WARM MIX ASPHALT: MECHANICAL PERFORMANCES ASSESSMENT AND BONDING QUALITY MEASUREMENT BY THERMAL CONTACT RESISTANCE

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ABSTRACT

The classical asphalt mix manufacturing commonly requires the heating and the complete drying of aggregates. The induced energy cost has opened the way to develop alternatives processes with low energy/ carbon materials such as Warm Mix Asphalt (WMA). Their manufacturing requires specifics techniques to achieve similar performances than Hot Mix Asphalt (HMA). However, manufacturing temperature reduction can locally lead to incomplete aggregate coating by bitumen, although the coating quality measurement remains a challenge.

This paper deals with modulus and fatigue performances of some bituminous mixtures manufactured at warm temperatures according to WMA processes in comparison with HMA. In addition, the binder has been extracted from asphalt and complex modulus has been studied. In a second step, an innovative thermal approach based on experimental and numerical method was studied. This approach is based on the Thermal Contact Resistance (TCR) assessment at the interface between the binder and the warm aggregate at the manufacturing step. This TCR is proposed as a coating quality indicator measurement. Our studies have shown that bonding quality depends on bitumen and aggregate temperatures during the contact. The higher the temperature, the lower the TCR and the better the bonding quality. Moreover, we found that TCR value is influenced by additives to modified bitumen properties.

Keywords: Additives, bonding, complex modulus, thermal contact resistance

1 INTRODUCTION

Hot Mixes manufacturing required the heating and the drying of the coarse aggregates. This operation induced high energy consumption. In the last decade, roads companies have developed new processes based on fuel consumption reduction. In these processes, coarse aggregates temperature can be reduced significantly. In addition specific additives are generally used to ensure mechanical performances equivalent to Hot Mix asphalt (HMA). The bituminous mixes mechanical performances depend on many parameters as mixing temperature, mix air voids and components and bonding quality between binder and aggregates.
During the heating and the mixing operations, hot bitumen has low viscosity (about 0.2 Pa.s) which allows it to wet aggregate surface and to penetrate into the aggregate roughness. As a result when the temperature mixture decrease down to room temperature, mineral aggregates are bonded. Nowdays, there is no test to assess the bonding quality between aggregates and bitumen during the mix manufacturing. Some tests such as pull-off tests are often conducted at room temperature to assess bonding between bitumen and aggregate [1]. To study the bonding from this test requires that the failure appears only at the interface between bitumen and aggregate. Meanwhile, the mean problem of this test is that the failure is both adhesive and cohesive.
This paper is composed of two parts. Firstly this paper deals with complex modulus and fatigue resistance of some bituminous mixes manufactured at warm temperatures according to Warm Mix Asphalt (WMA) processes [2] compared with HMA. In addition, bitumen were extracted from mixtures and characterized by complex modulus test. The second one aims to assess the bonding quality between aggregates and bitumen during the manufacturing condition. A device has been developed to heat bitumen and aggregate at different temperatures and then put them into contact. From the heat flux exchanged between the bitumen and the substrate, it can be concluded if the contact is perfect or not from the bitumen and substrate interface thermal resistance determination. This thermal contact resistance is interpreted as a bonding quality indicator. A similar method was previously used by Le Goff and al [3] to study thermoplastics material properties during their solidification on a metallic substrate at room temperature.
Our studies have shown that bonding quality depends on bitumen and aggregate temperatures at the contact. The higher the temperature, the lower the TCR and the better the bonding quality. Moreover, we found also that TCR value decrease when bitumen was doped.

2 MATERIALS

The bitumen was chosen to have 35/50 pen grade with a viscosity of 0.2 Pa.s at the mixing temperature, ie. 160°C. The aggregates were dioritic and came from the “La Noubleau” quarry (France). Five fractions were used: sand 0/2 mm and stones 2/4 mm, 4/6 mm, 6/10 mm and 10/14 mm. These materials are of very good quality (Los Angeles Abrasion from 9 to 13). The filler is of the limestone type (FILLOCARB-EB) and came from Méac (France). The control asphalt mixture was a GB which is a French dense asphalt mixture for base course characterized by a low binder content. Figure 1 presents the grading curves and Table 1 gathers informations about binder content, mix air voids and aggregates temperature. In this study, different binder contents, aggregates temperatures and additive content and origin have been used.

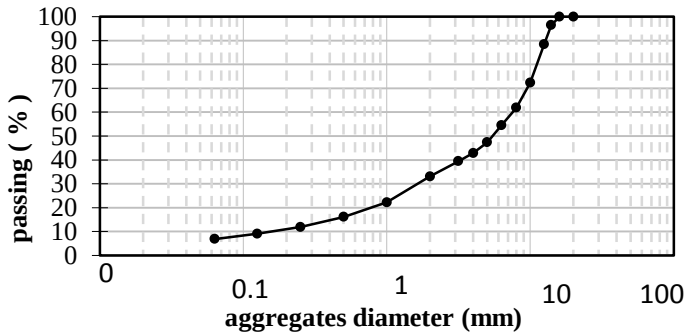

Figure 1: Grave-bitume grading curve

The mixtures A and B have been manufactured with a bitumen content of 3.8% and mixtures C to F are manufactured with 4.78% bitumen content. Mixtures A and C are classical hot mix asphalts with respectively 3.8% bitumen content and 4.8% bitumen content. Mixtures D, E and F are composed of humidified sand (about 25%) stocked at room temperature. The added water in the mixture is about 1.5% [2]. The additive effect has been studied on mixtures D and E and compared to a reference warm mixture F. Specific additives (A1 and A2) have been used to manufacture WMA. The additive content used is about 5% (bitumen mass). Table 1 gathers informations about mixtures.

Table 1: Binder content, mix air voids, aggregates temperature and additives used for mixes

Mix	Bitumen content (%)	Aggregate temperature (°C)	Manufacturing temperature (°C)	Wet sand addition (%)	Mix air voids (%)	additives
A	3.80	160	160	0	6.4	no
B	3.80	95	95	0	10.8	no
C	4.78	160	160	0	4.1	no
D	4.78	Coarse at 150°C and sand at 20°C	95	25	4.1	A1
E	4.78	Coarse at 150°C and sand at 20°C	95	25	5.1	A2
F	4.78	Coarse at 150°C and sand at 20°C	95	25	7	no

3 EXPERIMENTAL TEST FOR FATIGUE RESISTANCE ASSESSMENT

Fatigue tests are carried out with a two-point bending device monitored with an electronical system and linked to a computer (EN 12697-24). The system can applied a sinusoidal load at the top of the trapezoidal specimen. A thermal chamber is used to keep the specimen temperature constant during the test. The temperature is measured with a thermal sensor placed close to the sample surface. During the fatigue test, the temperature is fixed at 10°C and the frequency at 25 Hz. For trapezoidal specimens of bituminous mixtures A and B, two strain levels have been used because some of the specimens were non-compliant for testing. Three strain levels according to standard EN-1297-24 have been used for mixture C, D, E and F.

