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Opening Letter of RILEM TC MWP: Mechanical wave propagation to characterize bituminous mixtures

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Abstract

This technical letter investigates mechanical wave propagation (MWP) methods to characterize the stiffness of bituminous mixtures (BM), particularly using ultrasonic testing (UT) and impact resonance testing (IRT), as innovative alternatives to traditional quasi-static techniques. Recognizing the complexity of BM's viscoelastic behavior influenced by temperature and frequency, the paper presents critical scientific and technological challenges to the newly started RILEM Technical Committee on MWP to characterize BM. By addressing the need for standardized testing procedures and data interpretation guidelines, the anticipated impact includes enhanced quality control and characterization capabilities that promote cost-effective pavement design. Furthermore, with this first effort on laboratory procedures, it is expected to facilitate future integration of non-destructive assessment methods into field practices, thus advancing the state-of-the-art in pavement engineering. This work aims to provide a robust framework for future research and practical applications in the characterization of bituminous materials.

Keywords: Bituminous mixtures; Mechanical wave propagation; Impact resonance testing; Ultrasonic testing; Complex modulus.

1 Background

The characterization of stiffness parameters in construction materials is becoming critical for quality control in the context of the advancement of mechanistic design methods, especially when it comes to pavement materials. In the linear viscoelastic domain, bituminous mixtures (BM) stiffness behavior is characterized by their complex modulus (E*), a complex number that provides insight on both the stress-strain amplitude ratio and the damping properties with its absolute value (|E*|, sometimes called "dynamic modulus" even though this does not mean inertial effects exist) and phase angle (φ), respectively. Traditional laboratory testing methods for bituminous mixtures typically involve applying compressive, or flexural alternate bending, or tension-compression load cycles to specimens to determine stiffness properties. This is done using load cycles slow enough not to produce inertial effects on the measured loads and displacements, hence the test is called "quasi-static". In this case, homogeneous tests such as uniaxial loading of cylinders, produce load and displacement measurements that can be used to determine E*, without the solution of a boundary value problem (BVP), which would require prior knowledge of the form of the rheological model of the material. In the homogeneous testing case, stress and strain fields can be directly calculated from forces and displacements measured in the boundaries of the specimens, with the application of Saint Venant's principle. Otherwise, the solutions of the BVP with a given assumed rheological model yield form factor coefficients to use the measured forces and displacements to calculate stress and strain at a given point in the specimen. Such coefficients are unfortunately dependent of the assumed rheological models. In the meantime, testing techniques relying on mechanical wave propagation (MWP) have emerged as cost-effective and non-destructive alternatives, offering potential advantages over traditional methods of testing using quasi-static loading.

When a deformable solid is subjected to an external force, a deformation is induced in the solid. This deformation generates a disturbance of the matter around its equilibrium state. If this happens fast enough, as particles of the medium are deformed, the disturbance propagates through the medium as a wave, carrying energy through motions of particles and without any mass transport. This is called a mechanical wave and tests involving its interpretation are called "dynamic" tests, while |E*| can be called dynamic modulus. Since stress and strain fields at a given time are not

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homogeneous in the specimen, as for the non-homogeneous quasi-static testing case, it is not possible to have direct access to E* measurement through tests' load and displacement, and further analysis is needed for proper calculation of the material property. Such analysis requires the solution of elasticity (or viscoelasticity) wave propagation problems to calculate adequate E* and Poisson's ratio that fit the measured vibrations.

The study of the propagation of mechanical waves in elastic solids is very well documented in the literature [1-3]. Mechanical waves propagating through a finite volume of solid, such as laboratory specimens, are referred to as body waves, as opposed to surface waves (Love waves and Rayleigh waves) that are confined to the surface of a medium and guided Lamb waves that are confined within boundaries. Body waves are categorized into two distinct types based on their particle motion:

- Primary waves or compression waves called P-waves. They involve particle motion that is polarized in the same direction as the wave's propagation and are characterized by relatively small particle displacements. P-waves propagate in a longitudinal manner and are the fastest type of body wave. Figure 1 illustrates the particle motion associated with P-waves.
- Secondary waves or shear waves called S-waves. They exhibit particle motion that is polarized perpendicular to the wave's travel direction. Their mode of propagation is always transverse, creating a motion that is orthogonal to the wave's travel direction. S-waves are slower than P-waves, reflecting their distinct propagation dynamics. Figure 1 provides a visual representation of the particle motion characteristic of S-waves.

