

Fractional linear viscoelastic constitutive relations of anhydride-cured thermosetting rubber-like epoxy asphalt binders

Qiang Wu^a, Chong Wang^a, Rui Liang^a, Yongchang Liu^a, Jixiang Cheng^b, Yang Kang^{a,*}

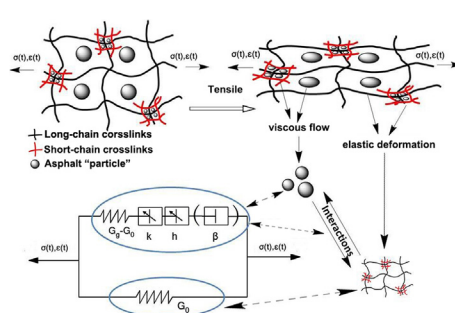
^a College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, Shaanxi, PR China

^b Jinan Urban Construction Group, Shandong, PR China

HIGHLIGHTS

- Fractional approaches were used to depict thermoset binders' constitutive relations.
- Fractional 2S2P1D degraded into Huet-Sayegh (HS) model for weak-crosslinking systems.
- Arc tangent function could fit temperature dependence with two inflection points well.
- Mapping from binders to mixtures can be built with arc tangent function and HS model.

GRAPHICAL ABSTRACT



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ABSTRACT

Epoxy asphalt binders (EABs) are thought to be a prior choice for long-life paving materials for their excellent performances. To facilitate design of epoxy asphalt pavement structures, anhydrides-cured EABs' (AC-EABs') linear viscoelastic constitutive equations were studied. Results indicated that, for weak-crosslinking AC-EABs, the fractional 2S2P1D model degraded into simpler Huet-Sayegh (HS) model, thus, HS model was selected to describe the constitutive relations at all reduced frequencies. Moreover, with HS model and arc tangent function for the temperature dependence of AC-EABs, properties of their concretes could be mapped from those of AC-EABs based on empirical correlation between binders and concretes.

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1. Introduction

With the increase of vehicle volumes, especially the heavy-load vehicles, and the extreme climate, conventional thermoplastic asphalt pavements suffer from serious damages quickly [1,2], which owes to the poor abilities of cracking resistance at low temperatures (e.g., lower than 5 °C) and rutting resistance at high temperatures (e.g., higher than 60 °C). Previous studies and engineering applications have indicated that epoxy asphalts

improve the service lives of roads significantly; consequently, they have been applied to road and deck pavements gradually [3,4]. However, the design of epoxy asphalts' pavement structures are still empirical and completed experimental dependent. Hence, it is necessary to study their rheological properties in broader frequency regions, which could provide a theoretical basis for predicting the viscoelastic behaviors of epoxy asphalts at various using conditions.

Usually, rheological properties of materials are obtained through creep and cyclic (oscillatory) tests [5], but these methods are time-consuming and need lots of experimental equipments. In this paper, firstly, time-saving dynamic experiments including amplitude sweeps, temperature sweeps and frequency sweeps of

* Corresponding author.

E-mail address: kangyang@nwsuaf.edu.cn (Y. Kang).

anhydrides-cured epoxy asphalt binders (AC-EABs) were conducted by MCR302 dynamic shear rheometer. Then, a more effective method, i.e., time temperature superposition principle, was used to build their master curves of rheological properties vs. broader frequencies, since they are thermorheological simple materials, which is verified by Cole-Cole plots [6,7]. The mechanical models or equations to describe these master curves are called constitutive equations.

Constitutive equations include nonlinear multivariable models (i.e., traditional empirical models or mathematical models) and mechanical element models. Typical mechanical element models include Maxwell model, Kelvin model, standard linear solid model, the Burgers model, generalised Maxwell model and generalised Kelvin model etc. [7] Thereinto, generalised Maxwell model and generalised Kelvin model are formed by Maxwell model in parallel and Kelvin model in series, when the number of elements increased to a certain degree, the generalised Maxwell models could achieve ideal results in simulating rheological behaviors of fluids, these models are called visco-elastic liquid-type models, which are mainly used for studying asphalt binders; and the generalised Kelvin models simulate solids well, they are visco-elastic solid-type models and mainly apply to describe asphalt mixtures [8]. However, when the number of mechanical elements are numerous, the computational effort in the analysis process will increase greatly [9]. Therefore, to reduce the number of parameters involved, the fractional-order mechanical element models, which replace the linear dashpots in the classic integer-order mechanical element models by using one or several fractional dashpots, such as Huet-Sayegh (HS) model and 2S2P1D model et al., have been published [8,10]. Especially, HS model has been mainly used for describing the rheological properties of solid asphalt mixtures [11,12], and the 2S2P1D has been used for both solid asphalt mixtures and flowable asphalt binders [13,14].

