Spherical indentation test for quasi-non-destructive characterisation of asphalt concrete

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Abstract The indentation test is a promising technique for the viscoelastic characterisation of asphalt concrete (AC). Indentation measurements are primarily influenced by the material properties in the direct vicinity of the indenter-specimen contact point. Accordingly, it may become a useful alternative for the characterisation of thin asphalt layers as well as for a quasi-non-destructive AC characterisation in the field. In this study, the spherical indentation test is used to measure the linear viscoelastic properties of AC mixtures extracted from a road test section. The measured complex moduli are compared to those obtained by the shear box test and are found to exhibit a linear correlation. The measurements are further analysed using the Gaussian mixture model to assign each indentation test to either aggregate-dominated or mastic-dominated response. The measurements attributed to mastic-dominated response are found to be more sensitive to the temperature and AC’s binder properties as compared to the average measurements. Accordingly, the proposed test method may provide a promising tool to measure AC viscoelastic properties and monitor the changes in AC binder phase in a non-destructive manner. A finite element micromechanical model is used to identify a representative scale for the response measured in mastic-dominated tests as well as to quantify the effect of measured properties on the AC damage propensity.

Keywords Asphalt concrete · Bitumen · Mastic · Multiscale · Indentation · Modelling · Viscoelasticity

1 Introduction

Asphalt concrete (AC) mixtures are viscoelastic composite materials, consisting of at least three distinct phases: bituminous binder, aggregates and air voids. The viscoelastic properties and their evolution during service life define, largely, the field performance of AC. Accordingly, accurate measurement of the viscoelastic AC properties for construction quality control, long-term performance prediction and monitoring is a priority area of ongoing research. Despite the considerable progress, several important research questions are not fully answered yet. In particular, the existing experimental methods cannot be applied for the viscoelastic characterisation of thin asphalt layers and asphalt overlays.

As also discussed in numerous previous studies, the rheology and volumetric proportion of the binder phase controls AC viscoelasticity. A considerable amount of recent research has focused on linking the AC properties with the rheology of their mastic and mortar phases [1, 2]. As shown in those studies,

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understanding the viscoelastic properties of mastic and mortar and their evolution in the field allows for gaining important insights into the mixture performance. At the same time, no experimental tools are available for measuring the viscoelastic properties of the AC phases, such as mastic or mortar, in situ within the asphalt mixture.

In the context of viscoelastic characterisation of small material volumes, indentation testing is a promising technique, as a highly localised stress field induced during the test allows for obtaining properties representative for the material in the immediate vicinity of the indenter-specimen contact area. Indentation tests have been applied for the characterisation of bitumen and bitumen-based materials, such as bituminous mastic, asphalt mortar and mixtures. For a comprehensive review on the application of indentation to bituminous materials, the reader is referred to a recent paper by Xu et al. [5]. The majority of the previous studies have focused on using the indentation tests for measuring the linear viscoelastic properties at the macroscale, e.g. [6–8]. There are, however, some attempts to apply spherical indentation testing for viscoplastic characterisation of bitumen and asphalt mixtures by Ossa et al. [8, 9]. In several studies, indentation tests performed at micro- and nano-scale have also been used to gain insight into the mechanical properties of different phases in bitumens and asphalt mixtures, e.g. [10–12]. As pointed out by Xu et al. [5], however, the reliable analysis methods allowing attributing individual indentation test measurements to different phases in bituminous materials are still lacking.

In two recent studies, the spherical indentation testing methodology has been extended to the characterisation of binder-aggregate composites: asphalt mortars and mastic asphalt mixtures, cf. [13] and [14] respectively. Fadil et al. [13] have shown that the indentation measurement scale is controlled by the size of the indenter-specimen contact area. Thus, performing indentation testing at different contact area sizes allows for reliable characterisation of the relaxation modulus of materials on both the macroscale as well as the scale of the mastic phase. For indentation tests on mastic asphalt mixtures, Fadil et al. [14] proposed that the measurements can be grouped tentatively into two categories: so-called “mastic-dominated” and “aggregate-dominated” measurements. In order to attribute the measurement to one of those categories, a statistical analysis methodology was proposed based on the Gaussian mixture model. As shown by Fadil et al. the viscoelastic properties of the mastic phase in the mixture can be obtained from the “mastic-dominated” measurements. The methodology proposed by Fadil et al. has, however, not been evaluated for dense graded AC mixtures. Hence, the focus of this study is on expanding the methodology developed by Fadil et al. [14] for the use on dense binder-aggregate composites such as AC mixtures. Presently, the feasibility of using the spherical indentation test for measuring AC viscoelastic properties is investigated experimentally and numerically. The intention is also to make a step towards establishing a test suitable for virtually non-destructive viscoelastic characterisation of AC layers in the field. As a first step in this direction, the experiments in this study are performed on laboratory scale and on specimens with smooth surfaces, in order to limit the number of experimental parameters.