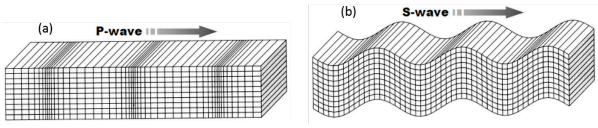

Figure 1. Particle motions characteristic of body waves propagation: (a) P-waves and (b) S-waves [4].

At the laboratory scale, ultrasonic testing (UT) and impact resonance testing (IRT) are amongst the most common MWP methods in the academic literature. UT is based on the measurement of the time-of-flight (ToF) of ultrasonic body waves through a specimen, as their velocities (ratio between ToF and the length of the specimens) are determined by the material properties. If the tested material is considered as isotropic linear elastic, the velocity of a P-wave can be directly linked to its density, Poisson's ratio (ν) and elasticity modulus (E). Since density can be easily measured with other techniques, testing P-wave velocity gives access to one equation relating ν and E. Since P-waves are the fastest traveling though the material, sending a compression pulse in one side of the specimen and measuring the correspondent arrival in the other can be considered a very simple test. Then, common standards adopt a fixed value of ν to calculate E, calling the obtained result the "dynamic Young's modulus". Varying the adopted ν has impact on calculated E. One way of avoiding such problems is to use a second independent equation relating ν and E, what can be done by determining another wave's velocity, for example S-waves. However, such task is much less simple due to the fact that when sending a shear pulse in one side of the specimen, several waves of different types (and velocities) arrive in the other side, which makes interpretation harder [5]. For viscoelastic materials such as BM, phase angle also intervenes in the equations, and this property could potentially be determined with further advanced analysis of UT data or it needs to come from other tests. For common applications with elastic materials, UT can be used to check the density, evaluate the stiffness or detect internal defects such as cracks and voids. Figure 2 (a) illustrates an existing UT set up proposed by Tavassoti et al. [6] to test BM and Figure 2 (b) shows an example of trigger and received signals from UT on a BM specimen.

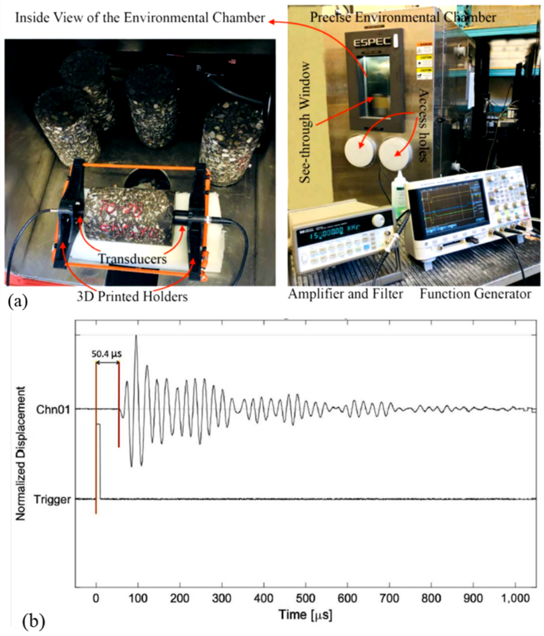

Figure 2. (a) Example of UT set up used on BM and (b) Example of trigger and received signals from UT performed on a BM specimen. [6].

Meanwhile, IRT relies on the resonance phenomenon. Resonance occurs when the loading frequency on a material is equal to one of its natural frequencies. This is traduced by oscillations of the matter at greater amplitudes for these natural frequencies also called resonance frequencies. In laboratory, these frequencies can be determined by recording the vibrations of a specimen subjected to an external loading such as an impact applied with an impact hammer. The resonance frequencies are a function of the geometry, of the density and of the material properties such as the stiffness (E or E*), the Poisson's ratio and the damping. Figure 3 (a) shows an example of IRT set up using an automated impact hammer developed by Carret et al. [7] and Figure 3 (b) displays an example of IRT data for a BM specimen.

