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# Recovery of asphalt mixture stiffness during fatigue loading rest periods

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## HIGHLIGHTS

- Introducing rest periods in fatigue loading of asphalt mixtures were examined.
- Neat and polymer modified asphalt was tested, with the polymer modified asphalt having a higher fatigue life.
- Rest periods extended fatigue life significantly at intermediate temperatures (10 °C and 20 °C).
- Rest periods at colder temperatures would have a detrimental effect on the fatigue life of the mixture.

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## ABSTRACT

Asphalt is a self-healing material that has the ability to restore part of its stiffness and strength during rest periods and elevated temperatures, leading to a significant extension in service life. The self-healing of asphalt mixtures has been investigated in this paper using a modified tension-compression fatigue test. Asphalt mixture specimens, prepared with different binders (neat and SBS polymer modified) and gradations, were sinusoidally loaded in strain control mode, with a rest period being introduced at the end of each loading period. Rest period temperatures varied at 0, 10 and 20 °C. This loading-rest sequence was repeated three or four times. For some tests, the samples were loaded to complete failure after the final rest period. The asphalt mixture with the polymer modified asphalt had much better resistance to fatigue loading compared to the samples with neat binder. The stiffness of the sample represented by the norm of complex modulus (|E*|) showed an increase during the rest periods. The fatigue life in terms of number of loading cycles was higher with an increase in rest time temperatures. Moreover, the fatigue life values of the samples with rest periods were significantly higher than for continuously loaded samples loaded under the same conditions.

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## 1. Introduction

The self-healing or stiffness recovery or intrinsic healing) of asphalt mixtures has been studied extensively during the last decade as a popular research topic. It is a process that counteracts the growth of fatigue cracks during rest periods [6] and elevated temperatures [26], leading to a significant extension in fatigue, and by extension, service life [32]. Therefore, it is important to investigate the fatigue behavior of asphalt mixtures in relation to their intrinsic healing properties.

In 2004, the "RILEM TC 182-PEB" Technical Committee conducted a test campaign featuring 11 different test setups with more than 150 fatigue results [15]. In their investigation, the presence of three distinct phases during fatigue test has been confirmed. The first phase is the initiation phase during which the rapid decrease of the modulus could not be solely explained by fatigue, but by the presence of other phenomena such as local heating and thixotropy [4]. During fatigue loading, micro-cracks will be initiated in the first phase and then start to propagate inside the material during the propagation phase. The first and second periods are related to crack-initiation, while the third period is related to "macro" crack evolution leading to sample failure [16]. The intrinsic healing has been found to have the greatest impact on fatigue life during the propagation phase [29].

During investigations of the complex modulus during the three phases of the fatigue test, [31] introduced the Poisson's ratio as a parameter. Their tests were conducted in tension-compression at 10 °C, 10 Hz in strain control mode. The Poisson's ratio was found to increase during the initiation phase, decreasing slowly during the propagation phase and rapidly decreasing during failure. Visible correlations were found between the volumetric strains and

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global damage in similar fatigue tests [32]. As the sample temperature increased during the test, the modulus decreased and the volume of the sample increased. The development of microcracks within the sample could explain the increase of volume obtained during fatigue test [32]. For the same tests, the temperature was found to rapidly decrease when rest periods were introduced [21].

Dynamic mechanical analysis DMA was performed by [19] on two SHRP-classified binders, AAD-1 which has a phase angle variation from 56° at 10 °C to 78° at 40 °C and AAM-1 which has a phase angle variation from 36° at 10 °C to 76° at 40 °C, to investigate fatigue damage and healing in asphalt mixtures during different rest periods. They found that the fatigue life was extended for both mixtures; however, AAM-1 healed considerably better than asphalt AAD-1. Another study by Shen et al. [28] used the dissipated energy approach and the dynamic shear rheometer test to investigate the healing of asphalt binder. The rate of dissipated energy recovery per unit of rest time was used as a tool to quantify the healing. Their study showed that the type of asphalt binder, the strain level applied, and the temperature all affect the perceived healing capability of asphalts.

The effect of rest periods to extend fatigue life has been investigated by a number of researchers. It was concluded by Brown et al. [8] that stress amplitude, frequency, *in situ* healing rate and rest periods are the main variables that affect the degree of fatigue life extension. For instance, the fatigue life was more than doubled increased by 118%) when the rest period was optimized in rapidly growing cracks. Also, the results indicated that when the cracking growth rate is slower than the *in situ* healing rate, the fatigue life was extended noticeably. Castro and Sanchez [10] found that the mixture fatigue life of samples with rest periods noticeably increased by five to ten times compared to samples that were loaded continuously.

