Assessing rutting susceptibility of five different modified asphalts in bituminous mixtures using rheology and wheel tracking test

ABSTRACT

Rutting is one of the most important distresses in asphalt pavements due to its frequency. Rutting or channeling, could be classified in three types: 1) mechanical deformation (rutting in subgrade or base), 2) plastic flow (unstable asphalt layer), and 3) wheel path consolidation.

The plastic flow of bituminous mixture depends on many factors; one of this is the type of asphalt used in the mixture. Actually, rheology studies are used for asphalt analysis and to predict rutting susceptibility in bituminous mixtures. With the rheology analysis; it could be possible to predict the maximum temperature at which asphalt works properly as a bituminous mixture constituent. In other words, the high temperature at which asphalt does not increase mixture susceptibility to rutting via plastic flow.

In this article, the authors describe the work done to analyze the susceptibility of different modified and unmodified asphalts using four different rheology methods. Also they analyze the resistance to rutting of bituminous mixtures (made with the same asphalts), at different temperatures using the Spanish Wheel tracking device. The main objectives were to verify if rheology analysis could be related to bituminous mixture resistance to rutting and to find differences between the four rheology methods used in this investigation.

Bituminous mixtures were made according to Mexican specifications. The wheel tracking device was constructed and performs according Spanish standard NLT-173.

INTRODUCTION

In Mexico, rutting is one of the most common distresses in asphalt pavements. Rutting does not influence immediately, the structural capacity of the pavement, but it can shorten significantly the pavement’s life cycle, besides causing an important loss in the ride quality of the road.

Rutting can be caused basically by three factors: 1) mechanical deformation, 2) consolidation of asphalt layer or 3) displacement of the bituminous mixture of the upper layers (plastic flow).

If rutting is caused by plastic flow of upper layers, then asphalt mixture has a lack of stability. The stability strongly depends on the following factors:

- Grading and aggregate characteristics
- Type and content of asphalt
- Type of traffic
- Work temperature
- Quality of construction

One of the most recent investigation areas on asphalt, studies the relationship between asphalt rheology and rutting in pavements. These investigations try to measure the contribution of asphalt in mixture stability.

In Mexico, some investigators are carrying out rheology analysis on conventional and modified asphalts to predict its field performance. SURFAX S.A. de C.V. has a line of investigation relating to this topic. This line of investigation basically points towards a rheology study of the most common modified and unmodified asphalts used in Mexico.

In the following section, there is a brief description of the different methods used by SURFAX S.A. de C.V. for rheology characterization of asphalts and the results of the analysis for five asphalts. Then, these five asphalts were analyzed with Spanish wheel tracking device to verify if there is a correlation between rheology characterization and rutting susceptibility in asphalt mixtures.

RHEOLOGY CHARACTERIZATION OF ASPHALTS

The rheology characterization of asphalts is not a new subject. However, it was not until the introduction of the SUPERPAVE design method, when it was gotten up of important way in the world of the asphalt mixtures.

The SUPERPAVE was the result of a research program known like SHRP (Strategic Highway Research Program), whose main objective was the development of a procedure for design of asphalt mixtures that intimately was related to the field performance. One of the most important contributions was the asphalt specification, cradle indeed in the rheology study of the asphalt. The objective of the specification is the determination of the Performance Grade (or PG) of asphalts. The nomenclature to express the PG of asphalt is the following one: PG XX-YY, where XX represent the high work temperature allowed for that asphalt (in Celsius degrees) and YY represents the low work temperature allowed for the same asphalt. In order to determine these high and low temperatures a series of tests are carry out. The high temperature (XX) is defined by rheology characterization.

In following section the rheology characterization method proposed by SUPERPAVE is described. Also other procedures used for the same aim are described.

Rheology characterization methods

In this section it will be described briefly four methods used for the rheology characterization of asphalts, these are: 1) the SUPERPAVE, 2) the refined SUPERPAVE, 3) zero shear viscosity and 4) repeated creep.

SUPERPAVE

In order to determine the maximum PG temperature of asphalt, SUPERPAVE proposes the use of **dynamic shear rheometer** (DSR). With this equipment is possible to obtain the complex module (G *) and the angle of phase (δ) of an asphalt at high and intermediate temperatures.

The asphalt sample first passes through the rolling thin film oven (RTFO) to age it. This aging process simulates the aging of asphalt during the plant production of bituminous mixture.

Specification SUPERPAVE is defined in terms of the complex module and the calculated angle of phase, on asphalts after RTFO. In equation 1 there is the specification defined by SUPERPAVE *(1).*

$$\frac{G^*}{\sin\delta} \geq 2.2\,\text{kPa}$$ **Equation 1**

The SUPERPAVE method establishes the measurement of the G * and δ at different temperatures (52, 58, 64, 70, 76 and 82º C), in such a way that degree PG for the high temperature, will be the greatest temperature for which the value specified in equation 1 is fulfilled.

One goal of SURPERPAVE was to make the specifications and tests “transparent” to the use of modified binders—that is, to ensure that the specifications would accurately measure the enhanced performance characteristics of the modified binders. However, the SHRP asphalt research was carried out almost exclusively with unmodified asphalt cements, so the applicability of the Superpave specifications and test methods to modified binders was not validated (2).