Spherical indentation tests are used in the present study for the viscoelastic characterisation of two dense AC materials. The tests are performed on field cores extracted from a road test section. In order to evaluate the sensitivity of the test to the changes in binder phase properties, the measurements are performed at two different temperatures \( T = 0 \) °C and \( T = 10 \) °C. The methodology developed by Fadil et al. [15] is employed to obtain shear relaxation moduli from the indentation tests and compare those values with the shear box test measurements as reported by Ahmed et al. [16]. A statistical analysis methodology is then used to identify the mastic-dominated indentation measurements. The sensitivity of the mastic-dominated measurements to changes in binder phase properties is examined and potential of the indentation test for evaluation of the binder phase evolution in the field due to, e.g. ageing or damage, is discussed.

In order to identify a representative length-scale of the mastic-dominated measurements, a micromechanical finite element (FE) model is employed. In this model, the AC mixture is represented as a three-phase material with elastic aggregates and air voids embedded into a viscoelastic matrix. Based on the obtained numerical results, it is shown that the mastic-dominated measurements correspond to the mixture phase containing binder and aggregates in the size range of 0.063–2 mm. The micromechanical model is furthermore used to gain quantitative insight into the effect of
the measured properties on the mixture damage propensity. In particular, the effect of measured matrix properties on the AC performance in terms of strain localisation under tensile loading is evaluated.

2 Methodology

In this section, the main principles of the spherical indentation test are briefly described along with the methodology to calculate the shear relaxation function $G(t)$ from the measured indentation force $P(t)$ and depth $h(t)$. Then the statistical analysis method proposed by Fadil et al. [14] is applied to group the indentation test measurements into an aggregate-dominated and mastic-dominated family.

As shown by Fadil et al. for the case of mastic asphalt (MA), the $G(t)$ measured in mastic-dominated tests correlated well with the mastic phase properties. Dense ACs are, however, more complicated as they contain a lower volumetric proportion of mastic as compared to MA. Furthermore, ACs are three-phase materials containing a certain percentage of air voids, while MA used in Fadil et al. [14] study was free of them. These two aspects make the extension of the statistical analysis procedure to AC materials non-trivial. Here, a micro-mechanical FE model is employed in order to interpret the mastic-dominated indentation test measurements on AC, as discussed at the end of this section.

A sketch of the indentation test is shown in Fig. 1. In the test, the spherical indenter is pressed into the specimen with a pre-defined indentation depth history, $h(t)$, generating a reaction force, $P(t)$. Both $P(t)$ and $h(t)$ are recorded continuously during the test. Assuming that the specimen is isotropic and linear viscoelastic, its material behaviour is fully described by any of two viscoelastic functions: the relaxation function $E(t)$, the shear relaxation function $G(t)$, the bulk relaxation function $K(t)$ or the viscoelastic Poisson’s ratio $v(t)$.

Furthermore, provided that the viscoelastic Poisson’s ratio is assumed to be constant and known, i.e. $v(t) = v_o$ only $G(t)$ needs to be calculated from the indentation test measurements. In the present study, the solution shown in Eq. (1) is developed by Fadil et al. [15] and is used to calculate $G(t)$ from the $P(t)$ and $h(t)$ measured in the test:

$$P(t) = \frac{8}{3(1 - v_o)} \sqrt{R} \int_0^t G(t - \tau) \frac{dh(t)}{dt} d\tau,$$  \hspace{1cm} (1)

where $R$ is the curvature radius of the spherical indenter, and $\tau$ is a dummy integration variable. Equation (1) is valid for arbitrary non-decreasing loading history and is relatively straightforward to solve numerically for $G(t)$ which is given the form of a Prony series function as in Eq. (2):

$$G(t) = G_\infty + \sum_{i=1}^{N} G_i \cdot e^{-t/\tau_i},$$  \hspace{1cm} (2)

where $N$ is the number of Prony series elements ($N = 13$ is used in this study), $G_\infty$ is the equilibrium shear modulus, $\tau_i$ is the relaxation time for the element and $G_i$ is the shear relaxation strength of the Prony series element. The details of the solution procedure may be found in Fadil et al. [15].

In the loading scheme used in this study, the piston position is ramped from 0, at the surface of the specimen to the target indentation depth $h_t$, the duration of the ramp used in this study is $t_r = 0.1$ s. The piston position is then kept constant for the duration of the test (200 s). However, in this particular setup, where, for simplicity, the piston position is observed instead of the indentation depth, the machine compliance, $C_m$, has to be taken into account. Therefore the real indentation depth is defined by Eq. (3):

$$h(t) = \begin{cases} 
\frac{t}{t_r} h_t - P(t) \ast C_m & \text{for } t \leq t_r, \\
{h_t} - P(t) \ast C_m & \text{for } t \geq t_r.
\end{cases}$$  \hspace{1cm} (3)

As demonstrated in [13, 17] the contact area in the indentation test dictates the measurement scale; as the stresses induced in the specimen are localised in the region within approximately $5a$ from indentation site ($a$ is the radius of contact area defined in Fig. 1). Thus, the indentation test is highly sensitive to the properties of the material located in the direct vicinity of the contact point. For composite materials such as AC, the measurements from the indentation tests performed at random points on the specimen surface are expected to have high variability, as illustrated in Fig. 2. In Fig. 2, the relaxation function value at $t = 1$ s, $G(t = 1)$, is presented as obtained from nine indentation tests performed at different points of the same AC
specimen. As can be seen in the figure, the obtained values vary in the range between 1250 to 2664 MPa, depending on the location chosen. These measurements can be classified as either mastic-dominated or aggregate-dominated depending on the local volumetric composition of the material at the measurement location. It is of interest to point out that the variability illustrated in Fig. 2, is significantly lower as compared to the one reported for MA mixtures in Fadil et al. [14], where the differences of up to three orders of magnitude between the measurement locations have been observed. This is due to the large volume fraction of aggregates in AC as compared to MA.

