Influence of asphalt rubber on the crushing of recycled aggregates used in dense HMA

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ABSTRACT. *This paper presents preliminary results of a research that investigates the feasibility of using aggregates recycled from civil construction and demolition wastes for manufacturing dense graded hot mixed asphalts (HMA) to be used in highways with low or medium traffic volume. Previous results showed that the tested material meets all Brazilian standard requirements for use in base layers, but it was prone to grain crushing, what is a major concern in the case of HMA. It is supposed that modified asphalt rubber binders might help to mitigate this potential problem. In order to check this hypothesis, several samples were prepared using binders with different amount or crumb rubber (0, 10 and 20%). The compaction energy was also investigated by varying the number of blows (35, 50, 75) during the Marshall compaction tests. The results were analyzed in terms of Marshall Degradation Index and show that the particle crushing is reduced with increasing amount of crumb rubber.*

KEYWORDS*: Construction and Demolition Waste (CDW), Recycled Aggregates, Dense Graded Hot Mix Asphalt, Asphalt Rubber, Particle Crushing, Marshall Degradation Index*

1. Introduction

Pavement construction demands large amounts of natural resources, including unbound granular material for sub-base and base layers and asphalt concrete for the surface courses. This has led to an exhaustion of materials within an economically acceptable distance in many regions of the world. This is especially the case in the region of the Federal District (DF), which hosts Brasilia, the capital of Brazil.

The Federal District region continues expanding at a very fast rate since its inauguration in the 1960s and now faces serious shortage of good aggregates for road construction. The only type of rock available in the area is calcareous and it is mainly exploited for the production of Portland cement. The portion which is not consumed for the production of cement is sold as aggregate chips for the ever expanding building industry. The road construction sector is left with the residues.

The shortage of natural aggregates for the construction of unbound and cohesive pavement layers in the many regions of Brazil has led to an increasing interest for the use of recyclable materials, such as construction and demolition waste – CDW (Motta, 2005; Oliveira, 2007; Gómez, 2011, Delongui, 2012). However, all these researches concentrated on the use of CDW for sub-base or base layers. Very little has been done about the potential use of CDW in HMA (e.g., Silva & Padula, 2011).

Previous researches by Gómez (2011) showed that a CDW from the demolition of the old National Soccer Stadium in Brasilia met all the requirements to be used as base layer, even in the case of heavy traffic, although the material showed clear tendency of changing grain size distribution depending on several factors, such as compaction energy and water content. These results encouraged the investigation about the feasibility of using the recycled aggregate from this CDW to produce dense graded hot mix asphalt (HMA) concrete for the surface course of medium and low traffic pavements in the region. However, particle breakage and high water absorption of the recycled aggregate remained a major cause of concern.

On the other hand the advantages of asphalt rubber for the reduction of permanent deformation and increase in fatigue life of flexible pavements has been widely reported in many paper journals and the proceedings of five editions of this Asphalt Rubber conference (for instance, Visser & Verhaeghe, 2000; Way, 2003; Souza *et al.*, 2006; Zareh & Way, 2009).

The main assumption in this paper is that asphalt rubber may also help to mitigate crushing of the recycled CDW aggregates due to the elastic behavior of the remaining particles of crumb rubber. In order to check this hypothesis the authors prepared several samples of dense graded asphalt concrete using recycled aggregates and asphalt rubber with different rubber contents. Different energies were applied during the sample compaction and the samples were later destroyed to recover the aggregates and the final grain size distribution curves were analyzed. The degradation was measured by the index described in the next section.

2. Particle Crushing

All relevant mechanical and hydraulic properties of granular and cohesive layers dependent directly on the grain size distribution curve. That is why the highway authorities prescribe gradation envelopes for the granular materials depending on their purpose or location in the pavement structure and on the level of traffic during the design life.

Unfortunately many materials undergo changes of grain size distribution during the compaction process, either due to changes in structure or due to particle crushing. Therefore it is important to investigate the effects of particle breakage on the behavior of granular materials (e.g., Lade *et al.*, 1996).

