MECHANICAL CHARACTERIZATION OF ASPHALT RUBBER - WET PROCESS

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ABSTRACT

In many countries all over the world, bitumen modified with crumb rubber from ground tires is widely and successfully used, as binder in hot mix asphalt (HMA).

Asphalt Rubber is commonly used as wearing course for HMA pavements in order to improve smoothness and skid resistance and to reduce cracking and traffic noise. As extra benefit, this bituminous mixture allows to recycle rubber from waste tires.

In Italy, to date, this kind of mixture is not employed yet, except for some isolated situations, in spite of the encouraging results obtained all over the world.

This paper focuses on the mechanical characterization of a wet process asphalt rubber. This material was taken from the first experimental pavement section in Italy and then analyzed in laboratory. For this evaluation, Asphalt Rubber was subjected to dynamic Indirect Tensile Stiffness Modulus test (ITSM), Indirect Tensile Fatigue Test (ITFT), Repeated Loading Axial Test (RLAT) and Wheel Tracking Test (WTT). For a better evaluation, the results obtained for ARFC were compared with those obtained with different mixes subjected to the same tests. In particular, two HMA mixes manufactured in laboratory with the same gradation curve and bitumen content of Asphalt Rubber (the first with a traditional pen70/100 binder and the second with a SBS modified binder), a SplittMastixAsphalt and a dense graded HMA with expanded clay taken from a plant mix, were used.

Results clearly showed that the use of Asphalt Rubber can noticeably improve the mechanical properties of asphalt mixtures suggesting potential advantageous applications also for the Italian road network.

Keywords: Asphalt Rubber, wet process, fatigue, stiffness modulus, permanent defromation

1. INTRODUCTION TO ASPHALT RUBBER TECHNOLOGY

According to the ASTM definition, Asphalt Rubber is "a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of total blend …".

This material can be used to seal cracks and joints, applied as a chip seal coat or added to hot mineral aggregates as a binder in Hot Mixed Asphalt (HMA) to reduce reflective, thermal and fatigue cracking, and to make a final wearing surface with virtually no rutting, good skid resistance, little maintenance, smooth ride and less noise. As an extra benefit, AR mixtures allow to save energy and natural resources by putting waste tires into a secondary use instead of contributing to tire stockpiles.

The limitations of this material are mainly related with higher initial costs due to mobilization and set up of asphalt rubber binder production equipment, notwithstanding several life cycle cost analysis (Way, 2000; Jung et al., 2002) have shown that an asphalt rubber pavement would be more cost-effective than a conventional one.

Bitumen modified with crumb rubber is nowadays extensively used in the highway paving industry, particularly in the states of Arizona, California, Texas and Florida as well as Portugal, South Africa, Canada and China. In spite of many encouraging results obtained all over the world, in Italy this kind of mixture is not employed yet, except in some isolated situations.

In the production of Asphalt Rubber as binder, crumb rubber is blended at high temperatures to straight asphalt in order to improve asphalt properties. After mixing, in fact, rubber particles absorb the lighter fraction of asphalt and swell, decreasing the interparticles distance and increasing viscosity: this type of blending process is called "wet". In fact, blending of rubber particles into Hot Mix Asphalt can be carried out using the so-called "wet process" or "dry process". The dry process replaces a small part of the aggregate in the asphalt mixture by rubber particles which act properly as a rubber aggregate, and are dry mixed with the stony aggregate before asphalt binder is added to the mixture. Although the dry process presents some advantages in relation to the wet process, mainly concerned with the cost involved and the higher amount of rubber to be used, the researchers all over the world have mainly concentrated on the wet process because of the irregular performance of some experimental sections built with the dry process contrary to the satisfactory results concerning the wet process.

In fact, the use of this kind of process has shown to give several advantages both on bitumen and asphalt concrete manufactured with AR as binder.

In particular, several researches (Souza et al., 2005; Giuliani and Merusi, 2006; Huang et al., 2005; Zborowski et al., 2004) have demonstrated that, at intermediate and high temperatures, rubber stiffens the binder and increases elasticity (proportion of recoverable deformation) with the consequent reduction of temperature susceptibility and improvement in resistance to permanent deformation and fatigue.