In order to classify the indentation test measurements as either aggregate-dominated or mastic-dominated groups, a statistical method based on the Gaussian mixture model is used [18, 19]. This probabilistic model allows for the separation of scattered measurements into two subpopulations/phases. In this study, it is assumed that two subpopulations exist: mastic-dominated and aggregate-dominated measurements. These subpopulations are assumed to have a Gaussian distribution of stiffness with a mean value $\mu_i$ and a standard deviation $\sigma_i$, where $i = 1, 2$ refer to each of the phases. The probability density function of each phase is given by Eq. (4):
where \( x \) is the measurement at a certain point in time, i.e., \( x = G(t = \text{const}) \).

When the probability density functions of the phases are combined, they form the Gaussian mixture model given by Eq. (5):

\[
PDF_c(x) = f \cdot PDF_1(x) + (1 - f) \cdot PDF_2(x)
\]

where \( PDF_c \) is the combined probability density function of the two phases and \( f \) is the proportion contribution of phase \( i = 1 \).

For measurements at a certain defined time, \( G(t = \text{const}) \), \( \mu_i \) and \( \sigma_i \) can be identified using the iterative Expectation–Maximisation (EM) algorithm. This study uses its implementation in MATLAB [20].

After calculating the statistical properties of the phases, the data is clustered using the Bayes rule. This is achieved by calculating the posterior probability, \( Pr_i \), of each data point as its membership score in each phase. Afterwards, each data point is assigned to the phase with the higher \( Pr_i \) value (hard clustering). \( Pr_i \) is calculated according to Eq. (6).

\[
Pr_1(x) = \frac{f \cdot PDF_1(x)}{PDF_c(x)}, \quad Pr_2(x) = \frac{(1 - f) \cdot PDF_2(x)}{PDF_c(x)}.
\]

In order to better account for the time-dependent viscoelastic properties of the specimens, the multivariate Gaussian mixture model is applied in this study for clustering based on the two data points simultaneously, i.e., \( G(t) \) at \( t = 0.1 \text{ s} \) and \( t = 200 \text{ s} \).

It may be hypothesised that the mastic-dominated measurements, identified with the clustering procedure outlined above, capture the viscoelastic properties of the binder, combined with aggregates smaller than a certain size, \( s_{\text{min}} \). The exact volumetric composition of the phase will depend on the mixture type and volumetrics as well as on the length-scale of indentation tests, as defined by the maximum indenter-specimen contact area radius.

In the present study, a micromechanical finite element (FE) model was used to interpret the mastic-dominated indentation measurements. In the model, the AC is represented as a three phases material, composed of elastic aggregates with sizes above \( s_{\text{min}} \), air voids and viscoelastic matrix, representing a mixture of binder and aggregates of sizes below \( s_{\text{min}} \). The viscoelastic properties of the matrix, have been assigned based on the mastic-dominated indentation test measurements. The effect of \( s_{\text{min}} \) on the resulting effective viscoelastic properties of asphalt mixture has been examined computationally. Once, the cut-off sieve size, \( s_{\text{min}} \), giving the best agreement of modelled and measured mixture viscoelastic properties are identified, the FE model is used to examine the effect of the measured properties on the strain localisations in the mixture. The modelling approach used is described in detail, in Sect. 4 below.

### 3 Experimental study

Spherical indentation tests were used to characterise extracted asphalt cores from the road test section built in 2005–2006 on E6 road in Sweden. 100 mm diameter cores extracted from a binder and an upper-base layer were used in this study. The AC materials from the binder and upper-base layers are denoted ABb22 and AG22 respectively, following the notation used in Ahmed et al. [16]. Both materials have a nominal maximum aggregate size of 22.4 mm and have been extracted in 2011 after 6 years of service. The mixtures have been characterised thoroughly as a part of separate research projects, cf. Ahmed et al. [16]. The properties of each mixture are shown in Table 1, while the mixtures’ gradation curve is shown in Fig. 3.

