CORRELATION BETWEEN BINDER AND BITUMINOUS MIXTURE FATIGUE BEHAVIOUR

Cardone F.
Assistant professor – Università Politecnica delle Marche – *f.cardone@univpm.it*
Cerni G.
Associate professor – Università di Perugia – gcerni@unipg.it
Colagrande S.
Associate professor – Università di L'Aquila – sandro@dau.ing.univaq.it
Virgili A.
Associate professor – Università Politecnica delle Marche – a.virgili@univpnm.it

ABSTRACT

Fatigue cracking, due to repeated traffic load, is the most common mode of failure for asphalt pavements. As it is well known this distress is mainly related to the rheological properties of asphalt binder. In order to better understand the influence of binder on fatigue behaviour of mixture, two experimental investigations were carried out. Each study was finalized to evaluate the effects of cyclic loading on the mechanical properties of binder and asphalt mixture. In particular, a first investigation was carried out to study the fatigue properties of traditional and polymer modified binders using a dynamic shear rheometer (DSR). A second experimental investigation was carried out to evaluate the fatigue performance of asphalt mixes for wearing courses, manufactured with the same binders, through repeated loading axial tensile test.

The analysis of results allowed to obtain analytic laws, achieved separately for binders and bituminous mixes, showing the decay of the mechanical properties of materials subjected to cyclic loading. Moreover, for each material the influence of the stress level and temperature was evaluated. Finally relationship between the mechanical behaviour of mixtures and binders have been discussed through the comparison of the above mentioned structural distress models in order to estimate the role of binder in fatigue behaviour of asphalt mixtures.

Keywords: fatigue, asphalt binder, asphalt mixtur, damage.

1. INTRODUCTION

Fatigue cracking and damage, due to repeated traffic load, is the main cause of distress in asphalt concrete pavements. As fatigue cracking is the structural distress traditionally used for the actual structural design of a pavement, a clear understanding of fatigue behaviour of the materials that are part of pavement is required. For decades, many efforts have been made by researchers to define experimental and analytical tools to evaluate the fatigue behaviour of bituminous binders and mixtures.

For many years, the single parameter G*senδ, according to SUPERPAVE binder specifications, was used to characterize the binder fatigue but it has since been severely criticized (Bahia at al.,2001, Bahia at al.,1999). A new method to predict binder fatigue by performing repeated loading tests by means of a Dynamic Shear Rheometer (DSR) was proposed by NCHRP 9-10 project. This procedure is appealing as it incorporates damage concepts that are in keeping with more recent studies on fatigue mixtures wherein fatigue is attribuited to microdamage (Bahia at al., 2001a, Bonnetti at al., 2002).

Numerous studies were performed to evaluate fatigue failure of asphalt mixtures too. The most commonly used criteria to define fatigue failure is to consider the number of cycles at which the initial stiffness modulus decreases by 50 percent (Ghuzlan and Carpenter, 2003). However, this criterion was found arbitrary and dial not have any relation with the damage accumulated in the material (Carpenter and Ghuzlan, 2000). So, several new approaches to characterize the fatigue behaviour of mixtures were developed. In particular, the most promising approaches present the criterion of fatigue based on the rate of change in dissipated energy (Van Dijk and Visser, 1997, Kim at al., 1997) or on continuum damage mechanics constitutive theory (Di Benedetto at al., 2004, Pronk, 1997). Even though these methods give a more accurate indication of accumulation of damage in the mixtures, they suffer from a high variability in the results. Therefore, a relevant specification criterion has yet to be defined.

Although there have been latest developments in fatigue characterization and it is well known that rheological properties of binder highly affects the mechanical behaviour of the asphalt mixture, only few studies were developed to find whether there was any correlation between fatigue properties of binders and mixtures. The purpose of this study is to relate the fatigue behaviour of two binders with the corresponding mixtures through a new analysis method. In particular, a simple analytical model to evaluate the distress of materials due to fatigue damage is proposed (Bocci at al., 2006, Bocci at al., 2006a). This model shows that the analysis of the loss in modulus is a valid tool to investigate the fatigue phenomenon and describes loss in the mechanical properties of bituminous materials.

