RTFOT BASED ON EQUIVISCOSITY WORKABILITY TEMPERATURE FOR WARM ASPHALT BINDER

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ABSTRACT

Simulation of short term aging with Rolling Thin Film Oven Test (RTFOT) is a widely used practice in asphalt binder characterization for predicting under controlled laboratory conditions its response to plant mixing and paving operations. With both Warm and High Viscosity Asphalt binders the plant mixing temperature and field work condition are not generally the same as for traditional binders and, consequently, the RTFOT standard temperature (163°C), could not have correlation with the asphalt mix bitumen performance, i.e. with its durability. The main purpose of this research project is the evaluation of a RTFOT procedure, associated with the tested binder viscosity, that justifies the appropriate lab conditions to simulate the effective short term aging during mixing and compaction.
In particular a Warm Asphalt binder, compared with a traditional one, were tested using the Dynamic Shear Rheometer (AASHTO T315 and EN 14770) and EN 13302 (Brookfield test) before and after short term aging with RTFOT (UNI EN 12607-1) at different temperatures. The evaluation of the rheological and physical properties of binder and respective mixes, affected by aging procedure, were conducted in order to validate the suggested test conditions.

Keywords: Warm Asphalt, RTFOT, DSR, Viscosity, Durability

1. INTRODUCTION

The origin of the equiviscous concept, which represents the standard method for determining appropriate temperatures for mixing and compacting in asphalt mixtures, was evolved through several decades in the mid 1900s. However, there is scarce documentation of the origin of this technique. During this time, many researchers have proposed different theories to define the correct temperatures. Nowadays, the second edition of the Asphalt Institute's Manual Series No.2 Mix Design Methods for Asphalt Concrete includes the equiviscous criteria for mixing and compaction of laboratory samples. The AI has used this practice in its Superpave mix design manual, SP-2. In 2009, AASHTO balloted a revision for T 312 to include viscosity criteria for mixing and compaction as 0.17 ± 0.02 Pa·s and 0.28 ± 0.03 Pa·s [1].
In these recent years, the Warm Mix Asphalt (WMA) are spreading widely in the new road constructions and pavement rehabilitations. The WMA base process is to modify the binder viscosity with additives, like waxes, that ensure lower mix and compaction temperatures. The mixes increase their workability, so to reach the viscosity values fixed by AI, the request temperatures are lower than that used with the traditional ones.
The European Standards fix an unique reference temperature to evaluate the binder properties after ageing by using the Rolling Thin Film Oven Test (RTFOT). The RTFOT are intended to simulate age hardening which occurs in the pug mill of a hot mix batch plant during mixing and compaction of HMA [1]. Excessive temperatures during processing and storage of binders as well as during HMA production have several serious consequences [2]. When materials are being laid at low ambient temperatures, or if haulage over long distances is necessary, mixing temperatures are often increased to offset these two factors. However, increasing the mixing temperature will considerably accelerate the rate of bitumen oxidation which will increase the viscosity of the bitumen. Thus a significant portion of the reduction in viscosity achieved by increasing the mixing temperature will be lost because of additional oxidation of the bitumen [3].
Applying the standard RTFOT at 163°C on a WMA, which is workable at lower temperature, the test could generates an "overaging" on the binder that increases the hardening and oxidation reducing its durability compared with the one that occurs during their mixing and compaction. It should be better for each wax added binder, establish a reference temperature, of equiviscous starting condition, to conduct the RTFO test, that simulates the effectiveness temperature value achieves during the processes for a given materials.

2. EXPERIMENTAL PROGRAM

This paper presents the results of a comprehensive study conducted on a Warm asphalt binder, in comparison with the Neat original one, and the respective mixes. The specific objectives are as follows:

- evaluate for each kind of binder its properties: penetration, softening point and viscosity in accordance to the European Standards;
- identify a characteristic binder temperature, called Workability Temperature (T_{work}), that corresponds to the relative temperature necessary to guaranty the binder workability in terms of mixing and compaction processes;
- mix and compact the aggregates with both binders at the T_{work} and evaluate the mixtures mechanical properties and durability;
- perform the short aging procedure on both binders using the European Standard Temperature and the defined T_{work};
- perform on aged and unaged binders rheological tests in order quantify the aging level to which the Warm Asphalt could be subjected;
- comparison between the binder Master Curves aged at T_{work}, T_{RTFOT} and on the extraction binder from respective mixes to validate the aging procedure.

The experimental program followed in this study is shown in Figure 1. Two binders were used, a traditional binder and a warm binder obtained by adding Wax to the previous one.
The research study was divided up into consequential steps that contain tests carried on both binders and mixtures. The traditional and mechanical tests used were performed in accordance to the European Standards. The base bitumen tested in this research is a binder with penetration grade of 70-100 dmm, commonly used in European road constructions. The Warm asphalt was obtained adding the 2% of Wax by mass of binder [4].

