Behaviour of an interface between pavement layers obtained using Digital Image Correlation

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Abstract To improve pavement design methods, the behaviour of the interfaces between pavement layers must be precisely taken into account. This paper describes the thermomechanical behaviour of an interface in the small strain domain. Thanks to the innovative 2T3C Hollow Cylinder Apparatus (2T3C HCA), the behaviour of an interface was observed directly with 3D Digital Image Correlation (3D DIC). The studied samples were constituted of two layers of bituminous mixtures with a bitumen emulsion at the interface. From cyclic tests performed at four different frequencies (from 0.01 to 0.3 Hz) and four different temperatures (from 10 to 40 °C), the complex interface stiffnesses in the tension–compression mode and in the shear mode were obtained. The time–temperature superposition principle was verified for the abovementioned stiffnesses. Knowing a 2S2P1D (2 Springs, 2 Parabolic elements, 1 Dashpot) model of the bitumen of the tack coat, the norms of the complex interface stiffnesses were modelled with 2S2P1D models by using a SHStS (Shift, Homothety, Shift and time Shift) transformation.

Keywords Pavement · Interface · Bituminous mixture · Tack coat · 2S2P1D · 3D digital image correlation

1 Introduction

When designing pavements, layers made of bituminous mixtures are usually assumed to be perfectly bonded in the mechanical calculations (i.e. continuity of displacements at the interface). In this case, the maximum strain is obtained at the bottom of the structure and strain in the top layer is reduced [1] which is advantageous for pavement durability [2]. However, premature degradations of pavements linked with bond failure have been observed. Understanding the mechanical behaviour of interfaces between pavement layers is necessary for designing more durable roads.

The experimental research on interfaces behaviour has focused on bonding strength measurements by testing the interface failure, for instance with the guillotine test [3–5]. The failure tests can be monotonic [6] or cyclic for fatigue characterisation [7–11]. Multiple factors such as temperature [12], dosage of tack coat or type of bituminous mixtures layers were investigated [13]. These tests were either done at high strain levels for monotonic failure tests or with an important number of cycles for fatigue tests. But it is also important to know the interface behaviour for a
few number of cycles at small strain amplitude. It allows computing more accurately the strain at the bottom of the structure due to a single vehicle which is an important piece of information in pavement design. Up to the knowledge of the author, very few authors attempted such a characterisation [14–16].

Concerning the mechanical modelling of interfaces, instead of the simple assumption of a perfect bond at the interface, an interface stiffness can be defined [1]. It links the stress applied to the relative displacement between the boundaries of the layers. This approach is easy to implement in a numerical simulation of a pavement. Interfaces can also be modelled as layers. Usually, a tack coat made of bitumen emulsion is applied to guarantee the bond at the interface between the layers. For a small number of cycles and for small strain amplitudes, bitumen presents a linear viscoelastic behaviour. It has been shown from in situ measurements that interfaces with a tack coat are better modelled by a homogeneous viscoelastic layer rather than an elastic layer [17]. Laboratory experiments also suggest that the behaviour of interfaces for small strain, assuming they have a thickness or not, is viscoelastic. Freire et al. [15] modelled the normal stiffness of the interface using the 2S2P1D model, which is a linear viscoelastic model, when Hristov et al. [16] used a sigmoid function to model the norm of the shear interface stiffness. However, it is not clear whether a linear viscoelastic domain exists for the interface since very few studies focus on the influence of the amplitude of loading. Isailović et al. [10] did not observe a linear viscoelastic domain since the shear interface stiffness changed with the amplitude of loading. Yet, their data was limited to one frequency and two temperatures, and the tested amplitudes were quite high.

The objective of this paper is to characterise the thermomechanical behaviour of an interface with a tack coat in the small strain domain using the innovative apparatus 2T3C Hollow Cylinder Apparatus (2T3C HCA). This work focuses on highlighting the relation between viscoelastic properties of the tack coat bitumen and the interface behaviour. It is part of a research project (chair between University of Lyon/ENTPE and the company Eiffage Infrastructures) dedicated to pavement materials and structures.

