler	2.5	0.0

Durability of aggregates is generally determined by a solidness test in sodium or magnesium sulfate. This test attempts to simulate aggregate deterioration process when subjected to freezing-drying cycles (Rondón and Reyes, 2015). Through data of reviewed literature, it is possible to evidence that solidness test results in sodium sulfate on RCA report an average value of 31.2% with a variation coefficient of 40.4%. Said values can be considered high and are due to the high level of mortar detachment during test.

Fractions of coarse and fine RCA aggregates report high absorption levels (5.3% and 7.3%, respectively). This generates high asphalt binder consumption within the mix (Nwakaire et al., 2020), and along with the presence of mortar, these promote low specific gravity values. Additionally Tahmoorian and Samali (2018) mention that aggregates with absorption values above 4% will rarely display a good performance in the asphalt mixtures.

3. RCA in asphalt mixtures

3.1. RCA content in asphalt mixtures

Most studies conclude that volumetric and resistance parameters meet the quality requirements demanded for the specifications used for the manufacturing of asphalt mixtures (mainly in low volume roads). However, given the great heterogeneousness of RCA, it has not been possible to establish an optimal replacement percentage of NA with RCA in asphalt mixtures. A summary of the main studies carried out is presented in Table 4.

Based on the information presented in Table 4, it is possible to evidence that in general, the coarse fraction of mix aggregates is replaced. In other words, particle sizes that are equal or above 4.75 which can represent between 40% and 50% of total mix mass. This occurs mainly because the fine RCA particles generally present more absorption and less specific gravity with relation to coarse particles, promoting an increase in asphalt binder content. On a different matter, Pasandín and Pérez (2013) advise a maximum of 30% RCA in an HMA, given that greater values would notably increase the optimum asphalt binder content of the mix. Other researchers recommend a substitution of 100% NA with RCA for asphalt mixtures (Lee et al., 2012; Paranavithana and Mohajerani, 2006). However, given a significant amount of optimum asphalt binder content (OAC), this can impact in a reduction of stiffness and permanent deformation resistance.

It is possible to evidence that partial or total replacements of NA with RCA in asphalt mixtures were analyzed by mass. However, given the reduction of RCA particle specific gravity, it is advised to evaluate RCA incorporation percentage by mass and volume (Mikhailenko et al., 2020; Rondón-Quintana et al. 2020; Zuluaga-Astudillo et al. 2021). This recommendation has been mentioned by other researchers using other high-porosity and low specific gravity recycled aggregates such as BFS (Rondón-Quintana et al., 2019a, b).

3.2. Asphalt binder content in asphalt mixtures with RCA

Asphalt mixtures with RCA require greater asphalt binder contents because of their elevated absorption and surface area (Alvarez et al., 2020; Bhusal et al., 2011; Ossa et al., 2016; Radević et al., 2017; Shen and Du, 2005). Through data obtained in the literature, regardless of asphalt binder type used and particle size distribution of aggregates, it is possible to establish a direct relationship between the OAC and the content of RCA, according to what Figs. 1–3 evidence for mixes with a fraction replacement of the fine, coarse and total, respectively. It is possible to observe that the greatest increase in OAC occurs for incorporation of RCA in the fine fraction, followed by 100% of the mix and lastly, for the coarse fraction replacement. Variation rates or slopes in figures (OAC percentage increase in relation to RCA percentage incorporated into the mix) correspond to 0.043, 0.034 and 0.029, respectively. This way, the greatest OAC increases occur for mixes with incorporation to the fine fraction. This can be explained because of the greatest surface area of aggregates in reference to the coarse fraction. Pasandín and Pérez (2013) mention that using 30% RCA in the asphalt mixtures causes an OAC increase between 0.5% and 1.0%. Additionally, in most cases, the increase of asphalt binder content in the mix generates lower mechanical resistance.

The low R^2 values presented in Figs. 1–3 can be attributed to the heterogeneousness of RCA particles studied by different researchers. In this regard, it is important to highlight the diverse extraction sources, size reduction processes and crushing processes for RCA. An essential characteristic of RCA

Table 4 – Summary of RCA mixtures.

