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Evaluation of an experimental hot asphalt concrete urban paving section using construction and works demolition waste (CDW) as a coating layer

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Abstract

Objective of the study: To present a proposal for the application of construction and works demolition waste (CDW) in the manufacturing of asphalt coating as an alternative for the use of these materials.

Methodology/approach: Physical, chemical and mineralogical characterization tests and dosage assessments by the Marshall method were applied. An experimental pavement stretch was then analyzed using a market feature adapted for CDW inclusion. Recycled aggregate (RA) containing gravel 1 and sand was then used to replace the same natural type of aggregate in an asphaltic coating layer.

Originality/Relevance: On a worldwide scale, the building materials industry is expected to increase two and a half-fold between 2010 and 2050 (UNEP, 2002). In Brazil, estimates indicate that the construction sector will double in size by 2022 (Cebeds, 2009), leading to increased waste generation. It is, thus, crucial to take measures aimed at solid waste management through cultural and technological changes, aiming to meet the needs of a society increasingly elucidated and demanding in regard to environmental preservation. One of the engineering sectors that can promote the use of RA, which requires less investments, is that of urban and road pavements (Rezende et al., 2016).

Main results: The proposed experimental program indicates that CDW aggregates exhibit adequate potential for use in hot asphalt coatings, based on volumetric parameters, Marshall dosage tests and experimental stretch assessments, in which traffic analyses and bearing conditions indicated quite satisfactory asphalt pavement results.

Theoretical/methodological contributions: During the analyzed period, only slight functional differences were observed between RA and non-RA containing asphalt coatings. Thus, the well-dosed use of a material that may result in environmental pollution on a low traffic-load pavement becomes viable from a sustainability point of view, due to reduced consumption of natural aggregates in the face of the benefits of recycled material.

Conclusions: The gravel 1 RA was adequate for asphalt pavement use, exhibiting some interesting properties, i.e. Los Angeles abrasion (35%) and shape index (0.87), in accordance to current Brazilian ABNT standards. Regarding the experimental stretch, although a small detachment of ceramic surface portions was observed, this subtle occurrence did not compromise the asphalt coating and, after 5 months of functional analyses, the asphalt pavement continues to perform very satisfactorily regarding vehicle bearing.

Keywords: RCD. Recycled aggregate. Paving. Sustainability.

Avaliação de um trecho experimental de pavimentação urbana em concreto asfáltico à quente com resíduos de construção e demolição de obras (RCD) como camada de revestimento

Resumo

Objetivo do estudo: apresentar uma proposta de aplicação de resíduos de construção e demolição de obras na fabricação de revestimento asfáltico, como uma alternativa para o aproveitamento desses materiais.

Metodologia/abordagem: utilizou-se o empregado de ensaios de caracterização física, química e mineralógica e dosagem pelo método Marshall. Em seguida, realizaram-se as análises de um trecho experimental com o uso de traço de mercado, adaptado para a inclusão do RCD. Nesse traço, foi utilizado agregado reciclado contendo brita 1 e areia em substituição ao mesmo agregado do tipo natural na camada de revestimento.

Originalidade/relevância: em escala mundial, espera-se que a indústria de materiais de construção cresça duas vezes e meia entre 2010 e 2050 (UNEP, 2002). No Brasil, a expectativa é que o setor da construção dobre de tamanho até o ano de 2022 (Cebeds, 2009), conduzindo a um aumento da geração de resíduos. Nota-se que é crucial tomar medidas que visem à gestão de resíduos sólidos por meio de mudanças culturais e tecnológicas, objetivando atender às necessidades de uma sociedade cada vez mais esclarecida e exigente em relação à preservação do meio ambiente. Um dos setores de engenharia que pode promover o uso de agregados reciclados (AR) que requerem menos investimento é o dos pavimentos urbanos e rodoviários (Rezende et al., 2016).

Principais resultados: a partir do programa experimental proposto, observou-se que os agregados oriundos de RCD desempenharam um bom potencial de sua utilização em revestimentos asfálticos à quente, baseado nas análises dos corpos de prova sob os parâmetros volumétricos, pela dosagem Marshall e do trecho experimental no qual, por meio de análises de tráfegos, bem como das condições de rolamento, o pavimento asfáltico obteve resultados bastante satisfatórios.

Contribuições teóricas/metodológicas: durante o período analisado, foi constatada pouca diferença funcional entre os revestimentos asfálticos contendo e não contendo agregado reciclado. Dessa maneira, o uso bem dosado de um material, que estava sujeito à poluição ambiental, num pavimento com baixa carga de tráfego, torna-se viável do ponto de vista da sustentabilidade, haja vista diminuir o consumo de agregado natural em proveito do reciclado.

Conclusão: quanto ao agregado reciclado brita 1 concluiu-se que este apresentou bons resultados para uso em pavimentação asfáltica no qual destaca-se algumas boas propriedades obtidas, Abrasão Los Angeles (35%), índice de forma (0,87) se enquadrando no que é estabelecido pelas normas (ABNT) vigentes. No que diz respeito ao trecho experimental percebeu-se que, embora tenha havido pequeno destacamento de placas cerâmicas presentes em sua superfície, este sutil ocorrido não comprometeu o revestimento asfáltico e após 5 meses de análises funcionais o pavimento asfáltico continua desempenhando de forma muito satisfatória bom rolamento aos veículos que por ele trafegam.