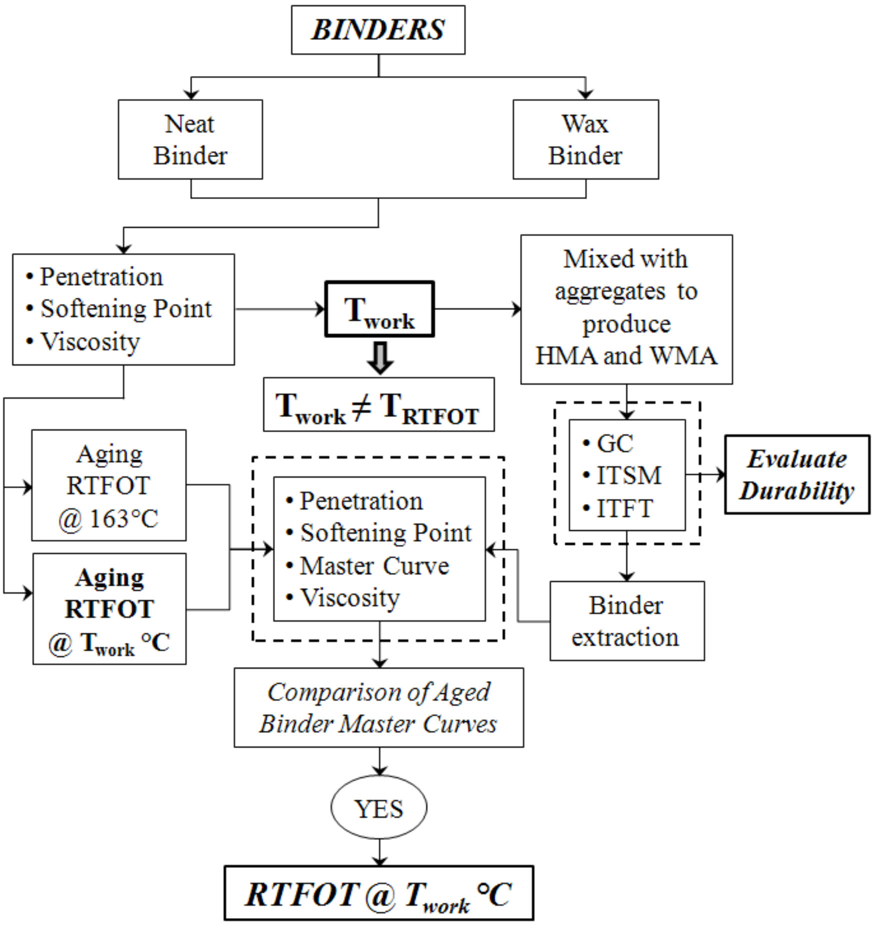

Figure 1: Experimental Program Flow Chart

3. FIRST STEP: T_{work} DEFINITION BY EN 12591 TESTS

Penetration, Softening Point (Table 1) and Dynamic Viscosity (Figure 2), were conducted in accordance to the European Standards. The wax generates a reduction of penetration grade and consequently an increase in softening point. This change in properties is due to crystallization of introduced wax.

Table 1: Binder properties: Penetration and Softening Point

Sample	**Penetration EN 1426**	**Soft. Point EN 1427**
Neat Binder	87.0 dmm	45.6°C
Wax Binder	72.0 dmm	59.2°C

Mixing and compaction temperatures are generally related with binder viscosity which depends on binder grade and composition. Consequently, the equiviscous temperatures or Workability Temperatures (T_{work}), for a viscosity reference assumed by the Asphalt Institute as 0.17 Pa·s, are not the same for all binders used on road construction. For example, a PmB needs of higher temperatures for mixing and laying than a neat asphalt cement. Instead, the wax addition, generating a decrease in viscosity at high temperatures, reduces the binders T_{work}.
The Dynamic viscosity test (EN 13302) was the application of choice in order to define the T_{work} for the study binders. In Figure 2 are summarized the viscosity curves found for the Neat and Wax binders.
The temperatures found in correspondence of the 0.17 Pa·s viscosity are: 140°C for the warm binder and 155°C for the neat binder, the studied Wax engenders a temperature decrease of 15°C. The obtained Workability Temperatures (T_{work}) are used to mix and compact two different mixtures in the following experimental step.

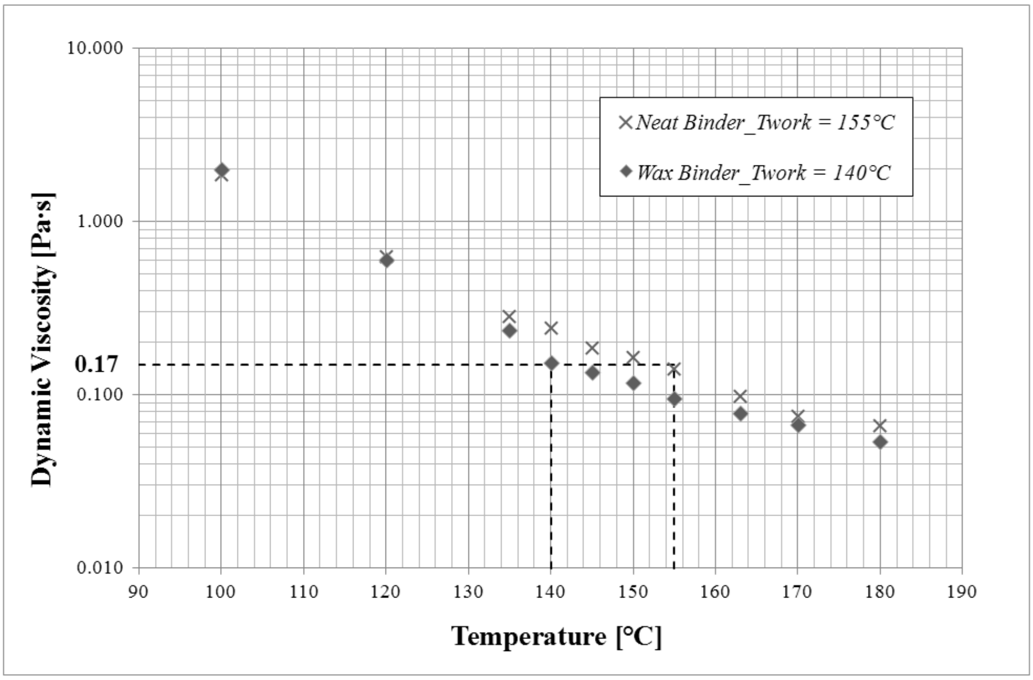

Figure 2: Binder properties – Dynamic Viscosity Curve

4. SECOND STEP: TESTS ON BITUMINOUS MIXTURES PRODUCED AT THE RESPECTIVE T_{WORK} AND RESULTS COMPARISON

In order to validate the Workability Temperature (T_{work}) obtained by Dynamic Viscometer, the studied binders were used to design two different asphalt mixtures based on the same gradation (Figure 3) with a binder content of 5.25% expressed by mass of aggregates.

