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Field assessment of oxidative aging in asphalt concrete pavements with unknown acoustic properties

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HIGHLIGHTS

- Nonlinear ultrasonics effective to evaluate aging in asphalt concrete pavements.
- Technique is truly nondestructive and easy to operate.
- Technique only requires access to pavement surface for aging evaluation.
- Oxidative aging evolution is plotted in a two-dimensional space.
- Approach has potential to evaluate rejuvenator efficiency.

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ABSTRACT

Because in the field asphalt concrete acoustic properties (*i.e.*, velocities and corresponding attenuations) are unknown, a modified version of the non-collinear wave mixing method is proposed to evaluate oxidative aging levels. Longitudinal transducers mounted on angle wedges are employed to launch subsurface dilatational waves to allow evaluation when there is only access to one side of the asphalt concrete pavement. For the mixture used, one fixed incident angle was found, which is suitable for the range of oven-aged asphalt concrete specimens, *i.e.*, 0–36 h. Theoretical explanation and experimental evidence supporting the validity of the proposed approach is presented.

1. Introduction

Thermal, block and top-down cracking in asphalt concrete (AC) pavements are major forms of distress that are highly detrimental to pavement quality and service life once initiated. Repeated exposure to environmental conditions accelerate the formation, growth, and coalescence of micro-flaws, which results in the development of damaging macro-cracks. Exposure to oxygen is one of the main contributors to micro-crack formation in asphalt concrete (AC) pavements, where the micro-flaw population is directly related to the amount of oxidative aging of the AC. Once degradation has progressed to the point where micro-cracks are present, the pavement is susceptible to further damage as moisture and oxygen can infiltrate further into its depth [1,2]. As a result, millions of dollars are spent annually in repair and maintenance of AC pavements. It is more cost effective to frequently provide maintenance on pavements that are still in "fair" condition than it is to defer maintenance until the pavement deterioration has reached a "poor" state; consequently, determining the proper time for repair and maintenance is a critical issue [3,4]. Visual inspection alone is not always adequate to evaluate the state-of-damage of a pavement, mainly because damage may not be visible despite the fact that diffuse micro-flaw populations may already exist in abundance. Furthermore, even if these diffuse flaw populations do not yet exist, the binder state-of-oxidative aging is such that diffuse flaw populations are just about to develop, mainly because of the increasing loss of binder viscoelastic relaxation capabilities and adhesive properties. Currently, there is no practical method to in-situ nondestructively evaluate the level of oxidative-aging of pavements before major deterioration has taken place. Clearly, there

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exists a need for a practical, easy-to-use method to nondestructively assess the level of oxidative-aging of AC pavements.

Asphalt concrete belongs to a class of materials named mesoscopic materials that are made of brick and mortar; in asphalt concrete the brick are the aggregates and the mortar is the binder [5,6]. In this class of materials, most of the deformation is concentrated in the mortar, which leads to these material to exhibit nonlinear response, even before any micro-flaws develop. Masad et al. [7–9] found that asphalt binders exhibit both linear and nonlinear viscoelastic behavior and the level of nonlinearity increases with stress or strain levels. Masad et al. [7–9] also observed that the average binder strain is 9-to-12 times the mixture strain, and that the maximum binder strain can be as high as 90 times the mixture strain. The nonlinear response of binders and mixtures was also studied by Delgadillo [10]. As aging progresses, the asphalt concrete increases in stiffness and loses adhesive properties. Initially, the increase in stiffness dominates the phenomenon; however, with continued increase in oxidation the loss of the binder's adhesive properties starts to dominate the phenomenon, which leads to the development of diffuse flaw populations. As these diffuse flaw population's increase in size with higher levels of oxidative aging, the asphalt concrete also increases its nonlinear response.

When an ultrasonic wave is transmitted through a material that exhibits nonlinear behavior, it also displays nonlinear behavior characterized by the nonlinear acoustic wave equation [11,12]. This nonlinear behavior can manifest itself in the form of the presence of higher order harmonics, or in the case when more than one wave intercepts at an angle, they may interact and produce a third wave of different mode, polarization and propagating in a different direction. When two waves interact to produce a third wave, *i.e.*, wave-mixing, the efficiency at which the third wave is generated is related to the presence of local material nonlinearities (*e.g.*, micro-flaws), whose characteristic lengths may be orders of magnitude smaller than the wavelengths traditionally used in linear ultrasonic nondestructive evaluation. This third wave is referred to as the "nonlinear scattered wave," and in order to be generated, the interaction between the two primary waves must meet resonance and polarization conditions [13–18].