The healing tests can be extended to different temperatures, load levels, and mix types [9]. Shan et al. [27] conducted fatigue tests with 10 Hz sinusoidal loading at temperatures of 20 °C and 25 °C to characterize a thixotropic model. The findings of their model showed that fatigue and healing were more likely associated with thixotropy, in which the microstructure of samples breakdown and build up causing the change of the sample behavior during fatigue and healing tests.

Daniel and Kim [13] conducted a three-point bending test using the impact resonance method, carried out with cycles of loading and healing on asphalt mixture beams. A total of 3000 load cycles were first applied at 1.7 Hz. The beams were kept at two different temperatures of 20 °C and 60 °C, for a rest period of 4 h, and then these beams were conditioned for 6 h at 20 °C. The exact procedure was repeated at 10,000 and 20,000 cycles, and finally, the beams were fatigue loaded until they failed. The results showed that the rate of healing and stiffness increased with the increase in temperature and rest time. Breysse et al. [7] applied rest periods to the two-point bending fatigue test, and then modeled the sequences of fatigue and recovery. The findings indicated that the re-damaging rate was a good indicator of non-recoverable damage.

Grant [17] used the indirect tensile fatigue and resilient modulus to characterize the fatigue and healing properties of asphalt mixtures. Two different temperatures (10 °C and 15 °C) were used in the indirect tensile fatigue test. At the beginning, a 0.1 s load period was applied with a recovery period of 0.9 s for 1000 cycles. Furthermore, resilient modulus tests were conducted after the load was removed for 2, 4, 6, 10, 20, 40, and 60 min. The results found the healing to be a non-linear process which is rapidly occurred at the begging of the rest period and decreased over time. Results also indicated a dependent relationship between healing and temperature, since healing at relatively higher temperatures is much faster than for lower temperatures.

Abo-Qudais and Suleiman [1] monitored fatigue damage and crack healing using stress control indirect tensile fatigue test along with ultrasound pulse velocity (UPV) measurements. The fatigue test was performed in two stages, with a recovery period in between. Five different recovery periods (1, 3 h, and 3, 7, and 14 days) and five different temperatures (0, 15, 30, 45, and 60 °C) were applied in the study. The UPV measurements were conducted continuously before and after each stage of the fatigue tests and after the rest periods. The results showed that when the load increased, the UPV decreased, and when rest periods/temperatures increased, the UPV increased. However, the values of UPV were susceptible not only to rest period length and temperature, but also the aggregate gradation.

Nguyen et al. [22,24] have shown experimental evidence of the validity of the time temperature superposition principle (TTSP) in the nonlinear domain, including crack propagation. This result may be of practical importance when modeling fatigue behavior.

Babadopulos et al. [5], Di Benedetto et al. [14], Nguyen et al. [23] and Tapsoba et al. [28,29] have developed an original approach to identify and quantify the different physical phenomena existing during fatigue tests on bituminous mixtures. Beside transient effects existing only at the beginning of cyclic loading [13], these phenomena can be separated in two groups, i) reversible phenomena, including: non linearity, self-heating and thixotropy, that can be considered as biased effects when analyzing fatigue damage during fatigue test and, ii) irreversible phenomenon called fatigue damage. The category of healing generally groups reversible phenomena. The authors considered the recovery to be a better qualification than healing in qualifying the observed recovery of complex modulus during rest period. Healing appears as more adapted when a "macro-crack" exists.

In general, characterizing fatigue-healing behavior would help pavement professionals to evaluate the fatigue life values of asphalt materials to effectively develop maintenance strategies and design long-lasting pavements [7]. In addition, long-lasting pavement will help to reduce $CO_2$ emissions and the energy consumption required for pavement maintenance, rehabilitation and replacement [20]. This paper investigates the fatigue and healing behavior of asphalt mixtures using a modified tension-compression fatigue test on three different mixes.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Asphalt mixtures

Three asphalt mixture formulations were selected for this study (Table 1), having been developed at ENTPE (known as "gradation 0/6), and used in several other projects. The mixtures E2 and E7 are dense-graded mixes, while E13 had very a similar gradation with a slightly larger proportion of course particles (passing 3.15–4 mm). Both the coarse and fine aggregates were diorite.

The asphalt binder content for all three mixes was 6.8% of the mass of the mix, with the binder having a penetration value (EN 1426) of around 60. E2 and E13 were fabricated with neat binder where the binder for E7 had 4% of SBS polymer.

#### 2.1.2. Sample preparation

Asphalt concrete slabs were compacted using the French laboratory compactor [12]. The dimensions of the compacted slabs were $150 \times 400 \times 600\ mm^3$. Two weeks after the compaction, cylindrical specimens with a diameter of 80 mm were cored vertically in the same direction as the compaction and then trimmed to a 120 mm height [3].

**Table 1**
Asphalt mixture binders.

| Mixture | Binder type |
|---|---|
| E2 | 60 Pen straight |
| E7 | 60 Pen with 4% SBS |
| E13 | 60 Pen straight |

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