The phenomenon of particle crushing is of particular relevance for brittle materials such as the wastes of construction and demolition due to the significant amount of bricks and ceramic debris. Besides composition, the particle breakage in the case of aggregates recycled from CDW is highly dependent on the initial gradation curve, on the compaction energy and on the water content. For a particular CDW, analyzed by Gómez (2011) for application as granular base material, it was shown that most of the particle crushing occurs during the compaction process and that the particle crushing increases with increasing compaction energy and decreases with increasing water content.

It is very hard to analyze particle crushing just by comparing the gradation curves before and after compaction, since there is redistribution between the percentages of coarse and fine particles. This is better captured by means of single numerical measures, generically called degradation indices.

The Brazilian Department of Transport Infrastructure (DNIT, former DNER) prescribes the so-called Marshall Degradation Index, denoted by ID_M, when the aggregate is unbound (without asphalt binder), or ID_{ML}, when the aggregate is coated with asphalt binder. The test is described in the Brazilian norm DNIT ME-401/99. It uses a standard gradation curve and determines the differences (D_i) between the percentages before and after compaction passing through six sieves with pre-determined openings. In the case of ID_{ML} the asphalt binder should first be extracted using an appropriate procedure. The degradation index ID is computed as follows:

$$ID_M \text{ or } ID_{ML} = \frac{1}{6}\left(\sum_{i=1}^{6} D_i\right) \qquad (1)$$

where D_i is the % passing before compaction - % passing after compaction. The following sieve openings are prescribed: 25.4 mm (1”), 12.5 mm (1/2”), 9.5 mm (3/8”), 4.75 mm (#4), 2.0 mm (#10), 0.425 mm (#40) and 0.075 mm (#200).

3. Materials and methods

The materials used in this research comprise recycled aggregates from construction and demolition waste, straight asphalt binder with penetration grade 50/70 dmm (CAP 50/70 in Brazilian Terminology) and crumb rubber recycled from scrap tires. The crumb rubber and the asphalt binder were mixed using the wet process under controlled laboratory conditions. A dense graded hot mix asphalt with asphalt rubber (AR-HMA) was designed using standard Marshall procedure. Several samples of AR-HMA were prepared with variable number of hammer blows and then subjected to asphalt binder extraction. The grain sized distribution curves of the recovered aggregates were analyzed and compared to the original curve to check the variation of grain degradation with the compaction energy. The detailed procedures and material characterization are described as follows.

3.1. Recycled aggregates from construction and demolition waste

The aggregates used in this researched were obtained from the demolition of Mane Garrincha Soccer Stadium. The old stadium was imploded for the construction of the new National Soccer Stadium at Brasilia, Brazil, one of the main venues of the next World Cup. The waste material was acquired by a private recycling company, where the unwanted materials such as plastic, wood and metals were first removed.

The recycling company generally uses the CDW for the production of sand, which is sold for building companies, but a portion of waste (around 8 tons) was especially crushed for this research to maximum nominal size around 7 cm in order to produce aggregate chips and sand at a secondary stage. The material was subjected to a secondary crushing process using a smaller equipment at the University of Brasilia, in order to conform the resulting aggregate mix to the prescribed limits of aggregates for dense asphalt concrete required by the Brazilian Specification DNIT ES-031/2006. The smaller jaw crusher and the resulting recycled aggregates are shown in Figure 1.

Figure 1 - a) Secondary crusher. b) Fractions of recycled aggregates.

Gómez (2011) analyzed the composition of the recycled aggregates and determined that it contained only 0.56% in weight of residual contaminants (wood, plastic and metals). The Sao Paulo city standard PMSP/SP ETS-001/2003 for recycled aggregates to be used in base course accepts a maximum of 3% of residual contaminants. As to the grain size distribution, course aggregates (greater than 4.8 mm) comprised 42% in weight. With respect to the composition, the resulting material in the coarse fraction comprised basically chips of Portland cement concrete and mortar (71%), natural gravel (25%) and pieces of bricks and ceramics (<5%). This composition qualifies the material as recycled aggregate according to Brazilian standard ABNT NBR 15116.