In order measure properly the performance of modified asphalts, new parameters and methods have been developed. The methods shown below are some of the most used to follow this objective.

Refined SUPERPAVE

There where various attempts to refine the SUPERPAVE parameter. One of such a refinement suggested by Shenoy (3) was the term show in equation 2.

$$G^* \Big/ \left(1 - \frac{1}{\sin\delta \cdot \tan\delta}\right) \geq 2.2\,kPa$$ **Equation 2**

This equation was developed in order to give more importance to the changes that appear in the angle of phase (δ). This change implies a greater influence in measurement of the elastic component of the complex module of asphalt.

Zero Shear Viscosity

The parameter Zero Shear Viscosity (ZSV) is a method for rheology characterization introduced in Europe. This specification could substitute SUPERPAVE specification with some advantages. The main advantage using this method is it is possible to determine in a correct way the maximum PG temperature for virgin asphalts and PMB.

Rheology characterization with ZSV method is based on a sweeping of frequencies to different temperatures, near maximum temperature of work (or failure temperature), determined with parameter SUPERPAVE. The detailed description of the procedure can be consulted in article published by Rowe, D'Angelo and Sharrock (4). For this general description it is sufficient to point out that failure temperature is obtained from the curve Log (ZSV) versus temperature. Failure temperature is defined when Log (ZSV) is equal to 2.39 Pa·s for the asphalt aged in RTFO.

Repeated Creep

Repeated Creep is a method of rheology characterization that is tried to use as a complement of other methods of rheology characterization, like SUPERPAVE method. Repeated creep is a method in which asphalt is put under a series of 20 cycles at two different stress levels (100 and 3200 Pa) according to D'Angelo, Dongré and Reinke investigation (5). In each cycle is applied a shifting effort followed by a period of recovery. Is important to state that during this period of recovery, rheometer does not apply any effort that helps the material recovers its original position, as it happens with other methods. The test runs at maximum temperature of work or high PG temperature, determined by rheology characterization method that is tried to complement, for example SUPERPAVE specification.

With Repeated creep test is possible to analyze the capacity of elastic recovery of asphalt under different levels of stress. This fact is important because when using this test as a complement of another asphalt characterization tests, like specification SUPERPAVE, is possible to establish differences between modified asphalts. PMB are characterized to have a greater elastic recovery than virgin asphalts. Even, the difference between the polymeric networks between different PMB can be established clearly at different stress levels and different temperatures.

There is a propose for a specification using Repeated Creep test, in which the **average of elastic recovery** at the end of the 10 cycles series **at 3200 Pa**, should be **at least 15% of the total deformation for each cycle**. Also the **difference** between **the average elastic recovery** between the **100 and 3200 Pa should be 70% maximum**.

Evaluation of modified asphalts commonly used in Mexico

SURFAX S.A. of C.V. has a line of investigation focused in the rheology characterization of asphalts through different methods, specifically on PMB. For this study, it was made the rheology characterization of 4 modified asphalts and one virgin, using the four tests described previously. The description of analyzed asphalts and the results obtained for each test are in the next tables.

TABLE 1 Asphalts used in the study

Asphalt/modifier	Type	Classification*	Particularities
AC-20 Salamanca	virgin	PG 70-YY	From Salamanca refinery
Elvaloy	PMB	PG 76-YY	Modified with Elvaloy (terpolymer) and polyphosphoric acid as catalyst
EVA	PMB	PG 76-YY	Modified with ethyl vinyl acetate
Oxidized asphalt	modified	PG 76-YY	Oxidized with polyphosphoric acid
SBS	PMB	PG 76-YY	Modified with Styrene Butadiene Styrene

* *Classification according SUPERPAVE with RTFO aged asphalt*

TABLE 2 Results of rheology characterization by SUPERPAVE method

Asphalt/modifier	PG	Failure temperature, ° C	G*, kPa	δ, °	G*/sin δ, kPa (at PG Temp.)	Classification
AC-20 Salamanca	70	71.3	2.527	80.8	2.56	5
Elvaloy	76	81.9	3.054	58.8	3.57	1
EVA	76	80.1	3.373	75.1	3.49	2
Oxidized	76	79.0	2.828	71.6	2.98	3
SBS	76	77.5	2.370	67.8	2.56	4

In TABLE 2 is possible to see that all modified asphalts are classified like PG 76-YY. The failure temperature and the angle of phase (δ) are different. It is important to notice that the phase angle is different for all asphalts; since this parameter offers an idea of how much elastic recovery can present the asphalt (asphalt with smaller angle of phase expects great elastic recovery).