Reference	RCA content (%)	Fraction	Particle size (mm)	Impact on the mixture
Sanchez-Cotte et al. (2020)	0, 15, 30 and 45	Coarse	Between 19.00 and 4.75	Increased resilient module. Reduction of tensile strength ratio (TSR)
Radevic et al. (2020)	0, 15, 30 and 45	Fine coarse	Between 0.075 and 4.00	Reduction of dynamic modulus and fatigue life of the mixture
		Fine-coarse	Between 4.75 and 22.40	
			Between 0.075 and 22.400	
Nwakaire et al. (2020)	0, 20, 40, 60, 80, 100 surface treatment	Coarse	Between 4.75 and 12.50	Increased Marshall stability and fatigue. Reduction of resilient modulus, indirect tensile strength (ITS), TSR and resistance to permanent deformation
		Fine-Coarse	Between 0.075 and 12.500	
Kareem et al. (2020)	0, 20, 40 and 60	Coarse	Between 4.75 and 19.00	Increased of permanent deformation and fatigue
Gopalam et al. (2020)	0 and 54	Coarse	Between 4.75 and 37.50	Marshall stiffness reduction, resilient modulus and TSR
Vega et al. (2020)	0, 15, 30 and 45	Coarse	Between 4.75 and 19.00	Reduced Marshall stability and increased resilient modulus, except for 45% RCA mixture
Bastidas-Martínez et al. (2019)	0, 21 surface treatment	Coarse	Between 9.5 and 19.0	Increased stability, Marshall stiffness, ITS and TSR
Bastidas-Martínez et al. (2021)	0, 43 and 51	Fine	Between 0.075 and 4.750	Reduced stability and ITS
		Coarse	Between 4.75 and 19.00	
		Total	Between 0.075 and 19.000	
Alvarez et al. (2020)	0, 20, 40, 60 and 80	Coarse	Between 5 and 13	Increased stability, Marshall stiffness, TSR and resistance to permanent deformation
Pasandín and Pérez (2020)	0, 5, 10, 20 and 30 surface treatment	Coarse	Between 4.75 and 22.00	Increased Marshall stability and TSR. Adequate resistance to permanent deformation
Giri et al. (2018a)	0, 54	Coarse	Between 4.75 and 26.50	Increased Marshall stiffness, resilient modulus, reduced TSR, and resistance to permanent deformation
El-Tahan et al. (2018)	0, 100	Coarse	Between 0.075 and 4.750	Increased Marshall stability in mixtures with new RCA
		Fine-Coarse	Between 0.075 and 19.000	
Al-Bayati et al. (2018)	0, 15, 30 and 60	Coarse	Between 4.75 and 25.00	Only the volumetric parameters of the mixture were evaluated
Pasandín and Pérez (2017)	0, 35 and 42	Fine-Coarse	Between 0.075 and 22.400	Increased fatigue
Pérez and Pasandín (2017)	0, 35 and 42	Fine-Coarse	Between 0.075 and 22.400	Increased TSR by modification asphalt
Radevic et al. (2017)	0, 15, 30 and 45	Fine	Between 0.075 and 4.000	Increased Marshall stability. Increased resistance to permanent deformation when using the Coarse fraction
		Coarse	Between 4.75 and 22.40	
		Fine-Coarse	Between 0.075 and 22.400	
Motter et al. (2015)	0, 25, 50, 75 and 100	Coarse	Between 4.750 and 19.000	Reduced Marshall stability and TSR. Increased resistance to permanent deformation
Razzaq (2016)	10, 20, 30, 40, 50, 60, 70, 80, 90 and 100	Coarse	Between 4.75 and 37.50	Reduced Marshall stability and increased ITS
Gul and Guler (2014)	0, 25, 50 and 75	Fine	Between 0.075 and 4.000	Reduction and increase of permanent deformation when using the Coarse and Fine fraction, respectively
		Coarse	Between 4.75 and 19.00	
Pasandín and Pérez (2014)	0, 5, 10, 20 and 30 surface treatment	Coarse	Between 4 and 16	The addition of a surface treatment with 5% asphalt emulsion in the RCA particles caused an increase in TSR and the performance to permanent deformation and fatigue
Pasandín and Pérez (2013)	0, 5, 10, 20 and 30	Coarse	Between 4 and 16	Marshall stability reduction (except for 5% RCA mixture), indirect traction reduction and TSR increase. Slight increase in resilient modulus and reduction in resistance to permanent deformation (except for the mixture with 5% RCA)
Arabani et al. (2013)	0, 6, 41, 53 and 100	Coarse	Between 4.75 and 19.00	Increased Marshall stability, resilient modulus, resistance to permanent deformation and fatigue, except in mixtures with substitution of the coarse fraction and 100% of the RCA
		Fine	Between 0.075 and 4.750	
		Filler	Between 0 and 0.075	

(*continued on next page*)

Table 4 – (continued)

Reference	RCA content (%)	Fraction	Particle size (mm)	Impact on the mixture
		Total	Between 0.075 and 19.000	
Lee et al. (2012)	0, 25, 50, 75 and 100 surface treatment	Coarse	Between 4 and 19	Reduced Marshall stability, TSR and resistance to permanent deformation. However, there is an increase in ITS
Arabani et al. (2012)	0, 41 and 53	Fine	Between 0.075 and 4.000	Increase in Marshall stability and stiffness, resistance to permanent deformation, fatigue resistance and reduction of resilient modulus when using the Fine RCA fraction However, the mixture with the coarse fraction of RCA exhibited contrary behavior
		Coarse	Between 4.75 and 19.00	
Rafi et al. (2011)	0, 25, 50 and 75	Total	Between 0.075 and 19.000	Marshall stiffness reduction
		Total	Between 0.075 and 25.000	
Bhusal et al. (2011)	0, 20, 40, 60, 80 and 100	Total	Between 0.075 and 19.000	The evaluation of the mechanical behavior was not carried out
Cho et al. (2011)	0, 40, 60 and 100	Fine	Between 0.075 and 4.750	Increased TSR and resistance to permanent deformation, except mixture with 100% RCA
		Coarse	Between 4.75 and 19.00	
		Total	Between 0.075 and 19.000	
Mills-Beale and You (2010)	0, 25, 35, 50 and 75	Total	Between 0.075 and 19.000	Lower dynamic modulus, resilient modulus, TSR and resistance to permanent deformation
Paranavithana and Mahajerami (2006)	0, 50	Coarse	Between 4.75 and 20.00	Reduction of the resilient modulus

is the quantity and quality of mortar coating of aggregate particles, as well as cement quality, initial resistance and concrete age, among others. Additionally, aspects related to the physical characteristics of recycled aggregates, such as shape and texture of RCA particles, affinity between RCA particles and asphalt binder, among others.

3.3. *Mechanical performance of asphalt mixtures with RCA*

According to the reviewed literature, incorporating RCA aggregates in asphalt mixtures is viable from a technical and environmental standpoint given that it allows for an environmentally safe final disposal. However, given the heterogeneousness of alternative materials due to their origin and extraction sources, there are studies that present contradictory conclusions in regards to their application in asphalt mixtures (Muniz de Farias et al., 2019). In this section, according to data reported in the technical literature, there is a description of results that experimented with RCA incorporations in terms of their volumetric composition and mechanical performance in marshall stability tests, indirect tensile strength, moisture damage resistance, dynamic modulus, resilient modulus permanent deformation resistance and fatigue tests.