AC-EABs studied in this paper are two-component composites which are stored separately; when used, asphalt component and epoxy component are mixed in proportion at certain temperatures, 3D chemical networks will be formed through complicated chemical crosslinking reactions, which makes the thermoplastic liquid asphalt transform into thermosetting solid composites [15]. Experiments

showed that when temperatures increased to 120 °C, the complex modulus of cured AC-EABs still approached to about 1 MPa, but traditional thermoplastic modified asphalts, e.g., SBS modified asphalt, became viscous flow state at 120 °C and the complex modulus decreased to about 0.1 kPa, when temperatures decreased to −30 °C, the complex modulus of AC-EABs approached to about 600 MPa, but those of SBS modified asphalt approached to 1000 MPa. Therefore, compared with other modified asphalts, epoxy asphalt exhibits better low and high temperature performances and lower temperature susceptibility [16]. It is worthy of noticing that AC-EABs keep in the solid state during the whole temperature range from −30 °C to 120 °C.

Thus, solid-type fractional rheological models, including the fractional linear solid (FLS) model, Huet-Sayegh (HS) model and 2S2P1D model were used to describe the master curves of AC-EABs of different asphalt contents in their linear viscoelastic regions. Also, their temperature dependences of characteristic times were studied.

2. Mechanical elements models

Three fractional solid-type models used in this paper are shown in Fig. 1(a)–(c). All of them are formed by finite numbers of fractional dashpots and Hook (linear) springs in series or parallel, so they have continuous spectrums [8], in other word, rheological quantities, like complex moduli, complex compliances, creep compliances and relaxation moduli, etc., within the LVE regions can be converted mutually according to the linear viscoelastic theory [17]. Compared with the FLS model (Fig. 1(a)), HS model (Fig. 1(b)) appends another fractional dashpot to the left side of model, and the 2S2P1D model (Fig. 1(c)) is equivalent to append a linear dashpot to the HS model. Thereinto, linear springs represent the elastic response, fractional dashpots reflect the viscoelastic response, and linear dashpots represent the viscous behaviors.

The fractional dashpot, as shown in Fig. 1(d), is also called parabolic dashpot or variable dashpot. Its mechanical response character is between those of the linear spring and linear dashpot. Adding the fractional dashpot to integral-order mechanical element models will enormously improve their ability to describe the linear vis-

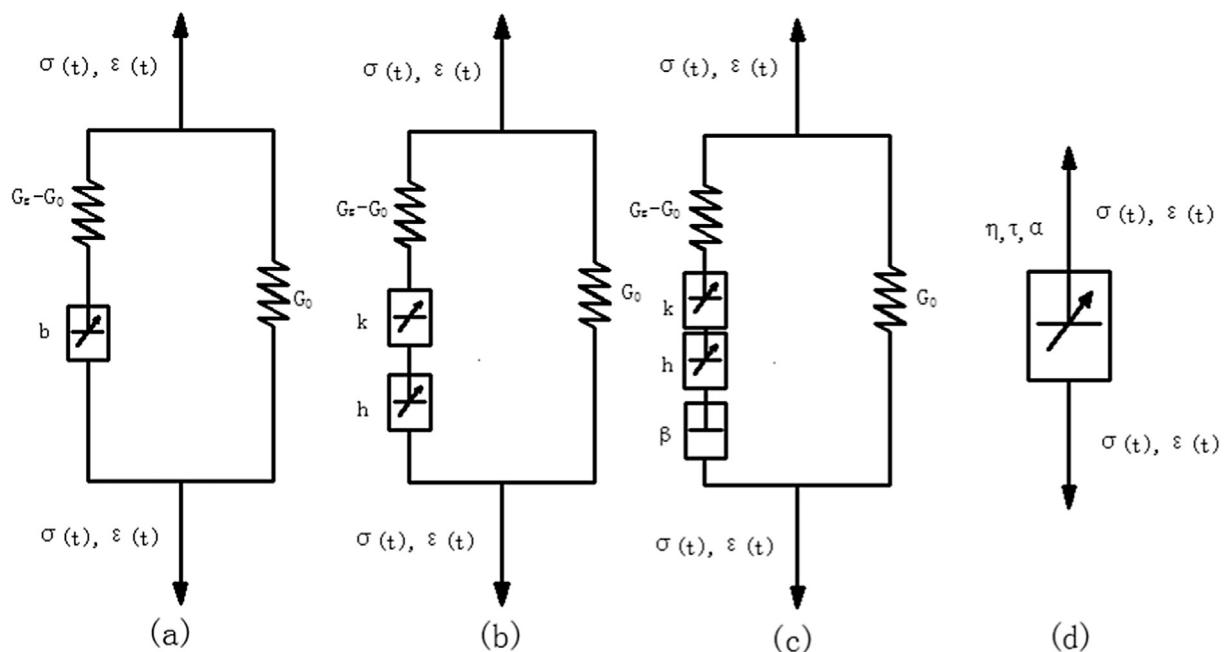


Fig. 1. (a) FLS model; (b) HS model; (c) 2S2P1D model; (d) fractional dashpot.

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