2. EXPERIMENTAL PROGRAM

The present work studied one of the main causes of distress in asphalt pavement, fatigue cracking. the purpose of this investigation was to compare and relate the mechanical behavior of binders with the corresponding asphalt mixtures when subjected to the fatigue phenomenon. The study focused on a new analysis method to evaluate fatigue. in particular a distress model that uses modulus as the main parameter was proposed to analyze the fatigue damage within the materials. the effect of the stress level and temperature on the fatigue behavior of each material was evaluated.

2.1 Materials

Two bituminous binders (indicated as A and B) were used in this experimental study, including a 50/70 penetration grade base binder, and the same binder modified with SBS elastomers.

Two asphalt mixtures, made with the binders described earlier and called MA and MB respectively, were considered. Crushed limestone aggregates, gradation for wearing course and one asphalt binder content (6% by weight of aggregates) in accordance with Italian technical standards were used to obtain both bituminous mixtures. A considerably high percentage of binder was chosen in order to better evaluate the effect of the type of binder on the mechanical behavior of the mixture.

2.2 Fatigue tests on binders

A Haake Rotovisco RT10 DSR was used for the determination of the fatigue properties of the bituminous binders. All samples were prepared according to the AASHTO TP5-98 standard and were tested in unaged conditions.

Fatigue tests consisted of time sweep tests performed by applying repeated sinusoidal shear loads on samples for a prefixed time. All fatigue tests were carried out until the sample broke completely or its modulus dropped to a limiting value. Measurements were performed with a parallel plate geometry (8 mm diameter) and with a 2 mm gap setting. All tests were carried out in controlled stress mode, by varying the stress level, at three different temperature (5°C, 15°C, and 25°C) and at constant frequency equal to 10 rad/s. Table 1 shows the summary of the experimental program.

Table 1: Summary of experimental program on binders

Binder	Loading Mode	Stress (kPa)	T (°C)
A	Stress	180 - 225 - 270 - 315	5
	Stress	64 - 80 - 96 - 144	15
	Stress	24 - 32 - 40 - 48 - 60	25
B	Stress	126 - 162 - 198 - 234 - 270	5
	Stress	56 - 72 - 88 - 104 - 120	15
	Stress	36 - 42 - 54 - 60 - 66	25

2.3 Fatigue tests on asphalt mixtures

Repeated sinusoidal tensile load test was used to measure the mixture fatigue behavior by means of Creep Tester set up in the road laboratory of Università Politecnica delle Marche. All tests were conducted in controlled stress mode at the same temperature and frequency used for binders on cylindrical specimens (ϕ 100mm, h 100mm). All samples were produced by means of a Shear Gyratory Compactor according to the UNI-EN 12697-31 standards with a target of 4 % air void. Strain measurements were obtained from a linear vertical displacement transducer (LVDT) placed on the sample. Each test was terminated when the sample broke completely. Table 2 shows the summary of the experimental program. For each stress level, two samples were tested.

Table 2: Summary of experimental program on asphalt mixtures

Mixture	Loading Mode	Stress level (kPa)	T (°C)
MA	Stress	600 - 650 - 700	5
	Stress	250 - 300 - 350	15
	Stress	50 - 100 - 150	25
MB	Stress	600 - 650 - 700	5
	Stress	350 - 400 - 450	15
	Stress	150 - 200 - 250	25

The choice of these stress levels, for both binders and mixtures, derived from operative reasons. In fact, the maximum and minimum load levels were selected in order to obtain analysis periods compatible with laboratory work constraints.

3. RESULTS AND DISCUSSION

3.1 Test results

It is well known that repeated sinusoidal oscillations, both for binders and mixtures, lead to a decrease in modulus after a certain number of load cycles due to the fatigue damage within the material. Such a drop in the modulus can be more or less sudden depending on the properties of the material and testing conditions. For binders, the values of complex modulus (G*) and phase angle (δ) as function of the load cycles were calculated. For mixtures, the accumulated permanent strains and stiffness modulus trend were measured. In particular, stiffness modulus was calculated by considering the visco-elastic strain (ε*) evaluated in the unloading phase of each load cycle during the test (see figure 1)

