

# Evaluation of permanent deformation of asphalt rubber using multiple stress creep recovery tests and flow number tests

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**ABSTRACT**

This study used the Multiple Stress Creep Recovery Test (MSCR) and the Flow number test to analyze the characteristics of asphalt rubber and its use in hot mix asphalt (HMA) regarding to their ability to withstand permanent deformation. MSCR tests were done in three commercial asphalt rubber and in the traditional asphalt binder 50/70. Flow number tests were performed in twenty four specimens of asphalt rubber mixtures and eight specimens of conventional asphalt mixtures. The results of these tests showed that all the asphalt rubber samples had lower compliance values (Jnr) in the MSCR test, which denotes that these modified binders improved the rutting resistance of HMA. This behavior was confirmed with flow number results, since the HMA produced with asphalt rubber had always higher flow number values, when compared to the conventional asphalt mixtures. The analysis of the data showed excellent correlation between Jnr values and FN values.

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## 1. INTRODUCTION

The use of rubberized asphalts has been doing for the past 50 years in the United States and for past 15 years in Brazil. Since then, the methodologies have been enhanced to increase the use of waste rubber in asphalt pavements. The experience around the world shows that the rubberized hot mix asphalt (RHMA) has higher durability, since it has better resistance to fatigue cracking, to reflective cracking and lower temperature susceptibility, withstanding better to permanent deformation.

Regarding the contribution of the asphalt binder to the rutting resistance, the investigation of the rheological parameters can help to estimate this behaviour. For example, the original USA Superpave system selected the correlation between complex modulus and phase angle ( $G^*/\sin\delta$ ) as the parameter to estimate rutting resistance. However, this parameter measured at low strain during oscillatory loading in the Dynamic Shear Rheometer (DSR) and could not accurately represent the ability of a modified binder to resist rutting (FHWA, 2011).

The Multiple Stress Creep Recovery (MSCR) test is the latest improvement to the Superpave Performance Graded (PG) Asphalt Binder specification. In this test, higher levels of stress and strain are applied to the binder, better representing what occurs in an actual pavement, mainly at the stress of 3.2 kPa, (D'Angelo et al., 2007). A major benefit of the MSCR test is that can be applied to any type of modified asphalt, independently of the level and type of modification (D'Angelo et al, 2007). The test specification parameter "J<sub>nr</sub>" has an improved correlation with rutting resistance in hot mix asphalt (FHWA, 2011). Asphalt binders modified with ground tire rubber have lower compliance values (J<sub>nr</sub>) in this test, (Tabatabaee and Tabatabaee, 2010; Ji et al 2012), which denotes good resistance to permanent deformation.

Table 1 show the J<sub>nr</sub> requirements for different Equivalent Single Axle Load (ESAL) and traffic speed whereas Table 2 shows the limits values of recovery for ranges of J<sub>nr</sub> values to evaluate delayed elastic response in the MSCR test.

**Table 1** – J<sub>nr</sub> requirements for different ESAL and traffic speed (AASHTO M332-14)

Traffic Level	Description	Maximum J <sub>nr3.2</sub>
Standard (S)	Less than 10 million ESAL and greater than 70 km/h traffic speed	4.5
Heavy (H)	10-30 million ESAL and between 20-70 km/h traffic speed	2.0
Very Heavy (V)	Greater than 30 million ESAL and less than 20 km/h traffic speed	1.0
Extreme (E)	As for very heavy but around toll plazas and port facilities	0.5

**Table 2** – Minimum recovery values from the MSCR test for ranges of J<sub>nr</sub> values

J <sub>nr</sub> @ 3.2 kPa	Minimum % Recovery
2.0 – 1.01	30%
1.0 – 0.51	35%
0.50 – 0.251	45%
0.25 – 0.125	50%

Rutting or permanent deformation of hot mix asphalt (HMA) is not only related to the asphalt binder and is also associated to poor selection of aggregates gradation, poor mix design, inappropriate quality control, high temperatures of pavement and heavy traffic loads (KANDHAL AND MALLIK, 2001; ASPHALT INSTITUTE, 1996; BROSSEAUD, DELORME, AND HIERNAUX, 1993; NETEMEYER, 1998). Laboratory tests can be performed to estimate the HMA permanent deformation potential. The most popular tests are wheel simulators, such as LCPC (*Laboratoire Central des Ponts et Chaussées*) and Hamburg, and creep tests, applying static or cyclic loads, such as the flow number test.

The flow number (FN) test uses HMA specimens that are compressed axially applying a haversine waveform with a wavelength of 0.1 seconds followed by a rest or period of 0.9 seconds, performed at temperatures usually ranging from 50°C to 60°C (Bonaquist, 2012). The number of cycles and the accumulated strain is recorded during the test until 10.000 cycles, or until the specimen reach 5% of axial strain, or until tertiary flow occurs, whichever comes first.