Palavras-Chave: RCD. Agregado reciclado. Pavimentação. Sustentabilidade.

Evaluación de un tramo experimental de pavimentación urbana en hormigón asfáltico caliente con residuos de construcción y demolición de obras (RCD) como capa de revestimiento

Resumen

Objetivo del estudio: Presentar una propuesta para la aplicación de residuos de construcción y demolición en la fabricación de revestimiento asfáltico, como alternativa para el aprovechamiento de estos materiales.

Metodología/enfoque: Se utilizaron las pruebas de caracterización física, química y mineralógica y dosificación por el método Marshall. Posteriormente se analizó un apartado experimental utilizando una función de mercado adaptada para la inclusión del RCD. En esta función se utilizó agregado reciclado que contiene grava 1 y arena reemplazando el mismo agregado de tipo natural en la capa de revestimiento.

Originalidad/relevancia: A escala mundial, se espera que la industria de materiales de construcción crezca dos veces y media entre 2010 y 2050 (UNEP, 2002). En Brasil, se espera que el sector de la construcción duplique su tamaño para 2022 (Cebeds, 2009), lo que conducirá a un aumento en la generación de residuos. Se advierte que es fundamental tomar medidas encaminadas a la gestión de residuos sólidos a través de cambios culturales y tecnológicos, con el objetivo de satisfacer las necesidades de una sociedad cada vez más instruida y exigente em relación a la preservación del medio ambiente. Uno de los sectores de ingeniería que puede promover el uso de agregados reciclados (RA) que requieren menos inversión son los pavimentos urbanos y de carreteras (Rezende et al., 2016).

Resultados principales: A partir del programa experimental propuesto, se observó que los agregados de RCD tenían un buen potencial para su uso en recubrimientos de asfalto caliente basados en el análisis de cuerpos de prueba bajo los parámetros volumétricos, por la dosificación del método de Marshall y el tramo experimental en que a través del análisis del tráfico y las condiciones de rodadura, el pavimento asfáltico obtuvo resultados bastante satisfactorios.

Contribuciones teóricas/metodológicas: Durante el período analizado, se encontró poca diferencia funcional entre los recubrimientos de asfalto que contienen y no contienen agregado reciclado. Por lo tanto, el uso bien dosificado de un material, sujeto a la contaminación ambiental, sobre un pavimento con baja carga de tráfico se vuelve viable desde un punto de vista de sostenibilidad, ya que reduce el consumo de agregado natural em beneficio del material reciclado.

Conclusión: En cuanto al agregado reciclado de grava 1, se concluyó que presentó buenos resultados para su uso en el pavimento asfáltico en el que destacamos algunas buenas propiedades obtenidas, Abrasión Los Ángeles (35%), índice de forma (0.87) que se ajusta al que se establece según los estándares actuales (ABNT). Con respecto a la sección experimental, se notó que, si bien hubo un pequeño desprendimiento de placas cerámicas presentes en su superficie, esta sutil ocurrencia no comprometió el revestimiento asfáltico y después de 5 meses de análisis funcional, el pavimento asfáltico continúa funcionando de manera muy satisfactoria con buena rodadura para los vehículos que lo atraviesan.

Palabras clave: RCD. Agregado reciclado. Pavimentación. Sustentabilidad.

Introduction

According to the Federation of Industries of the State of São Paulo (FIESP, 2017), civil construction is one of the main components of the Brazilian economy and its production chain associates a set of activities that add up to over 12 million people, of which 13% represent the workforce in the country. Civil construction activities require high amounts of inert materials, such as gravel and sand, which are usually extracted from alluvial sediments. Sand extraction, however, alters both river profiles and their equilibrium, as well as their hydrogeological structure, resulting in environmental issues (Cabral *et al.*, 2009).

Furthermore, the building materials industry is expected to grow two-and-a-half-fold between 2010 and 2050 on a global scale (UNEP, 2002). In Brazil, the expectation is that the construction sector will double in size by 2022 (Cebeds, 2009), leading to increases in waste generation. Thus, measures aimed at solid waste management through cultural and technological changes are crucial, aiming to meet the needs of an increasingly clarified and demanding society in what concerns environmental preservation. Worldwide, 60% of the raw materials extracted from the lithosphere are used in the construction sector (Bribián, Capilla & Usón, 2011). This percentage confirms that the use of finite natural resources is extensive and that methods capable of recycling this waste when disposed of in the environment are required. Materials that have already been used in civil construction and are then discarded are termed Construction and Demolition Waste (CDW) or Civil Construction Waste (CCW).

The difference between the major types of civil construction works results in highly variable residues. Silva and Fernandes (2012) state that CDW correspond to 60% of the total amount of solid urban waste. On the other hand, Cabral *et al.* (2009) established CDW rates at 50%.

One of the engineering sectors capable of encouraging the use of recycled aggregates (RA), which require less investments, comprises urban and road pavements (Rezende *et al*., 2016). In fact, the use of CDW as sub-base, base and road layering material is an efficient method to mitigate the environmental impacts of this type of waste, consequently increasing its consumption in order to avoid landfill disposal. However, the physical properties and composition of recycled construction and demolition aggregates vary according to their extraction location. This will, in turn, affect the quality of the residual material, which will certainly influence its mechanical properties.