The properties conferred to bitumen by the use of rubber as modifying agent clearly reflect on bituminous mixes manufactured with Asphalt Rubber in terms of rutting and cracking resistance compared with conventional bituminous mixtures, as showed by several studies (i.e. Souza et al., 2005; Zborowski et al., 2004; Potgieter et al. 2001; Kaloush et al., 2003; Cook et al., 2006; and Kumar et al., 2005; Bertollo at al., 2004)

Finally, as regards environmental benefits, besides waste tires disposal, AR mixtures present interesting advantages in reducing tire noise (Antunes et al., 2003; Leung et al., 2006), mainly related to the greater elasticity of the mix that attenuates all noise mechanical source generation mechanisms (Bernhard and Wayson, 2005).

2. EXPERIMENTAL PROGRAM

This paper focuses on the mechanical characterization of a gap graded Asphalt Rubber Friction Course (ARFC) taken during the construction of an experimental road section. For this assessment ARFC was submitted to a wide experimental program including:

- Indirect Tensile Stiffness Modulus (ITSM) test for the determination of load spreading ability;
- Indirect Tensile Fatigue Test (ITFT), to characterize fatigue cracking resistance;
- Repeated Loading Axial Test (RLAT) and Wheel Tracking Test (WTT), to evaluate permanent deformation resistance;

For a better evaluation, the results obtained for ARFC were compared with results obtained for different mix types, defined as follows, that were subjected to the same tests:

- P-HMA: Hot Mixed Asphalt manufactured in laboratory with a Plain 70/100 bitumen;
- M-HMA: Hot Mixed Asphalt manufactured in laboratory with a “hard” polymer Modified bitumen;
- ECFC: dense graded Friction Course containing Expanded Clay;
- SMA: SplittMastixAsphalt.

It is important to observe that SMA and ECFC were taken during production of experimental road sections, while the other two asphalt mixes tested (P-HMA and M-HMA) were manufactured in laboratory with the same gradation and bitumen content of ARFC. This fact is very important because, as a consequence, HMAs are not optimized from the point of view of binder content, unlike SMA and ECFC, affecting results analysis.

2.1 Materials

Asphalt Rubber Friction Course (ARFC)

ARFC was taken during the construction of the first experimental road section in Italy. Aggregate size, rubber distribution, binder and rubber content together with gap graded Technical Specifications are shown in table 1.

Table 1 ARFC characteristics

Sieves	Aggregates	Rubber	Gap graded Specification
mm	**% passing**	**% passing**	**% passing**
25	100.0	100.0	100.0
15	99.6	100.0	100.0
10	83.9	100.0	75.0 - 100.0
5	42.0	100.0	35.0 - 50.0
2	23.1	100.0	18.0 - 28.0
0.42	11.6	23.1	4.0 - 13.0
0.177	7.8	0.0	2.0 - 9.0
0.074	5.2	0.0	1.0 - 6.0
AR	8.6 % on mineral aggregates		7.5 % - 9.0 %
Rubber	18.0 % on bitumen		15.0 % - 22.0 %

Hot Mix Asphalts manufactured with Plain (P-HMA) and Modified (M-HMA) bitumen

Two traditional Hot Mix Asphalts were manufactured in laboratory mixing limestone aggregates with a Plain pen70/100 binder (P-HMA), which was the straight bitumen of AR, and a "hard" Modified binder (M-HMA) whose characteristics are listed in table 2. In order to give prominence to the role that the binder plays in the mechanical responses of the mixes, the bitumen content (7.3 % on mineral aggregates) and grain-size distributions were equal to those of ARFC mixture. The difference between ARFC and HMAs granulometric distributions was the replacement of the crumb rubber with mineral aggregates having the same volume, assuming the apparent specific gravity of the rubber and the mineral aggregates respectively equal to 10.0 kN/m^3 and 26.5 kN/m^3. However, the amount of rubber referred to the whole mixture was so little that, as a matter of fact, the difference between ARFC and HMAs gradation was negligible.