The accumulated permanent deformation or plastic strain can be defined by a primary, secondary and tertiary region. In the primary region the permanent deformation increases rapidly, but at a decreasing rate. At the secondary region, the permanent deformation rate is constant until it starts to increase, which indicates that the tertiary region or tertiary stage was reached.

The cycles number of the beginning of the tertiary stage is the Flow Number (FN). Table 3 shows minimum flow number cycles recommended for different traffic level.

**Table 3** – Recommended minimum flow number requirements (NCHRP 673)

Traffic Level <i>Million ESALs</i>	Minimum Flow Number <i>Cycles</i>
< 3	-
3 to < 10	53
10 to < 30	190
≥ 30	740

In Brazil, some field studies were developed to analyse the rutting resistance of RHMA (Balgauer, 2012; Camargo, 2016; Nascimento, 2008). The conclusions always indicate that the use of rubberized asphalt enhance the resistance to permanent deformation. Laboratory research also has been performed to predict the ability of RHMA to withstand rutting (Specht, 2004). However, there are few records about the use of the configuration of Flow Number Test to assess these types of mixtures.

In this study, the multiples stress creep recovery test and the flow number test were used to analyse the rutting properties of three commercial asphalt rubber available in Brazil. So that the main objective was achieved: (1) the asphalt binder was tested before and after the aging; and (2) a wide range of hot mix asphalt with different gradation, different aggregates, containing the asphaltic binders characterized.

## 2. TESTS AND MATERIALS

Since the 1960s, asphalt rubber has been used to improve the global performance of asphalt pavements. It has been added directly to de asphalt mixture as a fine aggregate or to the asphalt binder as a modifier, (Lo Presti, 2013).

In Brazil, terminal blending is the most used methodology to produce asphalt rubber (AR) industrially. Three samples were obtained from commercial suppliers (AR1, AR2, AR3) and their characteristics are shown in Table 4. Also, a conventional asphalt cement was used to produce control asphalt mixes, specified as 50/70 (PG 64-10) as shown in Table 4.

**Table 4** – Asphalt binder characteristics

Characteristic	Standard	Asphalt Binder			
		AR1	AR2	AR3	50/70
Rotational Viscosity at 160°C, 20 rpm, spindle 3 (cP)	ASTM D 6114	2140	2290	2250	N/A
Rotational Viscosity at 175°C, 20rpm, spindle 3 (cP)	ASTM D 6114	1360	1510	1470	N/A
Rotational Viscosity at 185°C, 20rpm, spindle 3 (cP)	ASTM D 6114	840	990	950	N/A
Rotational Viscosity at 177°C, 20rpm, spindle 21 (cP)	ASTM D4402	N/A	N/A	N/A	58
Penetration (100g, 5s, 25°C) (dmm)	ASTM D 5	44	43	57	53
Softening Point (°C)	ASTM D 36	57	61	59	49
Storage Stability (°C)	ASTM D 5892	4	4	3	N/A
High Performance Grade (°C)	ASTM D 6373	76	76	76	64
High True Grade (°C)	ASTM D 6373	79.5	79.5	78.3	65.2

The MSCR test was performed following recommendations of ASTM (D7405-15) and AASHTO (T350-14), in samples with diameter of 25mm and 1mm of gap. Twenty cycles of creep and recovery were applied at the stress of 100 Pa followed by ten cycles at the stress of 3,200 Pa. Each cycle consists of one second of creep and nine seconds of recovery. The samples were aged at the rolling thin film oven test (RTFOT) and then tested following the MSCR procedure at four temperatures, 58°C, 64°C, 70°C and 76°C. The parameters determined in the test are the compliance value (J<sub>nr</sub>) and recovery (R), calculated by equations given in the standards (D7405-15; T350-14).

The rubber particles used in this study pass entirely through 600 μm sieve. ASTM D 7175 method describe how to use DSR and its use is limited to asphalt binders that contain particles with largest dimension less than 250μm. Even though, many researchers are using 1mm gap for the measurements of MSCR with asphalt rubber samples, such as Mandal and Bahia (2015) have used the MSCR test with similar size gradation. Goli et al (2016) used the test to assess the addition of crumb rubber passing through 1,41mm.

Three dense gradation, specified as 19mm, 12.5mm and 9.5mm, accordingly to the aggregate Nominal Maximum Size and a 9.5mm gap graded (GG) gradation were used in this study to prepare the mixtures. Different gradations, aggregates sources, granitic and basaltic, and four asphalt binders were employed in this study which resulted in the analysis of 32 asphalt mixtures and Table 5 shows their characteristics.

