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Effect of Thermal Cycling on the Creep-Recovery Behaviour of Road Bitumen

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Abstract

Pavement performance and the viscoelastic behaviour of bitumen, transmitted to the asphalt wearing course, depend mainly on the qualities behind the binder and its thermal history on the site.

The current climate changes generate exceptional variations in temperature. Changes in the climatic environment, such as sudden changes in temperature, the surface layers exhibit a severe cyclical freeze/thaw in winter or in cold region. During the summer or in hot region the phenomenon of heating/cooling causes hardening of the binder and therefore the pavement.

The regional thermal factor and his instability, in the same day, have a significant role in the evolution of viscoelastic properties of the binder on site and remain the main causes of pavement deteriorations.

Two types of thermal cycles were simulated in the laboratory on samples of asphalt of the same origin, followed by a creep-recovery characterization using the DSR. An analogue model of three elements has been proposed to simulate the rheological behaviour of binders. We recorded significant differences in rheological response, such as the evolution of viscoelastic properties and deformability, according to the type of thermal cycle and the applied number. These differences are found between the original sample and all samples that have undergone thermal cycling on the one hand, and between the two types of heat treatment of the other.

The behaviour of the asphalt binder, after certain number of thermal cycle (operating period) depends on the nature and characteristics of climate in the region and the exposure time of the binder to thermal cycles.

The geo-climatic factor and its changes have become essential parameters in the prediction of pavement behaviour on site and estimation of their life.

Keywords: Bitumen Behaviour, freeze/thaw cycles, heating/cooling cycles, creep-recovery, rheological model.

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Nomenclature

θ_{inf}	inferior temperature (°C)
θ_{sup}	superior temperature (°C)
σ_0	imposed stress (Pa)
E_1	elastic modulus of the material (Pa), spring
η_1	viscosity component of the material (Pa.s), dashpot1
η_2	viscosity component of the material (Pa.s), dashpot2
ε	strain (-)
t	time (s)

1. Introduction

The variation of temperature on the road depends on weather conditions (uncontrollable). In cold or continental climate, snowmelt and snow removal during the winter exposes road to a phenomenon of freezing/thawing. In warm areas, summer is very severe. The surface temperature often exceeds 40 °C, through the peaks of 60 to 65 °C in the hot zones. The differences in temperature between day and night are very important. The weather is often unstable, combined with the rapid changes in temperature, leading to a phenomenon of heating/cooling due to sunlight and ventilation caused by the flow of air. These gradients cause thermal stresses and internal changes in the viscoelastic properties of the surface layers.

During operation, the structure of the surface layer suffers as a result of these thermo-cyclical phenomena and gradually deteriorates. This loss in quality may develop a poor performance. Bitumen is the most sensitive to changes in climate; he plays the biggest role in the phenomena of deformation and cracking of asphalt mix. The properties of this binder, like other organic substances, can be influenced by changes in temperature and the presence of oxygen, as well as ultraviolet radiation on site [1].

Knowledge of this evolution is necessary for understanding and controlling the behaviour of bitumen in specific climates, in different regions. It links the performance and binder quality with the climatic conditions of commissioning of the mix, and to take account of sustainability in a climate-specific sizing. This is expressed through rheological characterization, which can be directly related to the mechanical properties and evolution of the chemical structure.

However, current methods of pavement design traffic and aircraft do not take into consideration the specific climatic conditions and thermal history of bituminous materials, for each region. In reality the effect of this phenomenon adds to the effect of traffic and it is not considered when standard tests to characterize fatigue.

For all these reasons, it is useful to study the influence of these cyclical phenomenon that lead to thermal fatigue on the evolution of rheological and mechanical properties of a bitumen road. We will implement and analyze the results of a thermal conditioning cycle on different samples of the same origin. These samples will be subject to the application of thermal cycles of freezing/thawing and heating/cooling, in extreme temperatures and cycle times chosen. They will then be followed by a rheological characterization. To assess the effect of these thermal treatments on the viscoelastic qualities of the material, creep tests-recovery are performed using a rheometer plan/plan (DSR). The analysis of the response of the binder creep-recovery is based on a rheological model that will deduct viscoelastic parameters. The objective is to predict the behaviour of bitumen and assess properties for different thermal conditions compared with those of the control sample.

