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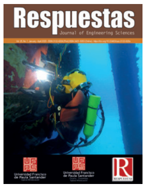

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Behavior of a draining mixture composed by recycled concrete aggregates and rubberized asphalt concrete

Comportamiento de una mezcla asfáltica drenante empleando agregado reciclado de concreto y asfalto modificado con grano de caucho

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ABSTRACT

Concrete waste is considered an environmental liability with a negative impact. However, this type of waste presents a high potential to be used as an alternative building material. Therefore, the present study aims to evaluate the applicability of substituting the conventional natural stone aggregate (CA) of a draining asphalt mixture (MD) by a recycled concrete aggregate (RCA). Firstly, RCA was physically characterized to be compared with the AC. Then, two MD mixtures were design with rubberized asphalt concrete (GCR by its spanish acronym): one using the conventional aggregate (control sample) and one with the RCA substituting entirely the CA. Experimental tests under monotonic load (indirect tensile strength - RTI) were conducted over the mixtures, as well as adhesion tests (susceptibility of RTI in wet and dry conditions and abrasion wear Cantabro). The results indicate that for MD mixtures with RCA, a higher content of asphalt is required than with CA. Additionally, it wasfound that the presence of higher asphalt content in MD-RCA mixtures increases its adhesion when compared with the control sample. Therefore, it can be concluded that the use the RCA for MD mixtures, in the proposed way, is technically and environmentally viable.

Keywords:

recycled aggregate concrete,
RCA,
open porous graded asphalt,
modified asphalt,
crumb rubber modifier,
CRM

RESUMEN

Los residuos de concreto son considerados un pasivo ambiental e impactan negativamente el medio ambiente. Estos residuos tienen un alto potencial para ser empleados como materiales alternativos de construcción. El presente estudio evalúo la aplicabilidad de uso de un agregado reciclado de concreto (RCA, por sus siglas en inglés) como sustituto de la totalidad del agregado pétreo convencional (AC) de origen natural en una mezcla asfáltica drenante (MD). Inicialmente, se realizaron ensayos de caracterización física del RCA y se comparó con el AC. Luego se realizaron los diseños de dos mezclas MD utilizando un asfalto modificado con grano de caucho reciclado de llanta (GCR): una MD empleando como agregado AC (muestra de control) y otra donde se sustituyó la totalidad del AC por RCA. Sobre estas mezclas fueron realizados ensayos de laboratorio bajo carga monotónica (resistencia a la tracción indirecta - RTI) y pruebas de adherencia (susceptibilidad de la RTI en condiciones húmedas y secas y desgaste a la abrasión Cantabro). Los resultados indican la necesidad de emplear un mayor contenido de asfalto en la MD con RCA con respecto a la mezcla de control. Empleando este mayor contenido de asfalto, se observa similitud en la resistencia a la tracción y aumento de adherencia en la MD con RCA con respecto a la muestra de control. Por tanto, se puede concluir que la aplicación del RCA en MD de la forma propuesta es viable desde el punto de vista técnico y ambiental.

Palabras clave:

agregado reciclado de concreto,
RCA,
mezcla drenante,
asfalto modificado,
grano de caucho reciclado de llanta,
GCR.

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Introduction

Construction and demolition waste (C&DW) is one of the main wastes generated in the world, and it negatively affects the preservation and conservation of the environment. Internationally, CDW is known as CDW (construction and demolition waste) and is a by-product of construction, demolition and renovation activities in civil works, which is mainly composed of concrete, bricks, wood, ceramics, plaster, glass, plastics and excavation soil waste, among others [1], [2]. According to [3], CDW represents approximately 40% of total urban waste in continental China, 26% of total solid waste in the United States of America (USA) and 34% of all industrial waste in European countries. On the other hand, in the United Kingdom and Australia, C&DW constitutes approximately 50% and 44% of solid waste generation, respectively [4]. According to information from the European Union (EU) [5], it is possible to show that in 2016 European countries generated an approximate amount of 322 million tonnes of C&DW, indicating that Germany is the largest producer of C&DW with an approximate amount of 86.4 million tonnes, followed by the United Kingdom, France, Italy and the Netherlands with generations of approximately 63.5, 60.2, 34.9 and 19.3 million tonnes, respectively. In view of this scenario, the EU proposes Directive 851 (2018) on waste management, in order to promote the sustainable management of materials and contribute to protecting, preserving and improving the quality of the environment and consequently the protection of human and animal health. To this end, adequate sustainable management of materials is essential, promoting the reuse and recycling of materials, in order to generate a circular economy. In the USA, the Construction Materials Recycling Association in 2014 has collected approximately 583 million tons of RCD waste for recycling. In China, the generation of 2.36 billion tons of C&D waste during 2003 and 2013 is reported [6]. In the case of Colombia, [7] it is reported that the main cities such as Bogotá, Medellín, Cali, Barranquilla, Bucaramanga, Pereira and Armenia generate more than 100,000 tons of CDW per day. Several technical studies have been conducted to reuse and recycle CDW as construction materials, mainly in road infrastructure projects [8], [9]. The studies found in the literature seek to establish diverse applications of CDW in conventional construction materials in an efficient and environmentally appropriate manner.