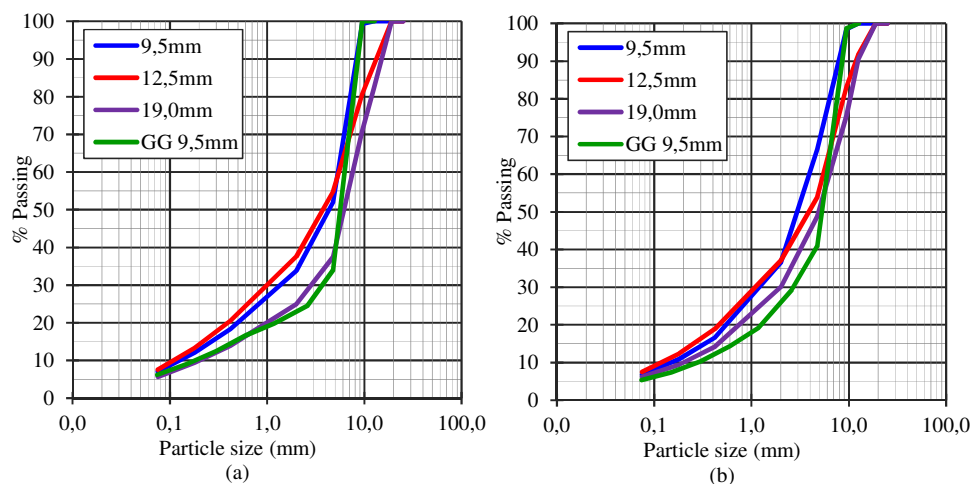


Figure 1. Hot mix asphalt gradation; a) granitic aggregates; b) basaltic aggregates

Table 5 – Characteristics of granitic and basaltic aggregates

Characteristic	Standard	Aggregates	
		Granite	Basalt
"Los Angeles" Abrasion Loss (%)	ASTM C 131	30	17
Flat and Elongated Particles (Ratio 1:5) (%)	ASTM D4791	3	7
Soundness of aggregates (5 cycles) (%)	AASHTO T-104-99	1.5	0.9

The use of four gradations, two aggregates sources and four asphalt binders generated 32 asphalt hot mixes. The Marshall compactor was used for the volumetric mix design of the asphalt mixes, using 75 blows on each side of the specimen. The design binder content was defined to obtain air voids of 4% for dense gradations and 5% for gap graded (GG). The selected binder content for the asphalt mixes is shown in Table 6.

**Table 6** – Selected binder content for the hot mix asphalts

Aggregates	Gradation	Asphalt Binder Content (%)			
		50/70	AR1	AR2	AR3
Granite	12.5mm	4.6	5.5	5.3	5.1
	19.0mm	4.5	5.0	5.4	5.2
	9.5mm	4.6	5.3	5.5	5.6
	GG 9.5mm	5.1	5.9	5.9	5.5
Basalt	12.5mm	5.0	5.6	5.4	5.4
	19.0mm	5.2	6.3	5.6	5.8
	9.5mm	5.2	6.3	6.3	6.2
	GG 9.5mm	5.8	6.5	6.5	6.1

Three specimens were compacted using the Superpave gyratory compactor at 150mm of diameter and 175mm of height and then cored to obtain 100mm of diameter and 150mm of height, for the flow number test, according to AASHTO T 342-11. Originally is recommended to use specimens compacted to 7,0% in the flow number tests, because this is the upper critical value usually permitted to compact dense gradations of asphalt concrete pavement layers. However, in this study the target air voids was 5.5%, since this is the upper limit observed in applications of these mixes in a specific highway in Brazil. The specimens were conditioned at 54°C and then tested applying an unconfined cyclic load of 600kPa. The flow number value obtained in this test corresponds to the number of cycles at which the tertiary flow starts or the number of cycles at which the rate of change of compliance is minimum (NCHRP, 2016).

### 3. RESULTS

Table 7 shows the results of the MSCR test performed at the temperatures of 58°C, 64°C, 70°C and 76°C, using the three asphalt rubber samples and the conventional 50/70 binder. In Figure 2 is noted that the compliance value ( $J_{nr}$ ) is increased in the asphalt rubber samples, as the temperature of the test increases, as expected. The three asphalt rubber samples showed almost the same values at the stress 3,2kPa that were lower than the values obtained at the conventional 50/70. This behaviour denotes the better resistance of asphalt rubber to resist rutting when used in a hot mix asphalt. According to Table 1, for example, all asphalt rubber samples are suitable to be used at highways with PG-70 and Heavy Traffic (H).

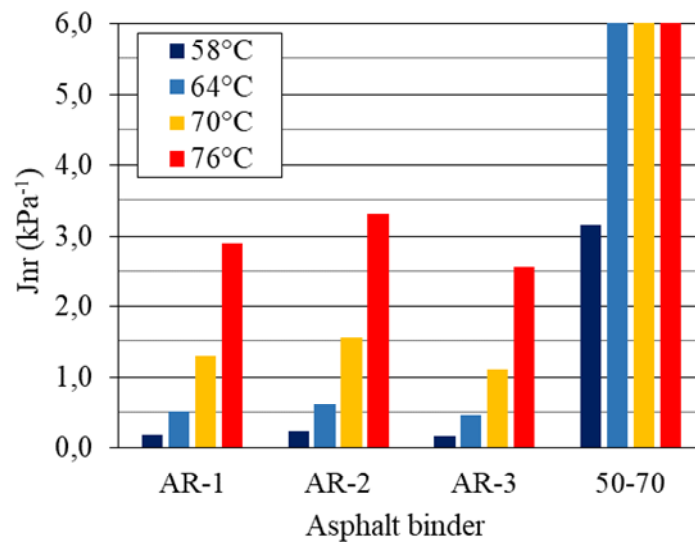
In Figure 3 is noted that the recovery of the asphalt rubber binders is reduced when the temperature is increased, as expected. The  $J_{nr}$  values at 58°C were below  $0.25\text{kPa}^{-1}$ , at the stress of 3.2kPa, and the recovery values were close to 50%, meeting the requirements of Table 3.