3.1 Fatigue results

The aim of this fatigue test is to determine the lifetime, defined as one million cycles (ε6) for which the asphalt mixture is able to sustain a given tensile strain level (ε). The test is conducted at 10°C and 25 Hz. The fatigue or Wölher curve is determined by statistical analysis of the pairs of results (strain amplitude and lifetime in number of cycles). Each curve represents the number of cycles at the failure (fatigue life) versus the applied strain amplitude in logarithmic axes. In these axes, the Fatigue curves for bituminous mixture are classically straight lines.From this analysis, the characteristics of the fatigue curve (y-intercept, a) are determined, particularly the slope of the fatigue curve 1/b (b is approximately -0.2 for bituminous materials), the value of the relative strain ε6 for a lifetime of 10^6 cycles. The fatigue or Wölher curve is given by the following equation:

$$LogN = a + \frac{1}{b} Log\varepsilon \quad (1)$$

Where ε is the axial strain amplitude, *a* and *b* are constants which depend on materials and the failure criterion. N is the number of cycles. Considering the failure at 1 million cycles, the strain is expressed as:

$$\varepsilon = \varepsilon_6 \left(\frac{N_f}{10^6} \right)^b \quad (2)$$

Where ε_6 represents the strain amplitude, for which the failure occurs after one million cycles.
The classical Fatigue curves for bituminous materials considering strain controlled tests are respectively plotted in figure 2 and figure 3. The *a*, *1/b*, and ε_6 values are presented in Table 2 for A and B, and C to F.

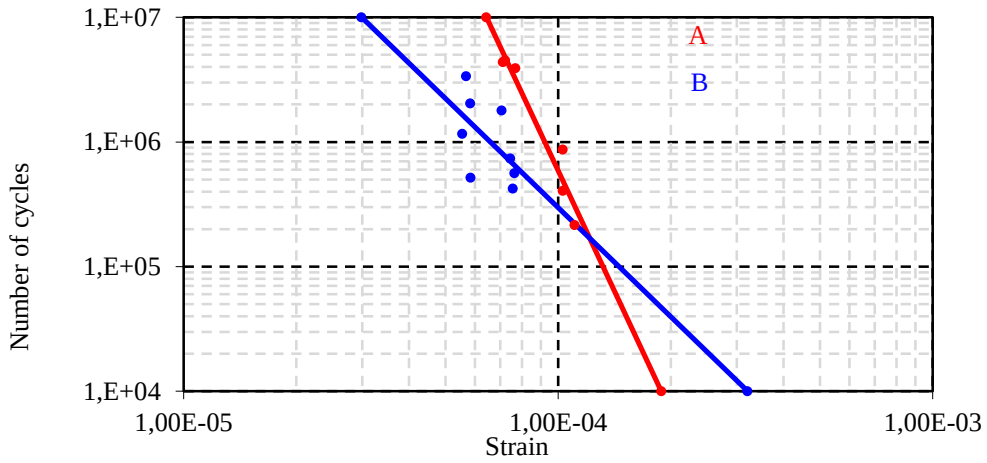

Figure 2: Fatigue curves for A and B mixes

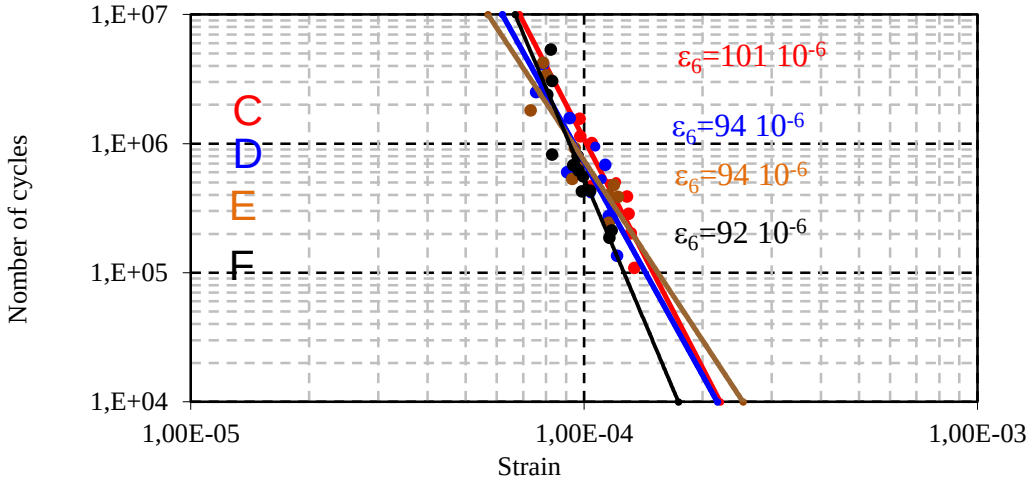

Figure 3: Fatigue curves for C to F mixes

Table 2: Values of fatigue parameters corresponding to fatigue test

Mix	**a**	**1/b**	**ε6 (x10^{-6})**	**Specification** (EN-1297-24) **ε6 (x10^{-6})**
A	-6.43	-0.156	92	≥ 80
B	-2.91	-0.344	66	≥ 80
C	-17.45	-0.17	101	≥ 100
D	-5.487	-0.182	94	≥ 100
E	-4.624	-0.216	94	≥ 100
F	-23.17	-0.138	92	≥ 100

3.2 Fatigue results analysis

In figure 2, the results show a large dispersion between the experimental values. This dispersion is due to the high air voids in the specimens due to the lower binder content (3.8%). In addition the fatigue curve of mix B is very different from the A one. Mix A shows good result according to the specification.The admissible strain at one millon cycles (ε6) for mix B (66 µstrain) is below the specification (80 µstrain). This may due to the highest of the air voids (10.5%) of samples, or the manufacturing temperature (95°C). In order to dissociated these two effects, Moutier air voids correction relation[4] has been used to correct the air voids value of mix B from 10.5% to 6.4% like mix A. The simplification of this relation leads to :

$$\Delta\varepsilon_6 = 3.3\Delta V \qquad (3)$$

Where ΔV is the specimens air void content difference expressed in %, and Δε6 the admissible strain at one millon cycles difference expressed in µstrain.

The correction of the air voids of mix B from 10.5% to 6.4%, leads to a ε6 value of about 79 10^{-6}. This is always quite lower than ε6 of mix A (92 10^{-6}) but very close to the specification value. According to these results, it can be concluded that in this case (low bitumen content 3.8%), the high reduction of the manufacturing temperature induces ε6 value decreasing.
Figure 3 shows a low dispersion on the experimental results. The results of the mixture C (reference HMA) can be compared to the mixes D, E and F. The ε6 value analysis shows that HMA (C) has a admissible strain at one millon close to the specification. Other WMA (D, E and F) present lower ε6 value in comparison with HMA(C) and the specification value (see Table 2). In addition, we found no additive effect on the ε6 values. To go further in our study to highlight the effect of additives, we studied the complex modulus of the mixes and the bitumen extracted from mixtures.