3.3.1. *Volumetric composition of asphalt mixtures with RCA*

In regards to evaluated volumetric composition in mix designs (Marshall Test and Superpave Methodology), asphalt mixtures with RCA comply with requirements demanded by some transport entities (Gopalam et al., 2020). However, there are some referred variations present in the control mix. In general, RCA mixes promote an increase in air voids volume (Va) and a reduction of voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) (Al-Bayati et al., 2018; Alvarez et al., 2020; Bastidas-Martínez et al., 2019, 2021; Bhusal et al., 2011; Ektas and Karacasu, 2012; Giri et al., 2018b; Mikhailenko et al., 2020; Mills-Beale and You, 2010; Nwakaire et al., 2020; Pasandín and Pérez, 2013, 2017; Qasrawi and Asi, 2016; Sanchez-Cotte et al., 2020). These volumetric changes are approximately proportional to the RCA content to be incorporated into the mix, and are mainly attributed to: i) when substituting by mass, the lower density of RCA particles produces a greater number of particles in the mix and in consequence, a greater surface area to be coated with asphalt binder (Arabani, 2011; Arabani et al., 2012; Bhusal et al., 2011; Rafi et al., 2011); ii) increased absorption of RCA, which causes a thinner coating layer of asphalt binder over the surface of aggregates. Despite the above, some studies (Radević et al., 2017, 2020) mention that fine RCA particles can undergo breaking or fragmentation during the compaction process, increasing the amount of fine aggregates and in some cases promoting the reduction of Va.

3.3.2. *Marshall stability*

The Marshall stability test evaluates the resistance to monotonic load at 60 °C, with the purpose of analyzing the cohesion of the asphalt mixture. Some studies (Alvarez et al., 2020; Arabani et al., 2012, 2013; El-Tahan et al., 2018; Giri et al.,

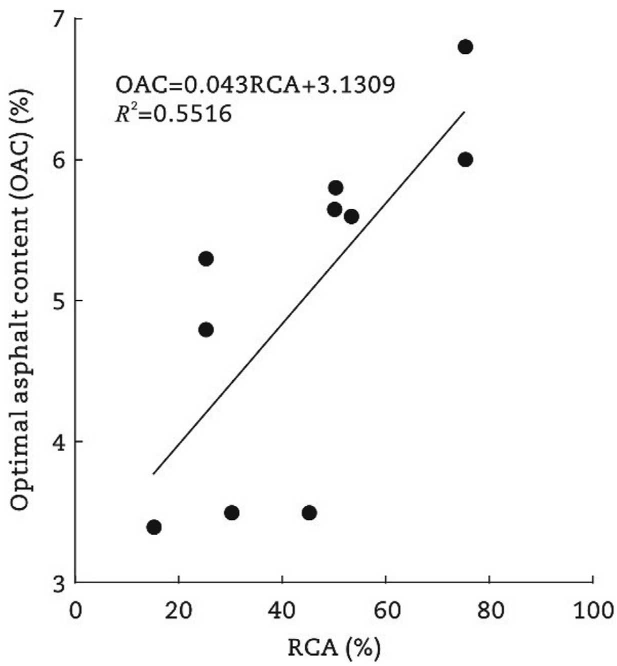

Fig. 1 – Evolution of optimum asphalt binder content with RCA content–fine fraction.

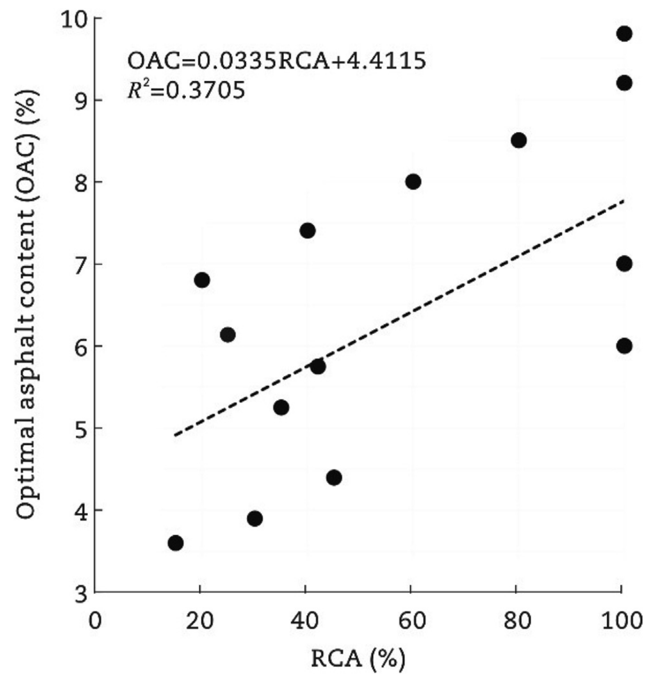

Fig. 3 – Evolution of optimum asphalt binder content with RCA content–total fraction.

2018a; Gopalam et al., 2020; Pasandín and Pérez, 2020; Radevic et al., 2017) report an increase of Marshall stability in HMA mixes that incorporated RCA. Said behavior was also evidenced in the manufacturing of SMA (stone mastic asphalt) type mixes, reaching an increase of 45% in stability when incorporating 80% RCA with relation to the control mix (Nwakaire et al., 2020). These increases are generally more notable when only replacing the coarse fraction of NA with RCA (Bastidas-Martínez et al., 2021; El-Tahan et al., 2018). In contradiction with the above, other studies have reported a reduction of Marshall stability in HMA mixes with RCA incorporation (Bastidas-Martínez et al., 2019, 2021; Ektas and Karacasu, 2012; Lee et al., 2012; Motter et al., 2015; Pasandín and Pérez, 2013; Rafi et al., 2011; Razzaq, 2016; Vega et al., 2020).