However, is observed that when the temperature is increased, the recovery is reduced to values below the criteria in Table 3. This could indicate that the network created between rubber particles and the asphalt is damaged at higher temperatures, reducing the elastic properties of the rubber asphalt. Some studies have studied the interaction between bitumen and rubber materials (Specht, 2004; Faxina, 2006). It is reported that this interaction depends on a number of basic factors, such as temperature, time of mixture, bitumen source, processing methods, particle size and the use of oil extenders. Rubber particles swell when added to the asphalt binder and due to the long exposure to high temperatures and then this swelling can be replaced by depolymerisation and devulcanisation which causes dispersion of the rubber. For example, Abdelrahman and Carpenter (1999) affirm that if temperature is high or time is long enough,

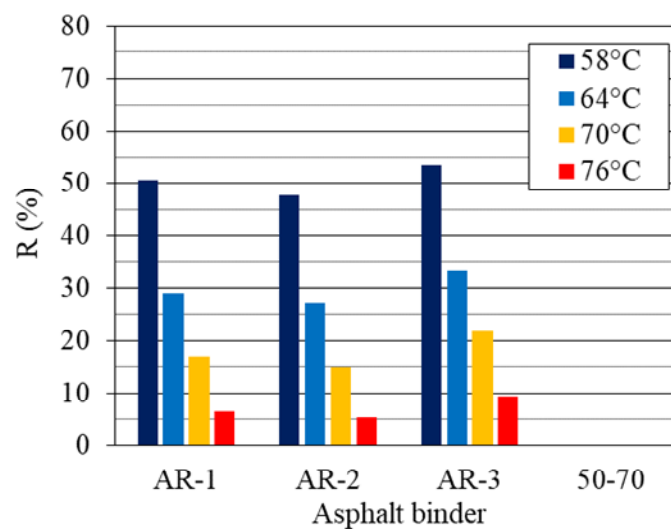
depolymerisation will continue causing more destruction of the binder networking and so the modification is lost.

**Table 7 – MSCR results at different temperatures**

Binder	Stress (Pa)	58°C		64°C		70°C		76°C	
		R (%)	Jnr (kPa <sup>-1</sup> )	R (%)	Jnr (kPa <sup>-1</sup> )	R (%)	Jnr (kPa <sup>-1</sup> )	R (%)	Jnr (kPa <sup>-1</sup> )
AR-1	100	74.1	0.09	67.4	0.22	57.7	0.55	48.7	1.20
	3.200	50.5	0.18	28.9	0.51	17.0	1.29	6.4	2.89
AR-2	100	73.6	0.11	64.8	0.28	55.9	0.66	47.0	1.41
	3.200	47.8	0.24	27.2	0.61	15.0	1.54	5.4	3.32
AR-3	100	67.6	0.11	64.9	0.23	57.7	0.51	49.9	1.11
	3.200	53.5	0.17	33.1	0.45	21.8	1.10	9.3	2.55
50/70	100	0.0	2.97	0.0	7.11	0.0	15.52	0.0	31.82
	3.200	0.0	3.15	0.0	7.52	0.0	16.40	0.0	33.64



**Figure 2.** Results of compliance (Jnr) in the MSCR test at the stress of 3.2kPa



**Figure 3.** Results of recovery (R%) in the MSCR test at the stress of 3.2kPa

Mandal and Bahia (2015) also performed MSCR test at 70°C to assess the behavior of binders modified with coarse crumb rubber particles (100% passing the 0,6mm sieve). They obtained  $J_{nr}$  close to 0.25 kPa<sup>-1</sup> when they added 10% of rubber to the asphalt binder, and when they increased this content to 20% they noted an increase in the compliance value, reaching values of about 1,5 kPa<sup>-1</sup>. The authors also noted that increasing the rubber content decreases the recovery obtained in the MSCR test. The  $J_{nr}$  values obtained in this study are very similar to the  $J_{nr}$  values obtained by Mandal and Bahia (2015) when they added about 20% of crumb rubber to the asphalt binder. Regarding the recovery parameter, the results here are quite similar to those obtained in samples with 15% of crumb rubber.

Goli et al. (2016) also found values of  $J_{nr}$  at 70°C close to 1.0 kPa<sup>-1</sup> when they modified a neat binder by the addition of 15% of crumb rubber, very close to the results obtained in this study in all rubberized asphalts. Willis et al (2014) performed the MSCR at 64°C in a rubber modified asphalt and obtained  $J_{nr}$  of 0.43 kPa<sup>-1</sup>, again, very close to the results shown in this study.