4 BITUMINOUS MIXES COMPLEX MODULUS

The measurements of the complex modulus were carried out in a two point bending frame. The measurement system is composed on a thermo-regulated chamber for the specimen temperature control. This chamber contains the sample load system. This system is linkedto a control system piloted by a computer (MPLC Sapratin technologies N°145). The principle is to apply a low strength load to a trapezoidal specimen according to the norm EN 12697-26 at different temperatures and frequencies. Complex moduli of the six mixtures defined in **Table 1** have been measured.

4.1 Interpretation of mixes C to F complex modulus results

The study carried out on the mixes C, D, E and F is represented in figure 4 and figure 5. The tests were performed in the linear viscoelastic domain and in the temperature range between -10°C to 40°C in which no macromolecular structural reorganization with temperature. The Cole-Cole representation shows a quasi-similar behaviour of all the mixes C to E. Cole-Cole curves show lower values of E2 for high E1 values (low temperature and/or high frequencies) for mixture F compare to other mixes. This result is due to higher air voids (7%) on this mixture F compared to the others (4.1 to 5.1%). This effect is noted on the Cole-Cole representation of mixtures A and B in which there is a great difference of air voids. However, even if the Cole-Cole representation is similar, the curvilinear abscissa are different at the same temperature for mixtures C, D and E. This representation allows to show clearly the material compactness effects. According to Black representation, results show a similar behaviour for all mixes (C to F). A continuous evolution is observed on the black curves. It means that the isotherms overlap themselves. All these mixes exhibit a thermorheologically simple behaviour, which indicates that Time Temperature Superposition Principle [5], [6] is checked.

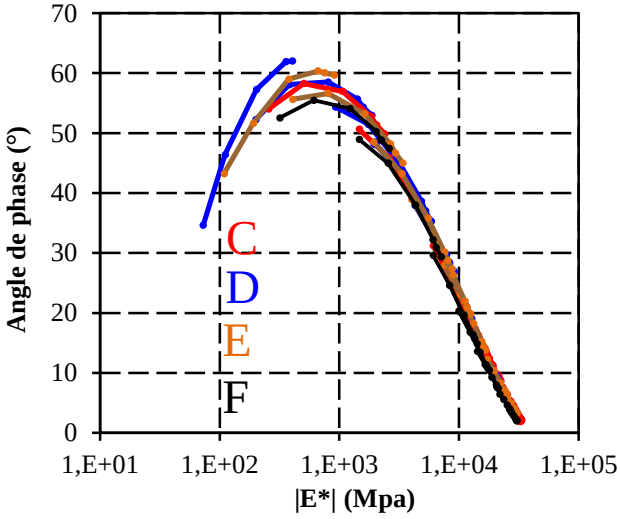

Figure 4: Black space representation of mixes C to F

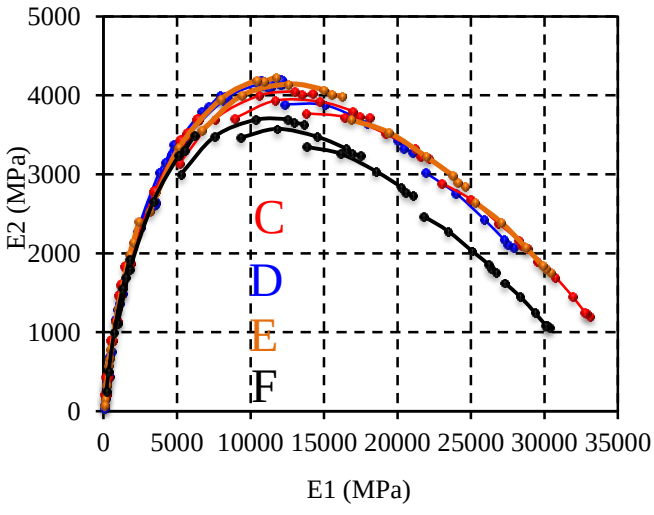

Figure 5: Cole-Cole results for mixes C to F

In these conditions, a master curve can be built (figure 6). Figure 6 shows that additives effects are predominant in the mixes D and E in comparison to the reference WMA (mix F). However, no significant difference can be noted between mix F and HMA (mix C) over 0.1Hz. This can be explained by the bitumen ageing in these two processes. Indeed, in HMA the coating is realised at 160°C where in WMA process the coating is realised à 150°C before the wet sand adding. The mixing temperature difference is too low to induce a hight bitumen ageing difference in the master curve representation. This leads to similar stiffness. The lower stiffness of mixtures D and E are due to the use of additives that reduce significantly the doped bitumen stiffness as we will see in section 5. Figure 6 reveals that complex moduli of all mixes are very close at high frequencies and/or low temperatures (equivalent frequency >10^4 Hz at Tref=15°C).