2. The phenomenon of thermal cycling

The design of conventional asphalt layers is based on the concept of average temperature equivalent, representing an average annual climate. However, rapid and repeated changes in temperature due to day/night create a thermal cycling of wearing marking accelerated degradation, which manifests itself over time by increasing a dangerous rigidity, fragility or rutting.

Extreme temperatures in daily and seasonal temperature variations are very important in some regions, as is the case in the larger world Sahara(North Africa, Middle East, and America,…), where the temperature prevailing in the road can reach 65 °C, with a gap during the night 30 °C. During the winter, temperatures can reach negative values at night, or even -10 °C or less in cold regions and highlands. The temperature difference is similar to that experienced in the summer. In Europe, according to the French National Group Bitumen [2], this phenomenon is crucial in the south than in the north, a difference of 5 °C can delay or accelerate the risk of cracking a period of about three years.

The asphalt is a material sensitive to thermal stress. The thermal factor acts as a parameter of history in its degradation. In extreme temperature conditions, the asphalt loses its linear viscoelastic:

- At low temperature it becomes more fragile and tends to crack (shrinkage),
- At high temperature it becomes susceptible to permanent deformation (creep).

The thermal solicitation in regions of strong temperature variations, the permanent deformation, the shrinkage of bitumen, and its physicochemical evolution can lead to accelerated damage due to thermal fatigue following to loss of viscoelastic and mechanical characteristics. This leads to dangerous deterioration resulted in rigid, fragile and anarchic propagation of cracks or rutting. It also remains a major concern for owners, especially with increasing aggressiveness of traffic and maintenance costs.

It's imperative to evaluate the intrinsic properties that contribute to better prediction of the evolution of in situ bitumen behaviour, under the influence of the phenomenon of thermal cycling [3]. Traditional measures (Temperature of Softening point Ring and Ball and Penetration) are not always relevant vis-à-vis the permanent deformation and cracking. Other elements of information are of course necessary, especially those that reflect the viscoelastic behavior and take into account the influence of cyclical history of thermal effects on the qualities of bitumen. This is true of measures that characterize the thermomechanical behaviour in a wide temperature range of operation.

Moreover, the determination of rheological parameters can be a good indicator of the risk of rutting, cracking and sustainability to extreme operating temperatures. The asphalt is a material susceptible to thermal stresses. The thermal factor acts as a parameter of history in its degradation. In extreme temperature conditions, the asphalt loses its linear viscoelastic. During the operation of an asphalt pavement, changes in temperature can lead to extreme thermal stresses as a result of shrinkage or expansion prevented:

At low temperature, the material becomes more elastic and more fragile and tends to crack, the stresses that develop can not dissipate, and the mix can not withstand the stresses that lead to restrained shrinkage and cracking. At high temperature, it becomes susceptible to permanent deformation (creep), thermal stresses generate dangerous irreversible strain (instability, rutting) and sometimes the mix can no longer support the tensile stresses created by the expansion effects prevented (cracking).

Simulating and modelling the behaviour of asphalt under thermal cycling is needed to predict the performance of the surface layers in time, and is very important to identify late arriving at the laws governing the behaviour of these materials, taking into account is significant for a better control of the durability of structures in their specific environment.

3. Material

The tests were performed on a single type of binding of the same origin. It is a pure bitumen class 40/50, often used in Algeria for the coated surface layers that are exposed to thermal effects.
Four samples of bitumen of the same origin were tested; three were subjected to different cycles of thermal cycling.

The usual characteristics of bitumen at the origin are:
- Temperature of softening point Ring and Ball (TRB): 51 °C.
- Penetration at 25 °C (P): 43 (1 / 10) mm.

4. Experimental program

4.1. Simulation of thermal cycles

This experimental work began with reproduction in the laboratory the phenomenon of thermal cycling, to simulate different thermal histories of the binders. The tests were conducted by varying the temperature of the samples between two extreme values of temperature, according to predefined thermal cycles, taking into account variations in temperature between day and night during the summer seasons and winter in different regions to specific climates.

Under this procedure the thermal cycles are not accompanied with development of significant stress. They only serve to change the physicochemical properties of the binder.