Table 8 shows the average results of the flow number test performed in the 32 HMA and the coefficient of variation, since the tests were performed using three specimens for each hot mix asphalt. These results are also shown in Figure 4 and 5, for asphalt mixes using granitic aggregates and basaltic aggregates, respectively.

Figures 4 and 5 show that hot mix asphalts produced with conventional asphalt binder (50/70), had always the lowest flow number value, independently of the size gradation and aggregate source. On the other hand, the mixes produced with rubberized asphalt had the higher flow number values, ranging from 400 to 3.800. It is well accepted that, the higher the flow number, the higher the rutting resistance of the asphalt mix. Then, the rubberized asphalt mixes have higher resistance to withstand distresses associated to permanent deformation. According to the recommendations of Table 3, for example, all the dense graded mixes with any asphalt rubber of this study could be used in highways with ESALs higher than 30 million.

The asphalt mixes produced with granitic aggregates had higher flow number values than asphalt mixes produced with basaltic aggregates. This behaviour can be associated to the percentage of flat and elongated particles of the basaltic aggregates, which is higher when compared to the granitic aggregates. However, it is also noted that basaltic aggregates have higher asphalt absorption, when compared to granitic aggregates. Additionally, Table 6 showed that hot mix asphalt with basalt had always higher binder content, this could have influenced to obtain a lower flow number value in these mixes.

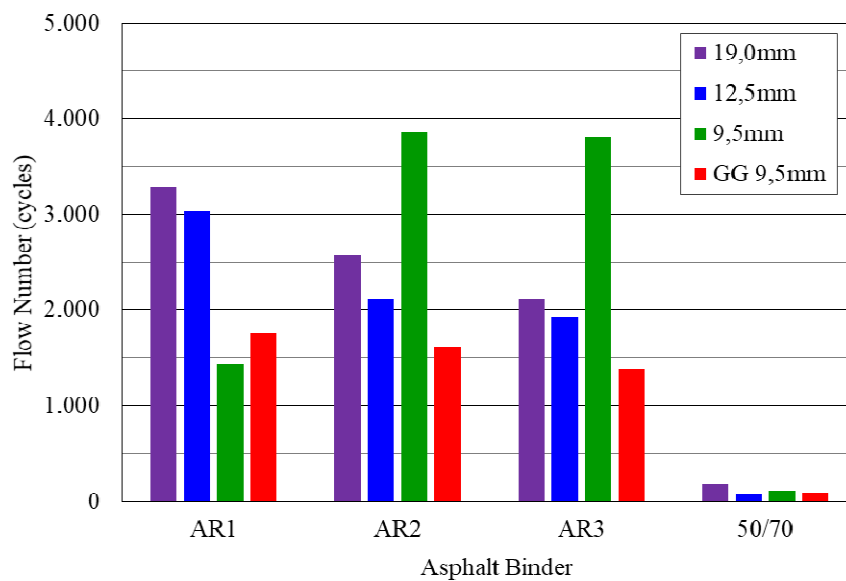
The influence of the size gradation of hot mix asphalt in the flow number values was not very clear. However, the GG 9.5mm had the lowest rutting resistances, except the hot mix asphalt with granitic aggregates and AR1. Regarding the source of the rubberized asphalt binder, there was not a very clear tendency that showed a better behaviour of one of the three samples.

Willis et al obtained flow number values of 600 cycles in asphalt 12.5mm dense asphalt mixes, using a PG 64-22 rubberized asphalt. Values are much lower than the ones obtained here, maybe because that study used 7,0% air voids specimens and the test was performed at 60°C.

Khalili et al (2016) performed an extensive research to evaluate the properties of rubber modified binders used in the State of Nevada (United States of America). The authors collected several samples from different modification processes. They found values of flow number at 59°C varying from 600 to almost 5000 cycles, according to the gradation and the process used to obtain the rubberized asphalt. Similar values and variations were also obtained in this study.