Table 2 Binders characteristics

Test	Standard	Unit	Plain Bitumen	Modified Bitumen
Penetration @ 25°C	EN 1426	dmm	70-100	50-65
Softening point	EN 1427	°C	43-51	70-85
Fraas breaking point	EN 12593	°C	≤ -10	≤ -14
Elastic recovery @ 25°C	EN 13398	%	---	≥ 75

Expanded Clay Friction Course (ECFC) & SplittMastixAsphalt (SMA)

For a more in-depth study, the Authors decided to compare the mechanical performance of ARFC also with that showed by two bituminous mixtures coming from experimental road sections and manufactured with polymer modified binder.

ECFC was a dense-graded asphalt mix for wearing course in which a part of coarse aggregate, sized between 2 and 10 mm, was replaced with a "resistant" type of granular expanded clay. The composition of these innovative mixtures is shown in table 3 while characteristics of SMA mix, coming from an analogous experimental road section, are listed in table 4.

Table 3 ECFC characteristics

Sieves	**ECFC**	**Technical Specifications**
mm	**% volumetric passing**	**% volumetric passing**
15	100.0	100.0 - 100.0
10	96.9	70.0 - 90.0
5	56.3	40.0 - 60.0
2	34.0	25.0 - 38.0
0.42	15.4	11.0 - 20.0
0.177	10.4	8.0 - 15.0
0.074	7.5	6.0 - 10.0
Bitumen	5.7 %	5.0 % - 6.0 %
Expanded Clay	39.1 % on mineral aggregate volume	

Table 4 SMA characteristics

Sieves	**SMA**	**Technical Specifications**
mm	**% passing**	**% passing**
12.5	100.0	100.0 - 100.0
9.5	96.0	90.0 - 100.0
4.75	42.0	30.0 - 48.0
2	28.2	18.0 - 28.0
0.42	17.3	10.0 - 20.0
0.177	14.0	9.0 - 18.0
0.074	8.6	8.0 - 12.0
Bitumen	7.3 % on mineral aggregate	6.5 % - 7.5 %

Given the different apparent specific gravity between expanded clay and mineral aggregates, grading curve of ECFC is expressed in terms of volumetric passing. It is interesting to note that the binder content of SMA was the same as that of HMAs. Nevertheless, in case of SMA, 7.3% was the optimum content of binder for this kind of mixture, unlike HMAs asphaltic materials.

2.2 Equipment and Testing Protocols

In the following paragraphs the Authors present the test protocols employed to assess mechanical properties of ARFC and control bituminous materials considering four fundamental aspects: load spreading ability; fatigue cracking resistance and permanent deformation resistance.

Stiffness Modulus and Fatigue Tests

In order to assess the load spreading ability and fatigue cracking resistance of the studied bituminous mixtures, the Indirect Tensile Stiffness Modulus (ITSM) test and

Indirect Tensile Fatigue Test (ITFT) were carried out on six cylindrical samples for each material at 20 °C by means of repeated load dynamic equipment.

ITSM tests were carried out according to EN 12697-26, Annex C considering two perpendicular diameters while ITFT tests were carried out according to EN 12697-24, Annex E applying 3 different stress levels for each material and considering 2 replications for each stress value.

The specimens were prepared with 100 gyrations of a shear gyratory compactor at 150 °C mixing temperature. The final dimensions of cylindrical specimens corresponded to a nominal diameter of 100 mm and to a thickness between 63 and 69 mm.

Permanent Deformation

The Repeated Load Axial Test (RLAT) and Wheel Tracking Test (WTT) were carried out to assess the permanent deformation resistance of the selected bituminous mixtures.

RLAT was carried out according to BS DD 226. Samples submitted to this test were a couple of 100 mm diameter cylindrical specimens manufactured with 100 gyrations of a gyratory compactor.

The WTT was carried out according to BS 598-110 for either 45 min has elapsed or until a 8 mm rut had developed. The test was carried out at 60 °C to better discriminate between materials responses, as found by Gibney et al. (1999). This test uses slabs (305 × 305 mm^2) for each material prepared with a roller compactor according to EN 12697-33.

3. TEST RESULTS AND ANALYSIS

3.1 Stiffness Modulus

In figure 1, the results of the stiffness modulus investigations are represented as mean values of 6 repetitions and the corresponding standard deviations *s* are also indicated.