TABLE 3 Results of rheology characterization by refined SUPERPAVE method

Asphalt/modifier	PG	Failure temperature, ° C	G*, kPa	δ, °	G*/(1-(1/sen δ tan δ)), kPa (at PG Temp.)	Classification
AC-20 Salamanca	70	72.3	2.527	80.8	3.02	5
Elvaloy	88	91.5	1.167	61.2	3.13	1
EVA	76	81.1	3.373	75.1	4.65	4
Oxidized	76	81.7	2.828	71.6	4.36	3
SBS	76	81.8	2.370	67.8	4.24	2

Results showed in TABLE 2 and TABLE 3 shows clearly that Refined SUPERPAVE specification gives more importance to the phase angle comparing to SUPERPAVE specification. It is important to note that Refined SUPERPAVE specification classifies the asphalt modified with Elvaloy as PG 88-YY, a great difference with the classification given before. The other modified asphalts was near to being classified as PG 82-YY. With this results it is easy exemplified the differences between both methods.

TABLE 4 Results of rheology characterization by ZSV method

Asphalt/modifier	PG	Failure temperature, º C	Classification
AC-20 Salamanca	70	71.3	5
Elvaloy	94	94.9	1
EVA	76	76.1	4
Oxidized	76	81.2	3
SBS	76	81.3	2

In TABLE 4 are shown the results ZSV characterization method. As it was observed with Refined SUPERPAVE method, the classification of asphalt modified with Elvaloy changed. It goes from PG 76-YY to PG 94-YY. SBS modified and Oxidized asphalt were near to be classified as PG 82-YY. EVA modified asphalt has a failure temperature near to 76º C.

TABLE 5 Results of rheology characterization by Repeated Creep

Asphalt/modifier	Test temperature, º C	Average elastic recovery at 100 Pa, %	Average elastic recovery at 3200 Pa, %	Difference between elastic recovery	Cumulative total deformation (20 cycles), %	Classification
		Specified values	*15 min.*	*70 max.*		
AC-20 Salamanca	70	2	0 (-6)	8	13683	5
Elvaloy	76	75	68	7	1339	1
EVA	76	27	0 (-3)	30	18260	3
Oxidized	76	26	0 (-3)	29	9608	4
SBS	76	32	11	21	8886	2

As it had been indicated before, Repeated Creep serves as complement of other methods for asphalt classification. For this study, it was considered as a complement of SUPERPAVE method. Then, the analysis of different asphalts by Repeated Creep indicates if asphalt has a minimum elastic recovery and if it is susceptible to different stress levels. In TABLE 5 is possible to observe that only Elvaloy modified asphalt fulfills the proposed specified value for average elastic recovery at 3200 Pa. It is important to notice that Elvaloy modified asphalt was the only one which changes its PG with Refined SUPERPAVE and ZSV specifications. In the same table it is also possible to appreciate that all analyzed asphalts fulfill the value specified for the difference between elastic recoveries at both levels of stress.

The results obtained by the rheology characterization under the four used methods are considered in a global evaluation. In tables 2-5 there is a classification based on PG, failure temperature and specification for each test. The number 1 corresponds to the best asphalt.

TABLE 6 Ranking of susceptibility to plastic deformations defined by rheology characterization of the asphalts analyzed in the study

Asphalt/modifier	Mean of each classification	Ranking
Elvaloy	(1+1+1+1)/4 = **1**	1
SBS	(4+2+2+2)/4 = **2.5**	2
Oxidized	(3+3+3+4)/4 = **3.25**	3
EVA	(2+4+4+3)/4 = **3.25**	3
AC-20 Salamanca	(5+5+5+5)/4 = **5**	5

The ranking shown in TABLE 6 defines the asphalt modified with Elvaloy the less susceptible and virgin asphalt AC-20 Salamanca as the most susceptible to permanent deformations.

The study of permanent deformations by wheel tracking device with mixtures made with the asphalts showed in TABLE 1, must verify or reject the tendency observed with rheology characterization.

ASSESING RUTTING IN ASPHALT MIXTURES WITH WHEEL TRACKING DEVICE

As it was previously mentioned, rutting is one of the most important types of failures on asphalt pavements. One of the processes that cause rutting is the lack of stability of the superior asphalt layer of the pavement.

Due the importance of rutting, investigators have been developed or adapted some laboratory tests to evaluate the susceptibility of an asphalt mixture to rutting (or plastic deformation) (*6).*

All the tests to evaluate rutting in asphalt mixtures have their advantages and disadvantages. Some of them reproduce in a better way the field conditions of the pavements. In such a way that the information can be obtained from them is more valuable for the prediction of performance of mixtures to rutting *(7)*.

For this investigation a simulation tests was used. The employed test was Spanish wheel tracking, because it offers valuable information about the susceptibility to rutting of the asphalt mixtures. With this information it can solve the objective raised in this investigation: to *distinguish the contribution to rutting of the asphalt mixtures of five different asphalts frequently used in Mexico*.

Evaluation of rutting using Spanish wheel tracking device

The Spanish standard NLT-173 (8), *Resistance to the plastic deformation of the bituminous mixtures by means of the wheel tracking tests*, was taken as the device for assessing rut resistance of 15 cm. diameter specimens made in laboratory with the gyratory compactor. In the Spanish standard NLT-173, it is specified that the testing specimen must be quadrangular of 30 cm. by side and compacted with vibratory equipment. For this study it was chosen to use specimens of 15 cm. diameter, compacted with SHRP gyratory compactor. This change was made due to the unavailability of vibratory equipment and because the SHRP gyratory compactor simulates better the field compaction.