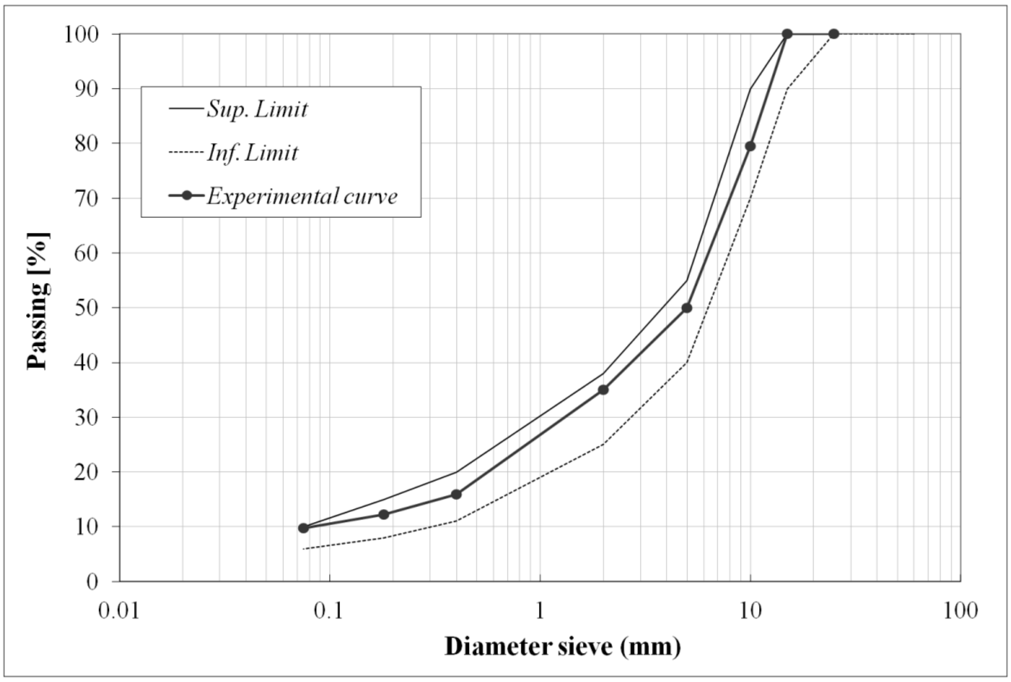

Figure 3: Mix gradation.

The main purpose of this research step is to evaluate if the difference in mixing temperature generates volumetric and mechanical variations on bituminous samples. This comprehensive study involves these primary tests:

- Gyratory Compaction (EN 12697-31);
- Indirect Tensile Stiffness Modulus Test (ITSM) (EN 12697-26 CY);
- Indirect Tensile Fatigue Test (ITFT) (EN 12697-24 CY).

A total of 6 specimens for each type of binder were compacted, having the following dimensions: 150 mm in diameter and 60 mm in thickness. Table 2 summarizes the air voids distributions and the Standard Deviation.

The Gyratory Compactor (GC) was the application of choice for the specimens preparation because it represents a well assessed test for workability control of asphalt mixes [5]. The GC operated by applying constant conditions of vertical pressure of 600 kPa, with an angle of gyration 1.25 deg, and rotational speed of 30 rpm, as suggested by EN 12697-31. In addition the norm suggests a compaction temperature related with the bitumen grade (EN 12591) which was respected during specimens production.

Table 2: mixes volumetric properties.

Results of Gyratory compaction					
Asphalt Mix Type	N° of Specimens [#]	Av. Air voids [%]	St. Deviation [%]	Mixing Temp. [°C]	Gyrations N°
Neat Mix	6	6.3	1.3	155	120
Warm Mix	6	6.6	0.8	140	120

In Table 2 are reported the compaction results: the volumetric properties of the specimens are not sensibly affected by the different Compaction Temperature. Both mixes exhibit almost the same average air voids content but different Standard Deviation. The Warm Mix Asphalt presents a Standard Deviation of 0.8 compared to 1.3 of the Neat one. This peculiarity could be consider highly related with the wax addition in asphalt binder. Its positive contribution is not only under the environmental and energetic point of view, with the reduction in workability temperature, but seems also related with the capability to obtain a more homogeneous and consequently durable asphalt mixtures. All the compaction curves of the study mixtures are summarized in Figure 4.

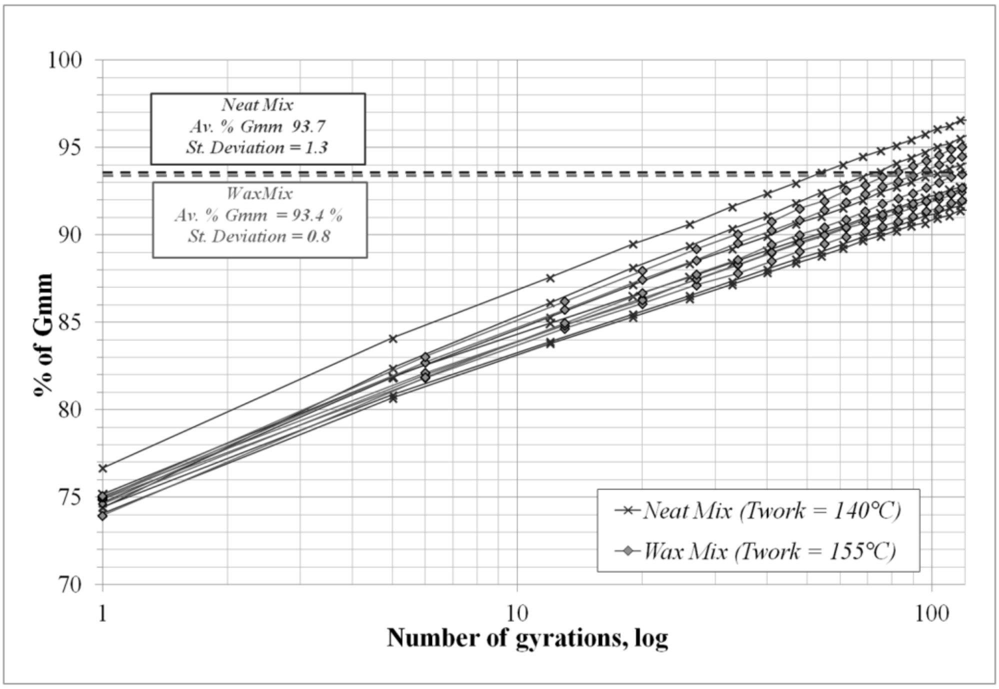

Figure 4: study mixtures compaction curves.