Chen, Lin and Wu (2011) investigated the potential of using powder extracted from the processing of RA in asphalt mixtures. They were then compared to a conventional mixture that used limestone as aggregate, through different laboratory tests, in order to ascertain the behavior of the mixture in relation to tensile strength, dynamic fluency, water sensitivity and fatigue. Characterization tests were also performed, such as DRX, FRX and SEM. Composed mainly of quartz and calcite, the RA powder contained in the asphalt mixture provided better properties in terms of water sensitivity and fatigue, although decreased performance at low temperatures was observed. Its application was, thus, recommended especially in hotter regions.

Souza *et al*. (2012) evaluated the use of CDW as an RA for developing Hot Bituminous Concrete (HBC) asphalt mixtures for use in road surface layers. Comparing RA specimens to conventional limestone natural aggregates, the authors observed that the former presented greater tensile strength determined through diametrical compression and lower rigidity when compared to the latter. In general, the recycled CDW aggregate met the standard specifications for aggregate use in asphalt mixtures, considering the possibility of use in roads undergoing low to medium traffic volumes.

Lourenço and Cavalcante (2015) analyzed the technical viability of CDW in substitution to the conventional aggregates used in hot-machined asphalt mixtures, aiming for road bearing layer applications. The optimal content of the asphalt binder CAP 50/70 was determined through Marshall dosing. Tests such as Marshall flow and dosing, tensile strength by diametrical compression, resilience module and cantabro wear were also performed. Among other results, the authors indicate that Marshall stability resulted in 1,468.7 kgf and cantabro wear of 2%, concluding that the RA has the potential to be used in bearing coating layers.

Fernandes, Júnior and Ferreira (2018) used residual material extracted from ornamental rocks (marble) as aggregate in asphalt mixtures. Two types of mixtures were compared, one containing a conventional aggregate and the other a 2% residual aggregate with a diameter similar to rock powder. Aggregates and CAP 50/70 were characterized, and tensile strength and resilience module were determined. The specimens containing marble residue exhibited higher tensile strength (11.69%) and resilience module (7.89%) when compared to conventional aggregate specimens, although the ideal binder content was increased, as the assessed residue is less dense and exhibits higher porosity.

In this context, this study presents a proposal for the application of CDW as RA in the manufacturing of asphalt coating as an alternative for the use of these materials, since the paving sector is responsible for 18.37% of the consumption of crushed rock in Brazil (DNPM, 2009).

Material characteristics

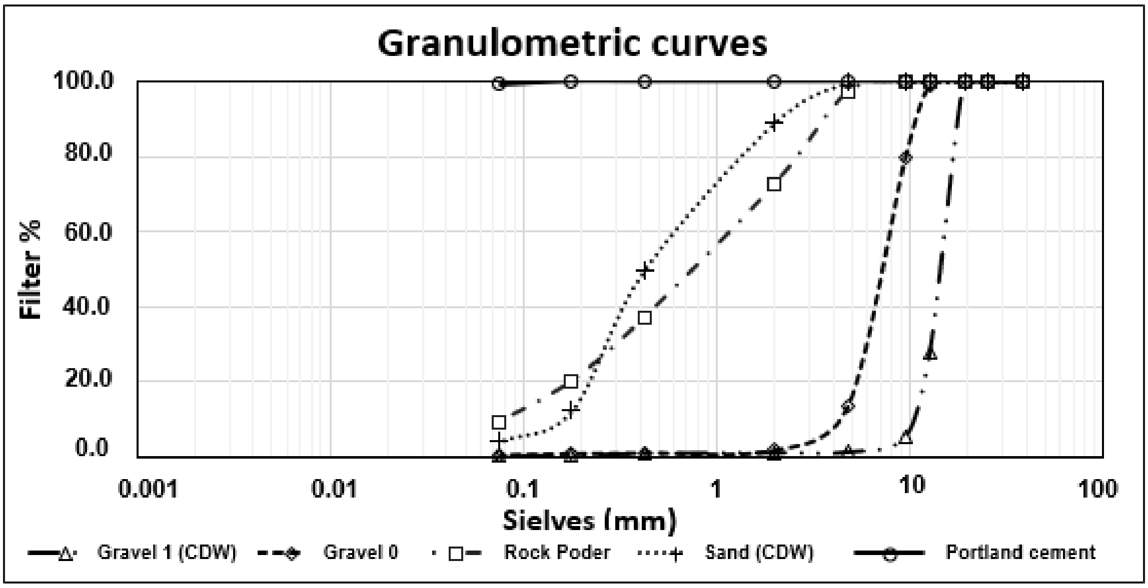
The scientific research activities listed in this topic were carried out in four main stages: natural and recycled aggregate characterization, asphalt binder characterization, dosing by the Marshall method and development of an experimental stretch in order to carry out practical analyses.

A partnership was signed with an aggregate-recycling company, where all the RA required to carry out this research was obtained. The provided aggregates comprised gravel 1 and sand, deposited at the binder supplying company plant.

The binder supplying company assisted in the donation of the asphalt binder (CAP 50/70) and, at the end of the laboratory research, developed an experimental stretch on an urban road in the city of Natal, in the state of Rio Grande do Norte, Brazil.

The X-Ray Diffraction (XRD) and X-Ray Fluorescence tests were performed at the Materials Engineering Department laboratory (DEMAT), at the Federal University of Rio Grande do Norte (UFRN). Relevant details to the physical material characterization assessments are displayed in Figure 1 and Table 1. It is important to note that the physical characterization values of the materials are within the limits established by Brazilian specifications, according to the Brazilian Technical Standards Association (ABNT) and the National Department of Infrastructure and Land Transport (DNIT).