The complex moduli of the mixtures have been measured by Ahmed et al. [16] with the shear box test. In the shear box test, described in detail in [21], the viscoelastic properties of asphalt mixtures are measured in a state of mostly pure shear. The test uses cylindrical asphalt concrete samples that are glued, using epoxy glue, to two loading steel disks mounted on guiding plates. The relative movement between the disks, representing the shear deformations, is measured by two strain gauges. A horizontal shear force is applied through one of the disks in a sinusoidal pattern while a compressive force is applied parallel to the axis of the mounted specimen on the stationary disk. AG22 and ABb22 materials have been tested by Ahmed et al. [16] at temperatures from \(-5 \text{ \degree C}\) to \(50 \text{ \degree C}\) and a frequency range of \(0.05–16 \text{ Hz}\). At least three measurements per material have been performed. The \( G'(\omega) \) measurements show a large scatter.
at lower frequencies, for example, at $\omega = 0.01$ rad/s the 95\% confidence intervals are $[986.5, 2027.9]$ MPa and $[394.8, 2270.6]$ MPa for ABb22 and AG22 respectively. The corresponding intervals at $\omega = 100$ rad/s are $[4617.4, 5174.5]$ MPa and $[4048.1, 4844.4]$ MPa. Thus, the difference in $G/C_3(\omega)$ between the mixtures is not significant when the shear box test is used. The master curves obtained from those tests are shown in Fig. 4. Due to the use of the 50/70 binder and lower air voids content, ABb22 is stiffer than AG22 that uses the 100/150 binder.

The indentation tests used 100 mm diameter field cores with a thickness of 39.5–41 mm. One core of AG22 and one core of ABb22 were used for the tests. Figure 5 shows the setup used for the indentation test. The setup utilises an $R = 15.875$ mm steel spherical indenter attached to an MTS 810 servo-hydraulic load frame. The indenter curvature radius is chosen to result in maximum contact area radius, $a_{\text{max}}$, in the order of 2–3 mm, in order to reduce the influence of the specimen surface roughness as well as the rigid support under the specimen. The indentation depth was measured using the piston position, while the load

| Mixture | Layer       | Binder type | Binder content (% weight) | Air void content (% volume) | Penetration @25 °C (l/mm) | Softening point (°C) |
|---------|-------------|-------------|---------------------------|-----------------------------|---------------------------|----------------------|
| ABb22   | Binder course | 50/70       | 5.2                       | 1.4                         | 55                        | 50                   |
| AG22    | Upper-base course | 100/150     | 4.5                       | 5.1                         | 127                       | 43                   |

Fig. 3 Aggregates size distribution for ABb22 and AG22

![Fig. 3 Aggregates size distribution for ABb22 and AG22](image)

Fig. 4 Master curves measured using the shear box test at $T = 10$ °C as measured in [16]

![Fig. 4 Master curves measured using the shear box test at T = 10 °C as measured in [16]](image)

Fig. 5 Instrumented indentation setup
was measured using a 10 kN load cell with a measured machine compliance, \( C_m = 3.7 \times 10^{-3} \) mm/N.

As described above, cf. Equation (3), the loading scheme was a linear ramp followed by a constant position relaxation period in displacement control. The maximum piston position reached was \( h_{\text{max}} = 0.3 \) mm ramped within 0.1 s. Assuming a linear viscoelastic specimen behaviour, the maximum contact area radius, corresponding to \( h_{\text{max}} = 0.3 \) mm, can be calculated from Eq. (7):

\[
a(t) = \sqrt{h(t)} \cdot R.
\]

where \( a(t) \) is the contact area radius between the indenter and the specimen surface, resulting in a maximum contact area radius \( a_{\text{max}} = 2.51 \) mm. The piston position was then held constant for 200 s, while continuously monitoring the reaction force \( P(t) \). The indentation depth, \( h(t) \), was obtained from Eq. (3) using \( h_{\text{max}} \). Based on the measured \( P(t) \) and the calculated \( h(t) \), the shear modulus \( G(t) \) was calculated according to Eq. (1) using linear programming. In Eq. (1), Poisson’s ratio, \( \nu_0 \), value was assumed to be 0.35 taken as representative value of AC Poisson’s ratio. It has to be pointed out, that the influence of \( \nu_0 \) on the \( G(t) \) calculated from Eq. (1) is limited. In particular, setting \( \nu_0 \) to 0.2 and 0.5 results in an approximately 20% change in the calculated \( G(t) \) as compared to the one calculated at \( \nu_0 = 0.35 \).

The indentation tests were carried out at two different temperatures: 0 °C and 10 °C. For each specimen surface, nine indentations were performed, with a single indentation made inside each square of the grid shown in Fig. 2. The grid size was \( 2 \times 2 \) cm, therefore, ensuring that the indentations are spaced from each other and from the edge of the core with a minimum distance of \( 10 \times a_{\text{max}} \). The distance of \( 10 \times a_{\text{max}} \) allows to ensure that the boundary effects on the measurements are small, below 5%, as shown experimentally and numerically in previous studies [15, 17]. In order to increase the total number of the tests performed, after the first round of tests, the core surface was cut, removing approximately 4 mm before the next test run. By using this method each sample was tested in four separate runs: two runs at 0 °C and two runs at 10 °C. Therefore, for each material and temperature, a total of 18 indentation tests have been performed.

### 4 Micromechanical modelling

A micromechanical model based on the finite element method (FEM) was used to interpret the results from the indentation tests. In particular, the micromechanical model simulates the asphalt concrete as a composite material consisting of three phases: (1) an aggregates phase, modelled as a linear elastic material, (2) a linear viscoelastic matrix and (3) air voids. In this model, the spherical aggregates and air voids are embedded into the viscoelastic matrix. The aggregates properties were taken as \( E = 52.7 \) GPa, and \( \nu = 0.2 \), as typical properties of granite [22]. The viscoelastic matrix properties were taken from the mastic-dominated results measure using the indentation tests.