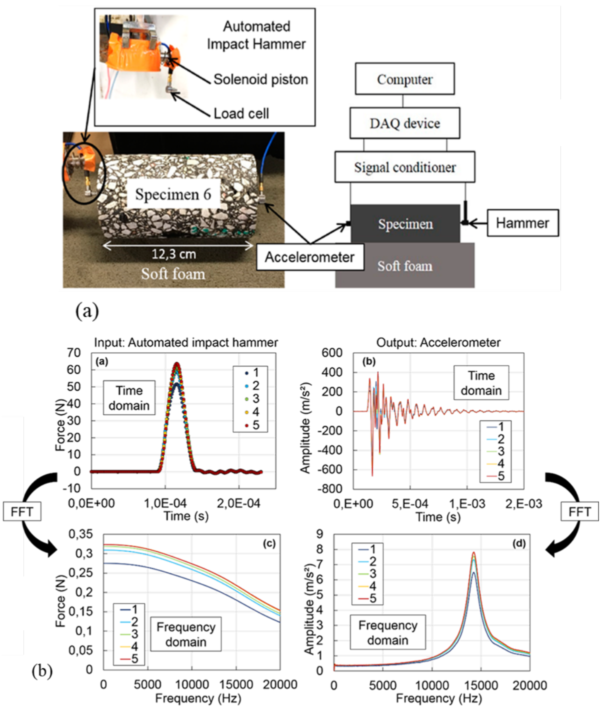

Figure 3. (a) Example of IRT set up with an automated impact hammer [7] and (b) Example of time and frequency domain signals obtained from IRT performed on a BM specimen [7].

Several international standards already exist for the characterization of materials considered elastic under small-strain loadings (like MWP) with UT [8-11] and IRT [12-14]. Consequently, UT and IRT have been widely used to successfully characterize materials considered as elastic such as cementitious materials, metals, soils and more recently for detection of defects in advanced composites [6; 15-18]. However, such standards are lacking for viscoelastic materials like BM. To address this gap, a technical committee (TC) of the International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) entitled *Mechanical Wave Propagation to characterize bituminous mixtures* (RILEM TC MWP) was officially approved in August 2024 and launched in the Cluster F meeting in Delft in 2-4 October 2024. Previous RILEM TC focused on the use of non-destructive evaluation methods – mostly MWP methods – to cement concrete [19-22]. RILEM TC MWP will be the first large-scale effort to apply such methods to BM.

BM exhibit a complex thermomechanical behavior, widely influenced by temperature and loading frequency. As stated, E* is the adequate material property for the investigation of linear viscoelasticity in this case, and such property contains information on the material with respect to its relaxation capability and creep [23]. Proper testing requires maintaining mechanical behavior in the LVE region for complex modulus evaluation. This is often achieved through small-strain quasi-static tests with servo-controlled hydraulic presses with different geometries and loads [24-28], although tension-compression tests seem to avoid problems existing in the other tests [29, 30]. Results may differ due to issues such as creep in compressive tests or nonlinearities in tension [31, 32]. Since BM exhibit viscoelastic and thermosensitive properties [33-35], their behavior must be studied across a wide range of frequencies and temperatures, typically represented using master curves [36]. Calibration of material constants, through rheological models such as the well-known 2S2P1D model, is then applied to describe their linear viscoelastic behavior [37, 38]. Meanwhile, for in situ auscultation, the most common methods focus on pavement performance evaluation and estimation of pavement quality index [35], or detection of surface anomalies [39-42]. These methods generally reflect the distress conditions of pavement surface rather than the internal stress/strain state and structural degradation of pavements [43]. Falling Weight Deflectometer (FWD) measurements offer this possibility, but they require a good knowledge of the structure design and auscultation campaigns remain expensive. In addition, the determination of the stiffness of pavement layers from FWD data requires advanced inverse analysis procedures [44, 45].