5.1 Asphalt Mixes Mechanical Characterization: Stiffness Modulus and Fatigue Strength

The mechanical characterization, Stiffness Modulus and Fatigue resistance, of the samples was completed using a simple closed-loop computer controlled pneumatic testing system. Stiffness Modulus is dependent on a number of factors such as: asphalt mixture composition, binder grade and level of compaction as well as of test conditions (temperature, loading time). Principle of ITSM test is that cylindrical specimen is subjected to repeated sinusoidal compressive loads through the vertical diameter plane, which develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane. The resulting horizontal deformation of the specimen is measured and a Poisson's ratio, assumed as 0.35, is used to calculate the tensile strain at the centre of the specimen. Prior to testing, all specimens were stored in a conditioning cabinet at the test temperature for at least three hours [6].
The ITSM test was performed respecting these configurations:

- Dry conditions;
- Five temperatures, namely 5°C, 10°C, 20°C, 30°C, 35°C;
- Loading rise-time 124 msec;
- Peak transient horizontal deformation 5 ± 2 μm.

Based on ITSM results (Figure 5), it is possible to infer as follows. The traditional asphalt mix is Stiffer than the one with Wax at all the studied temperatures. The temperature during mixing and compaction affects the binder aging and hardening consequently to an increase in T_{work} corresponds an increase in Stiffness modulus. The Neat mix, as a consequence of highest air voids standard deviation, exhibits highest Stiffness standard deviation strengthening the hypothesis of higher properties variability. Higher modulus not necessary guaranties better fatigue performance [9].

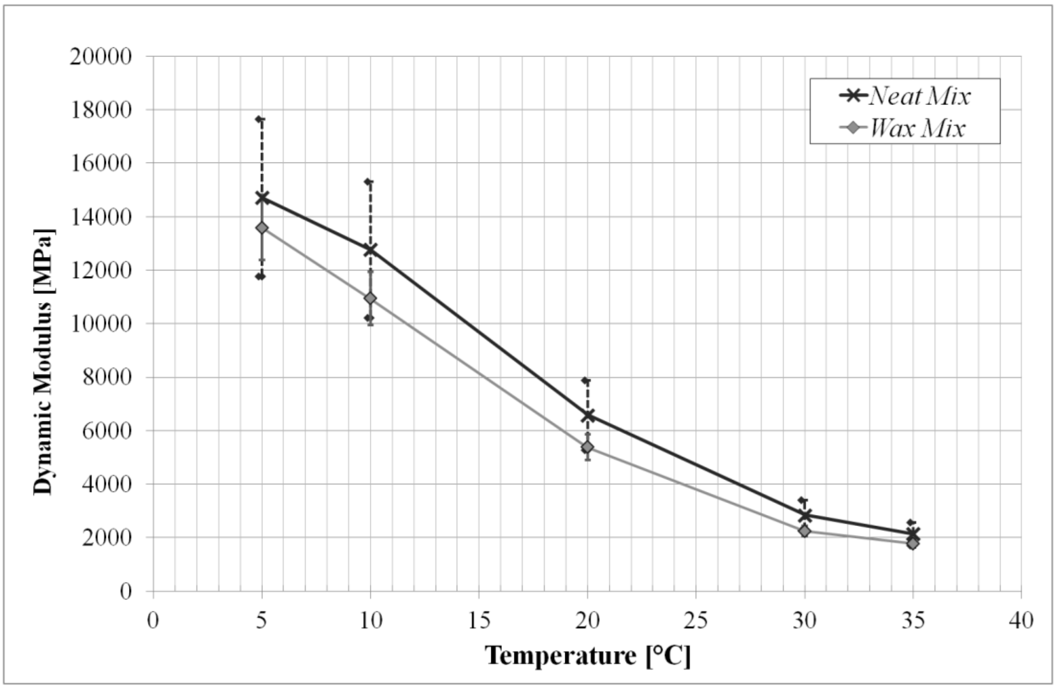

Figure 5: ITSM vs temperature.

In terms of Fatigue, the repeated load indirect tensile test (ITFT) is a simple and fast method for testing fatigue properties of asphalt mixtures. The procedure is used to rank asphalt mixes on the basis of resistance to fatigue to obtain data for estimating the structural behavior in the road and durability. The fatigue life is defined as the total number of load applications before fracture of the specimen occurs.

The fatigue test was performed in stress-control condition where the magnitude of the applied stress pulse is maintained constant until failure. According to UNI EN 12697- 24 the failure points were expressed as a function of initial horizontal tensile strain at the center of the specimen (ε_0) which is calculated as follows (1):

$$\varepsilon_0 = \frac{\sigma_0 \times (1 + 3\upsilon)}{S_m} \times 1000 \qquad (1)$$

where

σ_0 is the tensile stress at specimen center (kPa);

S_m is the Stiffness Modulus (MPa) at the test Temperature;

ν is the Poisson's ratio assumed 0.35.

The ITFT was performed respecting the following configuration:

- Dry conditions;
- One temperature, namely 20°C;
- Loading rise-time 124 msec;

The results, summarized in Figure 6, show that there are not sensibly differences between the studied mixes.

