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Linear viscoelastic creep compliance and retardation spectra of bitumen impregnated fiberglass mat and polymer modified bitumen

Sreehari Rajan [a], Michael A. Sutton [a,*], Alen Oseli [b], Igor Emri [b], Fabio Matta [c]

[a] Department of Mechanical Engineering, University of South Carolina, 300 South Main Street, Columbia, SC 29208, United States
[b] Center for Experimental Mechanics (CEM), University of Ljubljana, Pot za Brdom 104, SI-1125 Ljubljana, Slovenia
[c] Department of Civil and Environmental Engineering, 300 South Main Street, University of South Carolina, Columbia, SC 29208, United States

HIGHLIGHTS

- Creep compliance of bitumen impregnated fiberglass mat (BIFM) is investigated.
- Creep response of BIFM is compared with polymer modified bitumen (PMB) sample.
- Results show significant improvement in the performance of BIFM at higher temperatures.
- Retardation spectra obtained are capable of accurately reconstructing creep response.

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ABSTRACT

Temperature-controlled experiments are performed to characterize the viscoelastic response of materials commonly used in asphalt roofing shingles, including both creep compliance master curves and shear retardation spectra. Material systems characterized in this study include polymer modified bitumen (PMB) and bitumen impregnated fiberglass mat (BIFM). BIFM experiments are conducted using 3-point bend specimens in a TA instruments RSA III DMA, whereas PMB results are obtained from torsional loading of two cylindrical specimens in a MARS II controlled stress rheometer. Short term (duration of 1000 s) isothermal creep experiments are conducted at temperatures above the bitumen glass transition ($T_g = -42\,°C$) (a) on BIFM specimens in the range $-30\,°C \leq T \leq 30\,°C$ and (b) on PMB specimens in the temperature range $-30\,°C \leq T \leq 20\,°C$. Using the time-temperature superposition principle (TTSP), creep compliance master curves for both materials are obtained at a reference temperature of 0 °C. The results are then used to obtain the shift factors and develop both Williams-Landel-Ferry (WLF) and Arrhenius models. Results show that BIFM has $\approx 2.2X$ lower creep compliance than PMB at $T = 0\,°C$, with the difference increasing at higher temperatures. Furthermore, beyond the early, short-term creep times, significant deviations between the retardation spectra of BIFM and PMB are observed.

1. Introduction

Bitumen is a viscoelastic material consisting of different molecular weight hydrocarbons, which are mainly classified as asphaltenes, aromatics, saturates and resins [1]. It is commonly used as a binding agent in asphalt mixtures used in pavements and in roofing materials such as shingles and roofing felts. At low temperature and at high rates of loading, bitumen behaves as a stiff and brittle material, whereas at high temperature and low rates of loading it has a rubbery behavior. The temperature at which the transition from brittle (glassy) to rubbery behavior take place is known as the glass transition temperature (T_g) of the material [2]. The glass transition temperature and viscoelastic properties of bitumen depends on the proportions of different hydrocarbon groups [3]. Since most bituminous materials used in practice have their glass transition temperature in the range $-45\,°C \leq T_g \leq -20\,°C$, these materials will be highly viscoelastic while in-service. Thus, quantifying the viscoelastic properties of bitumen and bituminous mixes is important both to assess the relative importance of viscoelasticity in an application and to provide essential material properties for modeling the mechanical response of these materials. Given the potential for bitumen to behave viscoelastically while in service, there have been several studies regarding the viscoelastic properties of bitumen-based asphalt pavement [4–6]. For example, Costanzi and Cebon [6] developed a phenomenological constitutive

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* Corresponding author.
E-mail address: sutton@sc.edu (M.A. Sutton).

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behavior model for the bitumen matrix that includes both strain rate and temperature effects. The analog mechanical model used by the authors contained one Maxwell and Kelvin-Voigt element in series with a non-linear spring and dashpot. The authors also modelled the viscoelastic behavior of the asphalt pavement using the same analog mechanical model, with a slight modification to include the effect of dilation due to climbing of aggregates in a close packed (65% volume fraction) asphalt pavement material [5]. The modification involved addition of a strain component to account for dilation of the asphalt during shear loading.

In the last two decades, there has been an increase in the use of additives (modifiers) to improve the performance of bituminous materials [7]. It has been demonstrated that the addition of different polymers (polymer modified bitumen) can reduce cracking of bitumen at low in-service temperatures and reduce permanent deformation at elevated temperatures. For example, Qunshan et al. [4] investigated the rheological properties of asphalt binders reinforced with cellulose fibers (CF), polyester fibers (PF) and mineral fibers (MF). These fibers are discontinuous, having diameters from 5 μm (MF) to 45 μm (CF). They found considerable increase in the stiffness and viscosity of the asphalt binders and reduction in the permanent viscous deformation (flow) due to the presence of reinforcing fibers. The authors noted that changes in the rheological properties are more pronounced when the concentration of the fibers is more than 0.1% by mass of the asphalt binder.