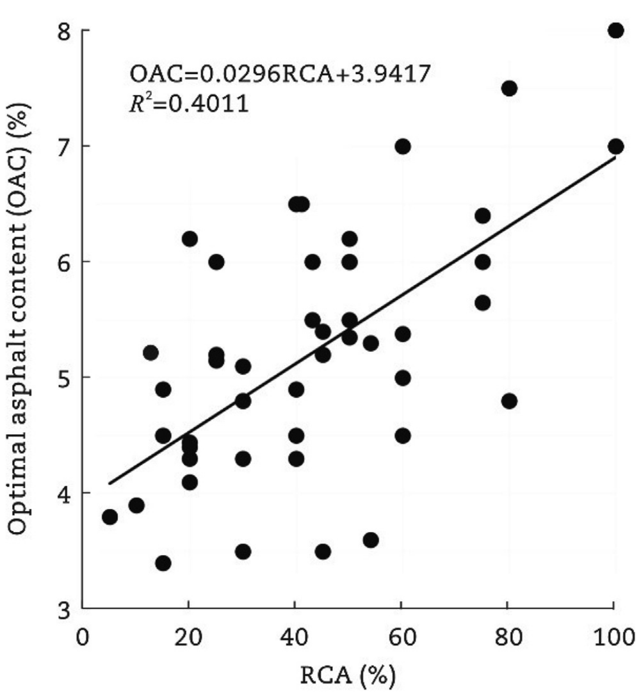

Fig. 2 – Evolution of optimum asphalt binder content with RCA content–coarse fraction.

Some authors conclude that the stability increases of mixes with RCA can be attributed to the angular and cubic shape of RCA particles. This way, RCA particles form a more stable granular skeleton in the asphalt mixtures (Martinho et al., 2018; Paranavithana and Mohajerani, 2006; Zhu et al., 2012). These increases can be attributed to the amount of cement present in RCA particles, given that the use of cement as a filler within the asphalt mixtures could increase its internal cohesion (Nwakaire et al., 2020). According to El-Tahan et al. (2018), the amount and age of concrete bear an influence in mix stability. In general, mixes with RCA that display greater stability require an OAC increase (Arabani et al., 2012; Alvarez et al., 2020). Studies that report a reduction of Marshall stability of mixes with RCA state that these generally comply with the minimum specification values considered for manufacturing asphalt mixtures for pavements (Bastidas-Martínez et al., 2019, 2021; Motter et al., 2015), and this reduction is mainly associated to the lack or excess of asphalt binder content and the lower resistance of RCA due to the mortar coating (Pasandín and Pérez, 2013).

Differences in behavior reported in the reviewed literature can be attributed, among other aspects, to the origin, source, chemical composition, mineralogy, particle size and physical characteristics of RCA as well as other mix characteristics such as: asphalt binder type, OAC, granulometric distribution, RCA content, type of NA, mix design methodology and mix volumetric composition parameters.

3.3.3. *Indirect tensile strength tests*

The indirect tensile strength (ITS) test evaluates the resistance to monotonic load at 25 °C in order to know the adherence between the particles of the mixture. Some studies (Bastidas-Martínez et al., 2021; Lee et al., 2012; Mikhailenko et al., 2020; Razzaq, 2016) evidenced a slight increase of ITS in dense and semi-dense mixes using RCA. This is attributed to the increase of OAC and the texture and shape of RCA particles. This way, it would be possible to attain a better particle fitting after compaction, improving the capacity of resisting sliding between aggregates (Lee et al., 2012; Mikhailenko et al., 2020). Additionally, the increase of ITS can be attributed to the asphalt binder capacity to adhere to the porous surface of RCA and to possible physical-chemical interactions between both materials. This way (Rodrigues et al., 2013; Zulkati et al., 2013) report that the presence of the following oxides: calcium (CaO), aluminum (Al_2O_3) and silica (SiO_2) promote pozzolana characteristics in the concrete and may contribute to adherence in the asphalt mixtures.

Contradictory to the above mentioned (Alvarez et al., 2020; Qasrawi and Asi, 2016; Bastidas-Martínez et al., 2019; Giri et al., 2018a; Gopalam et al., 2020; Nwakaire et al., 2020; Pasandín and Pérez, 2013; Sanchez-Cotte et al., 2020), report that asphalt mixtures with RCA present a reduction of ITS as its content increases. Said reductions can be attributed to the lower specific gravity values of RCA particles with relation to NA. This produces a greater number of RCA particles in the mix (when replacement is carried out by mass) and in consequence, a greater Va and lower VFA. During the testing process the detachment of particles is facilitated. Likewise, attribute the reduction of ITS to the possible detachment of mortar coating of RCA during the test (Alvarez et al., 2020).

3.3.4. *Tensile strength ratio*

Tensile strength ratio (TSR) is commonly used to evaluate susceptibility to water and moisture damage in asphalt mixtures. It is obtained as a percentage relationship between ITS in moist and dry conditions, respectively. Alvarez et al. (2020), Cho et al. (2011), Galan et al. (2019), Giri et al. (2018a), Motter et al. (2015), and Pasandín and Pérez (2013, 2017, 2020), evidenced TSR increases in asphalt mixtures with RCA. Said increases, in some cases, are proportional to the increase of RCA within the mix. According to the authors, the increase of TSR can be attributed to contact between water and adhered cement, which activates self-cementing properties and favors adhesion of RCA to asphalt (Alvarez et al., 2020). Likewise, the authors justify the increase of TSR with the increase of asphalt binder content.