3.2. Asphalt binder

The straight asphalt binder used in this project is classified as CAP 50-70, according to the penetration grade used in Brazilian standards. This was chosen because it is the main binder used in the region of the Federal District in Brasilia as well as in Brazil as whole. The binder is produced at a refinery of Petrobras (Brazilian Petroleum Company), located at Betim, Minas Gerais State. The original binder was tested at the Highway Engineering Laboratory (LER) at the University of Brasilia for quality control and to verify if it satisfied the Brazilian Standard requirements.

The binder was subjected to conventional tests such as penetration grade, softening point, ductility, flame and fire temperature, etc. Non-conventional tests prescribed by the Superpave Standards were also carried out, including Dynamic Shear Rheometer (DSR) for the determination of complex shear modulus (G*) and phase angle (δ), Rotational Viscosity and aging tests in a Rolling Thin Film Oven (RTFO). The results are shown in Table 1 and satisfied all reference intervals required by the Brazilian Petroleum Agency ANP N^{o}19/2005.

Test	**Unit**	**Reference limits for CAP 50-70 (ANP 19/2005)**	**Results for tested CAP 50-70**
Penetration (100g,5s,25°C)	0,1mm	50-70	53
Softening Point	°C	>46	47
Rotational Brookfield Viscosity			
@ 135 °C, sp21 (20rpm)	cP	>274	385
@ 150 °C, sp21 (20rpm)	cP	>112	165
@ 177 °C, sp21 (20rpm)	cP	57-285	60
G*/senδ (46°C)	kPa	>1	22
Fire point	°C	NA	385
Flash point	°C	>235	325
Density	-	NA	1,07
Ductility @ 15 °C	cm	>60	100

(RTFOT) @ 163°C, 85 min			
Loss of mass	%	≤ 0.5	0.16%
Softening point increase	°C	≤ 8	1.5
Retained penetration	%	≥ 55	73%
G*/senδ (46°C)	kPa	>2	33

Table 1. *Results of the asphalt binder characterization tests.*

3.3. Asphalt Rubber

The crumb rubber used in this research was recycled from scrap tires in a commercial recycling plant in Sao Paulo, Brazil. It was tested at the University of Brasilia according to the recommendations of the American Standard ASTM D 6114/97. The rubber grains were loose, dry and did not foam in contact with the asphalt binder. The results of these control tests are summarized in Table 2 and met all requirements for asphalt rubber.

The water content of rubber grains was determined by drying the sample to constant weight during 24 hours in an oven at a temperature of 57°C. The contents of textile and metallic fibers were determined by sieving and removing these contaminants manually and with the use of a magnet. The gradation of the crumb rubber grains was controlled in order to meet the standards prescribed by the Arizona Department of Transportation (ADOT) for asphalt rubber as described in Table 3. The used gradation fitted exactly the middle of the prescribed ADOT envelope. Figure 2 illustrates the rubber used in this research and Figure 3 shows the ADOT limits and adopted grain size distribution curves.

Properties	**Reference Values**	**Obtained values**
Water content (%)	< 0.5	0.46
Unit weight of rubber grains (KN/m^3)	11.5 ± 0,5	-
Fraction of textile fibers (%)	< 0.4	0.31
Fraction of metallic fibers (%)	< 0.01	0.00

Table 2. *Results of control tests of the crumb rubber.*

Sieve		Percentage passing (%) ADOT grading		Percentage passing (%) Used
ASTM	mm			
N° 10	2	100	100	100.0
N° 16	1.18	65	100	82.5
N° 30	0.6	20	100	60.0
N° 50	0.3	0	45	22.5
N° 200	0.075	0	5	2.5