Figure 1 - Particle size analysis of the aggregates used in the present study



Source: Own elaboration.

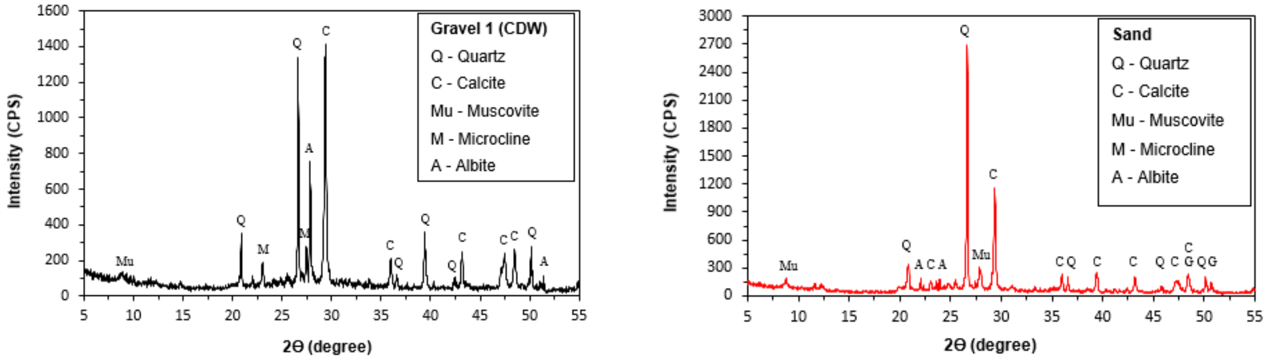
Table 1 - Characteristics of the materials used in the present study

Aggregate characterization			
Parameters	**Gavel 1 (CDW)**	**Gravel 0**	**Sand (CDW)**
Specific mass	2.19 g/cm³	2.56 g/cm³	2.54 g/cm³
MF	7,85	5.73	3.82
MCD	19 mm	9.50 mm	4.75 mm
Shape index	0.87	-	-
Abrasion Los Angeles	35%	-	-
Parameters	**Rock powder**	**Cement**	
Specific mass	2.63 g/cm³	2.86 g/cm³	
FM	3.92	-	
MCD	2.36 mm	-	
Asphalt Petroleum Cement characterization			
Parameters	**Results**		
Saybolt-Furol viscosity	135º C 250.5 SSF	150º C 131.0 SSF	177º C 42.4 SSF
Penetration	53 - CAP 50/70		
Specific mass	1.013 g/cm³		
Flash Point	Interrupted at 235 º C		
Softening Point	44.5 º C		

Note: MCD - Maximum characteristic dimension; FM - Fineness Module
Source: Own elaboration.

X-ray diffraction (XRD) was applied to characterize the crystallographic structures of the gravel 1 and sand materials. Figure 2 (a) and (b) indicate that the mineralogical compositions of both are complex, due to the significant crystalline and amorphous variability of their components (concrete, mortar and ceramic). The main components of gravel 1 and sand, both CDW, were quartz [SiO_2], calcite [$CaCO_3$], gypsum [$Ca(SO_4)(H_2O)_2$], muscovite [$KAl_2(Si_3Al)O_{10}(OH)_2$], microcline [$KAlSi_3O_8$] and albite [$Na(AlSi_3O_8$].

Figure 2 - (a) Gravel 1 diffractogram (CDW) / (b) Sand diffractogram (CDW)



(a) (b)

Source: Own elaboration.

Table 2 presents the chemical composition obtained by FRX analyses of the RA. Identified oxides are expressed as percentages. The results indicate the common presence of certain oxides at similar levels. The highest detected contents for both Gravel 1 (CDW) and recycled sand were calcium oxide (CaO), followed by silicon dioxide (SiO_2), iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3), similar to the results reported by Martínez et al. (2016), who identified that 70% of CDW oxides correspond to calcium oxide, silicon dioxide and aluminum oxide.

Table 2 - Chemical composition of the recycled aggregates used in the present study

Chemical Characterization by FRX			
Gravel 1 (CDW)		Sand (CDW)	
Oxides	%	Oxides	%
CaO	49.30	CaO	37.94
SiO_2	24.86	SiO_2	26.55
Fe_2O_3	9.65	Fe_2O_3	12.42
Al_2O_3	8.25	Al_2O_3	11.26
SO_3	2.89	SO_3	3.49
ZrO_2	1.05	ZrO_2	2.98
K_2O	1.34	K_2O	1.67
Other	2.66	Other	3.69

Source: Own elaboration.

The calcium and silicon oxides (CaO and SiO_2) that make up these residual materials are probably due to the presence of hydrated cementitious compounds (mortars, concrete).

Iron and aluminum oxides, in addition to calcium oxide, may originate from ceramic material (Martínez et al, 2016).