In this work, the samples underwent the same number of thermal cycles. These programs are obtained by fixed cycles with varying the type of treatment, margins and extreme temperatures. Cycles was carried out continuously by applying cycles of freezing/thawing on the one hand and heating/cooling on the other.

The goal is to approach the actual climate experienced by the pavement in different regions (cold regions in winter and regions was more or less warm to hot; Saharan or sub-Saharan). Three temperature ranges were chosen for the three samples:

- First range is the climate of cold regions or in winter sub-Saharan, sample of bitumen was conditioned by cycles of freezing/thawing (-15 / +20 °C);
- Second range (+25 / +45 °C) simulates the temperatures of the regions more or less warm;
- Third range (+45 / +65 °C), for the third sample in the hot climate regions.
- Sample, nine originally did not undergo treatment; it is intended as a reference.

Tests were performed using a fridge-freezer and an oven, ventilated and programmable. Initially, the number of thermal cycles was chosen in a short period of operation of roads (phase equivalent to months). The number of cycles is relatively low in order to test and monitor the impact and evolution in the early properties of the binder.

Table 1.Conditions of thermal cycling

Sample and type of thermal treatment	Extreme Temperatures	Number of cycle	Thermal cycle (h)
Freeze / Thaw	θ_{inf}= -15°C; θ_{sup}= +20°C	90	T = 12
Heat / Cooling	θ_{inf}= +25°C; θ_{sup}= +45°C	90	T = 6
Heat / Cooling	θ_{inf}= +45°C; θ_{sup}= +65°C	90	T = 6
Without treatment (Originally nine)	/	/	/

4.2. Creep-recovery test on bitumen

The creep test-recovery was carried out to characterize all the samples. Measurements were performed using a rheometer (DSR) plane-plane, equipped with an insulation system containing the sample to assess the effect of thermal history on the viscoelastic qualities of bitumen. Geometry of the device is such that the diameter of the plates used is 20mm with a fixed lower plate and an upper mobile.
Tests using the DSR can be performed in a wide temperature range, the range of 10 to 76 °C is recommended for asphalt aging [4]. The device is used in controlled stress mode of 100Pa [5], and a constant temperature of 30 °C. This temperature was taken as an average temperature of service on roadways, representative of a normal climate in the summer [3]. It is more convenient for DSR testing laboratory.
The bitumen sample is prepared and molded in the shape of flat disk; all samples were tested at a thickness of 1.00 mm (Fig. 1.a and Fig.1.b). The time to creep and recovery properties are equal, ie t= 900s. They aim to reach the stage of viscous flow for creep and stability of the deformation during the recovery properties.

Fig. 1. (a) sample preparation; (b) disk between the plates

The proposed model can be in the form of an element Kelvin-Voigt combined in series with a viscous element. According to Mercier and al. [6], the Kelvin-Voigt element is used to describe fairly well the creep under the effect of a constant stress.

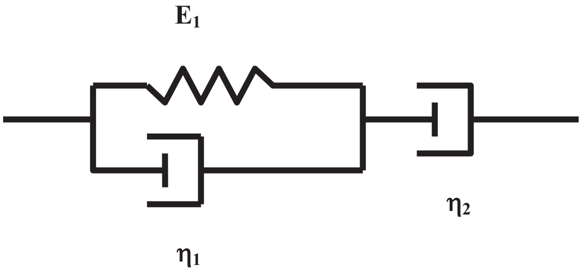

Fig. 2. (a) analogue model proposed

Solving the system of constitutive equations gives the total strain of creep [7]:

$$\varepsilon \ = \varepsilon_1 + \varepsilon_2 = \frac{\sigma_0}{\eta_2} t + \frac{\sigma_0}{E_1} (1 - \exp(-\frac{E_1}{\eta_1} t)) \qquad (1)$$

Where ε_2 is the strain due to the partial viscous flow η_2 and ε_2 is a partial strain due to the Kelvin element (E_1, η_1).

An examination and comparison of the party representing the partial creep $\varepsilon_1(t) = \varepsilon(t) - \varepsilon_2(t)$ and the curve of recovery give similar results, after inversion by a sign change. This confirms the validity of the model and measurement time [8].