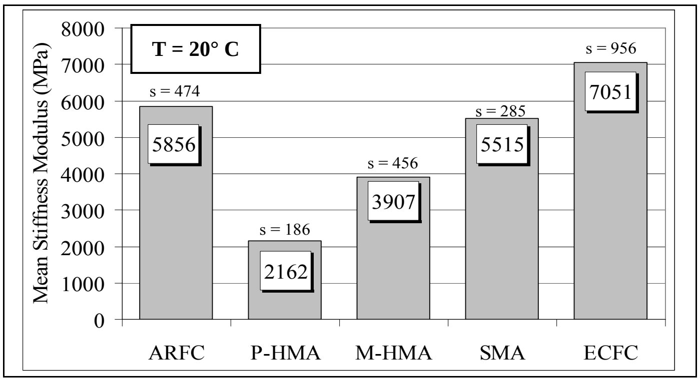

Figure 1 Mean stiffness modulus

As it can be seen, ARFC performance was comparable with that of SMA and ECFC both manufactured with polymer modified bitumen and suitable for heavy trafficked roads. ARFC load spreading ability was even more remarkable since it contained only calcareous aggregates instead of basalt used for SMA and ECFC. Difference between ECFC stiffness modulus and SMA and ARFC ones was probably due to the lower amount of binder in ECFC mixture. Moreover, due to laboratory handling, ECFC was heated more times than SMA and ARFC producing higher oxidation of bitumen and consequent stiffening of asphalt concrete.

With respect to HMA mixtures, ARFC clearly outperformed these bituminous materials. The binder certainly played a key role in ARFC performance but it should be remembered that both P-HMA and M-HMA were not optimized as regards bitumen content. The binder excess surely contributed to reduce the stiffness modulus values of P-HMA and M-HMA. Moreover, HMAs were manufactured in laboratory, so specimens of these mixtures underwent only one heating process while mixtures taken hot in situ were heated more times to manufacture specimens for laboratory tests. This further heating process probably contributed to the stiffening of the mixtures.

However, it is important to underline that, as regards load spreading ability, ARFC would have surely perform not worse than an analogous bituminous mixture manufactured with polymer "hard" modified binder.

3.2 Fatigue

In order to simulate the evolution of permanent deformation, a descriptive model (Virgili et al., 2007), based on the well-known power law, was adopted:

$$\varepsilon_p = at^b \quad \text{(Eq. 1)}$$

Through several mathematical elaborations and assuming:

$$1 - \frac{1}{b} = C \quad \text{(Eq. 2)}$$

It is possible to write the incremental equation in terms of permanent deformations that allows to describe permanent strain evolution:

$$\varepsilon_{i(p)} = \left((1+r)\varepsilon_{i-1(p)}^{1-C} - r\varepsilon_{i-2(p)}^{1-C}\right)^{\frac{1}{1-C}} \quad \text{(Eq. 3)}$$

where:

$$r = \frac{t_i - t_{i-1}}{t_{i-1} - t_{i-2}} \quad \text{(Eq. 4)}$$

$\varepsilon_{i(p)}$, $\varepsilon_{i-1(p)}$ and $\varepsilon_{i-2(p)}$ are the permanent deformations at times i, i-1 and i-2 respectively and *C* is the only material parameter expressed as a five order function of the number of cycles.

Therefore, equation 3 allows the Authors to describe the evolution of permanent deformation in fatigue test by means of two boundary values ($\varepsilon_{i-1(p)}$; $\varepsilon_{i-2(p)}$) and a material parameter (*C*).

Since the flex point of permanent strain evolution vs. time is conventionally considered to identify a critical state of asphalt concrete establishing a failure criterion (Kaloush et al., 2002), this model is adopted because it allows to find this flex point by monitoring the evolution of *C*.