Table 3. *Gradation of crumb rubber grains prescribed by ADOT.*

Figure 2. *Photos of the crumb rubber used in this research.*

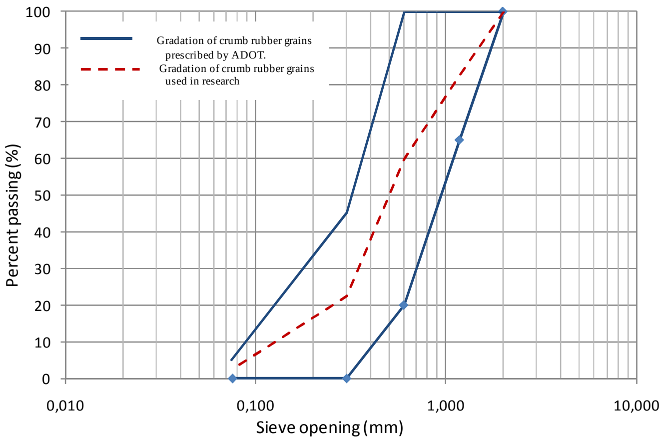

Figure 3. *Crumb rubber grain size distribution curve and ADOT limits.*

Figure 4 shows the equipment used to manufacture the modified asphalt rubber binder in laboratory. It consists of a mechanical agitator coupled with a rotational bar with a helicoidal blade at its ending, a metallic recipient to heat the binder and rubber mixture and a thermometer to control the mixing temperature. The mixing speed varied in the range of 250 to 300 rpm in order to assure a homogenous mixture. The digestion process was carried out at a temperature of 170^{o}C during a period of one hour following suggestions from Dantas Neto (2004). Modified binders were prepared mixing CAP 50-70 (penetration grade) with 10% and 20% in weight of crumb rubber (AR-10 and AR-20).

Figure 4. *Mixer used to prepared the wet process asphalt rubber in laboratory*

3.4. Hot Mix Asphalts (HMA)

Different types of hot mix asphalts were prepared in order to check the influence of the amount of crumb rubber and the compaction energy on the crushing of the recycled aggregates from civil construction and demolition wastes (CDW-RA). The aggregates grading fitted a dense gradation envelope (C) prescribed by the Brazilian authorities. The binders include the straight CAP 50-70, the modified CAP 50-70 with 10% of crumb rubber (AR-10) and with 20 % of crumb rubber (AR-20). The following cases were tested:

a) Case 0-0: Unbound CDW-RA (only the recycled aggregates)

b) Case 6-0: HMA 6% of straight binder (recycled aggregates + CAP 50-70)

c) Case 6-10: HMA 6% of asphalt rubber AR-10 (recycled aggregates + CAP 50-70 +10% of crumb rubber)

d) Case 6-20: HMA 6 % of asphalt rubber AR-20 (recycled aggregates + CAP 50-70 +20% of crumb rubber)

The case nomenclature uses two numbers B-R, in which B is the percentage of binder (0 or 6%) and R is the percentage of rubber in the binder (0, 10 or 20%). The idea was to test initially the crushing potential of the unbound recycled aggregate, then to verify the mitigating effect of the binder with different amounts of crumb rubber (0%, 10% and 20%) on the particle breakage process. Hence the binder content was kept constant at 6% in the HMA.

The amount of binder in the dense graded hot mix asphalt concrete was determined using the conventional Marshall Design procedure with an automatic compactor: 50 blows in each face of the sample using a 4.54 kg hammer falling from a height of 457 mm. The ideal amount of 6% was obtained using straight binder CAP 50-70 and it was kept constant for the asphalt-rubber mixes for the sake of comparison. The initial number of 50 blows was chosen because this HMA was intended to be applied in medium traffic highways.

This binder content of 6% is slightly higher than the usual amount (around 5%) obtained for hot mix asphalt concrete manufactured with calcareous aggregate chips, commonly used in the Federal District region of Brazil. This higher asphalt consumption is believed to be related to the porous nature of the recycled aggregate chips used in this research, which had water absorption of about 7%.

Besides the rubber content, the authors also investigated the influence of the compaction energy on the crushing of the recycled aggregate particles, by varying the number of hammer blows in each face of the sample (35, 50 and 75). According to the Brazilian standards, the number of hammer blows in each face of the Marshall samples varies with the forecasted traffic during the project life: 35 blows for low volume traffic, 50 blows for medium volume traffic and 75 blows for high volume traffic. Therefore the number of hammer blows varied accordingly for all combinations proposed. In the compaction of the unbound aggregates, it was necessary to use filter paper in both faces of the samples in order to avoid the loss of fine crushed particles.