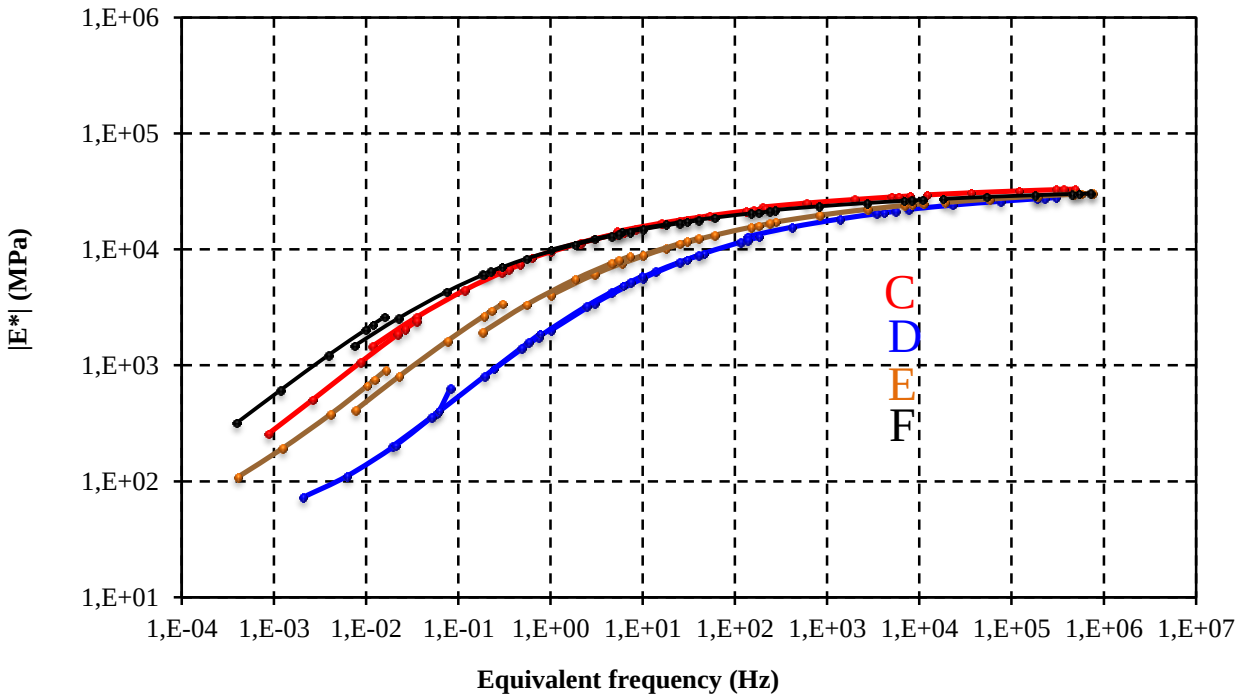

Figure 6: Master curves for mixes measured on 3MC at Ts=15°C

When temperature increases, reference mixes C and F exhibit a stiffer modulus |E*| than the doped mixes D and E. An interesting output of these results is that, the reference HMA (C) and the reference WMA (F) complex modulus results are high and very closed in a wide frequency range (equivalent frequency >0.1 Hz) while the results obtained with additives are lower for all frequencies. A significant reduction of the stiffness is observed for mixes with doped binder. Physically, the introduction of additives A1 and A2 at 5% decreases the stiffness at high temperature. This assumption will be verified in section 5. The additive A1 leads to lower stiffness than the additive A2. Contrary to results obtained from fatigue, complex modulus results highlight the additives effect on mixtures D and E.

4.2 Interpretation of mixes A and B complex modulus results

Complex modulus tests were also performed on the mixes A and B to study the influence the air voids and the manufacturing temperature. Mix A is a HMA manufactures at 160°C and mixture B is HMA manufactured at 95°C with bitumen heated at 160°C. According to Black (figure 7) and Cole-Cole (figure 8) curves, the Time Temperature Superposition Principle was checked for the two mixes. The Cole-Cole and Black curves show a significant difference between mixes A and B. Unlike the previous case, the results of mixes A and B do not overlap either in the Cole-Cole representation and in the Black space. This difference is due to the difference of the coarse aggregates temperatures (160°C for miture A and 95°C for mixture B) and the air void contents of the two mixtures (6.4% for mixture A and 10.8% for moxture B) as we explained previouly in the fatigue test results (figure 2). However the overlapping of the experimental results of each mix allows to draw master curves (figure 9).

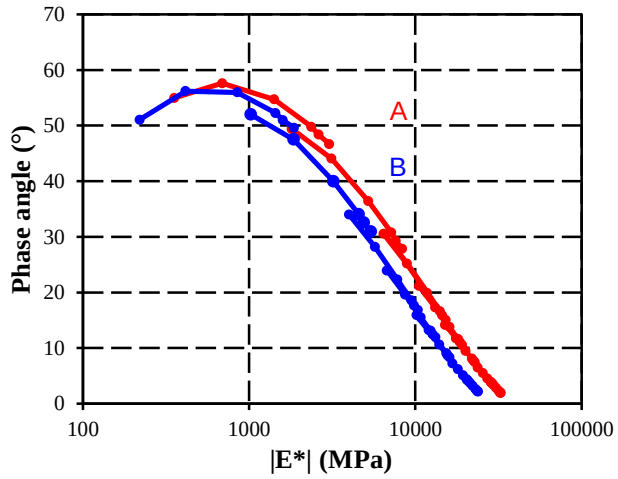

Figure 7: Black curves of A and B mixes

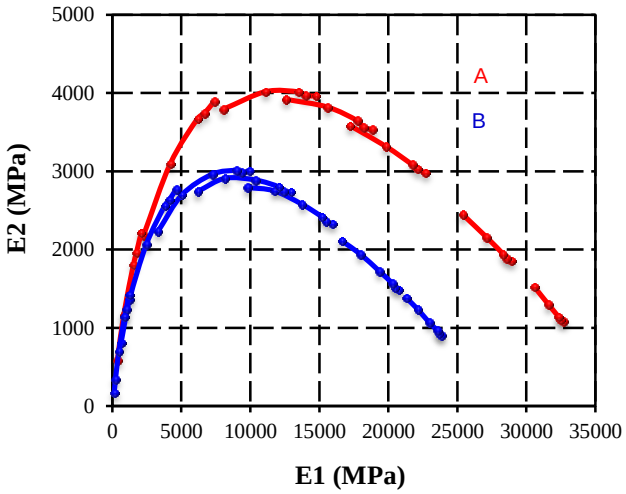

Figure 8: Cole-Cole curves for A and B mixes

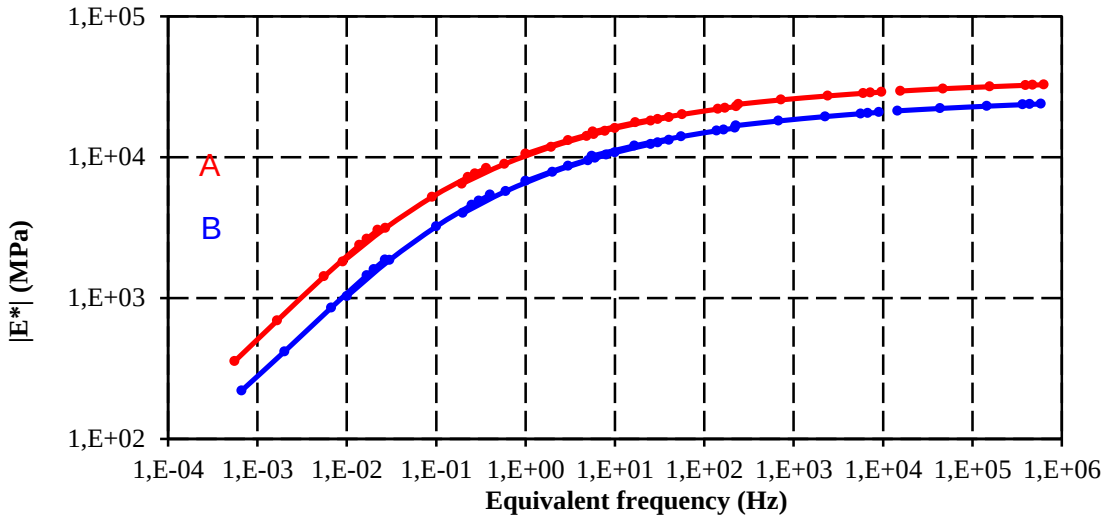

Figure 9: Master curves of mixes A and B at a reference temperature of 15°C

The master curves of mixtures A and B show great difference from low to high frequencies, due to the air void content difference of samples (6.4% for mix A and 10.5% for mix B) and the manufacturing temperature (160°C for mix A and 95°C for mix B) . To decorrelate the manufacturing temperature and the air voids influence, the Moutier relation [4] has been used. This equation allows to correct the difference of air voids between mixes A and B. Complex modulus is defined at a reference temperature of 15°C and for an equivalent frequency of 10Hz:

$$\Delta E = \Delta C\left(-0.078 + \frac{0.63}{TL}\right)\times 10^4 \qquad (4)$$

ΔE is the difference of modulus norm expressed in MPa
ΔC is the difference of void content expressed in %
TL is the binder content expressed in %
Using this equation, mixture B complex modulus can be recalculated at 15°C and 10Hz for an air voids of about 6.4% in comparison to mixture A modulus for a same air void. Thus, at 6.4%, the norms of complex modulus values are summarized in Table 3. According to the specification mixes A and B have good complex modulus results.