Whilst there is a substantial amount of data available in the published literature for characterizing viscoelastic properties of bitumen, polymer modified bitumen and asphalt paving mixtures [8–12], little information is available on the viscoelastic properties of bitumen impregnated continuous fibers [13]. The relevance and importance of quantitative characterization of the viscoelastic response of both bitumen and bitumen impregnated continuous fiber material systems to our understanding of the response of asphalt shingle systems can be explained most effectively by presenting results from a set of recent experiments conducted on a shingled roof system subjected to hurricane force winds [14]. Using stereo-vision with three-dimensional digital image correlation [15] to measure shingle displacements, Fig. 1 shows the measured time history of uplift displacement experienced by a three-tab shingle that is subjected to hurricane force winds. As shown in Fig. 1, as the shingle system is subjected to uplift forces during exposure to hurricane force winds [16,17], the uplift displacement of the shingle eventually begins to increase. Since the top shingle is attached to the lower shingle by a thin layer of PMB material known as a *sealant strip,* then the increase in measured shingle displacement over time could be due to (a) the combined viscoelastic response of the shingle (BIFM) and the sealant (PMB), (b) local failure/separation of the sealant strip resulting in increased influx of high speed air and higher up-lift forces or (c) a combination of both effects. Based upon the experimental data obtained in this study, the primary source of viscoelastic creep and the associated increased uplift of the shingle appears to be the sealant layer. Furthermore, viscoelastic data for both materials is necessary to perform simulations that are consistent with the physical system so that a direct comparison can be made between physical measurements and predictions of shingle-sealant response during long term loading.

In the enclosed work, the linear viscoelastic creep compliance of both polymer modified bitumen and bitumen-impregnated randomly oriented, glass fiber mats used in modern 3-tab shingles is quantified experimentally for a wide range of temperatures from −30 °C to 30 °C using data obtained from dynamic mechanical analyzers (DMAs). The measurements are used to develop linear viscoelastic models for both materials, quantify the relative importance of viscoelasticity in the response for the sealant and the shingle and support future modeling of shingle sealant system including viscoelastic effects.

2. Experimental considerations

The experimental section is composed of several sub-sections including Bitumen Impregnated Fiberglas Mat (BIFM) Specimen Preparation, Polymer Matrix Bitumen (PMB) Specimen Preparation, BIFM Creep Experiments and PMB Creep Experiments.

2.1. Specimen Preparation - BIFM specimens

Specimens used in creep experiments for the thermo-plastic BIFM specimens are extracted from a standard, commercially-available 3-tab fiberglass-mat shingle (Owens Corning Supreme AR 25415)[1]. Fiberglass shingles such as the one used in these studies have the following composition [18];

- 15–20 percent asphalt.
- 15–20 percent mineral filler within asphalt base (e.g., fly ash).
- 5–15 percent fiberglass felt mat.
- 30–50 percent mineral/ceramic granules on surface.

Three samples are cut from three separate shingles that were drawn randomly from a batch and at different locations in the shingles. All granules on the top surface of each shingle selected are carefully removed[2]. After removing the granules, three rectangular strip specimens, with nominal dimensions (40 mm (l), 13 mm (w), 1 mm (t_b)), are excised using a cutting tool consisting of two razor blades placed ≈ 13 mm apart and mounted on a rigid fixture (see Fig. 2(a)). The specimens are then heated to 65 °C on a heating plate to fill the cavities created when the granules were removed, thereby smoothing the top surface of the specimen. The specimen is then cooled at a rate of 5 °C/minute and stored at room temperature[3]. Three BIFM specimens are manufactured in this manner and the as-manufactured specimen dimensions are shown in Table 1; the width, length and thickness values for the specimens are the average of 12 separate Vernier caliper measurements. All experiments are performed within 3 days after specimen preparation. To determine the size of the glass fibers, fibers are extracted from the specimen by dissolving the bitumen in trichloroethylene. Optical microscopy performed on the as-extracted fibers shows that the glass fibers have a nominal diameter of ≈ 20 μm and are randomly distributed in multiple horizontal layers along the length and width, with no preferred orientation. Figs. 2(b) and (c) show images of the specimen and the glass fibers, respectively.

2.2. Specimen Preparation: Polymer matrix bitumen material (PMB)

The PMB sample used in the experimental program is a thermally activated self-adhesive or thermoplastic sealant used in the 3-tab shingles manufactured by Owens Corning (Supreme® AR 25415). The self-sealant adhesive material contains Styrene-Butadiene-Styrene block copolymer (5–10% weight) that forms a polymer network within the bitumen [20]. The specific polymer additives used in the mixing process for the PMB sealant layer are not provided by the manufacturer. Since the PMB specimens are characterized using torsional loading, right circular cylindrical

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[1] The Owens Corning shingles are obtained from a retail outlet. Thus, the shingles are exposed to a history of environmental conditions (e.g., stacking forces, storage time, thermal cycles) that are typical of most real-world applications but are unknown to the investigators. Even so, since the investigators performed experiments that defined the glass transition temperature of bitumen impregnated fiberglass as $T_g = -42$ °C, which is well below typical room temperatures that the shingles would experience in a retail environment. Thus, physical aging of the material due to extended storage is not expected [19].

[2] All granules are removed from the specimens since their primary function is to minimize UV degradation of the underlying asphalt material.

[3] The effect of rate of cooling on bitumen impregnated fiberglass constituent properties is not studied in this work.