The mixing temperatures for the binders and aggregates, besides the compaction temperature are summarized in Table 4. In order to assure statistical significance, each test was repeated two times, thus resulting in a total of 24 samples (4 cases, 3 energies, 2 repetitions). The samples are illustrated in Figure 5. The reader may see the recycled aggregates chips, including pieces of bricks and ceramics in the cut and polished samples on the right.

Temperatures (°C)	CAP 50-70	Asphalt Rubber
Binder temperature at mixing	153	170
Aggregates temperature at mixing	166	190
Compaction temperature	138	164

Table 4. *Mixing and compaction temperatures*

Figure 5. *(a) Photos of Marshall samples; (b) Cut and polished samples.*

3.5. Binder extraction and final grain size evaluation

After compaction, the samples were extracted from the metal cylinders and immediately taken to a centrifuge (Rotarex) with organic solvent. This facilitated the separation process. The binder extraction process continued with several solvent soaking and centrifuging stages until the aggregates were completely clear. Figure 6 illustrates the aggregate recovery process. The clean aggregates were then subjected to a new sieving process in order to determine any changes in the grading curves due to recycled aggregate particle crushing.

Figure 6. *Extraction of asphalt binder and aggregate recovery*

4. Results

Figure 7 shows the effect of the compaction energy on the degradation of the unbound recycled aggregates. The initial gradation fitted the coarser limit of the gradation envelope known as "gradation C", prescribed by the Brazilian Department of Transportation Infrastructure (DNIT). In normal cases, the ideal is to aim the center of the envelope when using conventional rock chipped aggregates, but the authors purposely choose to upper limit (lower curve in the figure) in order to account for possible particle crushing of the recycled aggregate. This was based on previous experience using this recycled material for granular pavement base layer (Gomez, 2011).

The reader can clearly see the shift of the gradation curve towards the center of the envelope in Figure 7. This shift increases with the increase in compaction energy, though this is not easy to see clearly in Figure 7 due to the log scale. However, the influence of compaction energy on the unbound particle breakage is evident when this is quantified by means of the unbound Marshall Degradation index (ID_M). The authors obtained: ID_M=6.98% for 35 blows; ID_M=7.81% for 50 blows and ID_M=8.59% for 75 blows.

The Brazilian standard for dense graded asphalt concrete (ES-031/2006) suggests "tentative" limiting values of $ID_M \leq 8$ % and $ID_{ML} \leq$ 5% (supposedly for 75 blows) for rock aggregate chips. However this condition should be verified only in cases when the rock aggregate fails the limit value of 50% for the Los Angeles abrasion loss. There is no standard for recycled aggregates for HMA yet in Brazil, but the aggregates used in this research presented maximum abrasion loss of 38% (Gómez, 2011) and therefore satisfies the requirements of ES-031/2006.

The introduction of asphalt binder leads to a significant reduction of aggregate crushing, irrespective of the compaction energy. This is illustrated in the grain size distribution curve shown in Figure 8 for the cases with 75 blows of compaction energy. Observe that the gradation curves of the HMA are below that of the crushed unbound aggregate (0% asphalt). Again the effect of the binder type on aggregate crushing is better captured by means a single numerical measure such as the ID_{ML}. The absolute reduction in crushing index varied between a minimum of 1.0% and a maximum of 3.5%, depending on the type of binder and compaction energy. The relative differences with respect to the original degradation indices vary between 14% and 41%.