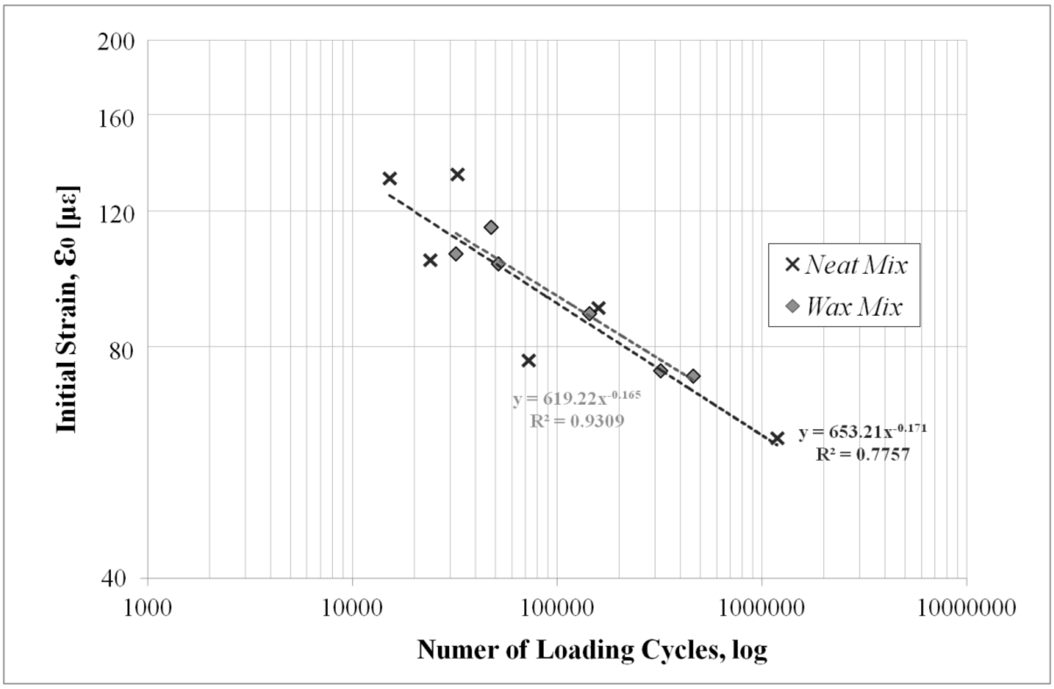

Figure 6: ITFT of the asphalt mixtures at 20°C.

The fatigue resistance of the Neat Mix confirms the non homogeneous behavior with the highest results dispersion.
The use of Warm Mix Asphalt, such as Wax Mix, permits to reduce the production temperature, conserving the mix mechanical performance. Furthermore, the Wax binder, being heated at lower temperature, is subjected to a reduced short term aging compared to the Neat one and consequently it will present improved long term resistance. Oxidative aging is an important factor in the long term performance of asphalt pavements. Oxidation and the associated stiffening can lead to cracking, which in turn can lead to the functional and structural failure of the pavement system. Therefore, a greater understanding of the amount of oxidative ("short term") aging in asphalt mixes can potentially be of great importance in estimating the performance of a pavement before it is constructed [7].
In order to verify and quantify how the reduction in workability temperature reduces the binder short term aging oxidation, Rolling Thin Film Oven Test (RTFOT) was performed at different temperatures and the aged binders were successively tested. Both binders were conditioned at 163°C, as prescribed by EN 12607-1, and at the respective workability temperatures (T_{work}) because these represents the real temperature reached during mixing and compaction.

5. THIRD STEP: AGING EFFECT ON BINDER PROPERTIES

The overall objective of the third step was to investigate the aging differences in binder properties after RTFOTs at different temperatures. Beyond Softening point, Penetration and Viscosity, the Dynamic Shear Rheometer was used for the study of Complex Shear Modulus.

6.1 EN12591 tests on aged binders

The same tests were conducted on both binders aged in accordance to the EN procedure at 163°C and on the bitumens aged at the workability temperature measured in the first step. The results recorded by penetration test, show that the choice of the aging temperature influences more the Wax Binder than the traditional one. It could be explained analyzing the different temperature used during the aging procedures (Tables 3 and 4).

Table 3: Penetration data on aged binders.

Penetration EN 1426					
Sample	Pre RTFOT	Post RTFOT @ 163°C	Δ% ref. to Pre RTFOT	Post RTFOT @ T_{work}°C	Δ% ref. to Pre RTFOT
Neat Binder	87.0 dmm	40.6 dmm	46.7 %	41.7 dmm	47.9 %
Wax Binder	72.0 dmm	35.0 dmm	48.6 %	42.3 dmm	58.7 %

Table 4: Softening Point data on aged binders.

Softening Point EN 1427					
Sample	Pre RTFOT	Post RTFOT @ 163°C	ΔT°C ref. to Pre RTFOT	Post RTFOT @ T_{work}°C	ΔT°C ref. to Pre RTFOT
Neat Binder	45.6°C	56.6°C	11.0°C	54.0°C	8.4°C
Wax Binder	59.2°C	78.7°C	19.5°C	73.0°C	13.8°C

The retained Penetration of Wax Binder aged at the T_{work} is 58.7% while the retained Penetration at EN 12607-1 RTFOT condition is 48.6%. The same binder aged in accordance to the European Standards seems to be overheated with a higher decrease in performance; the test carried out at this temperature could be not representative of the real aging that occurs during field mixing and compaction. In the Neat bitumen the difference recorded after the aging test is less marked, this is due to the lower temperature gap existent between the T_{work} (155°C) and the 163°C of the EN RTFOT (Figure 7).