Table 3: Correction of complex modulus using Moutier relation

Modulus	**B mix (10.8% air voids)**	**B mix (6.4% air voids)**	**A mix (6.4% air voids)**	**Specification** (EN 12697-26)
|E*| (MPa)	10770	14828	16049	≥ 9000

Despite the correction, it remains a small difference between the modulus of mix A (16049 MPa) and the modulus of mix B (14828 MPa). But it can be noted that this difference is very small when one takes into account the low dispersion of complex modulus results, the approximation made by Moutier formula, sample preparation and the

specimens heterogeneity. The complex modulus can not highlight the manufacturing temperature effect for mixtures A and B, however the additives A1 and A2 effects in mixtures C to F can be highlighted.
As pointed in reference [5], the mixes stiffness depend on the binder stiffness. In our study we found a decrease in stiffness of mixes D and E containing additives. In addition, we will study in the next section, the additive effects on the binder stiffness after extraction from the mixture.

5 COMPLEX MODULUS OF EXTRACTED BINDER

Four aged bitumen extracted from mixtures C, D, E and F were tested in this section. The
Complex modulus tests on binders were performed with DMA 450 (Metravib apparatus) over a frequency range from 1 to 125Hz. From -20 to 30°C, traction/compression tests were conducted on cylindrical samples. From 30°C to 60°C, the tests consisted of annular shearing of hollow cylindrical samples. The binder mechanical behaviour is characterized by a great thermal sensitivity. In the small strain domain (for strain amplitudes below 10^{-2} for bitumen) the behavior can be considered as linear, therefore, Linear Viscoelastic (LVE) theory can be applied. In addition, Time-Temperature Superposition Principle (TTSP) is verified with a good approximation. Our bitumen behave in respect with the TTSP. A unique shear modulus master curves of |E*| can be plotted at a reference temperature, hereafter named Ts, using a shifting procedure [5-6]. Figure 10 shows the experimental device, the test principle and the sample geometry.

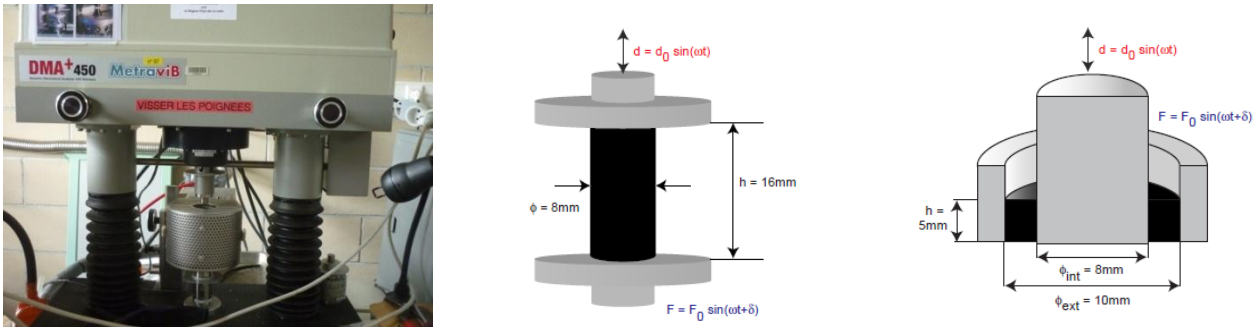

Figure 10. Metravib complex modulus apparatus used for binders (left) and principle of performed tests: traction/compression (center) from -20 to 30°C and annular shearing (right) above 30°C.

Figure 11 presents the complex modulus master curves of pure and doped bitumen extracted from mixes. This figure reveals that the HMA (C) manufactured at 160°C has the higher complex modulus than the other WMA (D, E and F) in which the aggregate coating is realized at 150°C before the wet sand addition. Moreover, it is known that temperature increasing causes a greater bitumen ageing, which increases its stiffness too. Figure 11 results confirm this conclusion. Regarding the WMA (D, E and F) manufactured at 150°C, the complex modulus difference could be explained by the bitumen doping by additives A1 and A2. These additives are less viscous compared to pure bitumen. These compounds lead to decrease the viscosity of binders.