Contrary to what was mentioned above (Gopalam et al., 2020; Hou et al., 2014; Lee et al., 2012; Mikhailenko et al., 2020; Mills-Beale and You, 2010; Qasrawi and Asi, 2016; Sanchez-Cotte et al., 2020) evidenced a reduction of TSR when incorporating RCA in dense and semi-dense mixes. However, some authors guarantee the minimum values considered for specifications are equal to or more than 80%, specially by AASHTO T 283. The reduction of TSR is attributed to a lower effective asphalt binder content in the mix and the thickness reduction in the asphalt layer, which allows for a greater saturation of the mix caused by water (Mikhailenko et al., 2020). On a different matter, Tahmoorian and Samali (2018) state that, an elevated absorption makes aggregates susceptible to degradation or breakage under wet/dry cycles or freezing/defrosting cycles. This occurs because some light or oleos components of asphalt can be introduced into surface voids of RCA. Other authors such as (Nwakaire et al., 2020) evidenced TSR increases and reductions based on different replacement percentages of the coarse fraction of NA with RCA. In the case of asphalt mixtures with 40% and 60% of RCA, TSR increases were reported, whereas for mixes with 20%, 80% and 100%, there were reductions. Among aspects that may impact these contradictory results, others to be considered are the microstructural interaction between the asphalt-aggregate within the asphalt mastic (Huang et al., 2021) and mineralogic composition of RCA and its chemical affinity to the asphalt binder (Pasandín and Pérez, 2020). For example, asphalt mixtures with RCA that report high percentages of silica oxide (SiO_2) could present a TSR reduction (Pasandín and Pérez, 2013). With the purpose of not affecting moisture damage resistance of asphalt mixtures with the incorporation of RCA, some researchers advise the following recommendations:

Not using the fine fraction of RCA because of the high content of mortar, cement and impurities (Pérez et al., 2012). Guaranteeing the coating of surface voids in RCA with asphalt (Pasandín and Pérez, 2013). Conducting a surface treatment on RCA particles (mechanical or chemical) before the replacement of NA with the purpose of improving adherence between the asphalt binder and aggregate. Promoting adherence between RCA aggregates and asphalt binder through surface treatments of aggregates using chemical additives, asphaltic emulsions, resins and cooking oil residues, among others (Eisa, 2018; Giri et al., 2018a; Kareem et al., 2019; Kavussi et al., 2019; Ma et al., 2019). Descriptions of treatments for RCA and their application in the asphalt mixtures are described below.

3.3.5. *Dynamic and resilient modulus*

Dynamic and resilient modulus allows to know the stiffness of the mixture in dynamic conditions subjected to different frequencies of load and temperature. Several studies indicate the reduction of dynamic modulus in mixes with RCA and in general, said reductions increase with RCA content (Giri et al., 2018a,b; Mills-Beale and You, 2010; Radević et al., 2017, 2020). This is attrituted to the increase of OAC and Va in the mix. Despite the above, some authors, e.g., Radević et al. (2017) mention that these reductions are not statistically significant.

Additionally, Arabani et al. (2012, 2013) report increase of resilient modulus in mixes (RM) of asphalt mixtures when replacing the fine fraction, mineral filler and fine-coarse fractions of aggregates with RCA. However, when the coarse fraction and 100% of aggregates are replaced, a reduction of this mechanical parameter was reported. Likewise, Vega et al. (2020) evidenced increases of RM in asphalt mixtures with replacements of 15% and 30% of RCA in their coarse fraction. Sanchez-Cotte et al. (2020) evaluated RM in asphalt mixtures with a replacement of coarse fraction of NA with 15%, 30% and 45% of RCA. Additionally, they evaluated RCA sourced from rigid pavement slabs and buildings. As a general conclusion, they report that mixes with RCA sourced from pavement slabs presented an increase in RM, whereas mixes with RCA sourced from buildings presented RM values similar to the control mix. This evidenced that mixture RM is directly related to the quality of the RCA source. Contrary to previous authors (Alvarez et al., 2020; Arabani and Azarhoosh, 2012; Erkatas and Karacasu, 2012; Mills-Beale and You, 2010; Nwakaire et al., 2020; Paranavithana and Mohajerani, 2006) report that mixes with RCA reduce their Mr. These reductions are presented in a proportional manner to the increase of RCA in the mix. This was associated to the presence of mortar coating, likewise the increase of voids volume in the mix. Similar results were obtained by Gopalam et al. (2020) when replacing the coarse fraction of NA with RCA in a dense bituminous macadam (DBM).

3.3.6. *Permanent deformation resistance*

Permanent deformation tests allow evaluating the resistance of the asphalt mixture under hot weather conditions (Arabani et al., 2012, 2013; Cho et al., 2011; Ertas and Karacasu, 2012; Gul and Guler 2014; Mikhailenco et al., 2020; Motter et al., 2015; Radevic et al., 2017) report an increase in permanent deformation resistance of HMA mixes with RCA. These behaviors were reported for mixes with RCA aggregates that replaced the coarse fraction (Mikhailenco et al., 2020; Motter et al., 2015) and fine fraction (Arabani et al., 2012, 2013; Radević et al., 2017). According to Radević et al. (2017) increases in permanent deformation resistance can reach 30% when replacing fractions of aggregates with RCA. Other authors report increases of up to 40% (Alvarez et al., 2020; Kareem et al., 2020). This was also evidenced in the manufacturing of semi-dense mixes and SMA (Ertas and Karacasu, 2012; Mikhailenko et al., 2020). The increases of permanent deformation resistance in mixes with RCA have been mainly attributed to the following i) the greater number of contact points between particles (due to the lower specific gravity of RCA in comparison to NA), which generates a greater contact between the asphalt binder and aggregate (El-Tahan et al., 2018); ii) the presence of fine RCA can generate a greater internal friction between particles due to their angled shape (increasing rigidness) (Arabani et al., 2012, 2013); iii) the best fitting between mix particles, during the application of number of gyrations applied to the specimen in the process of mix compaction (Radević et al., 2017).