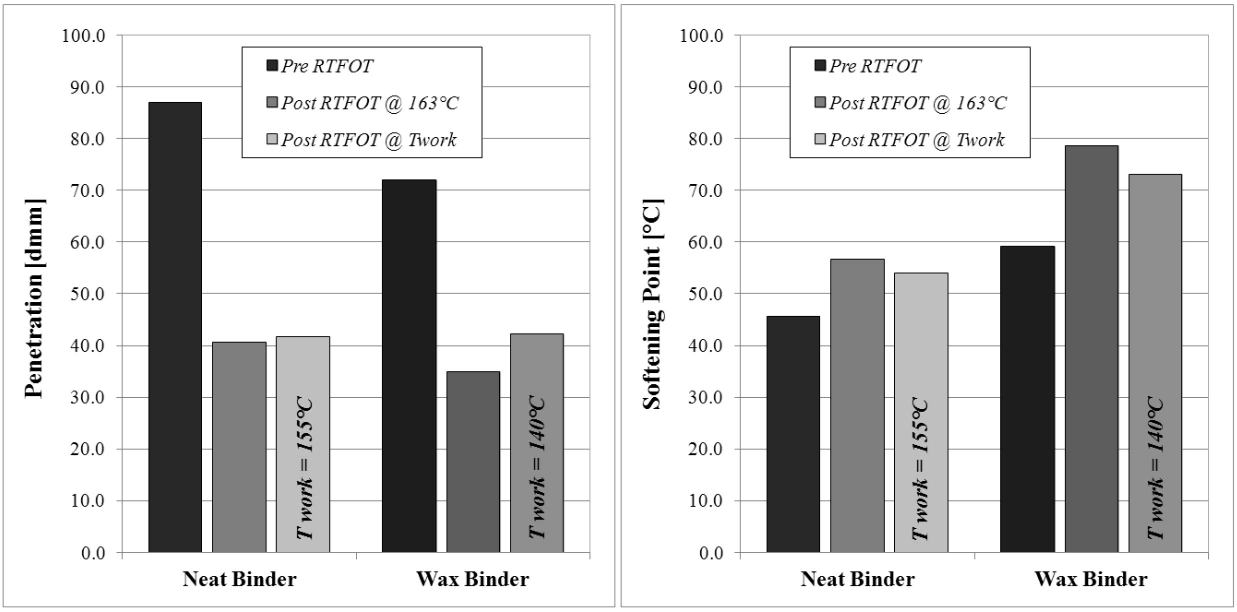

Figure 7: Comparison of penetration and softening data on aged binders.

The different results observed during the penetration test were confirmed by the softening point test, also made on the aged bitumens at the different temperatures. The lower aging temperature reduces the oxidation effect, that consequently generates a lower hardening in the bitumen [7].

6.2 Dynamic Shear Rheometer Test results

The DSR test was performed as follow:

- Frequency Sweep, from 0.01 to 10Hz;
- four temperatures, namely 10°C, 25°C, 40°C and 50°C;
- one strain level, related with the test temperature and type of binder;
- two replicates.

Dynamic Shear Rheometer (DSR) tests were conducted on both unaged binder (Neat and Wax Binder) and aged with RTFOT at T_{work} and RTFOT at 163°C. With the DSR test, Complex shear modulus, G^*, and Phase Angle, δ, of the binder were measured. A total of six Master Curves were calculated (Figures 8, 9).

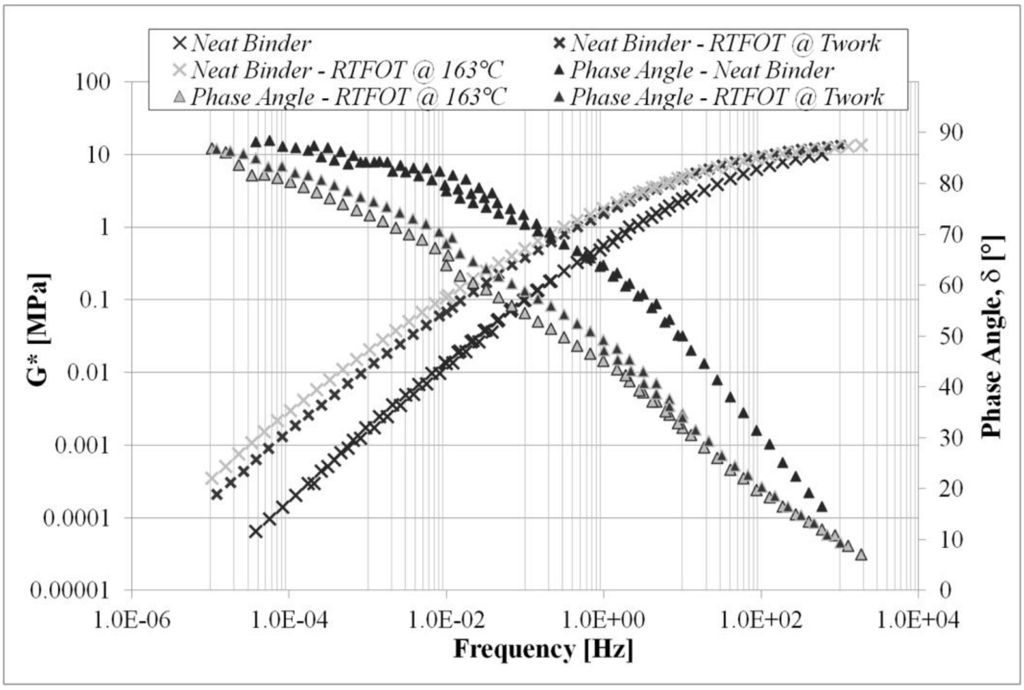

Figure 8: Neat Binder Master Curves data at 25°C.