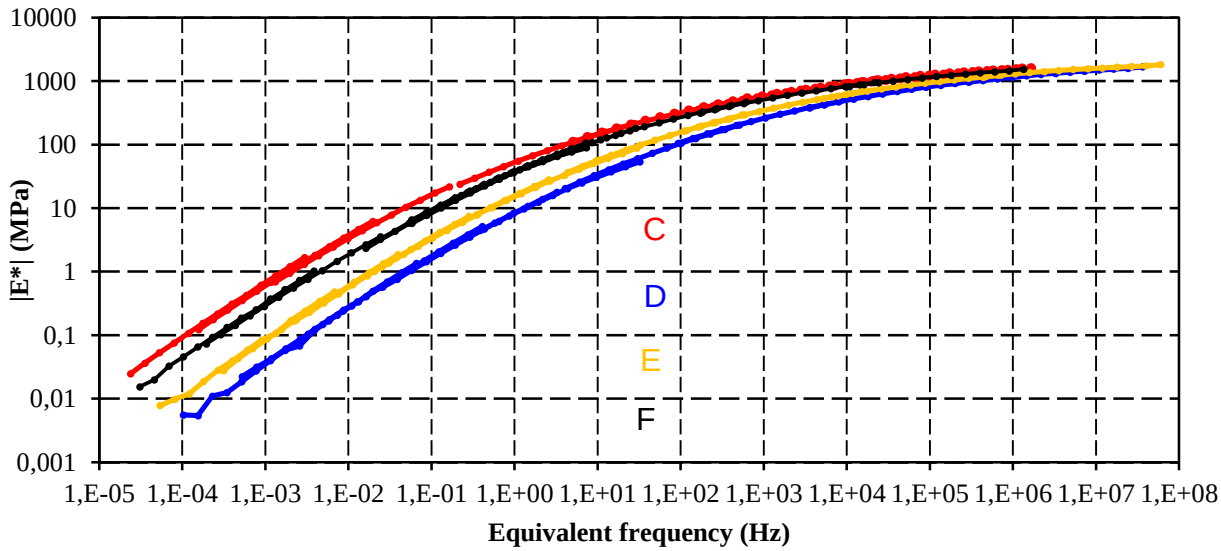

Figure 11: Master curves at 15°C for pure and doped bitumen extracted from mixes

From figures 6 and 11, we can confirm that stiffer binder leads to stiffer mix. It could be noted that additive effects are more observable on the complex modulus results than on fatigue results.
In specific asphalt mix processes, aggregate temperature can be reduced significantly from 160°C to 110°C. This temperature reduction induced bitumen cooling when bitumen comes into contact with aggregates. The consequence is an increasing of the bitumen viscosity. This increasing of the bitumen viscosity does not guarantee a good bonding with the aggregates because the binder does not penetrate easily into the aggregates roughness and then preserves the mixture against water damage. As mentioned previously, mechanical Pull-off tests are often conducted to investigate the adhesion properties between bitumen and aggregate at room temperature [1]. But, this test doesn't ensure a decohesive failure. It is therefore difficult to study the bonding defects at the bitumen and aggregate interface. The objective of the next section of our study is to propose a new method to assess the bonding quality between bitumen and aggregate in the asphalt mixture manufacturing condition when both bitumen and aggregate are heated and to study the wettability of doped bitumen at low bitumen and aggregate contact temperature. As the Pull-off test, this new method does not yet allows to establish correlations between the bonding quality and the stiffness or the fatigue test of the mixture.

6. COATING QUALITY MEASUREMENT

The purpose of this study is to investigate the bonding quality when hot bitumen is put into contact to hot or warm aggregate during the mixing operation of asphalt mix manufacturing. In the warm mix manufacturing, bitumen is generally heated to 160°C when aggregates are heated to a temperature range between 100°C and 150°C. This induced a low cooling of bitumen during the aggregates coating. The bitumen cooling leads to his viscosity increasing. This can limit the bitumen penetration in the aggregates microcavities. The consequence of bad aggregate coating is water sensitivity of the pavement at room temperature. Water is known to cause bitumen and aggregate stripping. It is then more important to ensure good bonding between bitumen and aggregates during mixing operation at high temperature. However, till now, no experiment permits to study the bonding quality during the manufacturing step. The experimental study we performed here permits to study bonding quality in the manufacturing step.

6.1 Materials

The bonding quality was carried out using bitumen with 35/10 mm pen grade and 53.6 °C softening point ring and ball temperature, and gneiss substrate. The bitumen specimen has 8mm average thickness and 50mm diameter.
The aggregate substrate consists in a cylinder core with 52mm high and 70mm diameter from a block. His base surface roughness was characterized by an optical profilometer. The arithmetic average of the absolute value of the measured profile height deviation Ra is 75µm. Four micro-thermocouples, constituted by wires of 80µm diameter, are placed into the aggregate along its vertical axis. For an accurate implementation of the wires, the substrate is cut along an axial symmetric plane, in two parts. On one of these parts and at different depths from the surface, each wire is soldered on its end on the center line and placed in a thin parallel groove to the aggregate surface (see figure 12). The exact positions of the sensor junctions with respect to the surface, given in Table 4, are measured by an optical profilometer before the two parts are precisely re-assembled. The first thermocouple which is the most important for the measurement sensitivity respect rather well the conditions described in the reference [3].

Table 4: Roughness and thermocouples position with respect to contact interface

TC1	TC2	TC3	TC4	Ra
1.48mm	2.91mm	4.39 mm	9.4 mm	75.3 µm

The bitumen specimen thickness is measured before each experiment and varied versus the specimen.

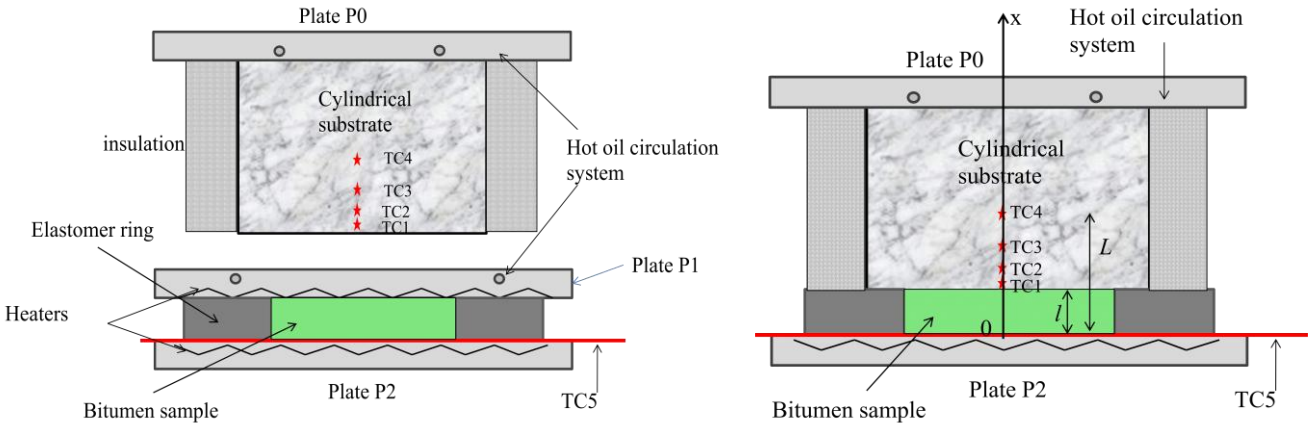

Figure 12: schematic view of test principle (before and after the contact)

6.2 Experimental device and operating principle

The granular substrate sample described in section 6.1 was insulated and fixed to plate P0 Figure 12. Hot oil circulation is ensured inside this plate. Then, the top side of the granular substrate is heated by the plate P0. Plate P1 is placed at the substrate bottom. The upper side of this plate P1 contains the same hot oil circulation system as plate P0. This allows heating the bottom side of the substrate and then getting uniform temperature (T1) in the substrate sample. The bottom side of plate P1 is equipped with a heater that allows heating the upper side of the bitumen to temperature (T2). A plate P2 located at the bottom of the bitumen sample, and equipped with heater ensure the bitumen bottom side heating to uniform temperature T2. The bitumen sample was placed in an elastomer ring before the heating. When all temperatures are uniform in each sample, the plate P1 is removed and the granular substrate is suddenly put into contact with the hot bitumen sample. After the contact establishment, the heat flux flows through the interface. A better thermal contact leads to an important heat flux flowing through the interface. The bitumen interface temperature decreases whereas the substrate interface temperature increases. Because of the imperfect contact due to the air trapped into the roughness of the substrate and the heat flux constriction, the bitumen interface temperature is different to the substrate interface temperature. Then, we can define the thermal contact resistance as the temperature gap in the interface over the heat flux at the interface. A small value of TCR means better contact between bitumen and aggregate.
All the experimental tests were done using the following conditions: holding pressure: 5 bars, bitumen temperature: always higher than the substrate temperature in asphalt manufacturing conditions, contact duration : 60s.