The Spanish wheel tracking device is composed by an environmental chamber. Inside this chamber there’s a frame with a movable car where the specimens are placed. These specimens pass in a swinging movement, under a rubber surface wheel for a period of 120 minutes, at rate of 21 cycles per minute. This machine was jointly constructed between SURFAX S.A. de C.V. and the San Nicholas Hidalgo Michoacan University.

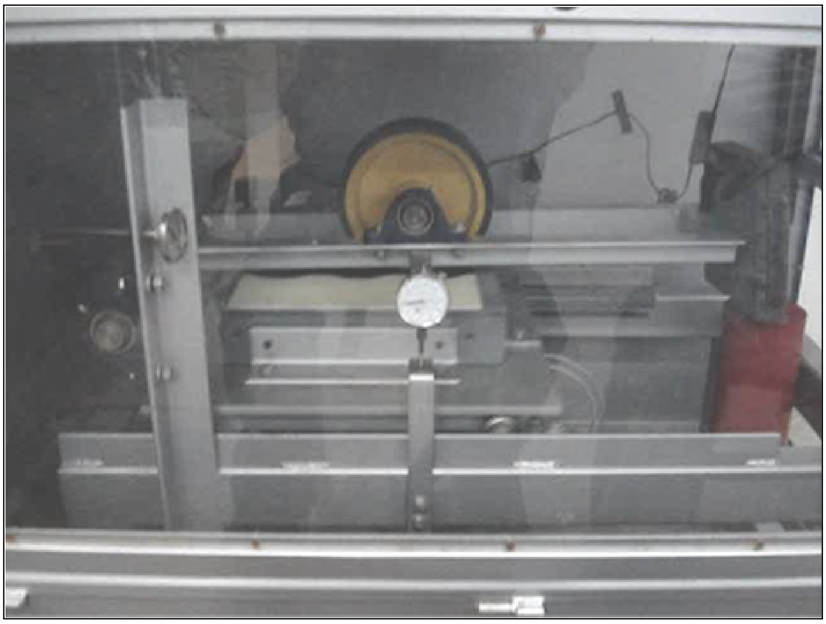

FIGURE 1 Spanish wheel tracking devise

Specimen preparation

Specimens were prepared in laboratory with aggregate from a quarry near Guadalajara city, Mexico; which had the following characteristics.

TABLE 7 Characteristics of aggregate used for this investigation

Test	Value	Required value in Mexican Specification
Los Angeles Abrasion, %	13.1	< 30
Elongated particles, %	13.8	< 35
Flat particles, %	18.1	< 35
Crushed particles, one face, %	92.5	Not specified
Absorption (coarse aggregate), %	1.9	Not specified
Density (coarse aggregate), gr./cm^3	2.7	> 2.4
Sand equivalent, %	68	> 50

The grading used is the established in Mexican Specification N·CMT·4·04/03 for a dense mixture, ESAL < 1x10^6, nominal maximum size of 12.5 mm and fitted to the upper limit (9). This grading was chosen because it is susceptible to deformation; this fact will allow to easily distinguishing the differences between the different asphalts used in this work.

The asphalts used for the manufacture of specimens were characterized previously by rheology. The asphalt content in the mixture was constant and equal to 8.5% the aggregates weigh, which was defined as optimum by Marshall Test. The mixing and compaction temperatures were 155 and 145º C respectively for AC-20, and 165 and 155º C for modified asphalts. These temperatures were established as is suggested on SUPERPAVE method for mixture design and also considering the experience in the use of modified asphalts.

Mixing was made with mechanical equipment and the compaction, as already indicated, was carried out with SHRP gyratory compactor. The parameters of compaction were an angle of **1.25º**, a pressure of **600 kPa** and **a revolution number of 28**. This revolution number was chosen in order to produce mixtures compacted with a high voids content (around 10%) so the mixture would be become deformed in the test period. All the specimens present bulk specific gravities between 2.051 to 2.083 (according AASHTO T-166) and air voids content of 9.2 up to 10.6%.

Selection of parameters for wheel tracking device

The objective of wheel tracking test was the determination of the differences between mixtures made with the same characteristics but with different asphalts. In Spanish wheel tracking device, it is possible to change the following parameters: a) test temperature, b) frequency of the passage of wheel and c) pressure of contact between the wheel and the specimen.

For this investigation it was considered suitable the parameters established in Spanish Standard NLT-173, where it states a frequency of wheel passage of **21 cycles per minute**, contact pressure of **9 kg/cm^2** and a test temperature of **60° C**. Additionally to this temperature other two were chosen: 1) the **high PG temperature** for each asphalt and 2) the **failure temperature plus three Celsius**; both established by SUPERPAVE method. These two temperatures were selected to verify if the results found by the rheology characterization of asphalts represent the performance of the mixture in wheel tracking device. Additionally, it could be possible to find some other differences between the susceptibility to rutting of the different mixtures (asphalts).

Experimental stage

All the tests on asphalt mixtures were made with the same type of aggregates, grading, asphalt content and compaction. The only changes between the tests were the type of asphalt and test temperature.

