ORIGINAL APPROACH TO PREDICT FATIGUE ENDURANCE LIMIT OF ASPHALT BINDERS CONSIDERING HEALING CAPACITY

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ABSTRACT

More phenomena interact (e.g. viscoelasticity, damage, healing) contributing to the overall behavior of binders in terms of fatigue endurance limit. However, currently there is no consolidated analytical approach inclusive of strength recovery during rest periods to characterize fatigue performance.

This research proposes a criterion to determine the resistance of binders subjected to monotonous cyclic loading with multiple rest times by using a Dynamic Shear Rheometer. Main rheological properties are measured and the modeling of their evolution during each stage is proposed. The experimental program includes different binders in order to investigate the effects of SBS modification levels and aged binder contents on healing potential.

Beyond the classical component related to damage analysis, the proposed criterion enables to identify other fundamental contributions, leading to a comprehensive fatigue endurance limit. This approach allows distinguishing binders taking into account their healing capacity and should provide a better correlation with in-service performance of mixtures.

Keywords: fatigue; healing; viscoelasticity; rest period

INTRODUCTION

Fatigue cracking is certainly one of the major causes of deterioration of asphalt pavements, caused by continuous application of traffic loads over a period of time. Although this problem has been widely studied, many doubts still exist about fatigue resistance definition and its determination through laboratory tests. These concerns result in the need of empirical calibration factors to correlate laboratory data and in situ measurements. There are many aspects (e.g. mixture composition, layer thickness, environmental conditions) that contribute to cracking initiation and propagation. However, bituminous binder is the component that plays a key role in determining the global fatigue endurance limit [1, 2]. Fatigue resistance can be measured by the maximum number of loading cycles that a material is able to endure until failure when is subjected to repeated loads (cyclic or random, below its ultimate failure strength). For polymeric materials and bituminous binders, the analysis of fatigue resistance shall consider time and temperature dependent phenomena that affect the overall material response. Among them, the self-healing capability must be surely taken into account. During rest periods, self-healing represents the potential of binders to recover part of the damage accumulated during the loading phase. However, this recovery may be partially affected also by other phenomena such as thixotropy or steric hardening. Thixotropy is associated to the behavior of a non-newtonian fluid in which the viscosity decreases with time during the application of a shear stress. Once the mechanical disturbing action is removed, the material becomes stiffer again recovering its original properties. Steric hardening refers to a slow heat-reversible structural hardening due to molecular rearrangements, that may occur over time leading to a more stable structure. Therefore, during rest periods the material starts to restructure with a consequent increase in stiffness. Although the occurrence of this phenomenon has been documented in binders, it is necessary to point out that steric hardening appears to significantly act only at high temperatures and it seems to be less consistent at intermediate temperatures [3]. Anyway, these time dependent phenomena can have a significant impact in the evaluation of self healing capability and, consequently, in the determination of the global endurance fatigue limit of binders. Therefore, it is necessary to develop an analysis method that allows to identify the extent of their contribution in order to achieve a more reliable assessment of fatigue resistance.

OBJECTIVES

This study is focused on the analysis of self-healing potential of various binders. The research aims to provide an interpretative criterion able to identify the true healing potential (taking into account also the viscoelastic phenomena that may concurrently occur) resulting from the application of multiple rest periods and to assess its real impact on the overall fatigue resistance. Therefore, this criterion should enable to define a global fatigue endurance limit better correlated with in-service performance of bituminous mixtures. Based on this approach, healing capability of different binders was discussed considering the influence of different levels of polymer modification. In addition, in order to investigate the healing potential of mixtures containing Reclaimed Asphalt, long term aged binders were also considered.

MATERIALS AND TEST METHOD

Healing is a several stages mechanism composed by short term wetting and cohesion at the crack interface and long term interdiffusion. Assuming the interdiffusion process as the main responsible for stiffness recovery, it is necessary to provide a certain amount of time to allow this phenomenon into the specimen. Additionally, based on previous studies [4], a single rest period does not appear able to have a significant impact on fatigue performance and could lead to erroneous predictions about the actual binder healing potential in a long term time-scale. Therefore, in order to obtain a more realistic estimate of this capability and to simulate what happens in field conditions (where pavements are subjected to more rest periods, random or cyclically alternated), applying multiple long rest times separated by loading phases is considered more suitable.

One base binder (B) and three SBS modified binders have been investigated. The modified binders are obtained from the same base bitumen (B) and three different modification levels, 1.8 % (S), 2.8 % (M) and 3.8 % (H) by weight of SBS radial polymer (Cf. Tab. 1). Moreover, binder H was long term aged through Rolling Thin Film Oven and Pressure Aging Vessel (R), to simulate in laboratory a binder obtainable by a milled highway pavement. Additionally, two fractions (30 % and 45 % by weight) of this "Artificial Reclaimed Binder R" were mixed with each one of the three abovementioned binders S, M, H, in order to investigate the effect caused by Reclaimed Asphalt (RA) on the fatigue performance of binder. Therefore, the study included a total of eleven binders.