**Table 8** – Flow number test results

Aggregates	Gradation	Asphalt Binder	Asphalt Binder Content (%)	Flow Point (Cycles)	
				Average Value	Coefficient of Variation (%)
Granite	12.5mm	50/70	4.6	81	21
Granite	12.5mm	AR1	5.5	3,034	26
Granite	12.5mm	AR2	5.3	2,125	22
Granite	12.5mm	AR3	5.1	1,931	26
Granite	19.0mm	50/70	4.5	184	12
Granite	19.0mm	AR1	5.0	3,286	14
Granite	19.0mm	AR2	5.4	2,576	29
Granite	19.0mm	AR3	5.2	2,123	30
Granite	9.5mm	50/70	4.6	113	27
Granite	9.5mm	AR1	5.3	1,436	19
Granite	9.5mm	AR2	5.5	3,855	24
Granite	9.5mm	AR3	5.6	3,808	3
Granite	GG 9.5mm	50/70	5.1	92	35
Granite	GG 9.5mm	AR1	5.9	1,762	6
Granite	GG 9.5mm	AR2	5.9	1,617	27
Granite	GG 9.5mm	AR3	5.5	1,387	29
Basalt	12.5mm	50/70	5.0	126	14
Basalt	12.5mm	AR1	5.6	2,856	30
Basalt	12.5mm	AR2	5.4	2,554	18
Basalt	12.5mm	AR3	5.4	1,252	4
Basalt	19.0mm	50/70	5.2	44	15
Basalt	19.0mm	AR1	6.3	921	26
Basalt	19.0mm	AR2	5.6	876	15
Basalt	19.0mm	AR3	5.8	831	3
Basalt	9.5mm	50/70	5.2	170	28
Basalt	9.5mm	AR1	6.3	1,205	16
Basalt	9.5mm	AR2	6.3	1,051	20
Basalt	9.5mm	AR3	6.2	897	25
Basalt	GG 9.5mm	50/70	5.8	70	20
Basalt	GG 9.5mm	AR1	6.5	419	15
Basalt	GG 9.5mm	AR2	6.5	569	24
Basalt	GG 9.5mm	AR3	6.1	718	29