Concrete is the most widely used construction material in the world and generates at the end of its useful life, the concrete waste [10]. In this sense, waste concrete from CDW can be considered a valuable source of construction material for use. Some studies indicate that the content of concrete waste found in construction, demolition, renovation and various civil engineering activities ranges from 40 to 75% [1]. Against this background, waste concrete is subjected to crushing and size reduction processes, generating recycled concrete aggregates, known as Recycled Aggregate Concrete - RCA [11], [12]. RCA can partially or totally replace Conventional Aggregate (CA). According to [10], Japan reports that 98% of waste concrete is processed, generating alternative aggregates for construction materials. Aggregates are produced mainly by the demolition of concrete structural elements resulting from construction, demolition and repair activities in civil works [10]. The lack of management of RCA produces environmental problems, reducing the useful life of landfills and final disposal sites, as well as contamination of water sources and changes in land use, among others. However, EWRs may have a high potential for use as alternative aggregates [5]. In this way, the use of RCA in civil construction contributes to the preservation and conservation of the environment, in terms of reducing the exploitation of natural stone aggregates, minimizing environmental liabilities, cleaning up and reducing abandoned land, and possibly economic growth through the incorporation of alternative materials in construction activities [13]. The incorporation of AACR into construction materials may be partial or total.

The demand for natural stone materials for the construction of civil works leads to the search for alternative materials that contribute to the reduction of the exploitation of virgin aggregates for the conservation of ecosystems. Various studies report the use of RCA as materials for civil engineering works, such as sub-base layers and bases for pavements [14] - [16], structural concretes [17] - [19], mortars, rigid pavements [20], [21], and asphalt mixtures [13], [22] - [24], among others. Asphalt mixtures with alternative materials have been a technique in constant research, whose objective is the addition and replacement of new alternative and recycled materials, in order to seek a solution to environmental liabilities and thus propose a sustainable civil engineering practice [25].

Respuestas, 25 (1), pp. 96-107, 2020, ISSN 0122-820X - E ISSN: 2422-5053

Various investigations [13], [22] - [24], [26] - [28] evaluated the partial and total incorporation of RCA aggregates into hot dense asphalt mixes. In general, the results obtained in these studies indicate that the volumetric and strength parameters meet the specifications for the manufacture of asphalt mixtures. However, asphalt mixes with RCA require higher asphalt content because they are aggregates with high absorption and surface area [27], [29]. According to the literature, the incorporation of RCA aggregates into dense asphalt mixes is technically and environmentally feasible because it allows for environmentally safe disposal. However, due to the heterogeneity of RCA material by origin and source, studies are presented with conflicting and conflicting conclusions on the application of alternative material in asphalt mixes [30]. Therefore, for the application of RCA in asphalt mixes, it is necessary to carry out a proper experimental campaign to evaluate the characteristics of its mechanical performance, which in some cases may limit the application to low traffic volume road pavements.

In addition to the fact that RCD and RCA recycling in developed countries is common, in Colombia studies and research on applications with recycled materials have been scarce, highly sectorized and limited in scope. The main studies on ADR and CDW materials in Colombia are focused on the evaluation and application of management models for waste production and reuse [31] - [34]. With respect to studies of CDW and ADR as construction materials in civil works, applications of recycled aggregates in blocks and prefabricated pavers are reported, in order to observe the behavior of the material with respect to bending strength and absorption rate [7], [35], [36].