Since the measurement scale, \( a_{\text{max}} = 2.51 \) mm, is close to the upper end of the mortar aggregate size distribution, i.e. 0.063–2 mm, it was tentatively assumed that the cut-off size between the matrix and the mixture scales was \( s_{\text{min}} = 2 \text{mm} \). Additional simulations have, however, been performed by taking \( s_{\text{min}} \) to be one sieve size below and above the 2 mm, i.e. resulting in the mixture scale range of (1) 1–31.5 mm, (2) 2–31.5 mm and (3) 3–31.5 mm.

A cubic representative volume element (RVE) is formulated from the aforementioned phases with dimensions of \( L \times L \times L \), with \( L = 80 \) mm. The aggregates as well as the air voids are idealised as spheres, as shown in Fig. 6b, c. The spheres representing the aggregates and air voids are randomly distributed within the RVE while the viscoelastic matrix fills the remaining cubic volume (see Fig. 6a). For computational efficiency, periodic boundary conditions have been employed, following the procedure proposed by Fadil et al. [23] for mastic. The periodic boundary conditions allow for obtaining representative results at smaller RVE sizes, therefore, considerably reducing the computational cost significantly [24].

The random distribution of the spheres within the RVE is achieved using the Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) [25]. LAMMPS is an open-source software used for molecular dynamics, therefore, it was used as a tool to generate dense spherical aggregates models. The sizes of spheres used were assumed to be the average size of the spheres within each sieve. As Table 2 shows, the sizes of the spheres were picked based on the aggregates’ sizes distribution and the sieve sizes, as
in Fig. 3, as well as their proportion to the total spheres’ volume.

The number of spheres was calculated based on the chosen RVE size, the sphere size and volumetric proportions of aggregates as a percentage of the total volume of aggregates (Table 2). The resulting volumetric composition of the RVE is given in Table 3. The proportions for the RVEs, shown in Table 3, are calculated based on the asphalt concrete mixtures design (Table 1). The spheres representing the air voids were chosen to be equal to the smallest particle diameter, \( d = 3 \) mm, to avoid generating a large number of spheres and to reduce the computational time, resulting in 507 spheres for ABb22 and 1847 spheres for AG22.

The models are generated in LAMMPS using three steps. At first, the spheres, for both aggregates and air voids, are dropped into a box with \( L \times L \times 2L \) dimensions in the \( x, y, \) and \( z \) coordinate correspondingly. The spheres are generated with a diameter that is 0.3\% larger than the target diameters shown in Table 2. In the second step, the wall in the \( z \)-coordinate is lowered from \( 2L \) height to \( L \), therefore, constricting the spheres into the final RVE volume. In the third step, the wall at the bottom of the RVE is vibrated to resettle and redistribute the spheres. The coordinates of the spheres are used as the basis to generate the RVE in ABAQUS. Afterwards, the diameters of the spheres are reduced, by 0.3\%, to their target size in ABAQUS. This extra step is performed to ensure that spheres are not in contact, therefore, simplifying the meshing process. Afterwards, the matrix is created around the spheres with a side dimension \( L \). Finally, the air voids spheres are subtracted from the RVE. Figure 6 shows the aggregates and air voids spheres as well as the viscoelastic matrix as generated in ABAQUS. The elements used for meshing were tetrahedral quadratic

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Fig. 6 The representative volume element for the mixture AG22 showing a the meshed viscoelastic matrix, b the spherical inclusions and c air voids

Table 2 Volume proportions of aggregates as a percentage of the total volume of aggregates as well as the corresponding number of spheres in the models

| Sphere diameter (mm) | 26.95 | 19.2 | 13.6 | 9.6 | 6.8 | 4.8 | 3 |
|----------------------|-------|------|------|-----|-----|-----|---|
| Volume proportion (%)| 5.5   | 28.4 | 24.5 | 11.9| 12.0| 6.6 | 11.1|
| No. of spheres (ABb22)| 2     | 25   | 60   | 84  | 238 | 372 | 3057|
| No. of spheres (AG22) | 2     | 24   | 59   | 82  | 233 | 365 | 4347|

Table 3 Representative volume element composition

| Component/mix | ABb22 (%) | AG22 (%) |
|---------------|-----------|----------|
| Inclusions    | 63.6      | 62.3     |
| Matrix        | 35.0      | 32.6     |
| Air voids     | 1.40      | 5.10     |
elements. The model for ABb22 used 643,480 elements and the model for AG22 used 944,809 elements.

The homogenised $G(t)$ of the RVE is obtained by loading it with a uniaxial effective strain of $\varepsilon_x$. The strain is applied instantaneously according to Eq. (8).

$$\varepsilon_x(t) = \varepsilon_0 \cdot H(t = 0)$$  \hspace{1cm} (8)

where $\varepsilon_0$ is the strain magnitude and $H(t)$ represents the Heaviside step function.