Experimental program

In order to investigate the incorporation of residual materials to asphalt concrete as a substitute for gravel 1 and natural sand, volumetric parameters, Marshall stability and an experimental stretch were analyzed, according to the standards established by the Brazilian Technical Standards Association (ABNT) and the National Department of Infrastructure and Land Transport (DNIT). The compositions of the traces used in this research are exhibited in Table 3. We chose to maintain at least 53%, 49.3% and 53% of the materials represented by the coarse aggregates as follows: laboratory trace with residue incorporation, experimental stretch trace with residue incorporation, and experimental stretch trace without residue incorporation -conventional, respectively, since in a bituminous mixture such as Hot-machined Bituminous Concrete (HBC) type, support capacity is provided more effectively by the coarse aggregate. Furthermore, we decided to set the amount of cement at 2% in the laboratory mix containing the residue to avoid problems due to excessive void filling, which could, in turn, result in the non-release of tension, increasing mixture rigidity. The fine aggregate percentages varied in regard to total mineral constituents, due to better granulometric framing within the C curve limits of the DNIT standard 031/2006 (2006) and greater proximity to ideal curves.

Table 3 - Composition of the HBC traces

Laboratory trace with residue incorporation	
Material	**Trace**
Gravel 1	13%
Gravel 0	40%
Rock powder	25%
Sand	20%
Cement	2%
Total	100%
Experimental section trace with residue incorporation	
Material	Trace
Gravel 1	13.5%
Gravel 0	35.8%
Rock powder	24.8%
Sand	19.9%
CAP	5.4%
Total	100%
Experimental stretch trace without residue incorporation – conventional	
Material	**Trace**
Gravel 1	12.5%
Gravel 0	40.5%
Rock powder	26.0%
Sand	22.0%
CAP	5.0%
Total	100%

Source: Own elaboration.

The experimental stretch is 46 m long and 2.80 m wide and was developed both with and without RA, aiming to assess surface wear and, consequently, functionality over time (Figure 3), due to natural weather conditions such as rain, sunshine, traffic by different types of vehicles and different loading frequencies.

Figure 3 - (a) Visual behavior of the experimental stretches containing and not containing recycled materials / (b) Functional behavior of the experimental section containing recycled materials

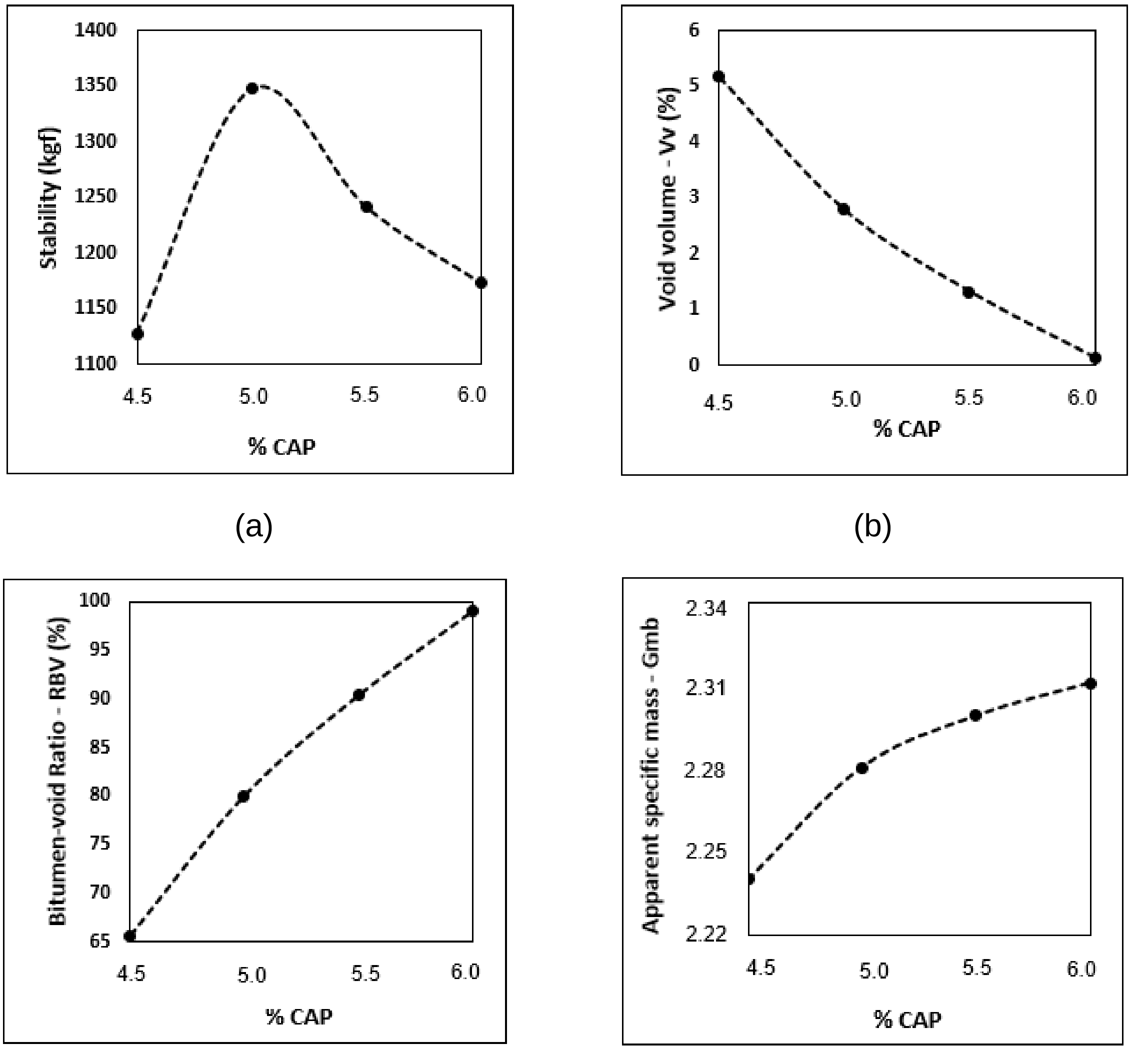
(a) (b)

Source: Own elaboration.