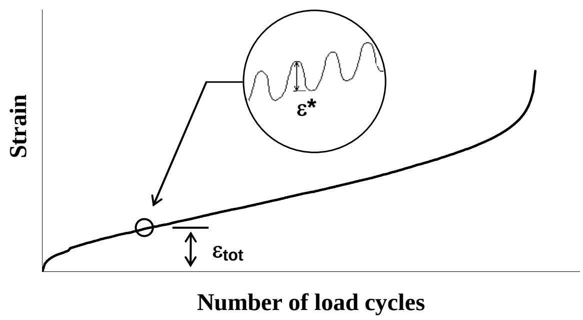


Figure 1: Typical strain curve for a fatigue test

For each material the complex modulus and stiffness modulus were evaluated as function of the stress level and temperature. Figure 2 shows a typical result of a fatigue test in terms of complex modulus for binder B and in terms of stiffness modulus for mixture MB under different stress levels at 15°C.

From these graphs it is possible to note that the complex and stiffness modulus tend to decrease as the number of cycles increases. This trend well expresses the fatigue damage accumulated within the material. In fact, the damage increases due to the increase in number of loading cycles, with consequent decrease in the measured modulus, arriving at a final condition where the damage level is so high that it causes the failure of the material. This stage corresponds to the sudden drop in the modulus.

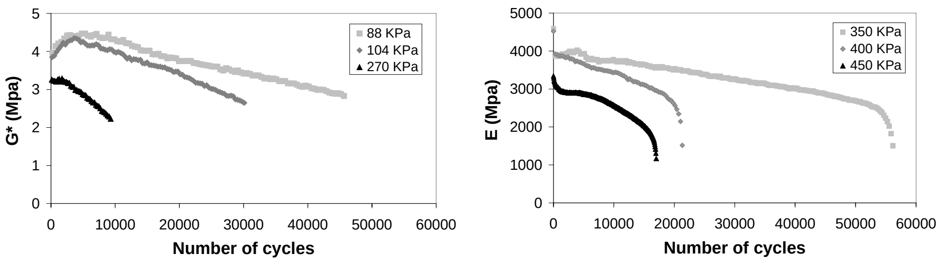


Figure 2: Effect of stress level on modulus (binder B and mixture MB at 15°C)

A further important consideration can be made looking at the figure. It is possible to note that the stress level has a high effect on the modulus trend. In particular, with an increase in stress level the modulus decreases faster. This is due to the fact that high stress level accelerates accumulation of fatigue damage and so causes failure of the material. By carefully analyzing the complex and stiffness modulus trend it can be seen that at the initial stage of loading the modulus tends to go up to a maximum value and over it tends to go down. The lower the stress level, the more pronounced this trend becomes. Probably, when the stress level is low, it seems that the material adapts itself to the load and opposes it, so showing an initial upward trend in the modulus; when the stress level is high there is a change in its internal structure so that it suddenly damages the material. Same results can be obtained at other temperatures.

For both binders and mixtures, the traditional approach to evaluate fatigue behavior is based on monitoring the trend of the modulus versus load cycles and to define N_f the number of cycles at which the modulus decreases to a prefixed value as conventional failure. Typically, the number of cycles corresponding to a 50% loss in modulus is used to define the fatigue life of the material.

This study proposes a new analysis method that uses the modulus as an indicator of material fatigue performance. As mentioned previously, the loss in the modulus as well as the speed with which it decreases can be well related to the distress of the material due to the fatigue phenomenon. This means that the study of the modulus trend and the search for a parameter capable of describing such a trend is certainly the most effective way to analyze the fatigue damage within the material instead of finding a conventional number of cycles as failure point that can not completely express the real behavior of the material as reported in previous works.

Analyzing both complex modulus for binders and stiffness modulus for mixtures, it is possible to verify that over the initial phase, depending on the stress level, where the modulus moves towards a maximum value (initial point in the test performed with high stress), until a decrease of 30% the modulus trend can be well fitted by a line (rarely does the regression coefficient dropped below 0.85). In many cases, a sudden drop in the modulus close to this value occurs due to the failure conditions of the material.