### 2 2T3C hollow cylinder apparatus (2T3C HCA)

The 2T3C HCA was developed at the University of Lyon/ENTPE to study interfaces between bituminous mixtures [18]. The tested samples are hollow cylinders composed of two layers of bituminous mixtures as illustrated in Fig. 1. Their dimensions are: external radius of 86 mm, internal radius of 61 mm and height of 125 mm. The dimensions were chosen to ensure rather homogeneous stress and strain fields in the hollow cylinder. Axial and rotation loadings can be applied to the sample independently using a servohydraulic press. Various loadings (cyclic or monotonic, from small deformation to failure) can be applied. The samples are placed in a climate chamber allowing to control temperature during the tests. PT100 sensors measure sample temperature on the inside surface and on the outside surface of the sample.

Load cells embedded in the servohydraulic press measure the axial force and the torque, up to 100 kN for axial force and up to 2 kN.m for torque. Four non-contact sensors (eddy currents sensors) are attached to the top of the samples (Fig. 2). Their targets are fixed to the bottom of the sample. The non-contact sensors measure the displacement between the top and the bottom of the sample in the axial and rotation directions with an accuracy of 0.1 µm on a 1000 µm range. Two pairs on opposite sides of the sample are used to calculate the average vertical displacement and the average rotation displacement. The press can use the sensors measurements to control precisely the applied loadings.

In addition to these global displacement measurements, the 3D Digital Image Correlation (3D DIC) is used to obtain the three-dimensional displacement field on the surface of the sample. The principle of DIC is to compare the pictures of a surface with a random pattern before and after transformation. A subset of the reference picture (captured before the transformation)
is chosen around a point of the surface where displacements are searched. Then a correlation algorithm finds the deformed subset after transformation in the following pictures and deduces the displacement of the point [19]. The subset is a window of $25 \times 25$ pixels in this study. For 3D DIC two pairs of cameras are used on opposite sides of the sample as shown in Fig. 2, with an angle of $30^\circ$ between cameras in each pair. The cameras have a maximum capture frequency of 10 Hz. They are placed outside the climate chamber (which has glass windows on its sides) at 600 mm from the sample surface. Considering the digital sensors characteristics, one pixel on a picture represents about 150 $\mu$m of material. The accuracy of the displacement measurements with DIC is about $1/100$th of a pixel which corresponds to 1.5 $\mu$m in our setup.

The application of DIC to study interfaces is scarce [20, 21] and for 3D DIC it is even more rare. From the displacement field, a method developed at the University of Lyon/ENTPE [18] is used to obtain the strain tensor components $\varepsilon_{zz}$ and $\varepsilon_{\theta z}$ in the layers and the displacement gaps at the interface in the vertical direction $\Delta u_z$ and for the rotation $\Delta u_\theta$, $(r, \theta, z)$ being the cylindrical coordinates. The example of calculation of $\varepsilon_{zz}$ and $\Delta u_z$ is illustrated in Fig. 3. Horizontal strips ($100 \times 4$ mm) are drawn on the digital images. The number of strips depends on the sample dimensions. For the samples tested in the present study, there are 12 strips in each layer. The displacement component $u_z$ is averaged on each strip and is affected to the coordinate $Z$ of the centre of the strip. By plotting the linear regression in the $Z$-$u_z$ diagram, the slopes of the two lines (see Fig. 3) give $\varepsilon_{zz}$ in each layer. The assumption of a homogeneous strain field is verified experimentally. The regression lines do not intersect at the interface and the gap between them at the level of the interface gives the vertical displacement gap, $\Delta u_z$. A similar procedure is used to get $\varepsilon_{\theta z}$ and $\Delta u_\theta$, based on the displacement related to rotation $u_\theta$ obtained with 3D DIC. The results from the two opposite sides of the samples are then averaged to have one value at each state of deformation.

3 Materials and procedure

3.1 Studied materials

In this paper, the studied double-layered specimens are composed of two bituminous mixtures layers and a tack coat at the interface. First, half of a slab of $600 \times 400 \times 75$ mm$^3$ of EME 20/14 is compacted using a French wheel compactor [22]. The EME 2 mixture is commonly used in France as a base course. Here it has a nominal maximum aggregate size (NMAS) of 14 mm, it contains 30% of Reclaimed Asphalt Pavement (RAP) and its binder is a bitumen with a 15/25 grade. The binder represents 5.6% of the total mix weight.