Results and discussion

Figure 4 presents a graphical summary of the results.

Figure 4 - (a) Marshall stability x% CAP / (b) Void volume x% CAP / (c) Bitumen-void ratio (RBV) x% CAP / (d) Apparent specific mass (Gmb) x% CAP



(a) (b) (c) (d)

Source: Own elaboration.

Examining the stability versus % CAP graph displayed in Figure 4 (a), specimens exhibiting greater stability contained 5.0% of the ligand. Motter (2013) reported greater stability, ranging between 1,200 and 1,310 kgf, at 6% bituminous material content. The graph behavior indicates a continuous decrease in stability when CAP contents exceed 5.0%, while a slightly higher percentage (5.05%) results in greater stability (1,350 kgf). Stability at 5.0% CAP is equivalent to 1,348 kgf, a high value that may be associated to friction between CDW aggregates. It does, however, comply with the DNIT 031/2006 - ES standard, which establishes a minimum stability of 500 kgf for the bearing layer of asphalt pavements.

Lourenço and Cavalcante (2015), also using RA for asphalt layering, reported stability results of 1,468.7 kgf, while Sinisterra (2014) reported similar results, exceeding 1,400 kgf. Both studies reinforce the results reported herein.

Costa Filho (2017), reported that levels ranging between 5.0% and 5.5% CAP meet the minimum stability requirements for asphalt mixtures containing residual materials, as they achieve values above 500 kgf. With this, the pavement becomes more resistant to external actions, such as high temperatures and loads.

An important parameter to be investigated in bituminous mixtures is void volume, since void volume percentage determinations can elucidate, when necessary, some forces to which asphalt pavements will be subjected. Figure 4 (b) illustrates the graph corresponding to the bituminous mixture containing RA. Increasing asphalt mixture CAP contents resulted in higher void volume decreases, a result also reported by Lourenço and Cavalcante (2015). This is probably due to the fact that the bituminous product fills the existing RA voids.

According to the DNIT 031/2006 – ES standard, void percentage rates for asphalt bearing layers should range between 3% and 5%. The means reported herein were of 4%. At 5.5% and 6.0%, adequate void volume reductions were noted, harmful to the asphalt coating due to lack of space to deform and relieve tensions when necessary. In other words, the asphalt pavement will then exhibit rigid behavior, which may generate cracks and, consequently, decrease asphalt durability. Costa Filho (2017) reported similar results for one of the assessed asphaltic mixtures, crediting this to the higher presence of fine gradation material in the asphalt composition, causing higher void filling. On the other hand, a 4.5% CAP content resulted in a void volume above that recommended by the applied standard, resulting in many voids, which may, in turn, lead to plastic deformations and water percolation susceptibility. However, Motter (2013), who analyzed the properties of hot-machined bituminous concretes containing recycled coarse concrete aggregates, attested that only a binder content over 5.5% can meet the DNIT 031/2006 - ES standard.

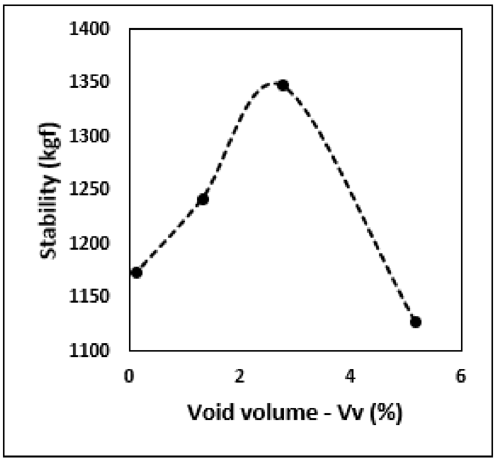
Figure 4 (c) illustrates the BVR x CAP ratio of the asphalt mixture at the different levels proposed by this study. A continuous increase in this relationship with increasing CAP contents was observed, which was also reported by Costa Filho (2017). This directly proportional result can be associated to inefficient compaction or to the simple fact of increased binder content. Based on this hypothesis, an adequate number of voids was established and filled with bitumen, since both recycled and natural and angular aggregates, such as gravel 0, were present in the mixture. This is noted more clearly in the asphalt mixture containing 6.0% CAP.

On the other hand, low BVR values can cause material breakdown and infiltrations in susceptible pavements, resulting in durability damage. Based on this, Figure 4 (c) indicates that the 4.5% CAP content resulted in a BVR of approximately 66%, below the minimum percentage required by the DNIT 031/2006 – ES standard, which establishes a minimum BVR of 75% for the bearing layer. Similar results were observed for the 5.5% and 6.0% contents, which exceeded the upper limit of 82%. Therefore, the CAP content that meets the adequate BVR is of 5%, with a BVR equal to 80.5%. In contrast, Motter (2013) required a CAP content of 6% to reach the limits established by the aforementioned standard, while Lourenço and Cavalcante (2015) only achieved a BVR of 75.2% and 77.2% using CAP contents of 8.5% and 9.0%, respectively.