Worldwide, rational design of pavement structures is incorporating more and more mechanistic considerations, and control strategies should accordingly incorporate determination of fundamental properties instead of only compositional characteristics. Such improvements should contribute to make pavements endure approximately their designed lives, thus facilitating meeting durability criteria, necessary for the sustainability (including environmental sustainability) of those structures. In this context, there is a need to develop alternative testing methods to improve the characterization of BM both at the laboratory scale and the real scale. Despite recent progress, the use of MWP methods such as UT and IRT to characterize BM remains yet marginal in the asphalt community in comparison to conventional methods. The advancement of MWP techniques to develop E* mastercurves for BM across broad temperature and frequency ranges remains an active research area [5,7; 46-50]. These techniques promise broader applications for assessing stiffness properties and offer possibilities for more rapid, cost-effective field tests compared to traditional methods [51-56]. In terms of test preparation, while classical quasi-static testing requires gluing and fixing apparatus, usually a day before of testing, MWP tests do not require very special test preparation procedures, just positioning the specimen adequately. In terms of testing at a given stabilized temperature, quasi-static testing is done in different frequencies, with a number of cycles for each of them, with the tests lasting from some tens of minutes up to about an hour, depending on testing protocol, while MWP techniques take seconds (time for wave pulses). Finally, in terms of temperature stabilization, some MWP techniques, especially IRT, allow using slender test specimens, which would have temperature stabilized faster and could save testing time.

In MWP methods, stiffness evaluation often involves measuring UT pulse velocities [56], as explained before. For asphalt materials, UT procedures are similar but are limited to analyzing only a high-frequency section of the |E*| mastercurve. In IRT, by studying different modes of vibrations (e.g.: longitudinal, flexural and torsional), both the modulus and Poisson's ratio can be derived from resonant frequencies [7; 46-49]. For purely elastic materials, existing characterization methods [9, 14] suffice to determine a single modulus value independent of frequency through ultrasonic pulse velocity or from impulse load response analysis. However, materials like BM, with viscoelastic behavior (hence frequency-dependent), necessitate more complex response assessments tied to input loading. Evaluating Frequency Response Functions (FRFs) offers one pathway for a future standardized method, connecting output vibration to input impulse ratios in transformed spaces. Research on these techniques for asphalt is still limited. Results from IRT for asphalt mixture viscoelastic characterization can be examined using analytical approaches [50, 51, 53, 57-59] or inverse analysis with FRF data [7; 46-49]. However, there are still several challenges on finding optimum setup configurations and modeling and inverse analysis methodologies.

2 Objectives and expected outcomes

As previously discussed, mechanical wave propagation methods are not widely applied to bituminous mixtures due to the absence of established guidelines for conducting ultrasonic testing and impact resonance testing in laboratory settings. Furthermore, in addition to the absence of testing procedures, there is a notable gap in the guidelines for interpreting experimental data derived from UT and IRT. This deficiency hinders the determination of essential properties used in pavement design, quality control, and performance assessment. The lack of such standards and guidelines represents a significant barrier to the adoption of MWP methods for BM characterization. Recognizing these challenges, the new RILEM TC MWP aims to address these gaps by developing comprehensive guidelines for utilizing UT and IRT to characterize bituminous mixtures at the laboratory scale. The primary goals of the TC include:

1. Compilation and analysis of current practices: collect and summarize existing practices related to the application of UT and IRT for BM characterization.
2. Development of laboratory procedures: propose and validate standardized laboratory procedures for performing UT and IRT on BM.
3. Calibration and equipment protocols: define foundational protocols for transducer characterization and equipment calibration specific to MWP methods.
4. Result interpretation: evaluate and refine methodologies for interpreting UT and IRT results to derive meaningful material properties for design and quality control.
5. Database establishment: create an internationally shared, open-access database containing UT and IRT data on various BM types.