The identification of viscoelastic model parameters from experimental curves of the creep test-recovery properties allows us to deduce the curves modelled.

A simple comparison of the curves obtained for each type of heat treatment, shows that the proposed model correctly adjusts the creep-recovery behavior of bitumen subject and not subject to thermal cycles.

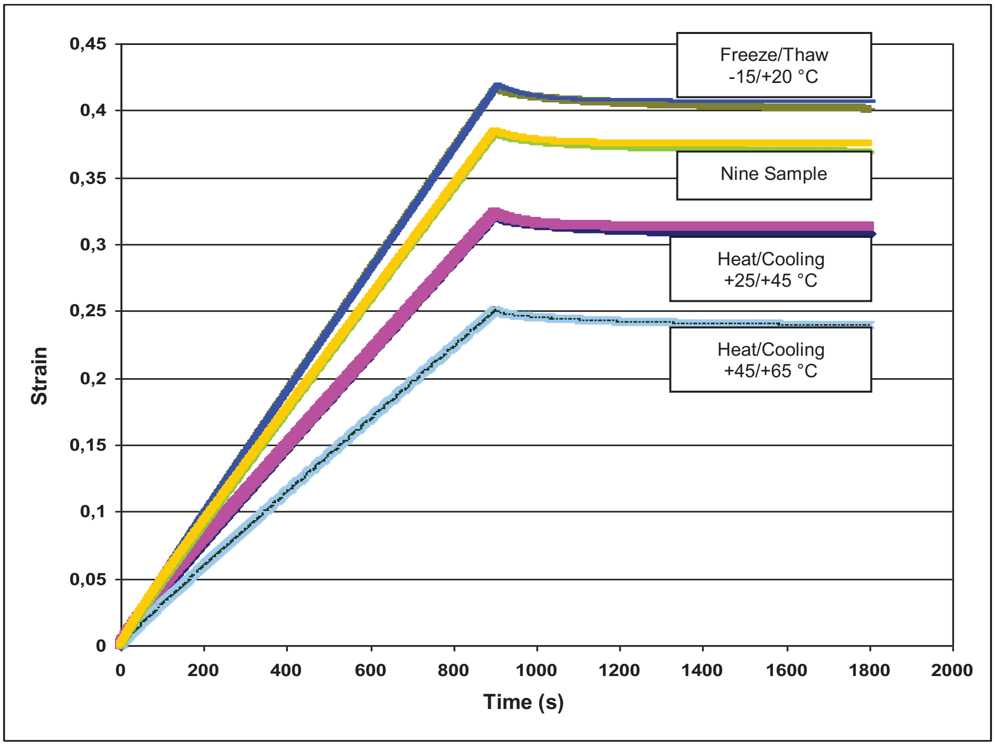

Fig. 3. Experimental curves and those of the model

A simple comparison of the curves obtained for each type of heat treatment, shows that the proposed model correctly adjusts the creep-recovery behaviour of bitumen subject and not subject to thermal fatigue cycles.

5.2. Influence of thermal fatigue cycles

For the sample of bitumen has undergone cycles of freezing and thawing, there is an increased susceptibility. Examination of the creep curve in comparison with that of the nine sample shows a difference in ability to creep (increase in the slope of the creep curve and therefore the total strain increases). The sample tested has not been hardened. On the contrary, it is becoming relatively more deformable, in proportion to the number of thermal cycles. This finding is relevant in the limit of the number of cycles applied.

The evolution of the response of bituminous binders in freeze-thaw is rarely cited in the literature, especially the microstructural changes that can cause changes in behaviour. The latter depends mainly on changes in the internal structure and the changes between the different proportions of chemical elements that constitute [9]. They often study the behaviour of the binder at cold without considering his thermal history and the evolution of its initial characteristics.

For the sample under the range +25/+45 °C, there is a cure on the applied temperature. The slope of the creep curve decreases compared to the reference sample.

