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Review

Modelling the linear viscoelastic rheological properties of bituminous binders

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ABSTRACT

An extensive literature review on the modelling of the linear viscoelastic (LVE) rheological properties of bitumen over the last six decades is presented in this paper. The use of reliable models can, in general, be considered as a valuable alternative tool for estimating the LVE rheological properties of bitumen. These properties are normally presented in terms of complex modulus and phase angle master curves at a particular reference temperature. The review in this paper consists of three nonlinear multivariable models, 13 empirical algebraic equations and four mechanical element approaches. The details as well as the advantages and disadvantages of the models are discussed. In general, all the models are able to predict the LVE rheological properties of unmodified bitumen as well as follow the time–temperature superposition principle (TTSP). However, the observations suggest a lack of agreement between predicted and experimental LVE rheological properties for materials that contain a phase transition, such as found for highly crystalline bitumen, structured bitumen with high asphaltenes content and highly modified bitumen.

Contents

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1. Introduction

Bitumen is traditionally regarded as a colloidal system consisting of high molecular weight asphaltene micelles dispersed in a lower molecular weight oily medium (maltenes) [1–11]. It is this colloidal structure that defines the rheological properties of bitumen ranging from sol (Newtonian dominated behaviour) to gel (non-Newtonian dominated behaviour). Although there are many methods available to determine the rheological properties, the cyclic (oscillatory) and creep tests tend to be the best two techniques for representing the uniqueness of bitumen behaviour [12]. However, recognising that testing is generally laborious, time consuming and expensive, requiring skilled operators, predictive models or equations can be a valuable alternative tool for quantifying the linear viscoelastic (LVE) rheological properties of bituminous binders [13,14]. Using this approach, the rheological parameters (complex modulus, phase angle, etc.) at any particular temperature and frequency (time of loading) of a bitumen can be estimated by means of the constitutive equations to an accuracy that is acceptable for most purposes.

In the 1950s and 1960s, nonlinear multivariable methods (also known as nomographs) were used to represent the LVE rheological properties of bitumen [15,16]. However, these nomographs became obsolete with time due to the invention of computational techniques and tended to be replaced by empirical algebraic equations and mechanical element approaches. In the empirical algebraic (also known as mathematical or phenomenological or constitutive) approach, any suitable mathematical formulation is simply adjusted to the experimental main curve, with the quality adjustment being the sole criterion of choice of formulation. Meanwhile, in the mechanical element approach (or analogical model), use is made of the fact that the LVE properties of material can be represented by a combination of simple spring and dashpot mechanical models, resulting in a particular mathematical formulation [17]. Most of these models rely on the construction of stiffness/complex modulus and phase angle master curves and the determination of temperature shift factor. In other words, they imply that the time–temperature superposition principle (TTSP) holds for the bituminous binders [18–23].

This paper provides a detailed description of the vast number of LVE rheological models that have been developed for bitumens over the years. These models range from nonlinear multivariable models (known as nomographs) to empirical algebraic equations and mechanical element approaches. The advantages and disadvantages of the various models are discussed and their applications to different materials are described. In addition to the various models, the concepts of bitumen rheology and TTSP are initially discussed to aid the readers' understanding of these important elements to data representation and modelling. It should be noted that the authors have used the word "bitumen" in the European sense throughout this paper and not "asphalt" or "tar" when referring to the binder. The word "asphalt" brings a similar meaning to "bitumen" in North America but in Europe, "asphalt" refers to the complex mixture composed of various selected aggregates bound together with different percentages of air voids. This composite is often referred to as "asphalt concrete" in North America. Meanwhile, "tar" is a liquid obtained when organic materials such as coal or wood are carbonised or destructively distilled in the absence of air [10].

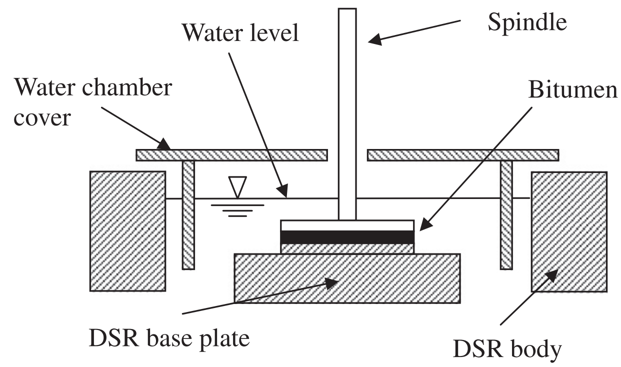

Fig. 1. Dynamic shear rheometer set-up [26].

2. Bitumen rheology

Rheology involves the study and evaluation of the flow and permanent deformation of time– and temperature - dependent materials, such as bitumen, that are stressed (usually shear stress or extensional stress) through the application of force [9,24,25]. The word rheology is believed to be originally from the Greek words "ρεω", which can be translated as "*the river*, *flowing*, *streaming*", and "λογοο" meaning "*word*, *science*" and therefore literally means "*the study of the flow*" or "*flow science*" [26,27]. Therefore, the rheology of bitumen can be broadly defined as the fundamental measurements associated with the flow and deformation characteristics of the material, with considerable research having been undertaken over the last five decades in studying the rheology of bitumen and asphalt [28].

Understanding the flow and deformation (rheological properties) of bitumen in an asphalt is important in terms of pavement performance. Asphalt that deforms and flows too readily may be susceptible to rutting and bleeding, while those that are too stiff may be exposed to fatigue and cracking. Nowadays, the LVE rheological properties of bitumen are usually determined using an oscillatory type testing apparatus known as a dynamic shear rheometer (DSR). The DSR is a very powerful tool used to determine the elastic, viscoelastic and viscous properties of bitumen over a wide range of temperatures and frequencies often using the testing configuration shown in Fig. 1.

The LVE rheological properties of bitumen are normally presented in the form complex modulus magnitude ($|G^*|$)[1] and phase angle (δ) master curves. $|G^*|$ by definition is the ratio of maximum (shear) stress to maximum strain when subjected to shear loading. Meanwhile, δ is the phase difference between stress and strain in harmonic oscillation. If δ equals 90°, bitumen can be considered to be purely viscous in nature, whereas δ of 0° corresponds to a purely elastic behaviour. Between these two extremes, the material behaviour can be considered to be viscoelastic in nature with a combination of viscous and elastic responses. $|G^*|$ and δ are defined as the following:

[1] Many authors use G^* to mean $|G^*|$ and refer to the magnitude as the "complex modulus".