During the simulation, the volume averages are obtained for the uniaxial stress $\sigma_x(t)$ and strains in the $x$, $y$ and $z$ directions $\varepsilon_x(t), \varepsilon_y(t), \varepsilon_z(t)$. These functions are used to calculate the homogenised properties of the RVE, i.e. the relaxation function $\overline{E}(t)$ and complex Poisson’s ratio $\overline{\nu}(t)$, according to Eqs. (9) and (10).

$$\overline{\nu}(t) = \frac{\overline{\varepsilon}_y(t) + \overline{\varepsilon}_z(t)}{2\overline{\varepsilon}_x(t)}$$  \hspace{1cm} (9)

$$\overline{E}(t) = \frac{\overline{\sigma}_x(t)}{\overline{\varepsilon}_x(t)}$$  \hspace{1cm} (10)

The elastic–viscoelastic correspondence principle was used to calculate $G(t)$, as in Eq. (11), by transforming the linear relation between the elastic material properties (Eq. (12)).

$$G(t) = L^{-1}\left\{\frac{\overline{E}(s)}{2(1 + s \cdot \overline{\nu}(s))}\right\}$$  \hspace{1cm} (11)

$$G(t) = \frac{E}{2(1 + \nu)}$$  \hspace{1cm} (12)

where $L^{-1}$ is the inverse Laplace transform and $\overline{E}(s)$ and $\overline{\nu}(s)$ are the Laplace transforms of $\overline{E}(t)$ and $\overline{\nu}(t)$ respectively.

The Park and Schapery interconversion method [26] is used to transform the time domain property $G(t)$ to is frequency domain counterpart, thus, the complex modulus $G'(\omega)$ is obtained from the shear storage modulus $G''(\omega)$ and the loss shear modulus $G''(\omega)$ using Eqs. (13), (14) and (15).

$$G'(\omega) = G_{\infty} + \sum_{i=1}^{N} \frac{\omega^2 \cdot \tau_i^2 \cdot G_i}{\omega^2 \cdot \tau_i^2 + 1}$$  \hspace{1cm} (13)

$$G''(\omega) = \sum_{i=1}^{N} \frac{\omega \cdot \tau_i \cdot G_i}{\omega^2 \cdot \tau_i^2 + 1}$$  \hspace{1cm} (14)

$$G'(\omega) = G'(\omega) + iG''(\omega)$$  \hspace{1cm} (15)

5 Results and discussion

An example of indentation test measurements is presented in Fig. 7a, where the individual $G(t)$ curves obtained in 18 tests performed on AG22 at $T = 10$ °C are presented. As can be seen from the figure, the results span two orders of magnitude. This is expected

$$G = \frac{E}{2(1 + \nu)}$$  \hspace{1cm} (12)
due to the inhomogeneity of the tested asphalt concrete at the small measurement scale ($a_{\text{max}} = 2.51$ mm). The mean value is shown by the solid line and drops from 1511 to 262 MPa in a span of 200 s due to the viscoelasticity. However, after applying the statistical separation method described in Sect. 2, it was possible to divide the measurements into two groups: the mastic-dominated phase and the aggregate-dominated phase as seen in Fig. 7b. The aggregate-dominated phase is stiffer than the mastic-dominated phase and the difference in stiffness increases with the measurement time. This indicates that the mastic dominated phase is much more affected by the binder within the asphalt concrete than the aggregate-dominated phase.

Figure 8 shows the average $G(t)$ values along with their 95% confidence intervals obtained from the 18 measurements for each material and temperature. As it can be seen, the indentation test is sensitive to the mixture type and temperature, with the ABb22 mixtures giving a stiffer response, as compared to AG22; and $G(t)$ for both mixtures, measured at $T = 0 \degree C$ being significantly higher than those measured at $T = 10 \degree C$. Therefore, the testing method provides a correct ranking of the materials. However, due to the high scatter of the measurements, as illustrated in Fig. 7a, the difference between the average $G(t)$ of ABb22 and AG22 measured at the same temperature is not significant at the 95% confidence level.

It is of interest to compare the results presented in Fig. 8, with the viscoelastic properties of the mixtures measured with different test methods. The complex modulus, $G'(\omega)$, of the materials used in this study has been measured by Ahmed et al. [16], with the shear box test. As also pointed out in their study, the shear box test resulted in the same ranking of the materials as the indirect tensile test (IDT).

In order to compare the indentation measurements with the shear box test, the time-domain results, presented in Fig. 8, were first converted to the frequency domain using Park and Schapery approximate method [26]. Afterwards, the time–temperature superposition principle was used to construct a master curve of the $G'(\omega)$ measurements of the indentation tests at a reference temperature of 10 °C. These master curves, as shown in Fig. 9, follow the same ranking as the shear box test, however, $G'(\omega)$ measured with the indentation is consistently lower than the one measured with the shear box test. This discrepancy is attributed to the localised nature of the indentation test, which possibly leads to not capturing fully the effect of the aggregate skeleton on the AC properties. At the same time, the ranking of the materials obtained with the two test methods is the same and the relative differences between $G'(\omega)$ measured for AG22 and Abb22 is very similar for the two test methods. The agreement between the two test methods is further explored quantitatively below.