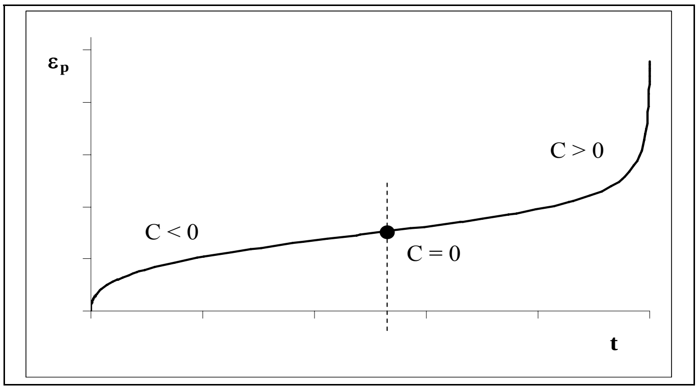

Figure 2 Typical evolution of permanent strain

By observing figure 2 three main cases can be noted:

- First case: $C < 0$ implies that the equation is a power law with exponent $b < 1$. The material is in hardening phase.
- Second case: $C = 0$ implies that the equation is a linear relationship ($b = 1$).
- Third case: $C > 0$ implies that the equation is a power law with exponent $b > 1$. The material is affected by a damage process.

So, when $C = 0$ the flex point is univocally definite. A typical evolution of *C* is plotted in figure 3a.

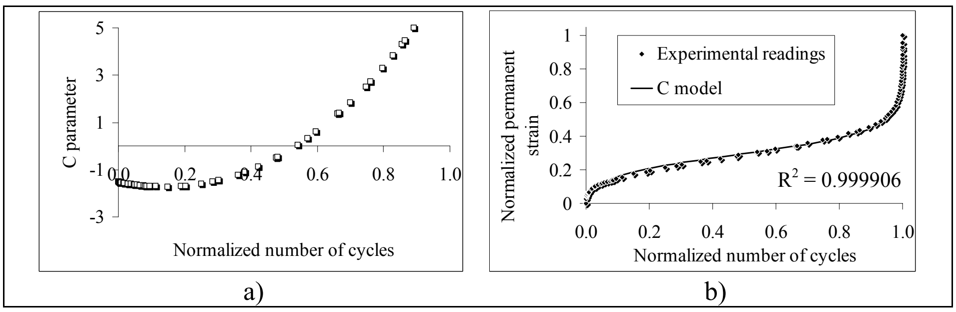

Figure 3 "*C* model"

The correlation factors between experimental evolution and the model are significantly high. Therefore, the model can appropriately simulate a fatigue test as shown in figure 3b.

In both figures 3a and 3b, the number of cycles and permanent strain are normalized with respect to the final values.

Figure 4 shows the fatigue laws of materials studied in terms of initial strain vs. number of cycles to failure where, as failure, the Authors intended the number of cycles corresponding to the flex point of the permanent deformation evolution law.

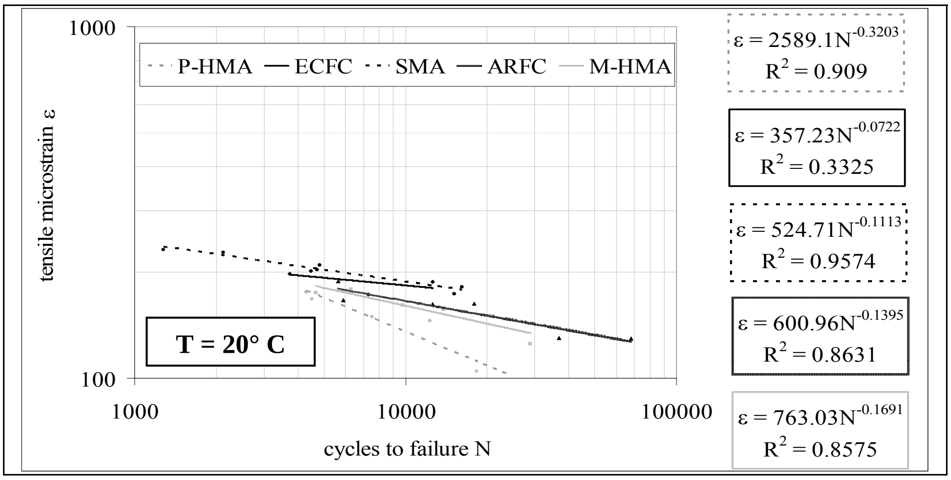

Figure 4 Fatigue laws

As it can be seen, ARFC showed performance comparable to SMA and M-HMA and they clearly outperformed the P-HMA asphaltic concrete, especially at low strain levels. It is important to underline that ARFC had similar fatigue resistance behaviour of M-HMA notwithstanding the high binder content, compared to its optimum content, and the consequent low stiffness value of M-HMA would normally be expected to impart very good fatigue resistance. The reduced slope of ARFC fatigue line indicated that beyond a high number of cycles this bituminous material should maintain greater fatigue life for a given initial strain value.