On the other hand, the use of recycled rubber tire grain modified (RRC) asphalts in asphalt mixtures contributes to improving technical aspects of pavement and the development of environmental practices in pavement engineering. On the technical side, incorporating GCR-modified asphalt into the asphalt mix increases resistance to fatigue and aging, as well as reduces permanent deformation [37] - [41]. On the environmental side, the use of GCR as an asphalt modifying material is considered a form of final and environmentally sound disposal of large quantities of used tyres. Despite the multiple benefits of GCR-modified asphalt in asphalt mixes, based on the literature consulted to date, only two studies were found that contemplated the use of RCD and RCA recycled aggregates with GCR-modified asphalt for the manufacture of dense asphalt mixes [24], [30]. It is important to note that no similar studies were found for MD mixes. In addition to the above, the authors of this study also assessed the susceptibility of water to indirect traction resistance in dense asphalt mixes with different percentages of substitution of conventional stone aggregate (CA) of natural origin by RCA. The results reported indicate reduced cohesion of the RCA mixes due to the high viscosity of the modified asphalt. On the other hand, [30] evaluated the mechanical behavior of a dense asphalt mix with 100% substitution of AC aggregates by RCA. As a major conclusion, the authors report an increase in resistance to permanent deformation. However, there is evidence of decreased indirect tensile strength in both dry and wet conditions, consequently reduced resistance to induced moisture damage, as well as reduced resilience modulus and fatigue resistance of the RCA sample in reference to the AC control mix. Given this panorama, the present study involves an innovative technique in Colombia, as it proposes to study the properties of a MD manufactured with partial replacement of AN by RCA and using GCR-modified asphalt as a binder.

In the 80s, in the USA, the trend began to build pavements with draining wearing courses that would allow the rapid evacuation of rainwater by infiltration on the surface and later on to channel it to the drainage works, reducing the phenomenon of hydroplaning and waterlogging in the roads. In this sense, the study of MD, also known by its acronym in English as open graded friction course (OGFC) and in Europe as Permeable European Mix, was developed. This type of mixture has been widely used in European countries such as Germany, Holland and France, as well as in Asian countries such as Japan, Korea and China, and in the United States [42]. MDs have a high volume of air (between 20% and 25%), which allows rapid evacuation and reduction of the water film, as well as reduction of the spray effect or water splash on the pavements. These characteristics contribute to the increase of the visibility distance, reduction of the braking distance and increase of the friction between the tyre and the pavement surface, which favours the safety of the users. In addition, the presence of MD in the pavement reduces the noise caused by vehicle traffic, strengthening the environmental aspect [43] - [45]. The design of MD according to Colombian specifications is regulated by Article 453 [46], which consists of determining the optimum asphalt content, starting with a minimum of 4.5%. The determination of optimum asphalt content is based on air volume and adherence tests. To this end, Marshall type briquettes should be made, compacted with 50 strokes on each face, which should guarantee: i) a volume of air between 20 and 25%, ii) interconnection between voids in the mix, allowing the passage of 100 ml of water in less than 15 seconds, and iii) wear to the Cantabrian abrasion should be less than 25% and 40% in dry and saturated conditions, respectively. For the design of the MD, polymer-modified asphalt should be used with the objective of presenting less susceptibility to aging by the action of oxidation by the effect of water, increasing its mechanical resistance and durability.

This document shows the technical feasibility of using RCA in MD, in order to help find another form of safe final disposal for these concrete products and contribute to the preservation and conservation of the environment. In the present study, the volumetric parameters, abrasion wear and resistance under monotonic load (dry and wet indirect tensile strength) were evaluated, when 100% of the aggregates were replaced by RCA in a MD. Only the replacement content of 100% of the aggregates was evaluated in order to obtain a better use of RCA in the MD. This was done in order to evaluate the influence of using different RCA contents on KO in future research. This technique could be considered innovative, since the total replacement of conventional aggregates by RCA in MD mixes using GCR-modified asphalt has not been studied.