**Figure 4.** Flow number values of asphalt mixtures with granitic aggregates



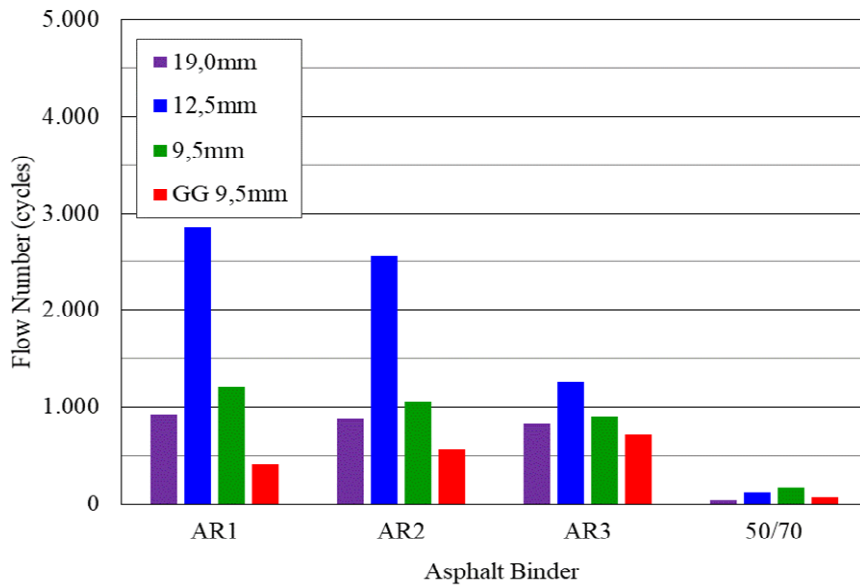


Figure 5. Flow number values of asphalt mixtures with basaltic aggregates

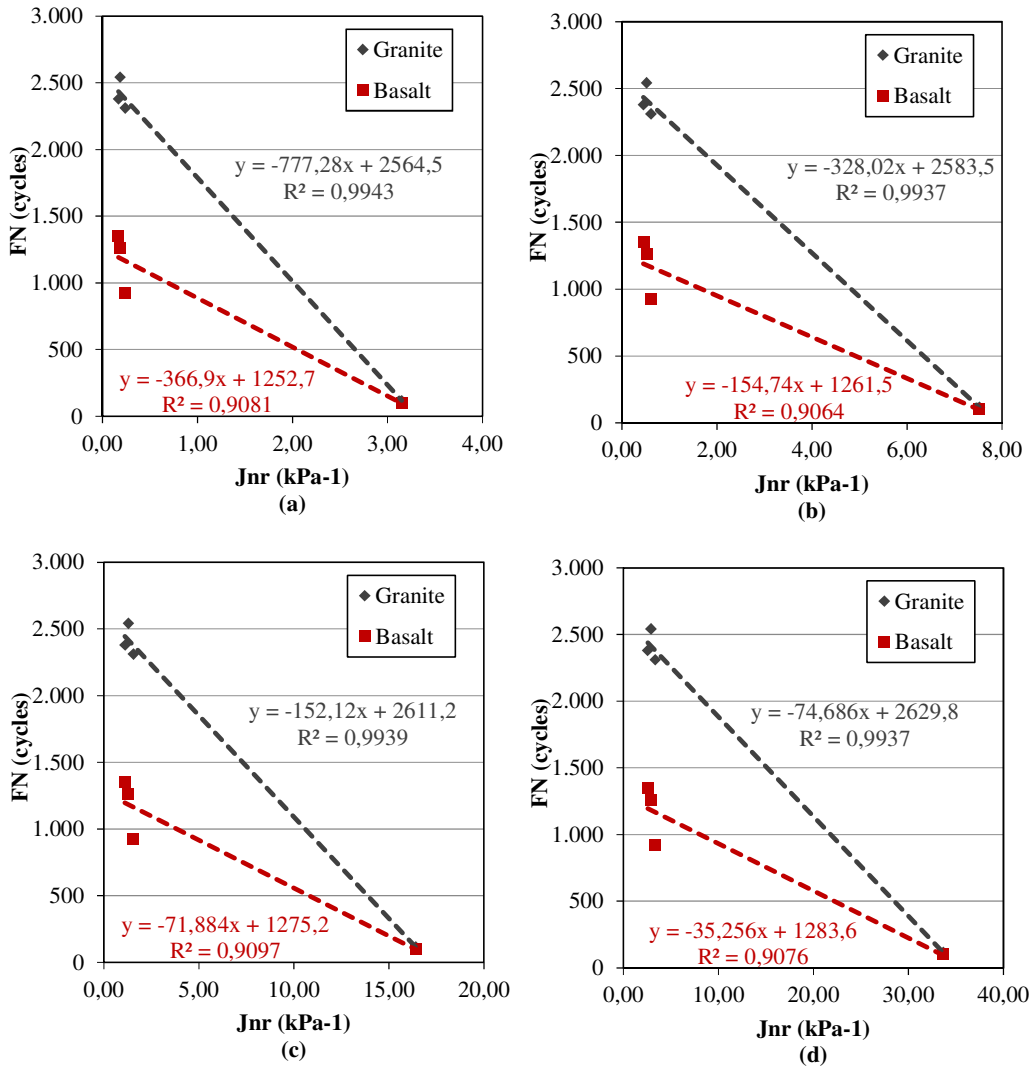


Figure 6. Linear correlation between flow number and Jnr obtained at: a) 58°C; b) 64°C; c) 70°C; d) 76°C

The average flow number values obtained at each sized gradation and which each aggregate type at 54°C were used to correlate with the Jnr values obtained at the MSCR test at different test temperatures.

Figure 6 shows that mixes containing Granite aggregates had higher flow number values at lower Jnr values, when compared to mixes containing Basalt aggregates. Even both aggregate sources attended to AASHTO R 35 recommendations, Granite aggregates are more cubic than Basalt aggregates, as showed in Table 5. Thus, this parameter may have influenced in the behaviour of mixes in the flow number test. However, at higher Jnr values, the aggregate source seems not to influence the FN values.

It is observed also in Figure 6 that the linear correlation between FN and Jnr were excellent, since the coefficient of determination were higher than 0.90 (Witczak et al, 2002). This behaviour reveals the asphalt binder contribution to rutting resistance could be accurately predicted by MSCR test. Others studies (LAUKKANEN et al., 2015; ADORJÁNYI AND FÜLEK, 2013; DOMINGOS, FAXINA AND BERNUCCI, 2017) confirm that the MSCR test method is capably to predict mixture rutting' behaviour.

#### 4. CONCLUSIONS

This study performed a laboratory program to assess the contribution of asphalt rubber in hot mix asphalt to resist rutting. The MSCR test was performed in three asphalt rubber and in a conventional 50/70 asphalt binder. The flow number test was selected to analyse 32 mixtures, with different source of aggregates, gradation and asphalt binder source.

The Jnr values obtained at the MSCR showed that asphalt rubber have better potential to withstand permanent deformation in hot mix asphalt at different temperatures. However, the recovery values at 64°C, 70°C and 76° were lower than recommended by FHWA (2010). This behaviour may denote that at higher temperatures there is not a well defined crosslink between the rubber particles and the asphalt binder

The flow number was dependant on the source of aggregates. In this study, it was noted that granite produced mixtures with higher resistance to permanent deformation, than mixtures produced with basalt. This behaviour can be associated to the shape of aggregates particles and asphalt binder content.

It was noted that hot mix asphalts produced with rubberized asphalt have higher flow number values, when compared to conventional mixtures. This means that the use of asphalt rubber can enhance the resistance to permanent deformation of hot mix asphalt. This behaviour was noted in all three rubberized asphalts, collected from commercial suppliers.

Finally, the linear correlation between the flow number results and the Jnr values at different temperatures was strong, which denotes that the Jnr is a good parameter to estimate the contribution of the asphalt binder in the HMA rutting resistance.

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#### REFERENCES

- Abdelrahman MA, Carpenter SH. The mechanism of the interaction of asphalt cement with crumb rubber modifier (CRM). *Transport Res Rec* 1999;1661: 106–13.
- ASPHALT INSTITUTE (1996) "Superpave Mix Design", Superpave Series No. 2 (SP-2), Lexington, Kentucky, 1996.
- Balaguer, M. (2012). *Avaliação estrutural de um pavimento flexível executado em asfalto-borracha, elaborado pelo Processo de Produção Contínua em Usina*. Master Dissertation. Instituto Militar de Engenharia. Rio de Janeiro, RJ.