Tests at 60º C

This temperature was selected on basis of the Spanish specification NLT-173, which is the high temperature at which the pavements are in warm seasons.

It’s usual to report the results of the wheel tracking test like the speed of deformation between: a) 30 to 45 minutes, b) 75 to 90 minutes, and c) 105 to 120 minutes. Another value that could give some information is the deformation at 120 minutes (the maximum).

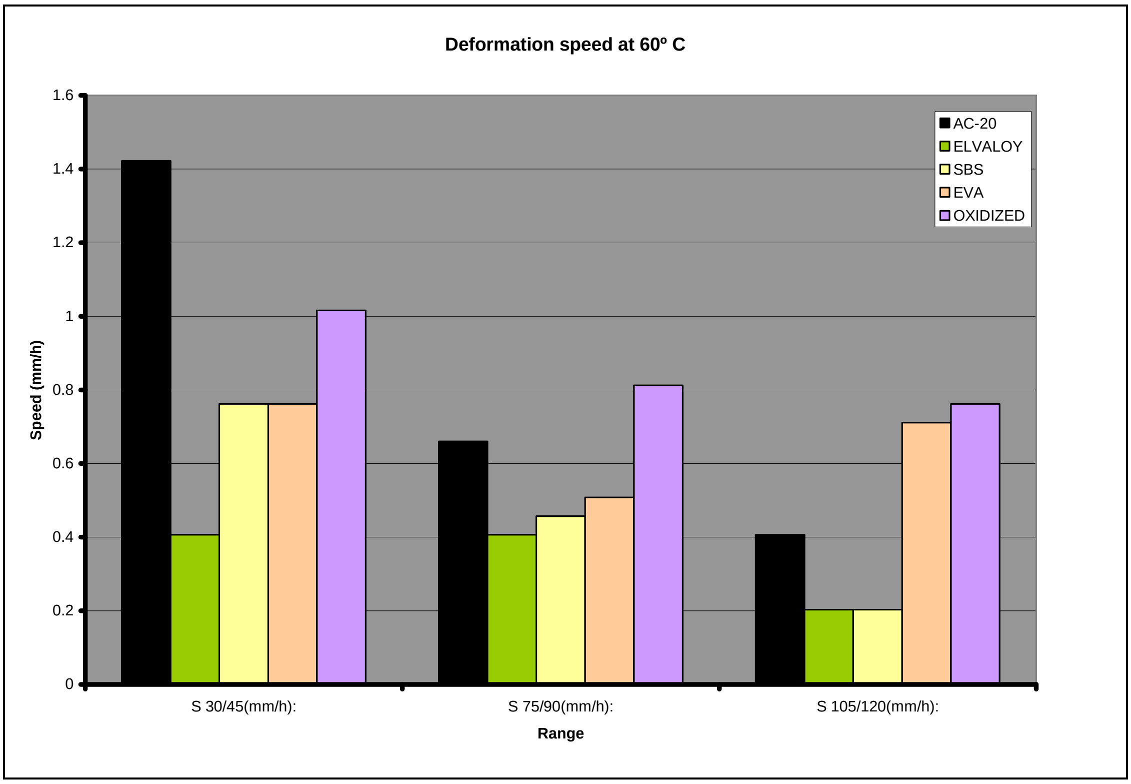

FIGURE 2 Speed of deformation at 60º C for different mixtures (asphalts)

In FIGURE 2, it is possible to observe that the mixture made with **Elvaloy** presents the **smaller speeds of deformation** in the three periods. Also, it can be observed that between 30 to 45 minutes the **greatest speed of deformation** belongs to **AC-20** (unmodified asphalt), in periods 75 to 90 minute and 105 to 120, the greatest speed of deformation is for **oxidized asphalt**, followed by **EVA**.

Tests at high PG temperature

The maximum PG temperatures, at which tests were run, were defined by the SUPERPAVE rheology characterization method. Thus virgin asphalt was tested at 70º C, whereas the other asphalts (the modified ones) were tested at 76º C. *It's important to consider this, because these temperatures would be different if other rheology method were chosen*.