As a wide range of modulus values were obtained from different test conditions and different materials (binders and mixtures) and in order to make a correct comparison between all the results, the percentage loss in modulus during the test was investigated. This percentage was obtained by ratio between the current and maximum value of the modulus. The slope of the regression line, that is the rapidity with which the modulus decreases, can express the ***distress level*** of the material during the test. In fact, as the slope of the line measures the percentage loss in modulus per load cycle, it can be considered a good rational parameter to express the fatigue resistance of the material. Figure 3 shows results of fatigue test carried out on binder B and the corresponding mixture MB at 5°C.

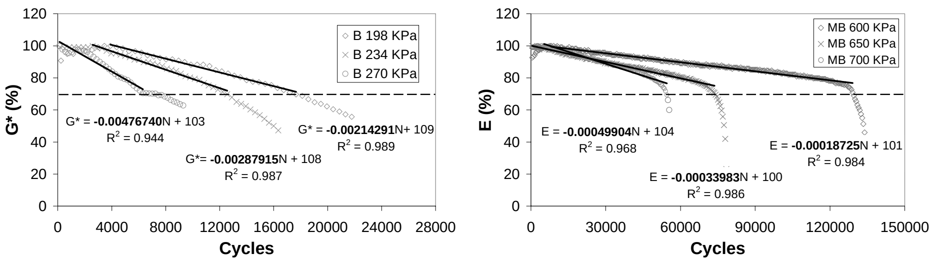


Figure 3: Percentage change in modulus vs. cycles (binder B and mixture MB)

In order to better evaluate the fatigue damage within the material during the test it is useful to plot the calculated distress level (slope of the regression line) versus the applied stress level at different test temperatures. Figure 4 (a) and (b) shows the results of tests on binder A and mixture MA respectively.

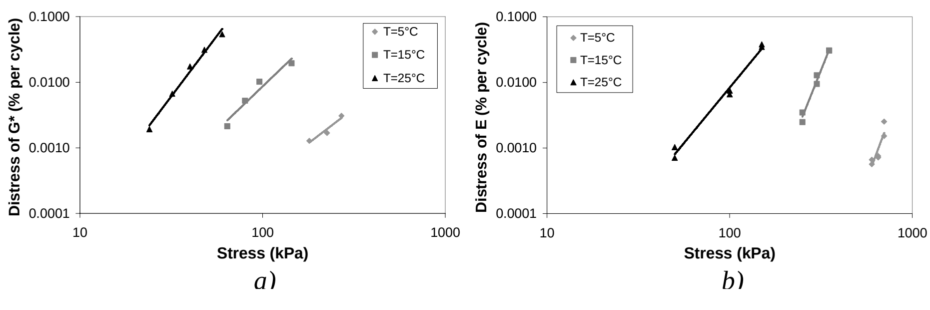


Figure 4: Distress vs. stress level (binder A and mixture MA)

Data results clearly show that an increase in both applied stress and in temperature results in an increase in distress level. Moreover, it is possible to note that in a bi-logarithmic plane all distress levels, for both binders (4-5 points) and mixtures (6 points), are related to stress by a linear trend at each temperature. As proven by the obtained high values of the regression coefficients, it is possible to evaluate the distress condition of the material quite well when the applied stress level is known according to the following power law equation: ***Distress = a · stress ^{b}*** .

In the case of binder the considered stress level is a shear stress (τ) while in the case of mixture the stress is a normal stress (σ).

By analysing figure 4 (a) and (b), it can be noted that the temperature variable acts on the position in the graph and on the slope of each line. Moreover, it is very clear that the lines are considerably shifted from each other and have a similar slope; this means that the temperature prevalently affects the position rather the slope of lines. Therefore, in order to find a simple distress law that depends on few parameters, it is quite right to consider only the scale factor (coefficient a) as function of the temperature and not the exponent (coefficient b) of the equation. In particular, for both binders and asphalt mixtures, the dependance of the multiplying factor of the power law on the temperature can be described through an exponential trend.

On the basis of these results, in order to describe the distress level of the material as function of stress and temperature, a model given by the following equations can be considered:

$$Distress = a(T)\sigma^{b} \qquad \text{(line in a bi-logarithmic scale)} \qquad \text{(Eq.1)}$$

where *a(T)* is defined as follows:

$$a(T) = c\, e^{d\,T} \qquad \text{(line in a semi-logarithmic scale)} \quad \text{(Eq. 2)}$$

Table 3 lists the distress equation obtained applying this model to all experimental data. It can be noted from high R^2 values that the model fits experimental data quite well for both binders and corresponding mixtures, but it is right to remark that the dependance of parameter *b* on temperature was neglected.