In Fig. 10 the correlation plot between the $G'(\omega)$ measured using the indentation test and the shear box test is presented for the $T = 10 \degree C$, from $\omega = 0.005$ rad/s to 2000 rad/s (ABb22) and 1250 rad/s (AG22). As may be seen in the figure, the indentation results have a more or less direct correlation to the $G'(\omega)$
measured using the shear box test. This correlation can be captured using a linear function, as presented in Fig. 10, following the form shown by Eq. (16):

$$G_{\text{indentation}} = a \cdot G_{\text{shear box}} + b$$

(16)

where $a$ and $b$ are fitting parameters, found to be 0.538 and $-95.53$ respectively. As seen in Fig. 10, the linear function fits the data well, with the $R^2 \geq 0.99$.

From the results presented in Figs. 9 and 10, it may be concluded that the indentation test can capture the effect of temperature and the binder phase on the AC properties well. The average $G'(\omega)$ measured in 18 indentation test correlates directly to the shear box test, with the same correlation coefficients for both tested mixtures, indicating that the AC properties can be captured well with indentation testing. Further comparisons to other testing methods would, however, be needed to further corroborate these results.

Using the statistical separation method described in Sect. 2, the resulting $G'(\omega)$ for the mastic-dominated indentation tests are obtained as illustrated in Fig. 7b. In Fig. 11, the average $G'(\omega)$ obtained from the mastic-dominated indentation measurements for each material and temperature are shown along with their 95% confidence intervals. Comparing the results presented in Figs. 8 and 11, it may be observed, that $G'(\omega)$ obtained for the mastic-dominated tests is approximately 1.2–3.2 times lower as compared to the average $G'(\omega)$ of the mixture. This difference is within range of the difference between asphalt mortar and asphalt mixture properties as measured by Underwood and Kim [27] where it was calculated that there is a ratio of 1.2–2.3 between $G'(\omega)$ of the mixture and mortar scales. Additionally, Gu et al. [3] found a ratio of 1.4–5.6 between these scales.

As may also be seen in Fig. 11, the differences between $G'(\omega)$ measured in mastic-dominated tests for different materials and temperatures become statistically significant. In contrast to the results presented in Fig. 8, the 95% confidence intervals in Fig. 11 do not overlap between different materials and temperatures. Accordingly, the statistical analysis procedure significantly improves the sensitivity of the test to the changes in binder properties. This increase in sensitivity is further explored quantitatively in Fig. 12.

Figure 12a shows the ratio of $G'(\omega)$ of ABb22 to $G'(\omega)$ of AG22, as measured with the shear box test [16], the average of indentation tests, and the average of mastic-dominated indentation tests. Analogously to Fig. 12a, in Fig. 12b, the ratios between $G'(\omega)$ measured at 0°C and 10°C with the three test methods are presented. The results in Fig. 12a, b are presented at a specific frequency of $\omega = 0.1 \text{rad/s}$; similar results are, however, observed for other values of $\omega$.

As stated in Sect. 3, the mixture design of ABb22 and AG22 differ primarily with respect to the properties of their binder phase. As seen in Fig. 12, indentation test measurements are more sensitive to the changes in mixtures binder properties as compared to the shear box measurements. Furthermore, identifying the mastic-dominated measurements allows for improving the test sensitivity further. For instance, as
shown in Fig. 12a, the ratio of \( G'/C_3(\omega) \) at \( T = 10^\circ C \) is 1.3 when the average of all the indentation tests is used and increases to 2.3 when only mastic-dominated measurements are used. At the same time, the ratios observed for the average of all indentation tests are closer to the ones found from the shear box test, corroborating the conclusion that the averaged indentation results capture the \( G'/C_3(\omega) \) of the asphalt concrete mixtures reasonably well. It has to be pointed out that complex moduli ratios presented in Fig. 12 are accompanied by a significant amount of scatter, due to variability of the measured complex moduli in Figs. 8 and 11. In order to find a confidence level corresponding to a statistically significant difference between the complex moduli ratios presented in Fig. 12, Fieller method [28] has been applied. The difference between the complex moduli ratios from the shear box and the mastic-dominated indentation tests were found to be significant at 90% confidence level. Concerning the sensitivity of the measurements to temperature, observations similar to the ones above may be made based on the results presented in Fig. 12b.

As seen from the results presented in Figs. 11 and 12, the mastic-dominated indentation test measurements are more sensitive to the mixtures’ binder phase properties as compared to the mixture tests. Accordingly, indentation testing, combined with the proposed statistical analysis procedure, is a promising tool to monitor the changes in the AC binder phase from the measurements performed in situ on asphalt mixtures. It is worth noting that, while in the present study only the changes due to base binder properties and temperature have been investigated, the technique may also be effective for capturing binder phase evolution due to e.g. ageing or moisture damage.