6.3 Mathematical formulation of the heat conduction problem

The samples are initially heated to the required temperatures. Afterward, the aggregate is put suddenly into contact with the hot bitumen. The temperature evolution is measured by the sensors located in the substrate and at the bitumen bottom. From the heat conduction equations in the aggregate and the bitumen, we can assess the bitumen and aggregate interface temperatures and the interfacial heat flux. The unknowns interfacial temperatures Tg(l,t), Tb(l,t) and heat flux $\varphi_{int}(t)$ need to be determined from the following mathematical formulation of the direct problem in the bitumen and aggregate regions between sensors TC5 and TC4. Index b and g refer to bitumen and granular substrate respectively. T and t are respectively the temperature in °C and the time in second.

$$(\rho(T)C_p(T))_b \frac{\partial T_b(x,t)}{\partial t} = \lambda_b \frac{\partial^2 T_b(x,t)}{\partial x^2}\ ,\ 0 < x < l\ ,\ 0 < t < t_f \tag{5}$$

$$-\lambda_b \left.\frac{\partial T_b(x,t)}{\partial x}\right|_{x=l} = \varphi(t)\ ,\ 0 < t < t_f \tag{6}$$

$$-\lambda_g \left.\frac{\partial T_g(x,t)}{\partial x}\right|_{x=l} = \varphi(t)\ ,\ 0 < t < t_f \tag{7}$$

$$(\rho(T)C_p(T))_g \frac{\partial T_g(x,t)}{\partial t} = \lambda_g \frac{\partial^2 T_g(x,t)}{\partial x^2}\ ,\ l < x < L\ ,\ 0 < t < t_f \tag{8}$$

$$T(x=0,t) = T_0(t)\ ,\ 0 < t < t_f \tag{9}$$

$$T(x=L,t) = T_L(T)\ ,\ 0 < t < t_f \tag{10}$$

$$T(x,0) = T2\ ,\ 0 \le x \le l \tag{11}$$

$$T(x,0) = T1\ ,\ l \le x \le L \tag{12}$$

$$TCR(t) = \frac{T_b(l,t) - T_g(l,t)}{\varphi(t)} \tag{13}$$

Where φ(t) is the heat flux density through the interface expressed in Wm^{-2}, TCR is the thermal contact resistance expressed in Km^2W^{-1}, λ is the heat conductivity expressed in $Wm^{-1}K^{-1}$, C_p is the specific heat expressed in $Jkg^{-1}K^{-1}$, ρ is the density expressed in kgm^{-3}, t_f is the contact duration expressed in second and T1 and T2 are respectively the initial temperature in the substrate and the bitumen. The boundary conditions $T_0(t)$ and $T_L(t)$ are the temperatures history measured by the sensors TC4 and TC5. This problem can be solved by Raynaud and Bransier inverse method [7].
The samples thermal properties (heat conductivity, specific heat and specific volume) need to be determined for the heat conduction problem solving. The aggregate and bitumen thermal conductivities are measured according to the guarded

hot plate method in the temperature range from 30°C to 160°C. The specific heat capacities were investigate by differential scanning calorimeter (DSC). Heating, as defined here, was heating of the samples at a moderated rate by the calorimeter, an average of about 10°C/min up from -80°C to 200°C. The specific volume was carried out by the PvT-α apparatus described in reference [3] in the temperature range from 30°C to 160°C. Apart from specific heat capacity, all other properties of bitumen and doped bitumen are similar.

6.4 TCR results and comments

6.4.1. Repeatability of the experiment

We have conducted two tests for bitumen temperature of 80°C and substrate temperature of 30°C. The aim is to test the repeatability of measurements. Figure 13 presents the obtained TCR results. We can note good agreement between the first and the second test for long time. After 40 seconds small differences can be noted due probably to two dimensions effects that can occur on the insulated surfaces sides. For simplicity of figures the following notation was chosen: B_iG_j. This mean that the bitumen (B) was heated to temperature *i* and the granular substrate (G) was heat to temperature j.

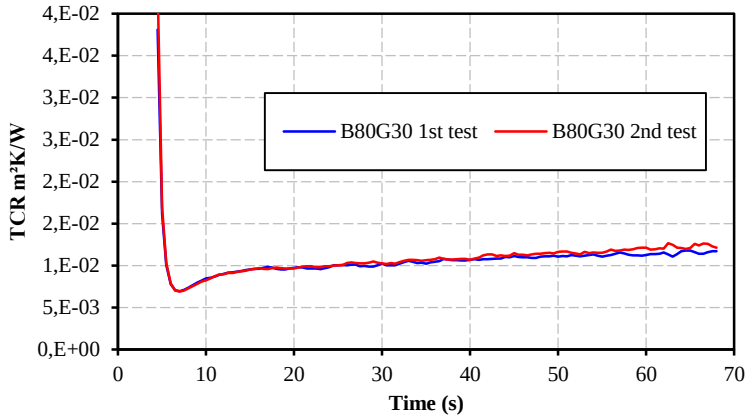

Figure 13: repeatability of measures conducts for $B_{80}G_{30}$

From figure 13 results, the following analysis can be done:
After the contact establishment quickly decrease of the TCR is observed. The air is expulsed at the interface this cause a high decrease of the TCR until a minimal value. Because of roughness of the substrate surface, there is an air layer at the interface between bitumen and substrate. This air gap acts as a thermal resistance between bitumen and aggregate. During the first time, TCR is a function of the substrate roughness, surface tension of the liquid bitumen, wettability of the substrate surface. At the end of this stage, the wetted surface and heat flux are maximum, ie. TCR is minimum. The TCR is established on the roughness picks and from these areas starts bitumen cooling and bitumen viscosity increasing.
The second step is characterized by TCR growing. As the substrate initial temperature is smaller than the bitumen temperature, the contact induces bitumen surface temperature cooling. The cooling causes small increasing of the entrapped air in the microcavities at the interface which causes an increasing of the TCR value. We assumed that TCR is totally established when the bitumen surface temperature becomes stationary. For all tests we have done, the steady state is achieved at 20 second maximum.

6.4.2. Effect of components temperatures

The study of the bonding quality was carried out for several heating cases. The substrate temperature varies from 30°C to 150°C and the bitumen temperature from 80°C to 160°C. Results are shown in figure 14. According to figure 14, we can note that the increase of the components temperatures induces a decrease of the TCR value and then good bonding. The higher values of TCR are obtained for $B_{80}G_{30}$ ($9.37\ 10^{-3}$ Km²/W). In this case the bitumen is more viscous and cannot penetrate into the micro-roughness of the aggregate. The smaller values of the TCR are obtained for $B_{160}G_{150}$ ($1.24\ 10^{-3}$ Km²/W). In this case bitumen is very liquid with low viscosity and ensures better wettability of the substrate rough surface. In the cases which the substrate temperature is greater or equal to 110°C, the first time TCR values are not very different. However for a long time these values become different due probably to the difference of the thickness of entrapped air. In these experimental tests, the temperatures of some warm mixes are reproduced. We note

that, the reduction of the temperature in the warm mixes can induce a loss of bonding quality. As we explained previously, the TCR is assumed to be established when the bitumen surface temperature is constant. These temperatures are stationary from 20 seconds.