24 h after the compaction of the first layer, an emulsion of bitumen graded 160/220 is applied with a brush to act as a tack coat. The residual bitumen content is 450 g/m$^2$. The linear viscoelastic behaviour of the bitumen 160/220 used for the tack coat has been characterised with a Dynamic Shear Rheometer (DSR) at the Eiffage Infrastructures laboratory in Corbas. The results are used and discussed in Sect. 4.
After another 24 h, the upper layer of the slab is compacted with the wheel compactor. It is a BBSG 30/10 mixture with a NMAS of 10 mm, a RAP content of 20% and a 50/70 bitumen. The binder content is 5.4% of the mix weight. The aggregate grading curves of both bituminous mixtures are presented in Fig. 4.

The sample coring takes place a few days later starting with the inside coring of the hollow cylinder and finishing with the outside. Three hollow cylinder samples are cored from the slab and named as G8, D8 and M8.

3.2 Advanced complex modulus test with 2T3C HCA

To characterise the viscoelastic behaviour of the interface in the small strain domain, sinusoidal cycles are applied to the samples. For each of the 3 samples, a temperature/frequency sweep was conducted at 4 different temperatures (10, 20, 30, 40 °C) and 4 different frequencies (0.01, 0.03, 0.1, 0.3 Hz) as described in Fig. 5. For each couple of temperature and frequency, 5 axial cycles and 5 rotation cycles were performed.

For axial cycles, a global vertical displacement amplitude of 25 μm (measured with the non-contact sensors) was imposed. This would correspond to a global vertical strain of 200 μm/m for a hollow cylinder sample with the same dimensions but constituted of one homogeneous material. The vertical strain in the layers and the displacement gaps could only be obtained from the DIC analysis after the end of the mechanical testing. For axial cycles, the measured vertical strain amplitudes εzz,0 were between 150 μm/m and 220 μm/m in the upper layer and between 100 and 170 μm/m in the lower layer. The vertical displacement gaps amplitudes at the interface were between 1 and 2 μm except for the test at 40 °C for the D8 sample where vertical displacement gaps were below 1 μm and could not be analysed. The latter
temperature was removed from the analysis. The amplitude values for strain and displacement gaps vary for each couple of temperature and frequency because they depend on the ratios between the layers’ moduli and the interface stiffness.

For rotation cycles, a global rotation displacement amplitude of 90 μm at the level of the non-contact sensors was imposed. It would correspond to a global shear strain of 200 μm/m in an homogeneous sample of the same size. The measured shear strain amplitudes ε₀z in the bituminous mixtures were between 200 and 275 μm/m in the upper layer and between 100 and 150 μm/m in the lower layer. The rotation displacement gaps amplitudes were between 5 and 10 μm.

During the mechanical loading, 50 pictures per cycle were taken with each camera except for tests at 0.3 Hz where only 30 pictures per cycle could be taken. Cameras can take pictures at a maximum rate of 10 Hz, preventing from testing at higher frequencies than 0.3 Hz. The capture time of a picture is about 6 ms. An acquisition system allowed obtaining the load cells measurements at the exact same time than a picture was taken. At the end of the mechanical testing, the pictures were analysed with DIC as presented above. For each picture the displacement gap at the interface is obtained, Δu₀ for rotation tests. The stresses are calculated using the assumption that they are homogeneous in the sample. An example of displacement gap and stress measurement is presented on Fig. 6, where each dot represents a state of deformation, i.e. an instant when pictures are taken. For one sample, about 28,800 pictures are captured during an advanced complex modulus test.

3.3 Overview of the performed tests

The behaviour of one interface configuration (see Sect. 3.1) was evaluated using the advanced complex modulus test performed with the 2T3C HCA. Three 2T3C HCA samples were tested for this configuration. In addition, the bitumen used for the tack coat was tested using a shear complex modulus test performed with a DSR. One sample of bitumen was tested. All the tests performed in this study are summed up in Table 1.

3.4 2S2P1D (2 springs, 2 parabolic elements, 1 dashpot) model

For small strain amplitudes and few cycles applied, bitumen and bituminous mixtures present a linear
viscoelastic behaviour. The strain limit of the linear domain depends on the temperature and on the frequency. Orders of magnitude for these limits are $10^2 \frac{\text{mm}}{\text{m}}$ for mixtures [23, 24] and $10^4 \frac{\text{mm}}{\text{m}}$ for bitumen [25]. The fact that the interface behaviour is linear in the small strain domain has not been proved and it is not the purpose of this paper. The complex modulus is considered as a linear viscoelastic property obtained by conducting a sinusoidal loading. In the case of small non-linearity, an equivalent complex modulus can be considered as both strain and stress signals are close to sinuses.