Table 1. Basic characteristics of main bituminous binders used in this study

Binder characteristics	Unit	B	S	M	H
SBS polymer content by weight	%	0	1.8	2.8	3.8
Penetration (25°C; 100g; 5s)	0.1mm	67.65	58.50	51.87	53.90
Ring and ball softening point	°C	45.48	66.75	68.60	70.75
Ductility @ 25°C	cm	82	97	> 100	> 100
Dynamic viscosity @ 135 °C	Pa s	0.22	0.81	1.02	1.24
Residue after RTFOT - Mass loss	%	-	0.08	0.13	0.05

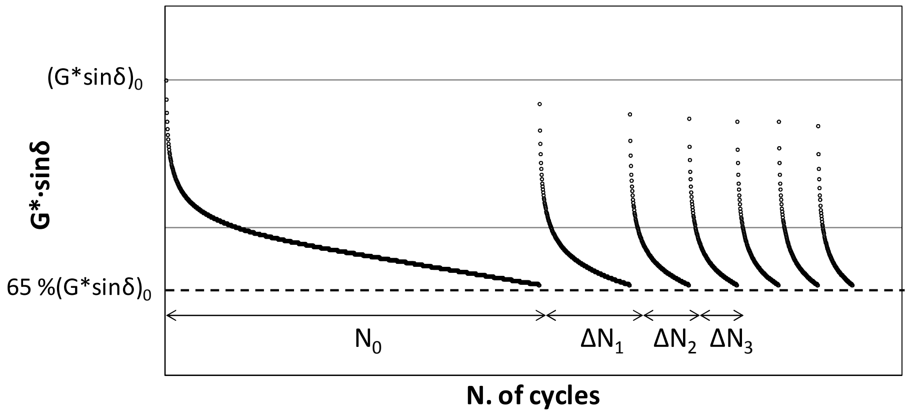
The selected binders were tested using a Dynamic Shear Rheometer (DSR) in a plate-plate configuration (diameter: 8 mm, gap: 2 mm). The tests consisted of a sequence of loading and rest phases. During the loading phase a sinusoidal strain with an amplitude of 5 % and a frequency of 10 Hz is applied and the stiffness of the binder is measured.

The loading ceases when the G*sinδ drops to 65 % of its initial value. A 30 minutes rest phase starts at this point. During the rest period the stiffness recovery of the material is monitored. A minimum of 12 load-rest phases were applied in all test condition. For each binder the initial stiffness was fixed at 3 MPa in order to avoid potential effects related to the stiffness dependency of the damage process [1]. This required an adjustment of the testing temperature to an iso-stiffness value that varied between 21 and 24 °C.

TEST PARAMETERS AND RESULTS

Typical test results are shown in figure 1. The complex modulus evolution as a function of time is recorded during both loading phases and rest periods. In the first stage of the test, a rapid decrease in the value of the complex modulus is recorded, mainly attributable to thixotropy. After this jump, the decrease slightly progresses with an almost linear trend, as shown by previous studies [1, 4]. This reduction is the macroscopic effect of the progressive accumulation of damaged surface in the sample [2]. Instead, during rest times a recovery of the modulus occurs, with a decreasing rate and an asymptotic tendency. Therefore, by monitoring the complex modulus trend during the loading phases, it is possible to evaluate the number of initial loading cycles (N_0) and after each rest (ΔN_i) necessary to achieve the set stiffness value (i.e. 65 % of initial G*·sinδ).

Figure 1. Evolution of G·sinδ vs Number of loading cycles.*



From the first results obtained, it was observed that ΔN_i decreases with the number of rest phases (i) with a gradually lower rate, until an almost constant value is reached (Cf. Fig. 1). Therefore, the ΔN_i value is assumed to derive from two contributions: one provided by healing and the other related to thixotropy and steric hardening. Since these latter phenomena are intrinsic properties of the material, they will continue to act even once the material has reached its fatigue endurance limit and lost its self-healing capability. In fact, after the applications of numerous rests, even if the sample damage is evident, a recovery in modulus is still recorded during rest time. Such recovery is attributed particularly to thixotropy, because the steric hardening is not so significant at intermediate temperatures [3], strongly reduced by the presence of SBS polymer [5] and prevented by high strain level. The extended number of cycles due to the thixotropic recovery after each rest time has been quantified equal to ΔN_i, with i very high (i.e. for a rather large number of rest periods). In sharp contrast with experimental evidence, this term would lead to an infinite endurance limit, as if the material never collapsed. Referring to the above considerations related to the behavior of the material, purifying the total number of cycles from this term ($i \cdot \Delta N_i$) appears quite reasonable, since it represents a fictitious contribution due to reversible phenomena which does not truly provide any benefits in terms of fatigue resistance. Following these observations, a simple equation was elaborated (Cf. Eq. 1), which allows to identify and separate the various contributions to the fatigue endurance limit of binders and to calculate the real total number of loading cycles to failure:

$$N_{TOT} = N_0 + N_{fH} \tag{1}$$

where N_0 is the number of cycles to reach the 65% of initial G*sinδ value during the first loading phase and N_{fH} is the maximum recovered number of cycles due to healing. N_{fH} is related to the recovered number of cycles due to healing after "*i*" rest periods (N_h) following the expression of Eq. 2 to fit the experimental data:

$$N_h = N_{fH} \cdot \left[1 - e^{\frac{-3 \cdot i}{i_{95}}}\right] \tag{2}$$

where i is the number of rest periods and i_{95} represents the number of rest periods to reach the 95% of N_{fH}. This formula (Cf. Eq. 2) translates the self-healing capability of materials and allows comparisons between different binders (Cf. Fig. 2). Results obtained for every binder with the proposed analysis criterion are shown in Table 2.

Figure 2. Effect of modification level and aging.

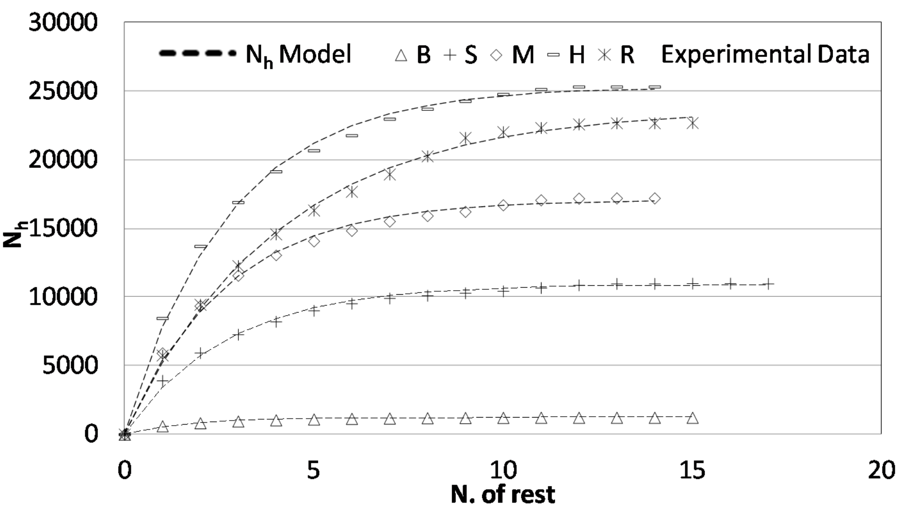


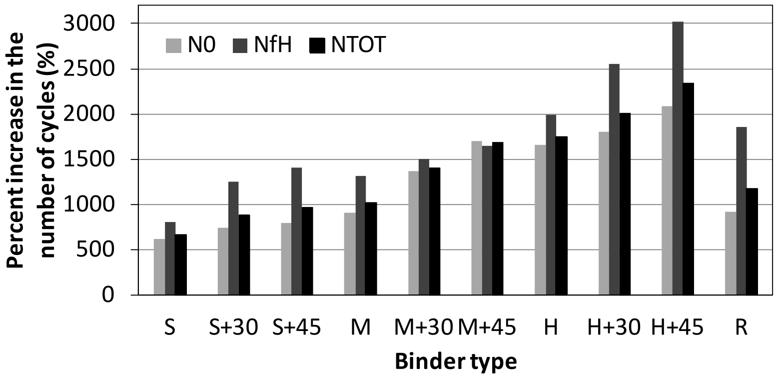
Table 2. Results obtained from the proposed analysis criterion

Binder	N_0	N_{fH}	i_{95}	N_{TOT}
B	3180	1211	5.30	4391
S	22780	10890	8.12	33670
S+30	26640	16385	8.14	36578
S+45	28260	18307	8.31	46567
M	32000	17113	8.07	49113
M+30	46540	19435	9.32	67164
M+45	57340	21188	8.41	78528
H	55780	25315	8.23	81095
H+30	60480	29524	9.46	90004
H+45	69520	37728	10.68	107248
R	32340	23696	12.31	56036

The parameter i_{95} seems to be a constant value of the material, affected by the presence or the absence of polymer and aging (S, M, and H have a i_{95} value almost constant, but higher than that one of base binder B; R is characterized by the highest value). Moreover, i_{95} value slightly increases with the increase of R percentage. High i95 values correspond to a binder able to preserve the healing capability for a higher number of rest periods, desirable behavior probably related to the chemical structure of the material. The highest i95 value of binder R could be due to the consequences of the aging process which causes shorter polymer chains through the oxidation of the butadiene block [6], allowing a better interdiffusion, main healing mechanism.