Contrary to the above (Arabani et al., 2012, 2013; Giri et al., 2018a,b; Gul and Guler, 2014; Mills-Beale et al., 2010; Nwakaire et al., 2020; Pasandín and Pérez, 2013, 2014; Radevic et al., 2017) report a reduction in permanent deformation resistance in mixes with RCA. This behavior was identified mainly in mixes with replacement of the coarse aggregate and when 100% of aggregates are replaced (Cho et al., 2011). In general, they associate this reduction of resistance to the high content of asphalt binder, volumetric composition of the mix (high Va content), reduction of stiffness (dynamic and resilient modulus) the detachment of mortar in RCA during the test, among others. Despite the above, reviewed studies generally conclude that mixes with RCA comply with requirements demanded in specifications for the manufacturing of asphalt layers in pavements (Giri et al., 2018b).

3.3.7. *Fatigue resistance*

Fatigue tests allow the evaluation of the damage of the mixture due to repeated loading. Compared to the previously mentioned properties, fatigue resistance has been the least studied. Fatigue resistance models for asphalt mixtures with NA and with RCA reported in the literature are shown in Table 5, as well as some test conditions. In general, most studies report a similar or even higher fatigue resistance when using RCA in asphalt mixtures. Few studies conclude the opposite e.g (Arabani et al., 2012, 2013), when the total coarse fraction of NA is replaced with RCA and the total NA. Fatigue resistance increases are mainly related to the increase of OAC. On a different matter, modified asphalt mixes presented higher fatigue resistance with relation to conventional asphalt binders (Pasandín and Pérez, 2017).

Arabani et al. (2012, 2013) studied controlled-stress fatigue resistance tests for five asphalt mixtures: i) 100% of NA (control); ii) replacing the coarse fraction of NA with RCA; iii) replacing the fine fraction of NA with RCA; iv) replacing the NA filler with RCA; v) replacing the total NA with RCA (100% RCA). According to results, mixes that had their fine fraction and NA filler replaced with RCA displayed greater fatigue resistance than the control mix. According to the authors, the reduction of Va caused by the breaking of fine particles during the compaction process could have produced the increase of stiffness in the mix because of the internal fitting of the fine particles. This greater amount of fine particles could have increased due the increase of OAC, improving aspects associated to adherence. In opposition to the above the RCA mix (coarse fraction) displayed lower fatigue resistance with relation to the control mix. This reduction was attributed to the detachment or breaking of mortar in the coating of RCA particles during the mixing and compaction process.

Pasandín and Pérez (2014) conducted controlled-stress fatigue tests in asphalt mixtures with a replacement of 5%, 10%, 20% and 30% of the coarse fraction of NA aggregates with RCA. In this study, RCA was pre-treated with 5% of asphalt emulsion. Fatigue curve results with RCA evidence a behavior similar to that of the control mixture.

Pasandín and Pérez (2017) conducted controlled-stress fatigue tests on asphalt mixtures with 0%, 35% and 42% of RCA, using modified asphalt with 10% rubber crumb. Based on the results obtained, the authors report that fatigue resistance increases in mixes with RCA. Furthermore, the mix with greatest RCA content (42% RCA) displayed the best performance. Additionally, the use of modified asphalt provided a significant increase in fatigue resistance of mixes that incorporated RCA. A similar study using modified asphalt with rubber concludes the opposite (Muniz de Farias et al., 2019). However, in this study, the replacement of NA with RCA was 100%.

Radević et al. (2020) conclude that asphalt mixtures with RCA incorporation (replacing 15%, 30% and 45% of the coarse fraction, fine fraction and a coarse-fine combination) display

Table 5 – Fatigue models for asphalt mixtures with RCA.

Reference	Mixture	Asphalt	Test condition	Model fatigue	R^2
Arabani et al. (2012, 2013)	Control	AC 60-70	The indirect tensile fatigue test	$N_f = 2.4*104\ (1/\epsilon)-0.62$	0.97
	Filler RCA	AC 60-70	Controlled-stress fatigue test	$N_f = 2.4*104\ (1/\epsilon)-0.57$	0.95
	Fine RCA	AC 60-70	Specimen's type Marshall.	$N_f = 1.9*104\ (1/\epsilon)-0.46$	0.96
	Coarse RCA	AC 60-70	Application load: 0.1 s loading	$N_f = 2.9*104\ (1/\epsilon)-0.76$	0.98
	100% RCA	AC 60-70	and 0.4 s unloading. Temperature 25 °C. Fatigue criterion: creating a vertical displacement that equals 1 mm.	$N_f = 2.5*104\ (1/\epsilon)-0.69$	0.97
Pasandín and Pérez (2014)	Control	AC 50-70	The indirect tensile fatigue test	$\epsilon = 10{,}279N_f-0.319$	0.92
	5% RCA	AC 50-70	Controlled-stress fatigue test	$\epsilon = 10{,}508N_f-0.326$	0.76
	10% RCA	AC 50-70	Constant stress levels (150 kPa	$\epsilon = 10{,}808N_f-0.326$	0.67
	20% RCA	AC 50-70	−350 kPa)	$\epsilon = 3579.1N_f-0.221$	0.81
	30% RCA	AC 50-70	Specimen's type Marshall. Application load: 0.1 s loading and 0.4 s unloading. Temperature 25 °C. Failure criterion: number of cycles to failure.	$\epsilon = 6604.4N_f-0.281$	0.81
Pasandín and Pérez (2017)	Control	AC 35-50		$\epsilon = 2487.4N_f-0.187$	0.87
	35% RCA	AC 35-50		$\epsilon = 2830.2N_f-0.192$	0.85
	42% RCA	AC 35-50		$\epsilon = 4699.5N_f-0.215$	0.88
	Control	AR 35-50		$\epsilon = 4516.8N_f-0.240$	0.95
	35% RCA	AR 35-50		$\epsilon = 6653.6N_f-0.257$	0.85
	42% RCA	AR 35-50		$\epsilon = 9550.6N_f-0.268$	0.89
Radević et al. (2020)	Control	AC 50-70	Strain-controlled fatigue	$\log(N_f) = 37.74-4.96\log(\epsilon)$	0.883
	15% RCA Fine	AC 50-70	Strain amplitudes: 130, 200 and	$\log(N_f) = 49.89-7.28\log(\epsilon)$	0.703
	30% RCA Fine	AC 50-70	300 um/m.	$\log(N_f) = 53.61-7.85\log(\epsilon)$	0.916
	45% RCA Fine	AC 50-70	Frequency of 10 Hz.	$\log(N_f) = 39.35-5.32\log(\epsilon)$	0.883
	15% RCA Coarse	AC 50-70	Temperature 20 °C.	$\log(N_f) = 43.25-6.06\log(\epsilon)$	0.839
	30% RCA Coarse	AC 50-70	Failure criterion: number of	$\log(N_f) = 45.73-6.41\log(\epsilon)$	0.902
	45% RCA Coarse	AC 50-70	cycles to failure.	$\log(N_f) = 46.32-6.60\log(\epsilon)$	0.949
	15% RCA fine-coarse	AC 50-70		$\log(N_f) = 48.83-6.97\log(\epsilon)$	0.911
	30% RCA fine-coarse	AC 50-70		$\log(N_f) = 41.84-5.66\log(\epsilon)$	0.859
	45% RCA fine-coarse	AC 50-70		$\log(N_f) = 47.59-6.60\log(\epsilon)$	0.858