For axial tests, when a sinusoidal normal stress with an amplitude of $\tau_{\theta z_0}$ is applied to the interface the rotation displacement gap response is sinusoidal with the same frequency, an amplitude $\Delta u_{\theta_0}$ and with a phase lag $\varphi_{K\theta z}$. The shear complex interface stiffness $K^*_{\theta z}$ is introduced in Eq. 2.

$$K^*_{\theta z} = \frac{\tau_{\theta z_0}}{\Delta u_{\theta_0}} e^{i\varphi_{K\theta z}} = |K^*_{\theta z}| e^{i\varphi_{K\theta z}}$$  \hspace{1cm} (2)

The 2S2P1D model developed at the University of Lyon/ENTPE is used to model the complex modulus dependency on the frequency for bituminous mixtures and binders [26]. The complex modulus expression for 2S2P1D model for the shear complex modulus $G^*_{2S2P1D}$, the normal complex interface stiffness $K^*_{zz_{2S2P1D}}$ and the shear complex interface stiffness $K^*_{h z_{2S2P1D}}$ are given in Eqs. 3, 4 and 5, respectively. There are 7 constants to the model: $G_{00}$ (resp. $K_{zz_{00}}$ and $K_{h z_{00}}$ for the normal and shear complex interface stiffnesses) the static modulus which is the asymptotic value for low frequencies, $G_0$ (resp. $K_{zz_{00}}$ and $K_{h z_{00}}$ for the normal and shear complex interface stiffnesses) the glassy modulus which is the asymptotic value for high frequencies, $k$, $h$ and $\delta$ that are calibration parameters, $\tau$ a characteristic time depending on the temperature and $\beta$ a viscosity parameter.
This model is used in this paper to model the bitumen shear complex modulus \( G^* \) and the complex interface stiffnesses \( K^*_{\text{zz}} \) and \( K^*_{\text{p}_z} \). In Eqs. 3, 4 and 5 \( \omega \) is the angular frequency.

\[
G^*_{2S2P1D}(\omega) = G_0 + \frac{G_0 - G_{00}}{1 + \delta(\omega \tau)^{-k} + (i\omega \tau)^{-h} + (i\omega \beta)^{-1}}
\]

(3)

\[
K^*_{\text{zz}_{-2S2P1D}}(\omega) = K_{\text{zz}_{-00}} + \frac{K_{\text{zz}_{-0}} - K_{\text{zz}_{00}}}{1 + \delta(\omega \tau)^{-k} + (i\omega \tau)^{-h} + (i\omega \beta)^{-1}}
\]

(4)

\[
K^*_{\text{p}_z_{-2S2P1D}}(\omega) = K_{\text{p}_z_{-00}} + \frac{K_{\text{p}_z_{0}} - K_{\text{p}_z_{00}}}{1 + \delta(\omega \tau)^{-k} + (i\omega \tau)^{-h} + (i\omega \beta)^{-1}}
\]

(5)

The dependency of the complex modulus on the frequency can be related to the dependency on the temperature. When a bituminous material respects the Time–Temperature Superposition Principle (TTSP), its behaviour is equivalent for low frequencies and high temperatures (and for high frequencies and low temperatures). At each temperature \( T \), it is possible to define a shift factor \( \alpha_T \) in order to superimpose isothermal curves of the norm (or of the phase angle) of the complex modulus, forming a unique curve called the master curve. The master curve represents the material behaviour at an arbitrarily chosen reference temperature. The Williams-Landel-Ferry (WLF) formula presented in Eq. 6 links the shift factors \( \alpha_T \) to the temperature \( T \) with regards to the reference temperature \( T_{\text{ref}} \) using two constants \( C_1 \) and \( C_2 \).

\[
\log(\alpha_T) = \frac{-C_1(T - T_{\text{ref}})}{C_2 + T - T_{\text{ref}}}
\]

(6)

The shift factors are determined for a reference temperature chosen amongst the experimental temperatures. In order to compare the results with other tests, it is necessary to obtain the shift factors and thus the constants \( C_1 \) and \( C_2 \) of the WLF formula for other reference temperatures. Equations 7 and 8 express the constants \( C'_1 \) and \( C'_2 \) for the WLF formula at a reference temperature \( T_{\text{ref}} \) from the WLF constants \( C_1 \) and \( C_2 \) at the reference temperature \( T_{\text{ref}} \).

\[
C'_1 = \frac{C_1 C_2}{C'_2}
\]