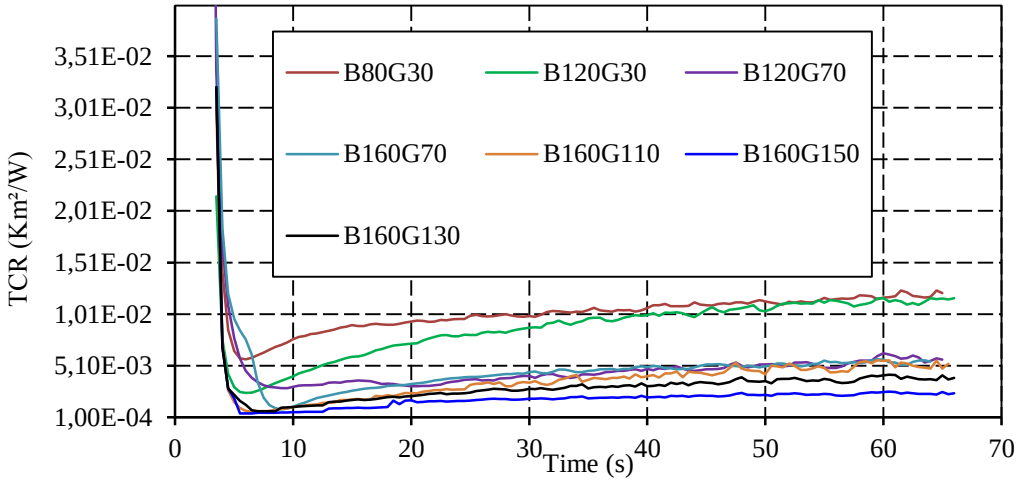

Figure 14: Effect of components temperatures on TCR results

6.4.3. Effect of additives

In the warm asphalt mix manufacturing, road companies generally add some additives into the hot bitumen before putting into contact with aggregates. The additives role is to reduce bitumen viscosity and / or to improve bitumen spreading properties over the aggregates. Our study proposes to study the effects of some common additives (A1 and A2) by TCR measurement. These additives are mixed with bitumen before putting the bitumen in the elastomer ring. They are totally soluble in the bitumen. The effects of the additives in terms TCR are shown in Figure 15.

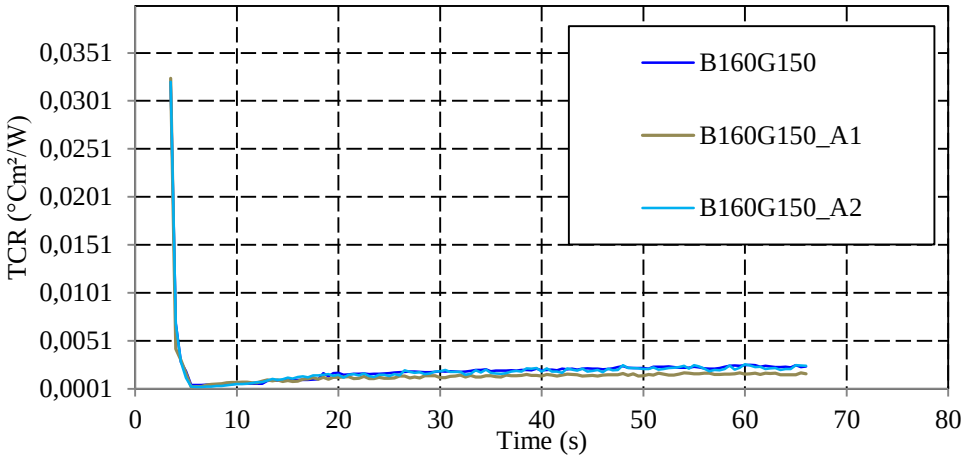

Figure 15: Effect of additives on TCR results

The effect of additives was studied for substrate temperature of 150°C and bitumen temperature of 160°C. For additive A2 no significant reduction of TCR can be noted compared to the case $B_{160}G_{150}$ without additive. Indeed, additive A2 modifies the bitumen viscosity. At 0.5% his effect was not found in our study. In contrast, the additive A1 seems to reduce significantly the TCR value after 20s. This additive is known to modify highly the viscosity, adhesion properties and the mechanical properties of bitumen. The presence of additive A1 at the interface contributes to improve the heat transfer rate by minimizing the effect of numerous microcavities filled with air. We had to precise that these TCR values depend on the roughness of the substrate surface and doesn't take into account the dynamic effect due to mixing operation. However, this experimental test has the benefit to assess the bonding quality at the manufacturing step. At 20s the TCR varies from 1.24 10^{-3} Km²/W ($B_{160}G_{150\_A1}$) to 9.37 10^{-3} Km²/W ($B_{80}G_{30}$). Although these resistances are important, they are consistent with our substrate surface roughness (Ra=75µm).

7. CONCLUSION

This study consists of two main parts. The first one is focus on the mechanical performances of WMA with doped bitumen in comparison with a reference HMA and the second one is dedicated to the role of the manufacturing temperature on the bitumen and aggregates bonding quality and the additives contribution to bonding quality.
The prime objective was to show the effect of additives and the process on the mechanical behavior and to compare WMA to HMA. The temperature and the air void content were studied on mixtures A and B. The temperature reduction effect was noted on mixture B fatigue test (comparison of ε6 values) results but not on the complex modulus test. The air void content influence has been clearly highlighted. The increase of air void content reduces the fatigue life and the stiffness of the mixture. However, the fatigue test results are similar in HMA (C) and WMA (D, E and F) while complex modulus results are different. We found that the addition of 5% of additive reduces significantly the bitumen and the corresponding mixture stiffness.
The second objective is to present and new coating quality measurement process. The experiments were conducted by varying bitumen and mineral substrate temperature. The results show that the increase of one of the components induces a decreasing of the thermal contact resistance and good bonding in the asphalt manufacturing operation. We also studied the influence of some additives A1 and A2 used for WMA manufacturing processes. The results show that additive A1 improves the coating quality by reducing the TCR value. For additive A2, no significant effect was observed. The TCR results show the importance of heating the components to ensure good bonding of the bitumen on the aggregates in WMA processes.
According to these results, the TCR device could be used to assess and select additive (nature and quantity) to manufacture bituminous mixture regarding influents parameters such as manufacturing temperature and aggregate origin.

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