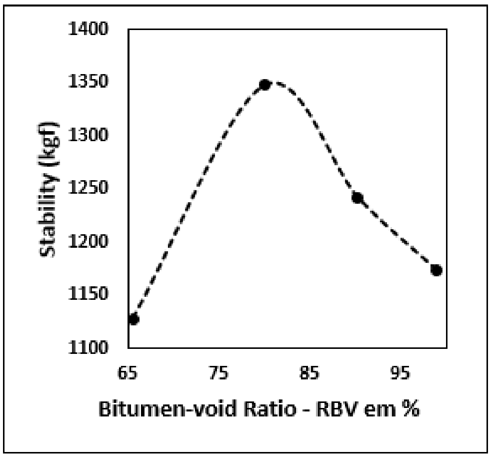
In regard to apparent specific mass, this parameter is initially directly associated to void volume, since both variables are inversely proportional. Figure 4 (d) illustrates the bituminous mixture at different levels, where a 4.5% CAP content resulted in the highest Vv (%) and the lowest Gmb, while a 6.0% CAP content resulted in lower Vv (%) and higher Gmb. Similar results have been reported by Costa Filho (2017) and Motter (2013). In fact, it was expected that increasing CAP contents would result in increased apparent specific mass, since the bituminous binder fills the voids between the aggregates, increasing its specific mass. In view of the graphs obtained herein, it was possible to calculate the optimum binder content by performing an arithmetic average between the levels corresponding to maximum stability, maximum apparent density, and an average of the limits of void volume and bitumen/void ratio specifications. These calculations indicate that the optimal CAP content is that of 5.15%.

Still regarding volumetric parameters, the influence of stability versus void volume percentage, the bitumen/void ratio and fluency were also assessed. Figure 5 illustrates the details of these results.

Figure 5 - (a) Stability *versus* %Vv / (b) Stability *versus* %BVR



(a)



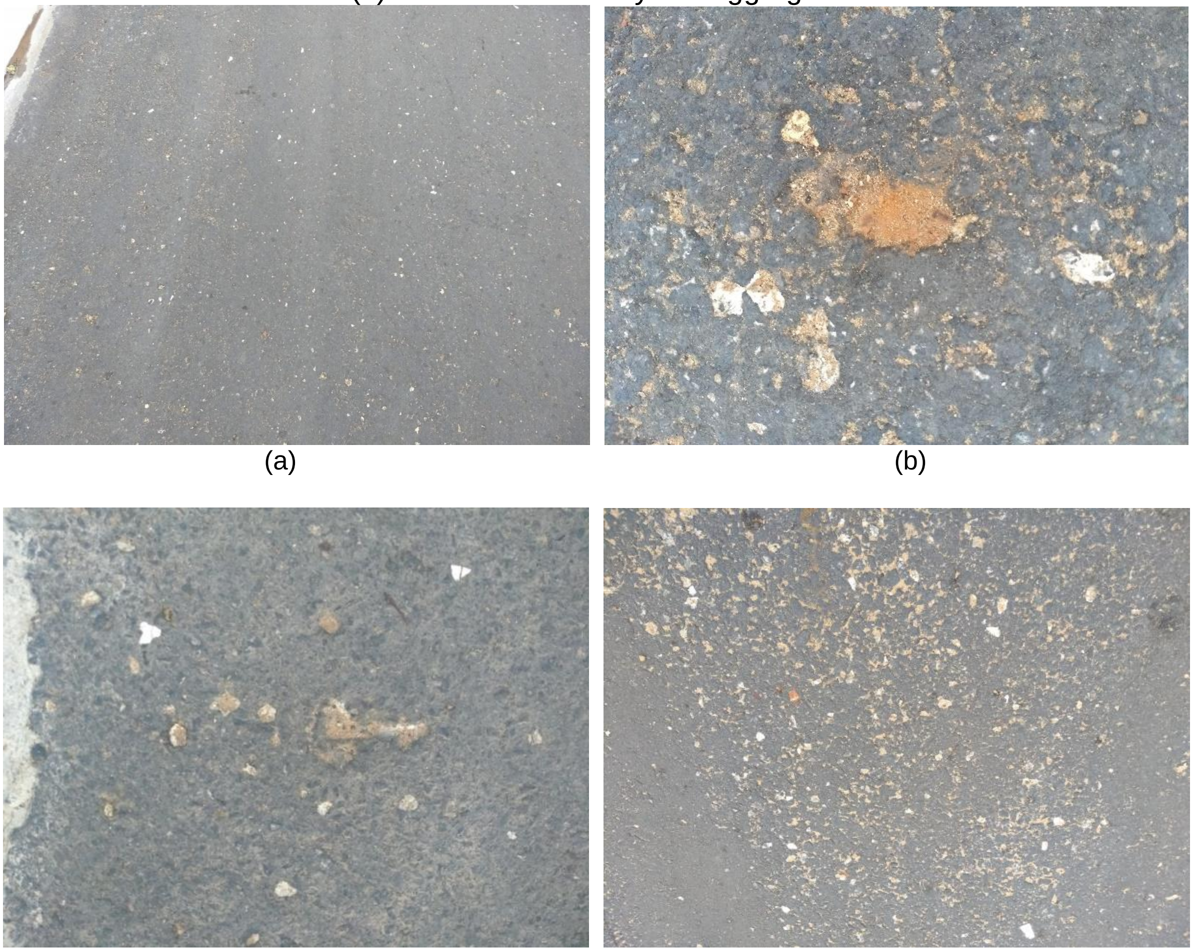
(b)

Source: Own elaboration.