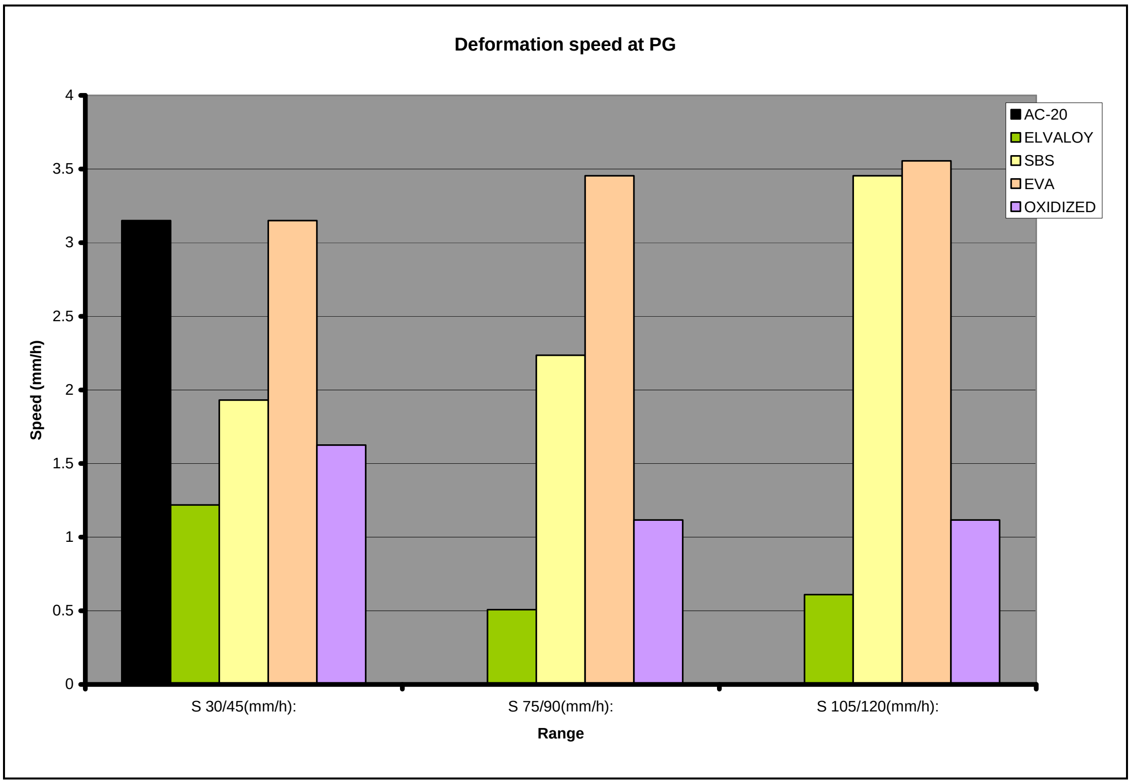

FIGURE 3 Speed of deformation at high PG temperature for different mixtures (asphalts)

In FIGURE 3 it is possible to observe that the **speed of deformation** for the three intervals is smaller for the mixture made with **Elvaloy**, followed by oxidized asphalt, SBS, EVA and finally **AC-20.** It is important to precise that for AC-20 it was not possible to collect deformation data after 75 minute. The deformation was extremely great and the machine was stopped around the 70 min. by the friction between the tire and the specimen rut. That's why, it was considered that AC-20 mixture fails.

In general, it is possible to assert that the mixtures with better results at the high PG temperatures were in first place the mixtures with Elvaloy, followed by oxidized asphalt, SBS, EVA and finally AC-20.

Tests at failure temperature plus 3º C

The failure temperature of an asphalt is defined as the temperature to which the G*/sin δ is equal to 2.2 kPa (for an asphalt aged in RTFO), in the specification defined in SUPERPAVE. If the rheology characterization predicts correctly the performance of mixture to rutting, when the test is run above the failure temperature, the plastic deformation that will appear on a specimen will be remarkably superior that the presented under that temperature.