As regards ECFC performance, it seems to be similar to that showed by ARFC but the low regression coefficient of its fatigue law prevents the Authors being more accurate on this subject before further studies.

As regards single fatigue tests fitted by the above mentioned "*C*-model", Table 5 summarizes the mean *C* values at the beginning (t=0) and at the end of the test (fracture), and the mean normalized time at the flex point (t_{flex}) for each kind of material studied. Mean regression factor ranged from 0.99985 to 0.99999 showing a very good correlation between model and experimental readings.

It is important to note that the *C* values at the beginning of the test were around -2 for all types of mixtures, so, at the beginning, the model nearly behaves as a cube root equation for all materials.

Table 5 Synthesis of *C*-model results

	ARFC	SMA	ECFC	M-HMA	P-HMA
***C* (t=0)**	-2.60	-2.46	-1.98	-1.85	-1.41
***C* (fracture)**	8.01	6.74	10.02	5.46	5.60
t_{flex} (*C*=0)	0.53	0.48	0.65	0.44	0.50

Another significant aspect to underline is that the flex point positions itself at nearly midway of physical fracture time, except for ECFC mixture. This fact could be explained considering two different aspects: 1) the high stiffness of this mixture that inhibits crack initiation but accelerates subsequent crack propagation; 2) the failure of ECFC specimens that occurred not only because of the breaking of the bituminous film but also because of the observed brittle breaking of expanded clay grains. This point seems to be confirmed also by the *C* value at the end of the test: in fact *C* at fracture of ECFC was significantly higher than those of the other asphaltic concretes, in particular with respect to HMAs, implying a faster growth of permanent deformation.

3.3 Permanent deformation resistance

Data coming from these tests are similar to those obtained from the fatigue test except for the last part of strain evolution since specimens subjected to RLAT and WWT tests, differently from ITFT tests, did not reach physical failure (see for example figures 5 and 6). As a consequence they could be interpolated with the same model presented before, filtering, in this way, eventual variations in experimental readings. Thus, from model values, the Authors are able to calculate two couples of equivalent parameters used to describe the performance of the materials: final permanent strain and strain rate for RLAT and final rut depth and rut rate for WTT.

A summary of test results for RLAT and WTT are given in table 6. All values presented were found through the above mentioned "*C*-model" fitting the experimental readings. RLAT results are presented in terms of mean values of two identical tests for each type of material studied.

Table 6 Summary of permanent deformation resistance tests results

	WTT @ 60° C			RLAT @ 30° C		
	Rut Depth (mm)	Rut Rate (mm/h)	R^2	Final Strain (µstrain)	Strain Rate (µstrain/cycle)	R^2
ARFC	0.41	0.27	0.9923	2753	0.46	0.9995
SMA	0.50	0.21	0.9875	1794	0.27	0.9994
ECFC	0.47	0.21	0.9992	854	0.13	0.9998
M-HMA	1.53	0.60	0.9977	4229	0.40	0.9999
P-HMA	4.99	3.21	0.9950	11192	1.43	0.9997

As regards WTT, it can be seen that ARFC performance was comparable with that of SMA and ECFC and that all three of them showed virtually no deformation. Moreover the ARFC mixture demonstrated deformation resistance 3 times greater than

M-HMA and about 10 times greater than P-HMA. This behaviour is clearer observing figure 5 where asphaltic materials rut depth vs. time is plotted.