Materials and Methods

Characterization of materials

Characterization of the aggregates (CA and RCA)

The conventional AC aggregates of natural origin are from the company Concrescol of the city of Bogotá D.C. The alternative aggregates type RCA are the result of the collection and crushing process of the company Reciclados Industriales in the city of Bogotá D.C. Physical characterization tests were performed on both types of aggregates, following the specifications of Article 453 [46], in order to evaluate their mechanical resistance (wear and tear on the Los Angeles machine), durability of the material (solidity against sodium sulfate), particle shape (flattening, elongation and fractured face indexes), cleanliness of the aggregate (methylene blue, sand equivalent and organic matter) and the mass/volume ratios in the different fractions. The physical characterization tests of AC and ARC aggregates are presented in Table I.

Table I. Physical characterization of CA and AACR aggregate.

Essay	Specification	Unit	Specification	AC	RCA
Flattening index	NLT 354	%	---	19	13
Elongation rate	NLT 354	%	---	14	12
Percentage of broken faces	ASTM D-5821	%	100	85.2	91,4
Specific gravity of coarse aggregate	AASTHO T85	---	---	2.55	2.40
Thick aggregate absorption	AASTHO T85	%	---	3.1	6.5
Fine aggregate specific gravity	AASTHO T84	---	---	2.79	2.64
Fine aggregate absorption	AASTHO T84	%	---	2.9	16.0
Sand equivalent	ASTM D-854	%	min 50	63	62
Los Angeles Machine Wear	AASTHO T96	%	máx 25	19.5	32.0
Solidity	AASTHO T228	%	máx 18	13.3	45.9
Organic matter content	ASTM C-40	---	máx 3	<1	<1
Methylene blue value	UNE 933-9	mg/g	máx 10	1,25	1,00

From the results obtained in Table I it is possible to conclude that: (I) In terms of particle shape, the RCA aggregates show lower percentages of elongated and flat particles than the results of the AC aggregates, due to the submission of the RCA to the crushing and size reduction process. The result, is verified by the increase of the percentage of fractured faces of the RCA with respect to the AC. In this sense, the RCA aggregates acquire a more cubic shape, consequently a reduction in the flattening and elongation index, with respect to AC aggregates. (II) The specific gravity of the coarse RCA aggregate is lower compared to AC, in this sense, the RCA particles are lighter compared to conventional material, possibly due to the presence of the mortar coating on the RCA aggregates. The presence of mortar leads to the generation of a volume of surface voids and consequently a higher percentage of absorption in comparison to conventional material in the coarse and fine fraction, respectively. III) As for the value of sand equivalent, both types of aggregates present similarity in the result, guaranteeing the minimum value of the specification (50%). In this sense, the result may favor adherence between the aggregate and the asphalt. However, the AC and RCA aggregates used in this research were previously washed and dried to a constant mass. (IV) The wear in the Los Angeles

Respuestas, 25 (1), pp. 96-107, 2020, ISSN 0122-820X - E ISSN: 2422-5053

machine for AC meets the specification requirement (maximum 25%) for MD manufacture. In the case of RCA the abrasion wear does not meet the specified value, which can be attributed to particle breakage and mainly due to the presence of the coating mortar. (V) As for the solidity wear test, the AC aggregate meets the values of the specification (maximum of 25%). However, the RCA aggregate presents a higher value than that stipulated in the specification, possibly due to the detachment of the mortar from the RCA particles when attacked by sodium sulphate. (VI) In terms of the presence of organic matter and methylene blue, AC and RCA aggregates show lower values than stipulated in the specification. The values of organic matter and methylene blue percentages lead to an improvement in the aggregate's adhesion to the asphalt cement.

Characterization of asphalt cement

GCR-modified asphalt is produced and marketed by the company IncoAsfaltos S.A.S. The physical characteristics of the GCR-modified asphalt used are presented in

Table II, which meet the quality requirements for the manufacture of MDs according to the specification [46].

Table II. Characterization of GCR-modified asphalt.