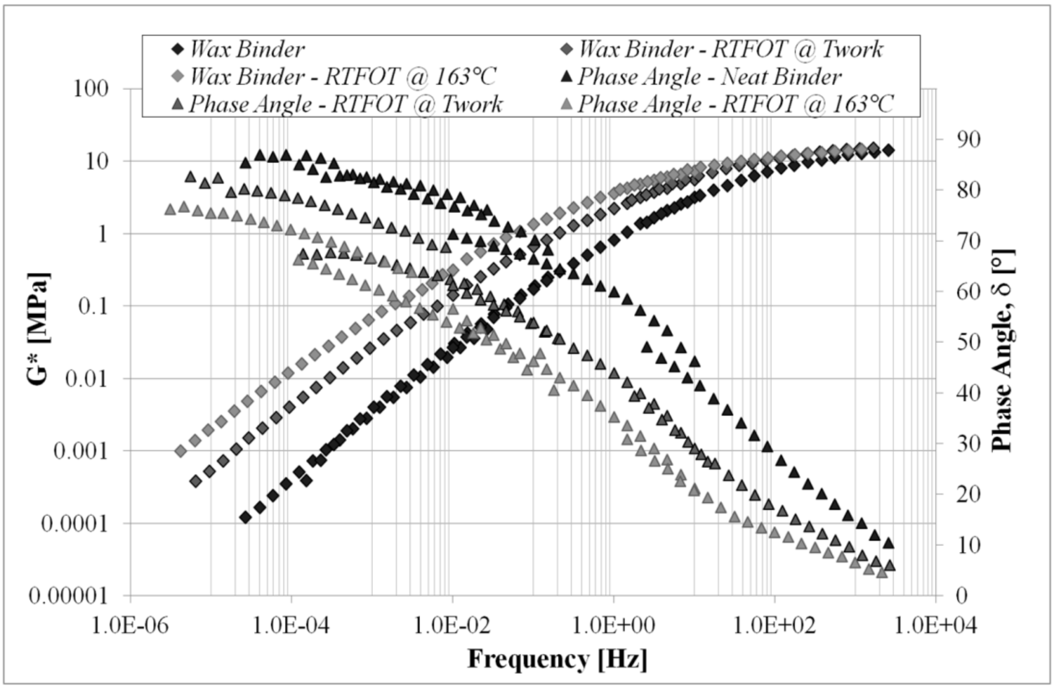

Figure 9: Wax Binder Master Curves data at 25°C.

In order verify and validate the RTFOT at T_{work}, the binders used for the asphalt mix specimens preparation, in the second step, were opportunely extracted, in accordance with EN 12697-3, and tested with the DSR.
Figures 10 and 11 summarize the Master Curves data for recovered binder.
Upon analyzing the results the following observations can be made:

- adding the Wax, the Complex Shear Modulus results increased at all the testing frequencies; in particular the Modulus variation is dependent on the shear frequencies.
- the binder aging level is affected by the RTFOT temperature. With regard to the Wax Binder, a reduction in RTFOT temperature from 163°C to 140°C, assumed as a T_{work}, permits to limit the binder short term oxidation and consequently to better preserve the binder properties. With the Neat one, the differences between aged binder Master Curves (at 163°C and 155°C) are less remarkable.
- The Wax appears to modify the typical thermo-rheological binder behavior. Its addition in the bitumen not only increases the Shear Modulus but even affects the Master Curves calculation making the Wax Binder not completely thermo-rheologically simple. In fact, it generates an interval of low frequencies where the principle

of time temperature superposition is not verified for the Phase Angle while being verified for the Complex Shear Modulus. This could lead to consider the Wax Binder a “Complex Binder” [10].

- Figures 8 and 9 show that the Wax Binder tend to suffer more the RTFOT at 163°C than the Neat one. In fact the increase in percentage of the Complex Shear Modulus, between unaged and aged (163°C) is sensibly higher with Wax Binder. Comparing the results, of both binders, considering RTFOT at T_{work}, the increase in Complex Shear Modulus are comparable. The Wax reduces the binder viscosity at high temperatures and consequently modify the behavior of the binder thin film during the RTFOT. The lower is the viscosity the higher is the binder exposed surface change rate inside the RTFOT glass. Could the viscosity be considered related with level of aging? Based on these assumptions, it is possible to infer that the aging of the binder in RTFOT is not only related to the type of binder and to the test temperature, but also to the viscosity of the binder itself at the RTFOT temperature. These results makes reasonable the hypothesis to evaluate the short term aging at the workability Temperature referred to 0.17 ± 0.02 Pa·s.

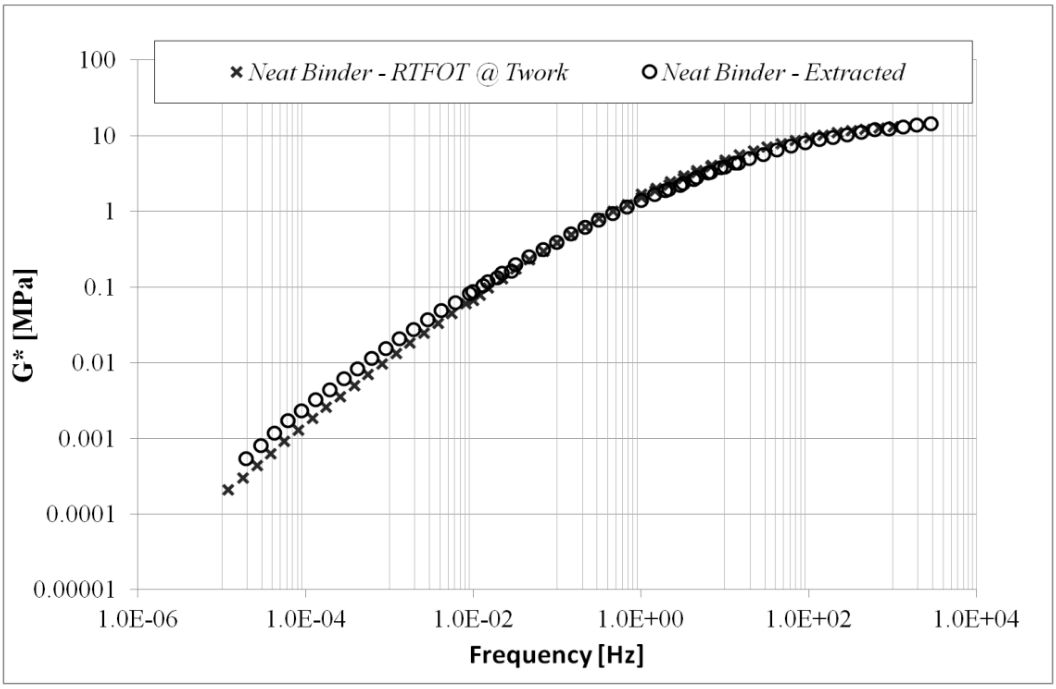

Figure 10: Master Curves at 25°C of Neat Binder Extracted and after RTFOT at T_{work} (155°C).