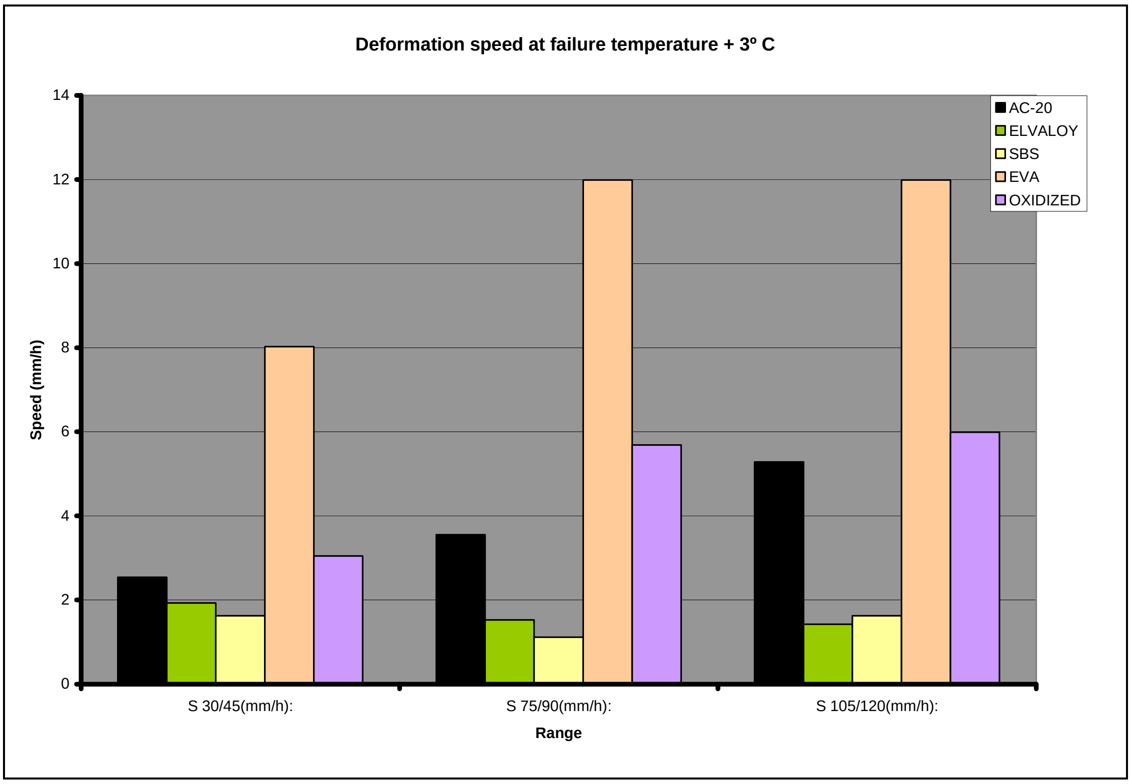

FIGURE 4 Speed of deformation at failure temperature plus 3º C for different mixtures (asphalts)

The graphic presented in FIGURE 4 shows that there are 3 asphalts more susceptible to rutting than the other 2. Checking up the results, the **SBS** has the smallest deformation speed followed by Elvaloy, AC-20, oxidized asphalt and finally **EVA**.

Maximum deformation at different temperatures

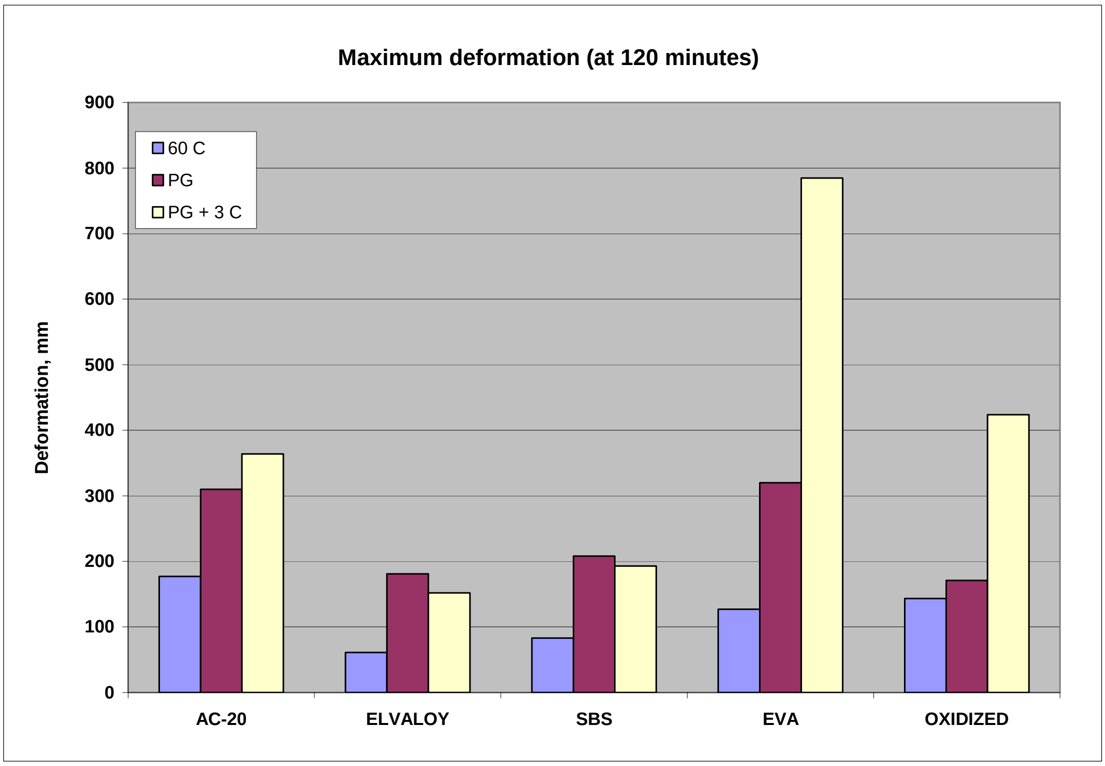

FIGURE 5 Maximum deformation at different temperatures

FIGURE 5 shows the deformation at 120 minutes. The general trend is Elvaloy and SBS present the less deformation, followed by oxidized, AC-20 and EVA. This trend is similar to the speed of deformation at all test temperatures.

RELATIONSHIP BETWEEN RUTTING IN WHEEL TRACKING DEVICE AND RHEOLOGY CHARACTERIZATION

In order to make the investigation objectively, the rheology characterization and wheel tracking test were made completely isolated, the only concurrence was the asphalts used in such analysis. In fact, the personnel who made the rheology characterization did not take part in wheel tracking test and vice versa.

The information presented in this article has been divided in two sections: 1) results obtained by rheology characterization and 2) results taken by wheel tracking test. For both sections it could be possible to order the results in a ranking, based on general trends. For rheology characterization this ranking considers the results of all methods and for rutting evaluation on wheel tracking device, it considers the maximum deformation and speed of deformation for each temperature. In the next table, both rankings are showed (1 corresponds to the best asphalt, that which fulfill the specifications for each test).