The outcomes of this initiative will promote the adoption of UT and IRT methods for BM characterization by academia, industry, and highway agencies. Specific deliverables include:

- State-of-the-Art (STAR) report: a comprehensive report summarizing the findings and progress of the TC's task groups (TG).
- Scientific publications: articles in the *Materials and Structures* journal and other outlets to disseminate the results of the TG activities.
- Standardization guidelines: development of guidelines for the future standardization of UT and IRT testing and result interpretation for BM. These guidelines will serve as RILEM recommendations and support harmonized methods for BM characterization.
- Educational resources: short courses and web-based training modules designed to educate stakeholders on UT and IRT methods, fostering their implementation in both academic and professional contexts.
- Conference contributions: dedicated sessions at RILEM conferences, including the RILEM ISBM conference, RILEM Week, and the RILEM Spring Convention. The TC will also organize focused sessions at international conferences on pavement materials and pavement design.

The TC's work is expected to significantly enhance the feasibility and practicality of using MWP methods for BM characterization. By providing validated laboratory procedures and robust analysis frameworks, the TC will lay the groundwork for future standardization of UT and IRT methods. MWP methods, specifically UT and IRT, have the potential to drastically reduce the costs associated with traditional BM characterization methods. Moreover, these methods hold promise as reliable tools for improving quality control and enabling faster, more efficient field testing. The TC's efforts will not only promote the use of innovative testing methodologies but also ensure the development of reliable, standardized approaches that align with the needs of modern pavement engineering and material science. By addressing critical gaps in testing and data interpretation, the RILEM TC will provide a valuable resource for advancing the state-of-the-art in BM characterization, driving cost-efficiency, and improving the quality and performance of bituminous materials.

3 Challenges

The application of UT and IRT for characterizing bituminous mixtures faces several challenges, as identified in the cited literature. Main ones can be summarized as follows:

- Complex thermomechanical behavior and data interpretation: The viscoelastic nature of bituminous mixtures, strongly influenced by temperature and loading frequency, presents a major challenge for interpreting UT and IRT data. Unlike elastic materials, BMs require advanced analysis methods (ranging from analytical models to inverse numerical procedures) to extract meaningful properties such as the complex modulus. However, these methods remain underdeveloped for MWP tests and need further validation and standardization. Additionally, the complexity of interpretation should be adequate to the intended results' quality: simplified approaches may suffice for single-point E* estimation, while more sophisticated techniques may be needed for constructing full E* mastercurves. Addressing this challenge is critical for defining practical and reliable data interpretation frameworks in future guidelines and this is a key point for the TC MWP.

- Best geometries and test setups: Accurate UT and IRT measurements depend on proper equipment calibration and test setups. More specifically, the coupling between the piezoelectric transducers or accelerometers and the specimen is critical for the accuracy of the test results. Yet, the measurement errors associated to the use of different adhesives (glue or wax) or to the rugosity of the surface of the tested specimens are still not clear. The influence of the characteristics (maximum force and damping) of the external excitation with an impact hammer on the quality and reliability of IRT data is also not well-documented. The geometry of the specimens also has an influence on UT and IRT results, and there is no consensus on what are the most suitable geometries for these tests. In practice, the geometry that are used correspond to geometries suitable for conventional test methods (e.g.: Marshall discs, Shear Gyratory compacted specimens, etc.).
- Influence of material heterogeneity: The heterogeneous nature of BM can affect wave propagation, leading to variability in measurements. Factors such as aggregate size distribution and air void content can influence the results, necessitating careful consideration during testing and analysis. These effects will be thoroughly evaluated and quantified in the framework of the TC MWP.

In addition, open questions in the literature on BM LVE behavior in general, such as the effect of moisture, aging, among other lacks of knowledge will also exist for newly developed tests. The RILEM TC MWP will not focus on those general gaps, but in specific gaps of the testing techniques and interpretation of results. Addressing such challenges should allow providing comprehensive guidelines for equipment setup and data processing, capable of providing reliable and practical use of UT and IRT for BM characterization.

Declaration of interest

The authors declare no conflicts of interest related to the research, authorship, and/or publication of this article.

Authorship statement (CRediT)

Jean-Claude Carret: Conceptualization, Writing – Original Draft. **Lucas Babadopulos:** Conceptualization, Writing – Review & Editing.

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