Note: N_f and ϵ correspond to the number of fatigue failure cycles and the strain in the fatigue test, respectively.

an increase between 12% and 26% of fatigue life under controlled-strain. This is evidenced by the increase of parameter ε (deformation amplitude required for material to fail at a million cycles) in asphalt mixtures with RCA, which is attributed to the increase of OAC.

Nwakaire et al. (2020) conducted a fatigue test in SMA mixes with an incorporation of 20%, 40%, 60%, 80% and 100% RCA with the purpose of measuring the accumulated deformation until failure of specimens. Results evidence that up to an application of cycle 100, analyzed mixes display the same behavior. After applying 100 load cycles RCA mixes displayed a greater fatigue life than the control mix, except for the mix with 20% RCA. Authors conclude that performance of asphalt mixtures in regards to fatigue is directly related to the OAC.

4. RCA surface treatment

As shown before, the physical characterization of RCA aggregates evidences a high surface absorption and lower mechanical resistance in comparison to NA, which is mainly attributed to the mortar coating of particles. This is considered an unfavorable characteristic of RCA for manufacturing asphalt mixtures, given that it implies the increase of OAC (Al-Bayati et al., 2018; Sengoz and Topal, 2007). In this regard, several studies have been conducted with the purpose of evaluating a surface treatment given to RCA, with the purpose of reducing surface absorption. Raman and Ramasamy (2020) describe chemical treatments through the use of calcium metasilicate slurry, carbonation and the application of silica grout over the surface of RCA. There are also mechanical treatments reported which use a grinding treatment or ball, milling method. Likewise, there are thermal treatments, which consist in subjecting RCA to high temperatures (above 200 °C) for a time period between 1 and 24 h. Finely, there are treatments that involve coating RCA with waterproofing materials e.g., “asphalt emulsions, waste oil, super-plasticizers, gel techniques” or hydraulic materials (“cement, lime, mineral additives, nano-materials and polymer solution, among others”. Some studies evidence the application of one or two treatments. Some studies are summarized below.

Lee et al. (2012) carried out a surface treatment of RCA incorporating slag cement paste. This had the purpose of reducing the aggregate's porosity and reducing the absorption of asphalt. For this purpose, coating layers with thicknesses of 0.25, 0.45 and 0.65 mm slag cement paste was applied on the surface of thick RCA aggregates. Treatment application provided a greater cohesion and adhesion between mix particles, evidenced with the increase of Marshall stability and ITS. However, TSR and permanent deformation resistance were reduced in function of the slag cement paste coating thickness increase.

Zhu et al. (2012, 2013) used a silane-based water repellent agent for pre-treating RCA with the purpose of reducing water absorption and increasing its resistance. Treatment improved physical properties and susceptibility to moisture of asphalt mixtures containing RCA. The results presented also evidence a better performance against permanent deformation and fatigue cracking.

Pasandín and Pérez (2014) studied a replacement of 5%, 10%, 20% and 30% of coarse aggregates with RCA particles. In order to avoid the problem of RCA surface porosity, the authors coat these particles with 5% asphalt emulsion. Fatigue curves under controlled-stress display a similar behavior to the control mix with NA. Additionally, the use of asphalt emulsion reduced water entry into aggregates and improved moisture damage resistance in the mix.

Hou et al. (2014) evaluated the mechanical behavior of an asphalt base using RCA aggregate treated with organic silicon resin, metatitanic resin acceptor and silane resin acceptor as activators. The authors observed that the application of these three materials as surface treatments reduced the absorption of aggregates and provided a greater adherence with asphalt binder. However, the mechanical performance (Marshall, RTI and low temperature resistance) of the asphalt base was reduced with the increase of RCA.

Giri et al. (2018a) studied the replacement of the coarse fraction of aggregates in a DBM mix. Previously, particles were superficially treated with asphalt emulsion, followed by manufacturing mixes with and without the incorporation of waste polyethylene from milk packaging. Authors report a slight increase in Marshall stability and resilient modulus for mixes that contain RCA. Likewise, an increase of moisture damage resistance is evidenced.

Al-Bayati et al. (2018) submerged coarse RCA particles in a chemical solution of acetic acid during 24 h at room temperature. Posteriorly, particles were washed with distilled water and subjected to a temperature of 300 °C in a conventional oven for 1 h. Particles were then subjected to a mechanical treatment in the Micro-Deval apparatus with steel balls during 15 min under dry conditions. Finally, the material was washed and dried in an oven (105 ± 5 °C for 24 h) with the purpose of being sieved in sieve #4. Authors conclude that RCA with and without treatment, meet the quality requirements demanded for the manufacturing of asphalt mixtures for pavements. However, economical costs for manufacturing mixes with 30% and 60% RCA are superior to the control mix cost, which is associated to the treatment carried out. However, mixes with 15% RCA have a lower manufacturing cost than the control mix.