TABLE 8 Ranking of asphalt characterization and general trend of susceptibility to rutting of the mixtures

Asphalt	Rheology characterization	Mixture rutting
Elvaloy	1	1
SBS	2	2
Oxidized	3	3
EVA	3	4
AC-20 Salamanca	5	4

This ranking show easily if there exists or not a correlation between the results obtained in rheology characterization and susceptibility of mixtures.

The ranking elaborated classifies asphalts approximately in the same order, this fact shows a **good correlation between the performance of the asphalt mixtures evaluated in wheel tracking device and the performance "predicted" by the rheology characterization of asphalts.**

It is well known that the asphalt rheology characterization method proposed by SUPERPAVE is not suitable to be used in modified asphalts, since, the G*/sin δ parameter does not give sufficient importance to the phase angle (δ). That's why the failure temperature established by this method is lower than failure temperature given by other methods. This fact was also verified in the mixtures tested in wheel tracking device, because it is possible to appreciate that two of the mixtures (the ones made with Elvaloy and SBS), do not show an evident failure of the mixture like the others. When observing the failure temperature defined by another method (refined SUPERPAVE or ZSV), it can be seen that the failure temperature is superior to the one defined by SUPERPAVE + 3º C method. Therefore, there are two mixtures did not fail, since they were tested at lower temperature that their failure temperature, defined by other methods that are more suitable for modified asphalts. With this study was possible to confirm that **SUPERPAVE parameter (G*/sin δ) for rheology characterization is not suitable for evaluation of modified asphalts**.

Finally, it could be said that there is a good correlation between the susceptibility to rutting at different temperatures of the asphalt mixtures and the information provided by repeated Creep, the rheology characterization method. **The accumulated total deformation in the 20 cycles of repeated creep test increases, asphalt (or the mixture made with it), becomes more susceptible to rutting at different test temperatures**.

CONCLUSIONS

1. There is a good correlation between the information given by the suitable rheology characterization methods for modified asphalts (refined SUPERPAVE, ZSV and repeated Creep) and rutting measured with Spanish wheel tracking device at different temperatures.
2. This investigation confirms that SUPERPAVE rheology parameter, G*/sin δ, does not characterize suitable modified asphalts.
3. Repeated Creep test offers valuable information about the susceptibility of asphalt mixtures to rutting when changes in temperature occur.

4. The tests results show that asphalt modified with Elvaloy was the one that performed better to prevent rutting. In rheology characterization, asphalt modified with Elvaloy was the only one that fulfilled the specified values of elastic recovery in repeated Creep test and had the higher failure temperatures. Finally, asphalt modified with Elvaloy has the best performance in wheel tracking test at different temperatures; in fact, asphalt modified with Elvaloy was evaluated at the highest temperatures.

ACKNOWLEDGEMENT

The authors of this paper want to thank: Eng. Pedro Limón, Eng. Omar López, Eng. Noé Hernández and Eng. Delia Cortés, for their invaluable support for carry out this investigation.

REFERENCES

1. *SP-1 Superpave Performance Graded Asphalt Binder Specifications and Testing*. The Asphalt Institute, Lexington, KY, 2003.

2. Bahia, H.U., Hanson, D. I., Zeng, M., Zhai H., Khatri M. A., and Anderson, R. M., *Characterization of Modified Asphalt Binders in Superpave Mix Design*. NCHRP Report 459. TRB, National Research Council. 2001.

3. Shenoy, A. Refinement on the Superpave Specification parameter for Performance Grading of Asphalt. Journal of the Transportation Engineering, American Society of Civil Engineers, volume 127, No , September/October 2001, pp. 357-362.

4. Rowe, D'Angelo and Sharrock, *Use of the Zero Shear Viscosity as a Parameter for the High Temperature Binder Specification Parameter*, 2nd International Symposium on Binder Rheology and Pavement Performance, September 2002.

3. D Angelo, J. Dongré, R. Reinke, G. Evaluation of Repeated Creep and Recovery Test Method as an Alternative to SHRP+ Requirements for Polymer Modified Asphalt Binders. *Proceedings of the annual conference- Canadian technical asphalt association*. Canada, 2006. pp. 143-162.

4. Sousa, J. Craus, J. Monismith, C. *Summary Report on Permanent Deformation in Asphalt Concrete*. Publication SHRP-A/IR-91-104. National Research Council, 1991.

5. Kandhal, Prithvy S. & Cooley, L. Allen Jr. Accelerated Laboratory Rutting Tests: Evaluation of the Asphalt Pavement Analyzer. In *National Cooperative Highway Research Program Report 508*. TRB, National Research Council, Washington D.C., 2003, pp. 2-7.

6. Centro de Estudios de Carreteras. Norma NLT 173/00 Resistencia a la deformación plástica de las mezclas bituminosas mediante la pista de ensayo de laboratorio. *Normas NLT. I.- Ensayos de Carreteras*. Madrid, España. 1992.

7. Características de los materiales para pavimentos. *Norma mexicana N·CMT·4·04/03 de la Secretaría de Comunicaciones y Transportes*. http://normas.imt.mx/carr.htm. Accessed May 20, 2007