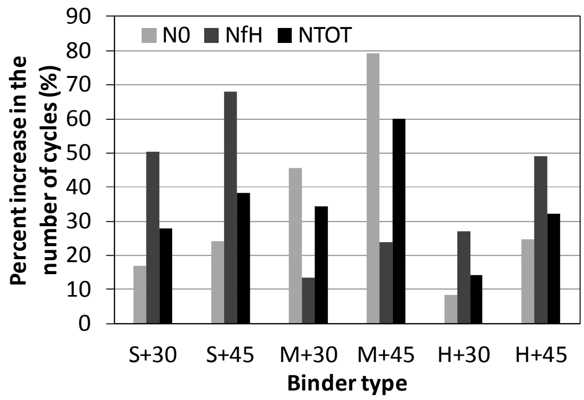
Considering the base binder B as reference material, some observations about the modification level and the addition of reclaimed binder effects can be drawn (Cf. Fig. 3). First of all, an increase in the global fatigue limit (N_{TOT}) with the increase in both polymer and R percentage is recorded. In fact, binder H+45 shows the highest N_{TOT} value, due to both an increase of N_{fH} and N_0. In addition, the increase of N_0 is always lower than that one of N_{fH} for almost all binders. The value of N_{fH} also increases with the increase of both polymer content and R percentage. With an increase in polymer content, an improvement in the healing potential is observed (Cf. Fig. 3). Apparently, polymer chains create a better capacity of rearrangements to reach the initial configuration and the modification enhances fatigue life of binders [1]. However, it is worth noting that by adding 45 % of artificial reclaimed binder to binder S or M, the same performance of respectively binder M and H are reached. At the same time, it should be noted the long term aging causes a weakening of the material and so a decrease in N_0 value of binder R (aged) compared to that one of binder H (not aged). Anyway, this decrease is not recorded in the healing potential parameter (N_{fH}), which remains approximately equal to that one of binder H. This behavior demonstrates the polymer does not suffer deterioration due to aging and is still able to provide completely its healing contribution. This ability is not enough to compensate the performance decrease caused by aging on the other components of aged binder and a decrease in the overall fatigue endurance limit is consequently observed (Cf. Fig. 3).

Figure 3. Percent increase in the number of cycles compared with reference binder B.



The percentage increase in the number of cycles (N_0,N_{fH} and N_{TOT}) due to the adding of different percentages of artificial reclaimed binder compared to the initial modified binder (respectively S, M, H) is depicted in figure 4.

Figure 4. Effect of artificial reclaimed binder on the modified binder (respectively S, M and H).



The artificial aged binder not only does not seem to penalize material performance, but indeed appears to enhance both fatigue and healing attitude. The simultaneous presence of shorter polymer chains (from binder R due to aging) and intact unaged chains optimizes the recovery capability creating a network even more effective for fatigue performance. In particular, the highest increase in terms of healing lies with binder S (both with 30 % or 45 % R), while binder M with reclaimed binder is that one which shows the lowest increment. On the contrary, binder M with different percentages of R demonstrates a better behavior in terms of initial loading cycles (the increase in N_0 value is the highest). Binder S+%R and H+%R show a similar behavior between each other. Thus, binder M with reclaimed binder appears to have a lower propensity to heal (even if an improvement compared with binder M is always recorded), but shows a greater progress in terms of “classic” fatigue concept. This compensates the lower healing attitude and gives finally a better behavior in terms of global fatigue life increase (N_{TOT}). Nevertheless, the absolute total number of cycles remains higher for binder H+30 and H+45 (Cf. Tab. 2).

CONCLUSIONS

This study provides an innovative criterion to identify the true healing potential and the global fatigue endurance limit of binders. The main conclusions are listed below:

- SBS polymer enhances healing capacity. The cross-linked polymer network seems to improve the recovery capability of material without suffering non-reversible damage.
- The healing potential is not affected by aging. The shorter polymer chains created by oxidation still contribute, allowing a better interdiffusion during rest periods. Specific chemical tests (FT-IR) are currently in progress in order to investigate the correlation of i_{95} parameter with the chemical properties of materials.
- Long term-aged binder does not negatively affect virgin binder performance, but improves both fatigue resistance and healing attitude. Thus, in terms of cohesive healing, there are no elements to discourage the use of recycled material.
- Multiple long rest periods are needed to properly simulate the real in situ behavior in a long-term time-scale and to obtain a more suitable and reliable endurance limit.

Further studies must be developed to validate the proposed analysis approach involving investigations on several binders to study the effects caused by different chemical structures, including the analysis of test temperature, strain and frequency.

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