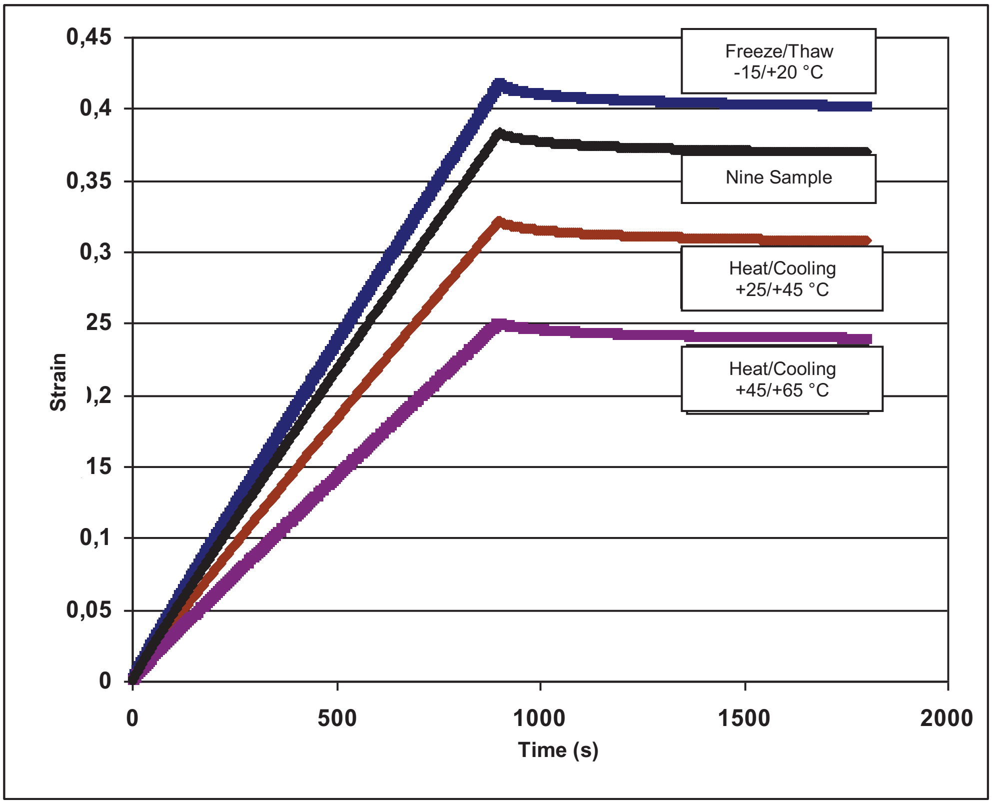

Fig. 4. evolution of behaviour in creep-recovery

To sample in the range +45/+65 °C, within this range the effect of temperature is more aggressive. The slope of the creep curve drops significantly. We recorded a greater change in the mode of behaviour, resulting in interesting changes in the internal structure of the sample in question [9].

Samples tired by heat/cooling experienced a hardening type "Steric Hardening," unlike the previous case (freeze/thaw), which is explained by a phenomenon of damage by oxidation at high temperature (aging). These results are consistent with those of several authors such as Dickenson [1], Verhasselt et al [10], Gordon [11] and Amy [12] concluded that the daily fluctuations coupled with extreme temperatures cause hardening during the summer and can cause a transversal cracks in the pavement due to thermal fatigue cycles.

6. Conclusion

This work was carried out to explore the effect of thermal cycles in the laboratory, which has highlighted the importance of this phenomenon in the evolution of the characteristics of the binder on site. We can draw the following conclusions pending the application of a greater number of thermal cycles and a broader diversification of binders:

The phenomenon of thermal cycle which can lead to thermal fatigue covers two types of solicitations. We have identified and separated at an early age, the effect of two phenomena of freezing/thawing and heating/cooling. Behaviors of samples of the same origin are completely different.

Jeffrey model is able to describe the behaviour of binders in creep-recovery, for the nine bitumen and two types of thermal cycling.

The phenomenon of freezing/thawing, at the young age of bitumen, increases susceptibility and promotes the risk of rutting when the temperature rises. Damage by freezing/thawing is marked by a loss of consistency.

The phenomenon of heating/cooling decreases the susceptibility of the asphalt and causes a hardening of the material (chemical hardening). Damage by heating/cooling is an oxidation such as "steric hardening"), according to the margin of operating temperatures. This stiffening increases resistance to creep (permanent deformation). Which reduces rutting, but the risk of thermal cracking increases due to lack of viscoelastic behaviour, when the temperature decreases.

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