Essay	Specification	Unit	Specification	Result
Penetration 25ºC	ASTM-D5	mm	25 – 75	45
Penetration 4ºC	ASTM-D5	mm	15 min.	16
Softening point	ASTM-D36	ºC	54 min.	64
Apparent Viscosity 175ºC	ASTM D-316	Pa.s	1.5 – 5.0	3.0
Resilience 25ºC	ASTM D-5329	%	20 min.	48
Ignition point	ASTM D 3143	ºC	230 min.	260
Penetration of the waste after loss by heating	ASTM D 2872	%	75 min.	77

Design of MD drainage asphalt mixtures

Initially, 48 Marshall briquettes were manufactured corresponding to two MDs made with GCR-modified asphalt: the control mix that used AC as an aggregate (called MD-AC) and the mix that used RCA as an aggregate (called MD-RCA). 12 Marshall briquettes were manufactured for the MD-AC control mix evaluating the minimum asphalt content of 4.5%, and another 36 were manufactured for the MD-RCAs evaluating asphalt contents of 4.5, 5.0 and 5.5%. The minimum asphalt content of 4.5% in the control mix ensured compliance with the design parameters, except for the void volume (see results below), which was slightly lower than that stipulated by [46]. The material's moisture content is then reduced to a fraction of that of the original material, which is then used as a stabilising agent for the recycled material. The pavement is then stabilised with a stabilising agent that is applied to the surface of the pavement and is then stabilised with a stabilising agent that is applied to the surface of the pavement. For the manufacturing of the mixes, the original particle size of the aggregates was modified, taking as a reference the average values in percentages of the particle size range required by the specification [46] (see Figure 1).

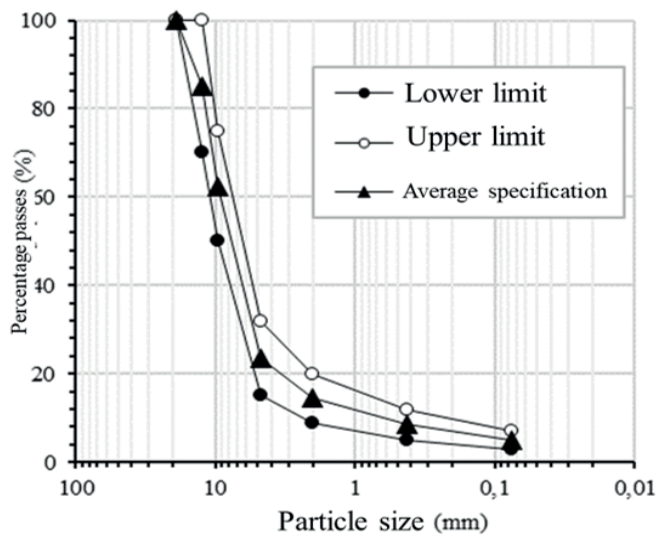

Figure 1. Stone aggregate granulometry for the manufacture of MD.

The mixing and compacting temperatures of the briquettes were 170°C and 100°C, respectively. These temperatures were established by trial and error on previously manufactured briquettes. This is because there is no specification recommending a methodology to define them for MD mixes using GCR and RCA modified asphalt. The mix temperature was determined in such a way as to ensure the total coating of the aggregate particles (AC and RCA) with asphalt. In addition, the compaction temperature was determined to ensure the proper viscosity to meet the volume of air required by the MD design specifications. With the 48 briquettes, non-destructive tests were performed for the physical-mechanical characterization, such as the determination of air voids and water infiltration time. Subsequently, destructive tests were performed with the same briquettes, such as Resistance to Indirect Traction RTI and wear and tear to Cantabrian abrasion at 25 and 40°C respectively. For the results of the destructive tests (RTI and Cantabrian wear) an average of three samples was determined.

The voids with air in the mixture correspond to the sum of the three types of voids: (I) interconnected or effective, (II) semi-connected and (III) ineffective, according to Figure 2. The interconnected voids refer to the voids that allow the passage of water, the semi-connected voids allow the storage of water and the ineffective voids do not allow the passage or storage of water. In the design of a KD, a volume of air between 20 and 25% must be met to ensure the required permeability.