Figure 5 (a) describes the behavior of the asphalt mixture associating void volume to stability. Increased stability occurs with increased Vv (%) up to approximately 2.6% Vv. Soon after, the opposite is noted. An analogous result was reported by Costa Filho (2017). From another perspective, it is important to note that part of the material composition of the asphalt originates from CDW, which is characterized as a heterogeneous material composed of several phases which can lead to unpredictable results. The curve indicates that stability is above 500 kgf as recommended by the aforementioned standard. Observing the relationship between BRV and stability, Figure 5 (b) indicates an increase in stability up to a BRV of approximately 82%. Loss of asphalt mixture stability is noted after this value. This result is in line with that recommended by the DNIT 031/2006 standard, which establishes an upper limit of 82%. Similar results were also reported by Costa Filho (2017).

In order to perform a practical assessment, two experimental stretches were implemented, one with a dosage similar to that of the laboratory material and another containing natural aggregates. Figure 6 presents a summary of these stretches. The photographic records first took place shortly after the asphalt concreting and were then obtained on a monthly basis in order to observe the functional structure of the asphalt layers. Following its implementation, the asphalt coating presented several white spots, characterizing RA that did adequately adhere to the binder, such as ceramic floor residues. Visually, it was possible to highlight the difference between coatings containing recycled materials (Figure 6 (b)) and those containing only natural aggregates (Figure 6 (a)). The CDW-free coating was darker and exhibited a uniform color surface. On the other hand, the coating containing RA exhibited a dark color interspersed by light spots.

Figure 6 - (a) Detachment of recycled aggregate in the 1st month / (b) Detachment of recycled aggregate in the 2nd month / (c) Detachment of recycled aggregate in the 3rd month / (d) Detachment of recycled aggregate in the 4th month



(a) (b)

(c) (d)

Source: Own elaboration.

One month after the concreting took place, few changes were witnessed regarding the functional and visual behavior of the entire coating. No cracks or RA detachment were observed. In the second month, detachment of surface RA was observed, mainly in the area with a slight turn of the road, caused by car wheels turning on the pavement curve. The surface aggregates originated from ceramic materials and a small amount of plaster, as displayed in Figure 6 (b). However, it is noteworthy that this detachment occurred in a timely manner, without compromising coating functionality, and may not be specifically associated to the use of RA. In the third month after asphalt concreting, the detachment of superficial RA gained a slight volume, and the surface ceramic aggregates began exhibiting breaks, indicating future detachments (Figure 6 (c)). Although this increase continued, the coating continued to operate satisfactorily concerning functional performance. Similar to the third month, increasing aggregate detachment was noted in the fourth month, mainly due to ceramic content (Figure 6 (d)).

Conclusions

Physical characterizations indicate that the gravel 1 recycled aggregate exhibited a lower apparent specific mass, as expected, when compared to the natural gravel 0 aggregate, at 2.56 g/cm³ and 2.19 g/cm³, respectively. The specific masses of recycled sand, rock powder and cement were of 2.54 g/cm³, 2.63 g/cm³ and 2.86 g/cm³, close to the values reported by Sinisterra (2014).

RA Los Angeles abrasion wear was of 35%, similar to the order of magnitude mentioned by Souza et al. (2012) and Motter (2013) and within the wear limits of the applied standard. This indicates that, at the observed levels for this parameter, which is linked to durability, the RA is proven effective.

The shape index, another evaluated RA gravel 1 parameter, was of 0.87, in accordance to the established standard, allowing for asphalt coating applications. With regard to particle shape, it is thought that the RA assessed herein approaches a more cubic shape, since none of the dimensions prevailed over another. Thus, the aggregate tends to support higher loads, leading to greater resistance. If this were not the case, the aggregate would exhibit a shape tending towards lamellar, which could contribute to grain fracture when subjected to loads and, consequently, decreased asphalt pavement useful life.

The chemical and mineralogical RA characterizations (FRX and DRX) were similar, with the main components identified as calcium oxide (CaO), silicon dioxide (SiO_2), iron oxide (Fe_2O_3) and oxide of aluminum (Al_2O_3). CaO and SiO_2 originate, in general, from mortar and concrete. $Fe_2O_3$and Al_2O_3 probably originate from the ceramic material present in the assessed composition (Martínez et al, 2016).

The asphalt dosage indicated an optimum binder percentage of 5.15%. This study also indicates that the higher the CAP percentage, the lower the void volume, due to void filling by the asphalt binder. As expected, higher CAP percentages result in greater mixture density.

The experimental stretch using RA was assessed for real scale results. Existing traffic, at an average of 25 vehicles per hour, was observed for 5 months, and functionality aspects were also evaluated. Although the analysis period was short, visual differences between the pavement containing natural aggregates and the one containing RA were noticeable, with the latter presenting superficial spots not totally involved by the binder. During the first two months of traffic, ceramic aggregate and surface plaster detachments were noted. That did not, however, damage the layering. Thus, in spite of these detachments, the asphalt pavement continues to perform very satisfactorily concerning vehicle traffic.

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