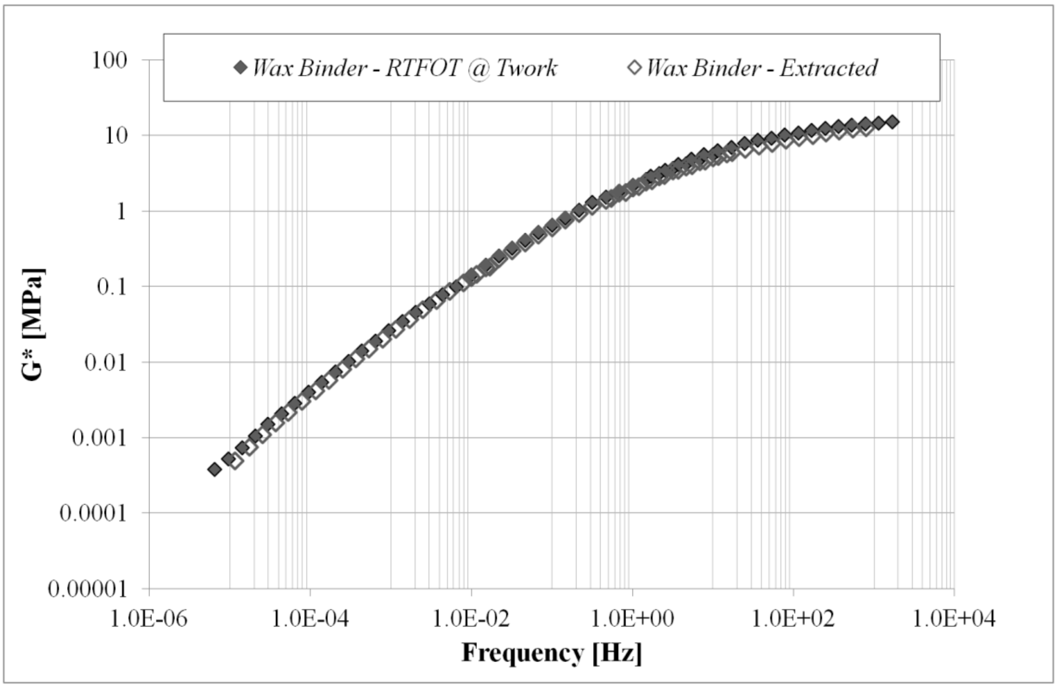

Figure 11: Master Curves at 25°C of Wax Binder Extracted and after RTFOT at T_{work} (140°C).

- The Master Curves from extracted binders are perfectly correlated with the respective Master Curves obtained from binder aged with short term procedure (RTFOT) at T_{work} (Figures 10, 11). These results confirm the appropriate choice of the T_{work} and justify the lab condition as representative to simulate the short term aging.

7. CONCLUSIONS AND RACCOMANDATIONS

The study Wax, added in small portion to the bitumen, reduces the binder viscosity at high temperatures improving its workability. In fact Wax Binder reaches the viscosity of 0.17 Pa·s, assumed by the AI as referring viscosity for mixing, at lower temperature respect the Neat one and consequently permits to decrease the relative bitumen oxidation. A reduction in initial oxidation could reduce cracking and thus improve the long term pavement durability [11, 12, 13].
In asphalt laboratory characterization, the binder durability is evaluated considering the aging resistance. The short term aging procedure (RTFOT), as suggested by EN, causes an "overaging" on the Wax Binder compared to the Neat one. In fact, based on tests results, the binder viscosity at the RTFOT temperature conditions the level of aging to which the binder itself results subjected. The RTFOT at T_{work}, founded on equiviscosity criteria, is more representative of the real short term aging that occurs during the asphalt mixing and compaction.
The tests results shown that:

- The Workability Temperatures (T_{work}) evaluated in the first step are different compared to the RTFOT temperature suggested by EN. The Wax Binder (T_{work} = 140°C) has a lower value than the Neat one (T_{work} = 155°C).
- Volumetric and mechanical properties were evaluated for both studied asphalt concretes mixed at the respective workability temperatures. The Wax Mix presents a more homogeneous behavior compared to the traditional one. The Neat mix presents a Stiffness Modulus higher than the Warm mix due to the higher workability temperature and consequently higher binder hardening. The fatigue results, related with the test configuration used, show that the Wax Mix performance are comparable to those exhibit from the Neat one.
- the Wax Binder presents a higher Complex Shear Modulus than the Neat one. Even the behavior, in terms of Master Curves, seems affected by the additive making the Wax Binder "not completely" thermo-rheologically simple. After short term aging test, the variation in rheological properties are not only dependent by the binder characteristics and temperature but also from the binder initial viscosity at the aging temperature (Table 5).

Table 5: Binder initial Viscosity at RTFOT aging temperatures.

Sample	Viscosity at T_{work}°C [Pa·s]	Viscosity at 163°C [Pa·s]
Neat Binder	0.170	0.100
Wax Binder	0.165	0.078

- The extracted binder Master Curves are comparable with the binder aged at T_{work} confirming that the RTFOT at 163°C is not representative of the real short term aging to which the asphalt binder are subjected.

In summary, the Authors state that:

- traditional binders conditioning by RTFOT well represents short term aging because the limits in EN 12951 specifications are fitted for each grade. The results obtained on the Neat Binder sample are in accordance with this assumption;
- Warm Asphalt binders conditioned according to EN 12607-1 are penalized in durability performance evaluation. The equiviscosity concept in RTFOT should be applied in order to consider and represent the reduced temperature advantages during field application;
- Polymer Modified binders conditioning should be investigated because their high viscosity could cause a durability overestimation at current EN 12607-1 conditions.

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