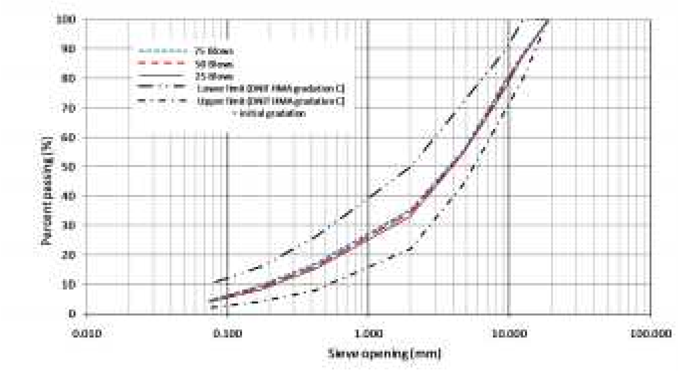

Figure 7. *Unbound recycled aggregate. Effect of compaction energy*

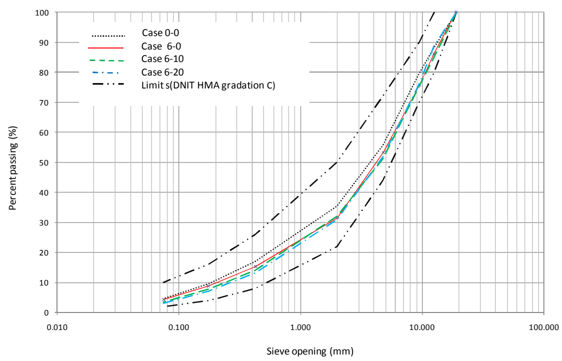

Figure 8. *Effect of binder on the crushing index of the recycled aggregate. 75 blows.*

Table 6 summarizes the results for all cases investigated. The overall picture is illustrated in Figure 9. Here the effect of compaction energy and type of binder can be clearly appreciated. It is interesting to observe the effect of the crumb rubber on the degradation index of the recycled aggregate. For 75 blows, for instance, the ID_{ML} was 6.47% in the case with straight binder (case 6-0), 6.15% in the case with 10% of rubber (case 6-10) and 5.05% in the case with 20% of crumb rubber (case 6-20). The differences are statistically significant using ANOVA. Hence it may be concluded the rubber grains act as elastic springs, absorbing the shock impact from the compacting hammer and therefore reducing the crushing of the recycled aggregates.

Case B-R	Binder Content, B(%)	Rubber Content in the Binder, R(%)	Degration ID_{ML} or ID_M (%) Number of blows		
			35	50	75
0-0	0%	0%	6.98	7.81	8.59
6-0	6%	0%	5.69	6.39	6.47
6-10	6%	10%	5.94	6.07	6.15
6-10	6%	20%	5.63	5.69	5.05

Table 6. *Marshall degradation index for all cases investigated.*

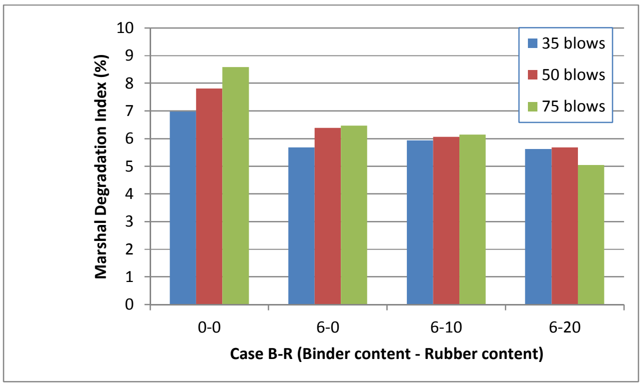

Figure 9. *Marshall degradation indices for all cases.*

5. Conclusions

Particle breakage is a major concern when using recycled aggregates from construction and demolition wastes (CDW) in hot mix asphalts (HMA). In this paper this subject was investigated taking into account the compaction energy given the by the number of hammer blows in a Marshall compacter and the type of binder by including different amounts of crumb rubber. The hot mix asphalt was dense graded, fitting the coarser limit of grading envelope or band C of Brazilian standards.

The results of Marshall Compaction in the unbound recycled aggregate effectively showed a high level of particle crushing reflected in a Marshall Degradation Index (ID_M) increasing from around 7.0% for 35 blows to 8.5% for the 75 blows. The grain size distribution curve shifted towards the center of the desired gradation envelope, thus showing the correct strategy of starting at its upper (coarser) limit.

The bound aggregate in the HMA shows a decrease of particle crushing due to the viscous damping effect of the asphalt binder. The ID_{ML} (with binder) of all HMA varied between 5% and 6.5%. These degradation indices were little or not dependent on the energy employed, but dependent on the amount of crumb rubber in the modified asphalt binder.

The results prove the basic assumption of this paper that asphalt rubber helps to mitigate the problem of particle crushing when using aggregates recycled from construction and demolition waste. The rubber grains act as elastic springs, absorbing part of the impact, thus sparing the particles from a higher crushing.

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