- Bonaquist, R. (2012). *Evaluation of Flow Number (Fn) as a Discriminating HMA Mixture Property*. Final Report WHPR 12-01 for the Wisconsin Department of Transportation. Wisconsin.
- BROSSEAUD, Y., DELORME, J.L.; HIERNAUX, R. (1993) "Use of LPC Wheel-Tracking Rutting Tester to Select Asphalt Pavements Resistant to Rutting", Transportation Research Record #1384, TRB, National Research Council, Washington, D.C
- Camargo, F. F. (2016). *Field and laboratory performance evaluation of a field-blended rubber asphalt*. Doctoral Thesis. Escola Politécnica da Universidade de São Paulo. São Paulo, SP.
- D'Angelo, J.; Kluttz, R.; Dongré, R.; Stephens, K.; Zanzotto, L. (2007). *Revision of the Superpave high temperature binder specification: the multiple stress creep recovery test*. Journal of the Association of Asphalt Paving Technologists, Vol. 76, pp. 123-162. 2007.
- Domingos, M. D. I.; Faxina, A. L.; Bernucci, L. L. B. (2017). *Characterization of the rutting potential of modified asphalt binders and its correlation with the mixture's rut resistance*. Construction and Building Materials, Vol. 144, pp. 207-213.
- FAXINA, A. L. (2006). Estudo da viabilidade técnica do uso do resíduo de óleo de xisto como extensor em ligantes asfalto-borracha. Tese de Doutorado. Escola de Engenharia de São Carlos da Universidade de São Paulo, São Carlos, SP.
- FHWA.(2010). *The multiple stress creep recovery (MSCR) procedure*. Federal Highway Administration Tech Brief FHWA-HIF-11-038. Washington, D.C.
- Goli, A.; Ziari, H.; Amini, A. (2016) Evaluating the Performance of Crumb Rubber Modified Binders used in Isfahan Province. In: International Journal of Transportation Engineering, Vol.4/No.2. Autum 2016.
- Khalili, M.; Amirkhani, S.; Karakouzian, M.; Xiao, F.; Jadidi, K. (2016). Evaluation of New Innovations in Rubber-Modified Asphalt Binders and Rubberized Asphalt Mixes for Nevada DOT. NDOT Research Report No. 513-13-803. Carson City, NV, USA.
- KANDHAL, P.S.; MALLIK, R.B. (2001) "Effect of Mix Gradation on Rutting Potential of Dense-Graded Asphalt Mixtures", Transportation Research Record #1767, TRB, National Research Council, Washington, D.C.
- LAUKKANEN, O.V.; SOENEN, H.; PELLINEN, T. HEYRMAN, S.; LEMOINE, G. *Creep-recovery behavior of bituminous binders and its relation to asphalt mixture rutting*. Materials and Structures (2015) 48:4039-4053  
DOI 10.1617/s11527-014-0464-7.
- LO PRESTI, D. (2013). *Recycled Tire Rubber Modified Bitumens for road asphalt mixtures: A literature review*. Construction and Building Materials Journal. Volume 49, Pp. 863-881. doi:10.1016/j.conbuildmat.2013.09.007.
- Mandal, T. and Bahia, U. (2015). Effect of Crumb Rubber on Rheological Properties of Asphalt Binder and Aggregate Packing of Asphalt Mixtures. In: Road Materials and Pavements Design. Volume X – No X/2015.
- NASCIMENTO, L.A.H. *Nova Abordagem da Dosagem de Misturas Asfálticas Densas com Uso do Compactador Giratório e Foco na Deformação Permanente* Master Thesis dissertation. Rio de Janeiro: UFRJ/COPPE, 2008.
- NCHRP (2016). *Simple Performance Tests: Summary of Recommended Methods and Database*. Final Report. National Cooperative Highway Research Program NCHRP 09-19, National Research Council. DOI: 10.17226/13949. Washington, D. C.
- NCHRP. (2011). *A Manual for Design of Hot Mix Asphalt with Commentary*. National Cooperative Highway Research Program NCHRP 673. Washington, D.C.
- NETEMEYER, R.L. (1998) "Rutting Susceptibility of Bituminous Mixtures by the Georgia loaded Wheel Tester", Missouri Department of Transportation, Field Office Investigation F.O. 95-06, SPR Study No. SPR 96-03, Jefferson City, Missouri, May, 1998.
- Specht, L.P. (2004). *Avaliação de misturas asfálticas com incorporação de borracha reciclada de pneus*. Doctoral Thesis. Universidade Federal de Rio Grande do Sul, Porto Alegre, RS.
- Willis, J. R.; Rodezno, C.; Taylor, A.; Tran, N. (2014). Evaluation Of A Rubber---Modified Mixture In Alabama. Interim NCAT Report 14---03. Auburn, Alabama.
- Witczak, M.; Kaloush, K.; Pellinen, T.; El-Basyouny, M.; Von Quintus, H. (2002). *Simple Performance Test for Superpave Mix Design*. NCHRP, Report 465. Washington, D.C.