Table 3: Summary of results of distress model

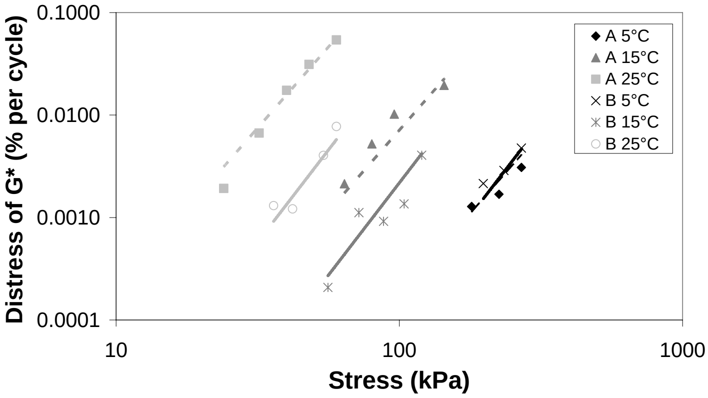
Material	**Model**	**R^2**
A	$D = 1.3278\ 10^{-11}\ e^{0.3692\,T}\ \tau^{3.1617}$	0.9451
B	$D = 2.0267\ 10^{-12}\ e^{0.2813\,T}\ \tau^{3.5988}$	0.8761
MA	$D = 2.9891\ 10^{-16}\ e^{0.4945\,T}\ \sigma^{4.0961}$	0.9014
MB	$D = 6.4196\ 10^{-13}\ e^{0.2527\,T}\ \sigma^{2.8765}$	0.9016

Figure 5 shows plots of the model for two binders (a) and corresponding mixtures (b). These plots provide information on the influence of polymer-modification and temperature on the distress condition of both binders and mixture. By analyzing graphs (a) it is clear that the addition of modifier induces a decrease in distress and so leading to an increase in the fatigue life of the material as compared to the original binder, and this effect is amplified at higher temperatures. At 5°C it seems that the modification does not affect the performance of the binder. In fact the two model lines overlap.

As regards temperature, it is possible say that its effect on fatigue performance can be evaluated from the position of the model line in the graph area. In particular, the changes in temperature affect the distress level of the unmodified binder more than that of the modified binder. In fact the broken lines (related to unmodified binder) turn out to be more shifted from each other.

The same consideration can be made for the corresponding mixtures. But in this case the effects of both polymer-modification and temperature are more visible as opposed to the binders, as it is possible see from graph (b). In fact, by considering the model equation of the mixtures, the temperature variable is multiplied by 0.49 for unmodified mixtures while by 0.25 for modified mixtures and this results in a greater shift of lines. Moreover, the model lines of the unmodified mixture show a higher slope which means that the effects of the stress level on the distress condition are greater than those for modified mixtures.

a)



b)

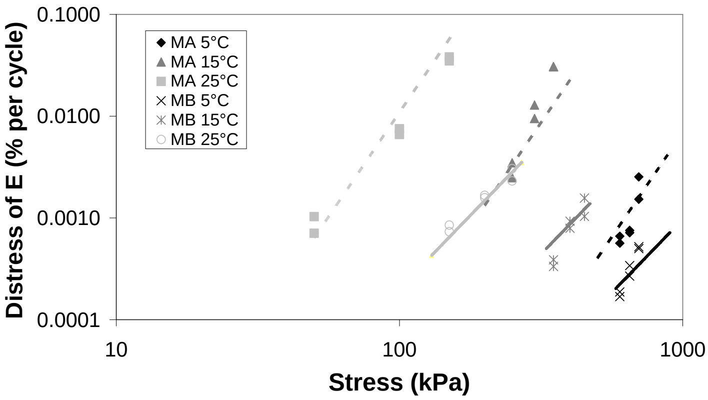


Figure 5: Distress model for binders and mixtures

As it is well documented in the literature that binder properties have an influence on fatigue properties of asphalt mixtures, it is appropriate to evaluate whether this new analysis approach allows to find any direct correlation on fatigue properties between binder and corresponding mixture. Figure 6 (a) and (b) show comparison between the distress condition of unmodified and modified binder and of unmodified and modified mixtures respectively at each temperature.