In a previous study [19], it was shown that non-collinear wave mixing of dilatational subsurface waves can be used to estimate the nonlinearities in AC. Due to oxidative aging, most of the damage occurs in the binder, which with increasing levels of oxidative-aging becomes increasingly stiffer, less relaxant and less adhesive. The material nonlinearities increase with oxidative-aging, *i.e.*, the rate of damage accumulation increases. Therefore, characterizing these nonlinearities provides a tool to assess the level of oxidative-aging of the AC. In AC pavements, there is only access to one side, *i.e.*, the pavement surface; therefore, in order to be truly non-destructive, the measurements should only be taken from the surface by employing transducers mounted on variable angle wedges. As shown in Fig. 1, the incident angle of the wedges should be set to an angle close to the first critically refracted angle so that a majority of the wave energy propagates near and parallel to the surface allowing for the signals to be transmitted and received on the same side [20–25]. The most suitable incident angle corresponds to an angle slightly larger ($\approx 1^\circ$) than the first critically refracted angle [25].

In McGovern et al. [19], angle wedges were set to one degree above the respective first critical angle based on the amount of oxidative aging the specimen underwent. Because the ultrasonic velocities of asphalt concrete change with the level of oxidative aging [26], the first critical incident angle also changes correspondingly. Clearly, the aforementioned study [19] was performed with a prior knowledge of the level of oxidative-aging of the specimens. To apply this technique to the field for in-situ pavement testing, there is no prior knowledge of the oxidative-aging level of the asphalt concrete, rendering the appropriate incident angle also unknown. In this study, a systematic approach is proposed to address the issue of the unknown incident critical angle when there is access to only one side of the test specimen, *i.e.*, pavement. This method will allow the technique to be employed by practitioners in the field for pavement inspection, where the only preexisting knowledge of the pavement is its mixture-type. The use of a fixed angle removes the need to determine the critical angle, which reduces implementation time and makes it more practical for field use. Experimental validation is presented which support the validity of this approach.

2. Assessing the amount of oxidative aging in ac pavements via non-collinear wave-mixing of subsurface dilatational waves

To obtain the fundamental background of non-collinear wave-mixing, the reader is referred to references [13–18], and to references [19,27–32], where some applications can be found. When two monochromatic waves $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ with frequencies f_1 and f_2, respectively, are propagated in a medium with nonlinear elastic constants, such that they intersect at an angle φ, they can generate a scattered wave $\boldsymbol{k_3}$, with a sum or difference frequency ($f_3 = f_1 \pm f_2$). The scattered wave propagates at an angle γ with respect to $\boldsymbol{k_1}$. The type and polarization of the scattered wave depends on the type and polarization of the two primary waves. Jones and Kobett [14] found that for interaction to be possible, resonance and polarization conditions must be met. Consequently, out of fifty-four potential interaction cases, there are only nine interaction cases which satisfy both the resonance and polarization conditions.

In this study, two dilatational waves, $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$, with frequencies f_1 and f_2, respectively, are transmitted such that they cross paths at an angle φ. In a nonlinear medium (*i.e.*, the higher order terms in the wave equation are not neglected), the two dilatational waves can interact to produce a third wave $\boldsymbol{k_3}$, with the frequency $f_3 = f_1 - f_2$. The third, scattered wave is a shear wave, polarized in the $\boldsymbol{k_1}$-$\boldsymbol{k_2}$ plane, and travels in the direction γ with respect to the direction of $\boldsymbol{k_1}$. For the case where two dilatational waves interact to produce a shear wave, the resonance and polarization conditions are met when the following two equations are satisfied,

$$\cos[\varphi] = \left(\frac{c_L}{c_S}\right)^2 \left[1 - \frac{1}{2}\frac{f_1}{f_2}\left(1 - \frac{c_S^2}{c_L^2}\right)\left(\frac{f_2^2}{f_1^2} + 1\right)\right] \tag{1}$$

$$\tan[\gamma] = \frac{-f_2 \sin[\varphi]}{f_1 - f_2 \cos[\varphi]} \tag{2}$$

where c_L and c_S are the dilatational and shear wave ultrasonic velocities of the medium, respectively. It is noted that the parameters of the two equations are interrelated, where when one is chosen (*e.g.*, φ), the other two are fixed (*e.g.*, f_2/f_1 and γ).

It has been shown that dilatational waves used for the interaction can be generated such that they propagate parallel to the surface by mounting the transducers on angle wedges set close to the first critically refracted angle [19]. A strong subsurface dilatational wave is generated by setting the incident angle 1° above the first critical angle [25]. Dilatational waves that propagate nearly parallel and near to the surface are also termed subsurface dilatational waves.

$$[\theta_{Inc.}]_{Critical} = \left[\sin^{-1}\left(\frac{c_{wedge}\sin(\theta_R)}{c_L}\right)\right]_{\theta_R = 90^\circ} \tag{3}$$

Two subsurface waves can be transmitted such that they interact and generate a third scattered shear wave, which propagates in the same plane as the two subsurface waves, *i.e.*, close to the surface. Implementing the non-collinear wave mixing technique in