Bastidas-Martínez et al. (2019) carried out mechanical treatments over the coarse fraction of RCA through subjecting it to 50, 100 and 200 cycles in the Los Ángeles machine. This produced surface wear, detachment of adhered mortar, and in consequence, reduction of RCA absorption. Posteriorly, authors performed HMA designs which evidenced a better mechanical performance in mixes with treated RCA. As a general conclusion, the authors report that treating RCA in the Los Ángeles machine impacts the volumetric composition of the mix (lower Va, greater VAM and VFA). Additionally, increased resistance under monotonic load (stability and stability/flow ratio) and improves adherence and Cantabro wear resistance.

Kareem et al. (2020) conducted a double treatment for reducing surface absorption of RCA coarse particles. For such purpose, there was an initial surface coating of RCA with asphalt emulsion at 155 °C during 90 min. Posteriorly, a second treatment similar to the previous was carried out. With pre-treated RCA, asphalt mixtures were manufactured with aggregate replacements of 20%, 40% and 60%. Results evidenced an increase in dynamic modulus, permanent deformation and fatigue resistance.

5. Conclusions

Based on the bibliographical review made, conclusions are the following.

RCA have a broad use potential in the manufacturing of asphalt mixtures. In most studies, RCA fulfill the quality requirements demanded for specifications needed in each country in order to replace NA in the manufacturing of asphalt mixtures. This mainly takes place in low volume roads.

The desirable properties that make RCA use viable as an alternative aggregate in the manufacturing of asphalt mixtures are: i) the predominant shape or geometry of its particles (cubic, angled), which allows for a compact granular skeleton that is less prone to deformation under the action of monotonic, static and dynamic loads; ii) RCA particles do not present contents of clay or organic material, favoring adherence between the aggregate and asphalt binder; iii) surface porosity could benefit adherence with asphalt binder; iv) displays a good compatibility with asphalt binder. On a different subject, its main limitations are related to lower hardness and fracture resistance compared to NA, as well as high porosity and surface absorption, which increases OAC in the mix (which can make its use non-viable from an economic standpoint).

Some researchers report benefits in mechanical behavior when replacing the coarse fraction of NA with RCA, while others report that the best option is replacing the fine fraction. However, most studies consider the replacement of the coarse fraction of NA aggregates with RCA. This is mainly because: i) replacing the fine fraction would increase the surface area of aggregates and in consequence, could increase the asphalt binder absorption problem of RCA; ii) in general, RCA production plants use coarse aggregate particles predominantly; iii) crushing RCA into finer particles increases production and use costs, as well as energy consumption, negatively impacting the environment.

Given the environmental problematic caused by the production of CDW, it is ideal to use total replacement of NA with RCA. However, studies carried out with 100% RCA report problems from technical and economical standpoints. This is because of the elevated use of OAC in the mix. Additionally, there are reports of durability reductions in mixes (reduction of stiffness, permanent deformation resistance, moisture damage resistance and fatigue damage resistance).

When using RCA in asphalt mixtures, OAC use increases. These increases are approximately proportional to the increase of RCA in the mix. This is attributed to the high absorption of aggregates and the reduction of specific gravity (which increases the number of particles in the mix which are to be replaced by mass). In order to counteract this issue, and with the purpose of increasing performance in mixes (mainly moisture damage resistance), studies of RCA particle pretreatment have been conducted (using thermal, chemical and mechanical techniques).

Based on the information in the reviewed literature, it is not possible to correlate mechanical performance of the asphalt mixtures in function of the fraction or amount of RCA incorporated. This is because the inherent physical properties of RCA are highly heterogenous and vary depending on aspects such as: source and origin of concrete obtained, initial characteristics of concrete out of which RCA is extracted from, physical characteristics of particles, chemical and mineralogic composition of RCA. Other aspects that make this correlation difficult to establish are mix characteristics (volumetric and granulometric composition, type and dosing of asphalt material) and aspects associated to the system or technique used for obtaining and producing it in recycling plants.

Given the above, the referenced literature is ambiguous regarding the influence of RCA as a replacement of NA in asphalt mixtures. Some researchers report the increase in evaluated mechanical properties (Marshall stability, dynamic and resilient modulus, permanent deformation resistance, moisture damage resistance and fatigue resistance), while others report the opposite. Despite the above, the general consensus is that when replacing NA with RCA, there is an adequate content for replacement in which mixes fulfill quality requirements demanded by specifications of each country (mainly for low volume roads).

Based on the bibliographic review and the conclusions presented, future research should lead to a better understanding of the performance of the mixtures with RCA, in this way it is proposed that: i) carry out studies where replacements by mass and by volume are compared with the purpose of establishing the best method for incorporating RCA in the mix; ii) evaluate the influence of surface texture, roughness, and intergranular friction of RCA particles in mix performance; iii) evaluate the effects of RCA on long term properties in the mix (aging, durability); iv) estimate the effects of RCA as a mineral filler and/or asphalt mastics; v) evaluate physical-chemical interactions of the surface which are generated between RCA particles and the asphalt binder and its micro-structural properties; vi) studies required that allow the incorporation of total NA replacement; vii) said studies can consider using previous surface treatments, additives and modified asphalts, among others. Additionally, in order to enhance environmental benefits, there must be a deepening of research efforts such as those made for warm or cold mix asphalts (WMA or CMA, respectively).

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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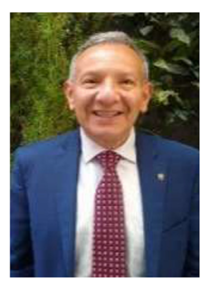

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