a)

b)

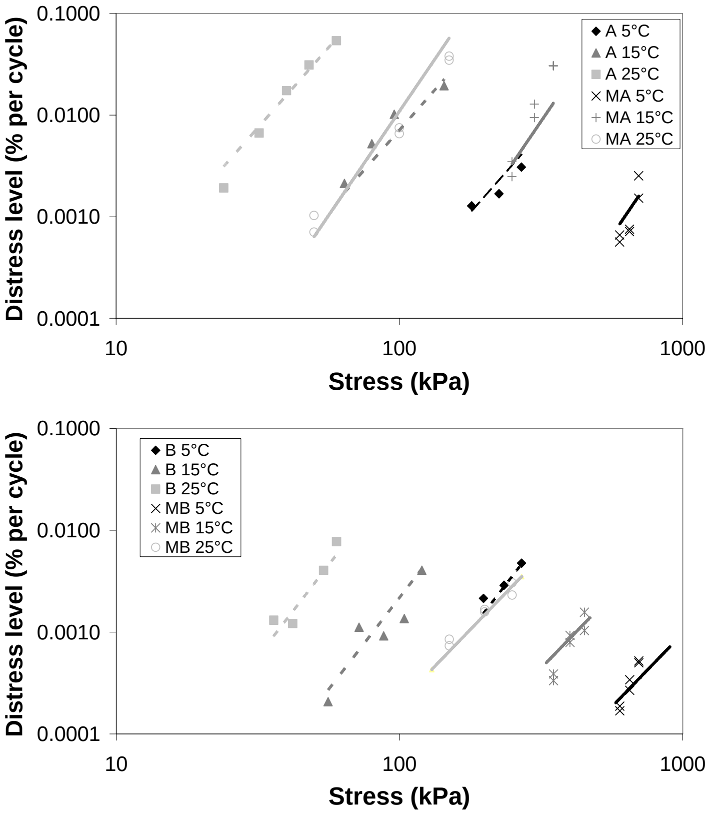


Figure 6: Comparison of distress model between binders and mixtures

It is possible to see that in both cases all model lines related to the mixtures are shifted toward the right. This means that the mixtures are able to reach the same distress level at the same temperature as they are subjected to higher stress levels, but it can not be ignored that the kind of stress is different. In fact if we remember, binders were subjected to a shear loading mode while the mixtures were subjected to a direct tensile loading mode. Furthermore, in the mixture many factors such as adhesion binder-aggregate, cohesion bituminous mastic and hardness of aggregate contribute to fatigue properties, while in the fatigue test on binder only the inner cohesion of the material is considered. A further evident result is that the use of modified binder in the mixture amplifies this difference in performance. In fact, a clear separation between the model lines related to mixture as regards those related to binder can be seen.

Important considerations can be made by using the model so as to relate the stresses that produce the same distress level on both binders and corresponding mixtures at each temperature (see figure7). It is to be noted that the model law was only evaluated in a stress range comparable with the stress levels chosen to test binders at each temperature.

The graph shows the two correlations related to the unmodified and modified materials. These correlations let us easily know, for every increase in stress on binder, the relative increase in stress on mixture needed to produce the same distress level at each temperature.

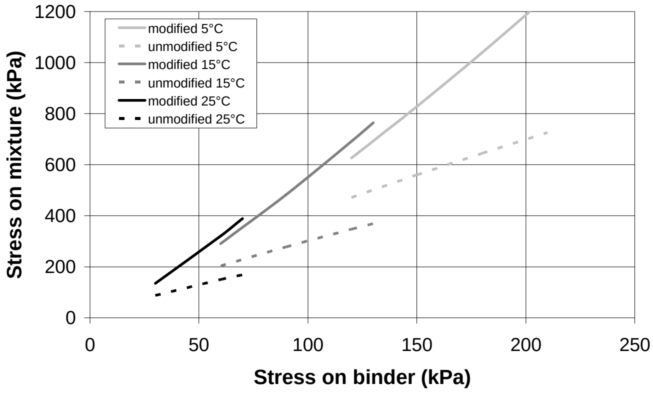


Figure 7: Correlation between binder and mixtures for the same distress level

A further consideration can be made on the effects of the temperature variable on the fatigue performance of materials. In particular, it is clear that lines related to unmodified materials are farther from each other which means that once the stress on binder is fixed the increase in stress on mixtures depends highly on temperature. As regards the modified materials, the corresponding lines are so close that the changes in stress on mixtures due to the changes in temperature are very low. This result confirms that the fatigue properties of modified materials are less affected by the temperature variable.