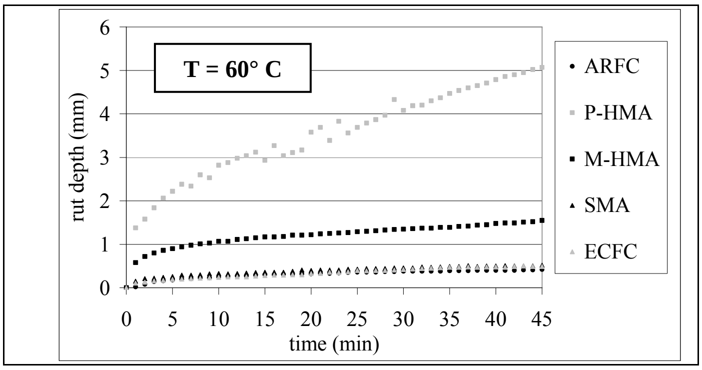

Figure 5 WTT experimental results

From RLAT results, discrimination between ARFC, SMA and ECFC was possible. ECFC clearly outperformed the other materials, as it could be expected from its high stiffness modulus (see figure 1), while SMA performed slightly better than ARFC. It is important to remember that SMA is a high rut resistant material thanks to its strong interlocking coarse aggregate structure. So, ARFC performance wase very promising from this point of view. Moreover, ARFC, in its turn, performed better than HMAs but the difference between these mixtures resulted much lower than what came out from WTT test. Also in this case figure 6 illustrates, in an exhaustive manner, performance levels of asphaltic materials studied. Each curve is the result of the mean of two different tests.

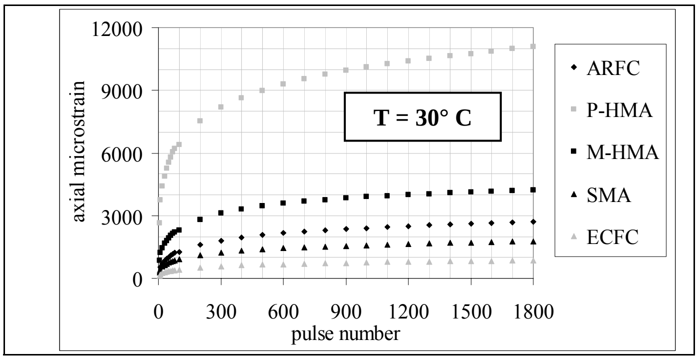

Figure 6 RLAT mean experimental results

However, it is necessary to underline that the test temperature and stress level of RLAT, as suggested by the British Standard, seem to be too low to clearly give an accurate picture of permanent deformation behaviour of bituminous materials, as remarked also by Collop and Khanzada (1999). In fact, also P-HMA, which was the mixture that showed higher deformation, underwent very low vertical displacements at the end of the test (about 0.75 mm).

It is important to state that, in both cases, the excess of the binder in HMAs, compared to their optimum content, surely played a negative role in permanent deformation resistance of these mixtures. However, it is possible to assert that ARFC would not surely perform worse than M-HMA because the difference showed by the two materials was significant.

4. CONCLUSIONS

In many countries all over the world, bitumen modified with crumb rubber from ground tires is widely and successfully used, as binder in hot mix asphalt (HMA).

This paper focused on the laboratory mechanical characterization of a wet process asphalt rubber, taken from the first experimental pavement section in Italy, in terms of load spreading ability, fatigue cracking resistance and permanent deformation resistance.

The main results of this study can be summarized as follows:

- ARFC showed high value of stiffness modulus that means a good load spreading ability, comparable with that of asphaltic concretes suitably designed to withstand heavy traffic load;
- In spite of its high stiffness, ARFC performed very well also as regards fatigue cracking resistance. This is probably due to the elasticity of this asphaltic concrete coming from the presence of rubber inside the mixture;
- Analyzing permanent deformation resistance, ARFC demonstrated high rutting resistance notwithstanding its high binder content. Again, the presence of rubber in the bitumen was fundamental because it noticeably increases the bitumen viscosity that, as a consequence, allows greater amount of binder without danger of excessive permanent deformation.

So, according to many experimental studies on Asphalt Rubber all over the world, this study has shown very encouraging results on the mechanical properties of bituminous mixture manufactured with rubber modified bitumen suggesting potential advantageous applications also for the Italian road network.

This first mechanical characterization needs to be completed by investigating into durability properties such as aging, aggregate loss or water damage as well as into functional properties such as smoothness, skid resistance and quietness of ARFC.

Moreover, the assessment of the performance of open-graded bituminous concrete manufactured with asphalt rubber could also be another very interesting aspect to be studied in depth.

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