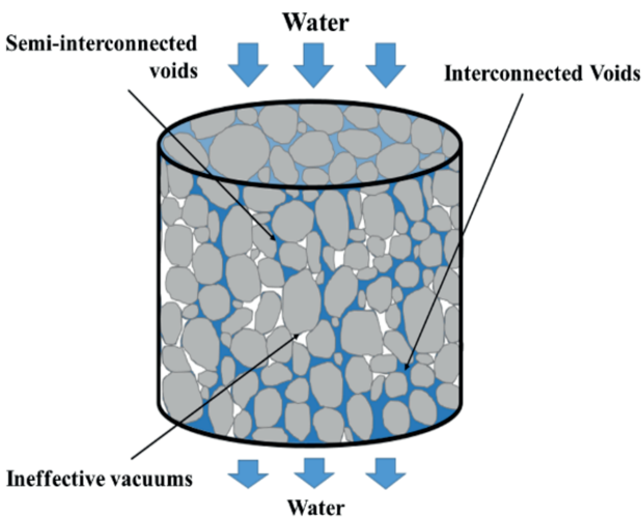

Figure 2. Diagram of Air Volume within an asphalt mix.

In order to guarantee the communicating voids in the mixture, the time of infiltration of the water into the briquette was determined, in order to guarantee the passage of water in a given time and the elimination of the water film on the surface of the pavement. The laboratory test consists of determining the time it takes to infiltrate 100 ml of water into a Marshall briquette. For the design of the MD, the water infiltration time (100 ml) should be less than 15 seconds.

Over 24 Marshall briquettes (6 briquettes for the MD-AC and 18 briquettes with MD-RCA mixture), wear tests (without abrasive load) were performed in the Los Angeles machine, applying 300 turns at 33 revolutions per minute [46]. The briquettes used the minimum asphalt content of 4.5% in the MD-AC mix and 4.5, 5.0 and 5.0% in the MD-RCA mix. The temperatures of the samples during the test were 25 and 60 °C respectively. The pavement's structure is designed to withstand the stresses and strains of traffic and is therefore suitable for use as a stabilising agent. The test simulates the behavior of an open mixture when subjected to the abrasive effects caused by the action of traffic and temperature.

Resistance to Indirect Traction – RTI

Although the design of the MD does not contemplate the performance of the RTI test, it was evaluated in order to assess the susceptibility of water in the MD with JI and ADR. To this end, 24 Marshall briquettes were manufactured, of which: 6 used asphalt content of 4.5% in the MD-AC mixture and 18 used asphalt contents of 4.5, 5.0 and 5.0% in the MD-RCA mixtures. The RTI test was carried out in a loading press, following the guidelines established by [46]. The pavement's structure is designed to withstand the stresses and strains of the road, and is capable of withstanding them for up to five years. Test temperatures were 25°C on failed samples in dry condition, and 60°C on pre-conditioned or water-immersed samples. For the determination of the indirect tensile strength at 60°C, the Marshall briquettes were heated in a water bath for 24 hours.

Results and Discussion

Infiltration time and air volume

Figure 3 illustrates the air volumes (total, communicating and inefficient) and water infiltration time evaluation for JI and ADR MDs, respectively.

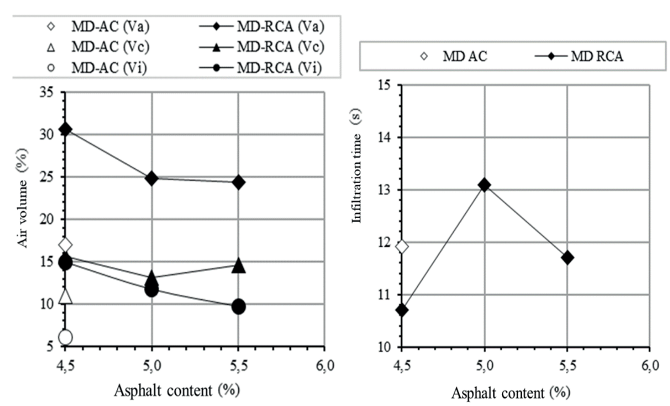

Figura 3. Evolución del Volumen de Aire y tiempo de infiltración con el porcentaje de asfalto.

Respuestas, 25 (1), pp. 96-107, 2020, ISSN 0122-820X - E ISSN: 2422-5053

From the results illustrated in Figure 3 it is possible to deduce that: The AC control mix with the minimum modified asphalt content of 4.5% has a Va lower than the 20% stipulated by the specification [46]. This phenomenon is attributed to the high heating and compaction temperatures that guarantee the workability of the modified asphalt cement. It should be noted that the specifications for the manufacture of MD of INVIAS (2013) do not contemplate a minimum viscosity for heating and compacting that guarantees control of air volume. For an asphalt content of 4.5%, the asphalt mix with RCA presents approximately a twofold increase in Va with respect to the sample with AC. This phenomenon can be attributed to the high absorption of asphalt into the RCA aggregate and consequently the reduction of the asphalt layer thickness, resulting in a lower Va with reference to the AC mixture. This is also due to the lower coating of particles with asphalt as a result of the higher absorption and mass replacement of AC by RCA (this process generates an increase in the number of particles in the mix due to the lower specific gravity of RCA compared to AC). In asphalt mixes it is possible to show that Vv decreases with increasing asphalt content. On the other hand, logically, the time for water infiltration into the MD is directly proportional to the Vc.