Another way to compare the fatigue properties of these materials is to use this model so as to find all stress levels as function of temperature that cause the same distress level in all investigated materials (see figure 8).

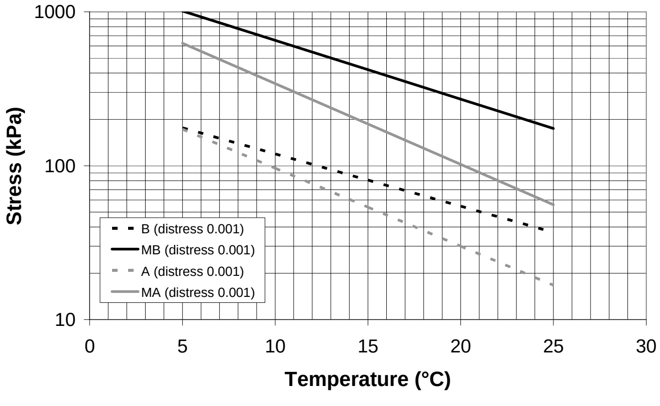


Figure 8: Model results leading to a distress level equal to 0.001

It can be noted that, for all materials, an increase in temperature results in a decrease in stress in order to produce the same distress. This is a likely result as it is well known that the structural capacity of an asphalt pavement tends to decrease when temperature increases which results in a loss of mechanical properties and leading to a greater internal distress.

This graph clearly highlights the significant improvement in the fatigue resistance of bituminous binders and mixtures due to polymer modification. In fact, the modified materials need to be subjected to a higher stress level to reach the same distress at the same temperature. Moreover, it can be seen that an increase in temperature results in a greater gap between the performance of the unmodified and modified materials. In particular, as already mentioned above, at 5°C the two binders reach the same distress for comparable stress levels.

4. CONCLUSIONS

The main purpose of this work was to compare and relate the fatigue properties between binders and corresponding asphalt mixtures. The fatigue behaviour of these materials was investigated through a new analysis approach. In particular, this method is based on the research and analysis of a rational parameter which can well describe the distress condition of a material when subjected to the fatigue phenomenon. To this end, a plain and polymer-modified bitumen and corresponding mixtures were tested at different temperatures and stress levels by performing dynamic fatigue tests. Fatigue tests on binder consisted of dynamic time sweeps in shear by using a DSR, while fatigue tests on asphalt mixtures were performed through repeated direct tensile loads.

The data results showed that fatigue behaviour of binders and asphalt mixtures can be investigated through the analysis of the change in complex and stiffness modulus respectively. In fact, the trend of the loss in modulus as well as the rapidity with which it decreases well express the accumulated fatigue damage in a material during a repeated load cycles.

The analysis of the modulus shows that it tends to decrease up to a failure condition as the number of load cycles increases and it decreases faster when the initial stress level is higher regardless of the temperature; which results in a shorter fatigue life. Moreover, the modified materials, binder and mixture, showed a slower loss in modulus at each temperature thereby assuring higher fatigue resistance.

Starting from these results, the percentage loss in modulus per load cycle was considered to measure the distress level due to fatigue damage. This rational parameter, related to the test variables (stress level and temperature), allowed to define a simple analytical model aimed to evaluate the distress of each material.

The use of this model allowed us to clearly express the response in the fatigue of each material and to show well the effects of stress level, temperature and polymer modification on their fatigue performance. Moreover, it provides correlations between binders and corresponding mixtures aimed to predict the stress levels needed to cause the same fatigue damage in both materials.

Such an approach could be useful in the context of pavement design since it would allow to evaluate the fatigue life by monitoring the distress of bituminous materials that is loss in the structural performance of pavement due to traffic load.

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