(7)

\[
C'_2 = C_2 + T_{\text{ref}} - T_{\text{ref}}
\]

(8)

3.5 SHStS (Shift, Homothety, Shift and time Shift) transformation

It has been shown that the viscoelastic properties of a bituminous mixture depend directly on the binder behaviour. The mixture complex modulus \( G^*_{\text{mix}} \) can be derived from the bitumen modulus \( G^*_{\text{binder}} \) using the SHStS transformation according to Eq. 9 for given angular frequency \( \omega \) and temperature \( T \) [27]. The glassy moduli \( G_{0,\text{mix}} \) and \( G_{0,\text{binder}} \) as well as the storage moduli \( G_{00,\text{mix}} \) and \( G_{00,\text{binder}} \) of both the mixture and the binder appear in Eq. 9, independently of any rheological model, along with the parameter \( \alpha \) introduced for the time shift.

\[
\frac{G^*_{\text{mix}}(\omega, T) - G_{00,\text{mix}}}{G_{0,\text{mix}} - G_{00,\text{mix}}} = \frac{G^*_{\text{binder}}(10^\alpha \omega, T) - G_{00,\text{binder}}}{G_{0,\text{binder}} - G_{00,\text{binder}}}
\]

(9)

If the linear viscoelastic behaviour of both mixture and binder are modelled using 2S2P1D, then the SHStS transformation implies that the constants \( k, h, \delta, \beta \) are the same in the mixture model and in the binder model. If the TTSP is verified for the binder, then it is also verified for the mixture and the shift factors \( \alpha_T \) are the same. In this case, the relation between the characteristic times \( \tau \) of mixture and binder for any temperature \( T \) is the Eq. 10.

\[
\tau_{\text{mix}}(T) = 10^\alpha \tau_{\text{binder}}(T)
\]

(10)

The SHStS transformation is used in Sect. 4 to obtain the norm of the complex interface stiffnesses from the shear complex modulus of the bitumen of the tack coat.

### 4 Results and discussion

4.1 Normal and shear complex interface stiffnesses

Shifting the isothermal curves, it was possible to build the master curves of the norm of the normal complex interface stiffness, Fig. 7, and of the norm of the shear
complex interface stiffness, Fig. 8. In both cases, the TTSP is valid. The shift factors used to plot the master curves of the norm of the complex interface stiffnesses at the reference temperature 15 °C are presented in Fig. 9. They were obtained from the WLF formula, first obtained at the experimental reference temperature (one for each sample) and then expressed for the reference temperature 15 °C using Eqs. 7 and 8. The WLF constants of all samples were averaged to plot the WLF formula on Fig. 9. The constants at a reference temperature of 15 °C are $C_1 = 7.22$ and $C_2 = 112.00$.

A good repeatability was observed between the samples, especially for shear tests. Interfaces are consistently more rigid in the tension–compression mode than in the shear mode at the same temperature and frequency.
4.2 Interface behaviour modelling

The objective of this section is to model the interface behaviour with a 2S2P1D model from the bitumen behaviour.

From the results of the DSR testing, the shear complex modulus of the 160/220 bitumen was modelled with a 2S2P1D model. The parameters of this model are presented in Table 2, G00 was found to be nil as it is commonly seen for bitumen. To compare the bitumen behaviour and the interface behaviour, the norm of the bitumen shear complex modulus and the norm of the complex interface stiffnesses are normalised. The phase angle is not taken into account in this study. For the bitumen, the expression of the normalisation depends on the static modulus $G_{00}$ and on the glassy modulus $G_0$ that were estimated when calibrating the 2S2P1D model. This expression of the normalised norm of the shear complex modulus $|G^*|_{\text{norm}}$ is presented in Eq. 11, taking into account that $G_{00}$ is nil.

$$|G^*|_{\text{norm}} = \frac{|G^*|}{G_0} \quad (11)$$

For the interface, the normalised norms $|K^*_zz|_{\text{norm}}$ and $|K^*_h\theta|_{\text{norm}}$ of the interface stiffnesses were obtained using Eqs. 12 and 13.

$$|K^*_zz|_{\text{norm}} = \frac{|K^*_zz| - K_{zz,0}}{K_{zz,00} - K_{zz,0}} \quad (12)$$

$$|K^*_h\theta|_{\text{norm}} = \frac{|K^*_h\theta| - K_{h\theta,0}}{K_{h\theta,00} - K_{h\theta,0}} \quad (13)$$

$K_{zz,0}$ and $K_{zz,00}$ for the interface are found with the master curves of the three samples on Fig. 7, whereas $K_{h\theta,0}$ and $K_{h\theta,00}$ are found with the master curves on Fig. 8. These constants are presented in Table 3. The equivalent frequencies of the master curves of the interface stiffnesses were then multiplied by 50,000 to superimpose the master curves of interface and bitumen on Fig. 10. This corresponds to a time shift with a coefficient $\alpha = 4.69$ as defined in the SHStS transformation. The result of the transformation is plotted on Fig. 10.