Abrasion wear

Figure 4 presents the results of abrasion wear and adhesion by means of the Cantabrian test of asphalt mixtures with AC and RCA at temperatures of 25 and 60ºC respectively. Based on the results obtained, it is possible to deduce that (I) Logically, in mixtures with AC and RCA, abrasion wear is inversely proportional to the asphalt content and directly proportional to Va In this sense, the higher wear is attributed to the lower asphalt cement content and the higher Va of the mix. (II) For an asphalt content of 4.5%, asphalt mixes with RCA show a significant increase in abrasion wear with respect to the control mix with AC. The amount of aggregate used in the recycling process is determined by the amount of aggregate used in the process and the type of material being recycled. This result may be correlated with the high abrasive wear of the RCA aggregate relative to AC. (III) Asphalt mixtures with AC and RCA with 4.5% and 5.5% of asphalt respectively, showed wear values of less than 25% and 40% at temperatures of 25°C and 60°C, meeting the specifications for the design of MD.

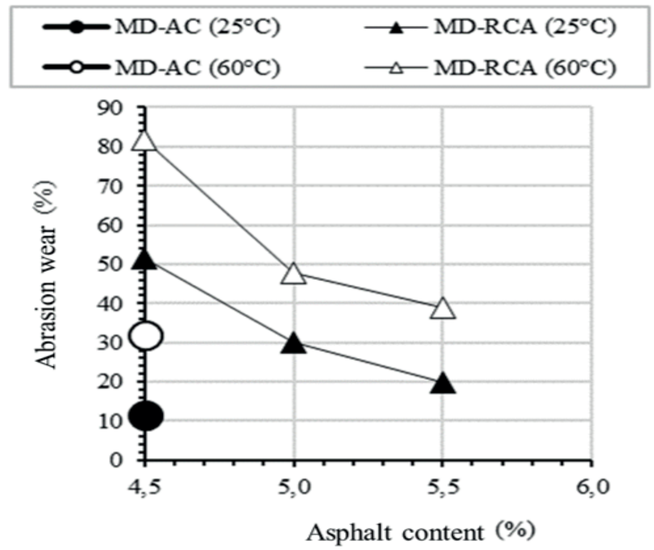

Figure 4. Evolution of wear to abrasion at 25°C and 60°C with the asphalt content

Determination of optimum asphalt content

Based on the results reported for MDs with AC and RCA aggregate, referring to Va and wear to Cantabrian abrasion at temperatures of 25°C and 60ºC, it is possible to conclude that the contents of 4.5% and 5.5% of GCR-modified asphalt respectively, guarantee compliance with the specifications for the design of MDs, according to Table III.

Table III. Specifications for the design of a KM.

Feature	Specification	Unit	MD-AC	MD-RCA	Specification
Asphalt content	Articulo 453	%	4.5	5.5	Min. 4.5
Voids with air in the mixture	INV E-736	%	17.03	24.36	20 – 25
Communicating air voids	Article 453	s	11.92	11.07	Máx. 15
Loss due to wear and tear in the Cantabrian test at 25°C	INV E-760	%	11.66	19.79	Máx. 25
Loss due to wear and tear in the Cantabrian test at 60°C	INV E-760	%	32.00	38.79	Máx. 40

Resistance to Indirect Traction - RTI

Figure 5 presents the evolution of the ITR determined at temperatures of 25°C (dry samples) and 60°C (saturated samples), for MDs with CA and ARC aggregates, respectively.

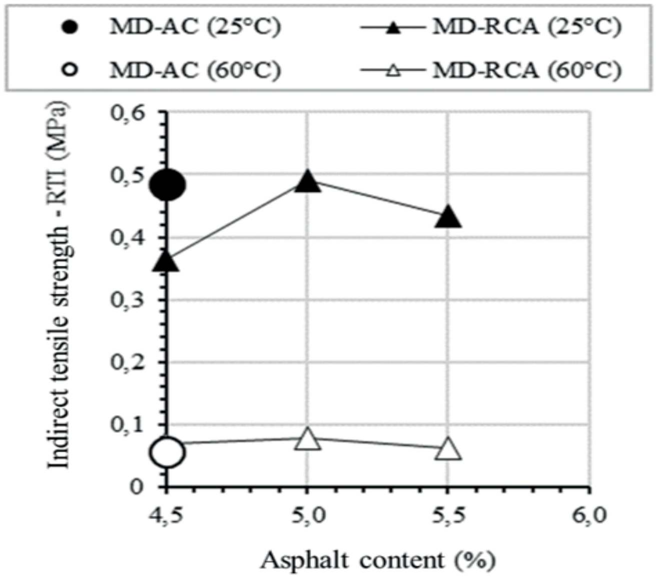

Figure 5. Evolution of tensile strength at 25°C and 60°C with asphalt content.

According to the results of the Figure 5, it is possible to deduce that: (I) For the minimum asphalt content of 4.5%, the RTI at 25°C of the asphalt mix with RCA is reduced by approximately 20% with respect to the control mix with AC. The reduction in RTI in the RCA mix is attributed to the increase in Va with reference to the control mix. The increase of Va in the RCA mix with respect to the AC mix is attributed to the high absorption of the RCA aggregate and consequently the reduction of the asphalt cement sheet, which causes loss of adhesion between the particles. (II) For the minimum asphalt content of 4.5%, the RTI at 60ºC of the MD with AC is similar to the RCA mix, inducing that the behavior at high temperature or in saturated condition is attributed mainly to the performance of the asphalt cement and not to the aggregates. In this sense, it is evident that the test temperature is close to the temperature of the softening point, with which there is a greater detachment of particles and consequently a lower RTI value in relation to the RTI test at 25°C. (III) An optimum asphalt content of 5% can be observed in the asphalt mix with RCA at the temperature of 25 and 60°C respectively, which guarantees the maximum RTI value. In this sense, the increase in asphalt content contributes to the coating of the particles and consequently to the adhesion of the mix. (IV) Conventional mixes with RCA present less variation of RTI due to the influence of the change in temperature from 25 to 60ºC, compared to the control mix with AC. Less variation of the RTI in the face of temperature changes is indicative of better conditions of adhesion. In this sense, the mixtures with RCA present less susceptibility to adherence to temperature changes. (V) Asphalt mixtures with AC and RCA present similar RTI values at 25 and 60 ºC as they contain 4.5 and 5.0% of asphalt, respectively. The same response to monotonic loading can therefore be observed for both conventional AC and alternative RCA mixes.

Conclusion

By means of the evaluation of the object of study concerning the use of 100% of the RCA aggregates in MD using a GCR-modified asphalt, it is possible to conclude that: i) In general, the application of RCA when subjected to the pre-crushing process meets the minimum requirements for the manufacture of MD, except for wear due to the action of sodium sulfate and wear in the Los Angeles machine. Additionally, RCA particles have higher absorption and lower specific gravity compared to AC. The above is an indication that MD-RCA will require a higher asphalt content with respect to MD-AC, in order to guarantee the coating of the particles by the asphalt layer. ii) The cubic shape of the particles of the RCA aggregates contributes to the mechanical performance of MD by allowing a better accommodation of the same, evidenced by presenting results of wear to the Cantabrian abrasion and resistance to indirect traction similar to the control mix. However, MD-RCA requires a higher asphalt content in reference to the MD-AC control mix. iii) The total replacement of AC aggregate by RCA in MD increases the asphalt content by 1.0% due to increased absorption. However, MD-RCA mixtures guarantee similar values of tensile strength at 25 and 60 ºC, and adhesion determined with wear to Cantabrian abrasion with respect to the MD-AC control mix. iv) The application of RCA in draining asphalt mixtures in the proposed manner can be considered viable from the technical and environmental point of view, as it presents similarity in the physical-mechanical behavior of the conventional material and allows for a safe and environmentally correct final disposal alternative.

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