On Fig. 10 there is a good match between the normalised shear modulus of the bitumen $|G^*|_{\text{norm}}$ and the normalised norms $|K^*_zz|_{\text{norm}}$ and $|K^*_h\theta|_{\text{norm}}$ of the interface stiffnesses. The interface behaviour dependency on time and temperature is thus the same than for the bitumen of the tack coat. Based on this observation, the behaviour of the interface was modelled with a 2S2P1D model using $K_{zz,0}$, $K_{zz,00}$, $K_{h\theta,0}$ and $K_{h\theta,00}$ from Table 3, the parameters $k$, $h$, $\delta$, $\beta$ of 2S2P1D model of the bitumen (Table 2) and $\tau$ computed with Eq. 10 using $\alpha = 4.69$. These operations correspond to a SHStS transformation to obtain the interface behaviour from the bitumen behaviour. The parameters of the 2S2P1D models for the interface (one for the normal stiffness, one for the shear stiffness) are presented in Table 2.

2S2P1D models were plotted in Fig. 7 for the axial modulus and in Fig. 8 for the shear modulus. The models fit well the experimental data.

5 Conclusions

Cyclic tension–compression tests and cyclic rotation tests at small strain amplitude were performed on hollow cylinder samples. Three samples of the same bilayered material composed of two bituminous mixtures layers and a bitumen emulsion at the interface were tested. The tests were done at four different frequencies (0.01 to 0.3 Hz) and four different temperatures (from 10 to 40 $^\circ$C). The viscoelastic behaviour of an interface between bituminous mixtures layers has been observed thanks to the Digital Image Correlation. This optical measurement technique made it possible to evaluate precisely the displacement gap at the interface.

The normal complex interface stiffness $K^*_zz$ and the shear complex interface stiffness $K^*_h\theta$ of the studied interface were obtained. The TTSP was verified for the

| $G_{00}$ [MPa] | $G_0$ [MPa] | $k$ [-] | $h$ [-] | $\delta$ [-] | $\tau$ [s] | $\beta$ [-] |
|----------------|-------------|---------|---------|--------------|---------|---------|
| BP Lavera 160/220 | 0 | 850 | 0.20 | 0.53 | 2.30 | $2.10^{-6}$ | 300 |
norm of both these moduli and it was quantified with WLF formula. Knowing the 2S2P1D model of the bitumen of the tack coat, the norm of the shear and of the normal interface stiffnesses were also modelled with the 2S2P1D model by using a SHStS transformation. This approach allows modelling the interface viscoelastic behaviour from the viscoelastic behaviour of the bitumen used for the tack coat.

This study shows that the interface between two bituminous mixtures with a tack coat presents a thermo-viscoelastic behaviour for small strain. The norm of the normal and of the shear interface stiffnesses can be modelled using the 2S2P1D model. The interface behaviour is related to the viscoelastic behaviour of the bitumen used for the tack coat.

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Compliance with ethical standards

Conflict of interest  The authors declare that they have no conflict of interest.

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Table 3  2S2P1D constants for the interface at the reference temperature 15 °C

|                  | $K_{XX,00}$ [MPa/mm] | $K_{XX,0}$ [MPa/mm] | $h$ [-] | $k$ [-] | $δ$ [-] | $τ$ [s] | $β$ [-] |
|------------------|-----------------------|----------------------|---------|---------|---------|---------|---------|
| Normal modulus “XX = zz” | 22                    | 3500                 | 0.20    | 0.53    | 2.30    | 0.1     | 300     |
| Shear modulus “XX = 0z”    | 2.2                   | 420                  | 0.20    | 0.53    | 2.30    | 0.1     | 300     |

Fig. 10  Master curves of the normalised norm of the normal interface stiffness (all samples), of the shear interface stiffness (all samples) and of the bitumen modulus along with the normalised 2S2P1D model of the bitumen in continuous line.
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