At the same time, the mastic-dominated indentation measurements, presented in Fig. 11, result in \( G'/C_3(\omega) \) which are, at least, roughly in a range of what would be expected for the corresponding mortar materials, as discussed in connection to Fig. 11. This result differs from the previous finding by Fadil et al. [14] for the case of mastic asphalt mixture, where the mastic-dominated indentation test measurements were found to correlate linearly with the mastic properties measured with Dynamic Shear Rheometer (DSR). This difference is attributed to the mixture volumetric composition, as AC mixtures studied presently have much lower binder (and mastic) content as compared to mastic asphalt used in Fadil et al. study.

Combining the results of mastic-dominated indentation tests with the micromechanical FE model described in Sect. 4, provide further insight into the mechanical behaviour of AC. Regarding the identification of the representative length-scale of mastic-dominated indentation tests, it was assumed that the mastic-dominated tests capture the viscoelastic properties of a binder mixed with stones of sizes smaller than a certain aggregate size \( s_{\text{min}} \). Trial FE simulations have been performed, with \( s_{\text{min}} = 1, 2 \) and 4 mm. It was found that the simulations with \( s_{\text{min}} = 2 \) mm result in the best agreement of the \( G'/C_3(\omega) \), obtained computationally from the shear box test. In Fig. 13a and Fig. 13b the computed and measured \( G'/C_3(\omega) \) are shown for the ABB22 and AG22 respectively. The simulation results presented in Fig. 13 are obtained with \( s_{\text{min}} = 2 \) mm. The corresponding average mastic-dominated indentation test measurements are also
included in Fig. 13. As can be seen, the calculated $G'(\omega)$ is reasonably close to the one measured in the shear box test. Furthermore, the computational and measured differences in $G'(\omega)$ of ABb22 and AG22 are very close, with AG22 showing a difference that does not exceed 29% and ABb22 being in a range of 29 to 67%, with the exact values depending on frequency and temperature.

It may thus be concluded, that the mastic-dominated measurements correspond to the material phase, resembling a mortar, i.e. the mixture of the binder and aggregates smaller than 2 mm. Furthermore, the proposed modelling procedure allows for capturing the effect of measured mastic-dominated properties on the viscoelastic properties of AC. The developed micromechanical model may also be used to gain additional insight into AC damage propensity. Several important AC failure modes, for example, adhesive and cohesive fracture, are governed primarily by the tensile strain accumulation in the binder phase of the material. In what follows the effect of the viscoelastic properties on strain localisations in the matrix phase of the model is investigated briefly.

To evaluate the strain localisations, the RVE has been loaded with a constant effective tensile stress, $\overline{\sigma}_t(t) = \sigma_t$, for 200 s. The local strain distribution on the direction of loading, $\epsilon_x$, is shown in Fig. 14 for both ABb22 (Fig. 14a) and AG22 (Fig. 14b) at the end of the loading time. From the figure it is clear that the strains in the matrix of AG22 are much higher as compared to the ABb22 material, exceeding 10% in narrow matrix regions between the spherical inclusions. These higher strain concentrations in the AG22 matrix are due to its lower viscoelastic modulus as shown in Fig. 11.

The behaviour shown in Fig. 14 is further evaluated quantitatively in Fig. 15, which illustrates the volume percentage of the RVE exceeding a specific value of $\epsilon_x$. For both ABb22 and AG22, 60% of the volume (corresponding to the aggregate phase volume) is subjected to strains below 0.1%, this is due to the fact that both models use the same elastic properties for the aggregates and the volume fractions of the aggregates are very close. At the same time, strain levels in the viscoelastic matrix are much higher for the case AG22 material. In AG22 roughly 17% of the matrix is subjected to strains exceeding 2%, while for the ABb22 material only 5% of matrix volume is subjected to those strain levels. The results in Figs. 14–15, indicate that the differences in viscoelastic properties measured in mastic-dominated indentation tests may have a profound influence on the strain localisations in the AC mixtures, and thus, on their damage resistance. The proposed micromechanical model provides a relatively simple method to quantify those effects.

6 Conclusions

Spherical indentation testing has been evaluated in this study as an alternative tool to measure the viscoelastic
properties of asphalt concrete (AC) mixtures. Tests have been performed on field cores of two AC mixture types and the shear relaxation moduli of the materials have been measured. While the measurements have been accompanied by a significant scatter, it was shown that the indentation test can capture the same ranking of relaxation moduli of AC mixtures as measured in the shear box test.

A statistical analysis procedure has been used to separate the indentation measurements into two groups, corresponding to mastic- and aggregate-dominated measurements. It was shown that the relaxation moduli measured in the mastic-dominated tests were more sensitive to temperature and binder type. In order to evaluate a representative length scale for the mastic-dominated indentation tests a micromechanical FE model has been employed. It was shown numerically that, for the measurement setup used in this study, the mastic-dominated indentation test measurements correspond approximately to viscoelastic properties of the mortar phase, consisting of binder and aggregates smaller than 2 mm.

Furthermore, the influence of viscoelastic properties, measured in mastic-dominated tests on strain localisation in AC has been investigated numerically. It was observed, that the differences in viscoelastic properties measured in mastic-dominated indentation tests have a strong effect on the strain localisations in AC mixtures, and thus, on the materials damage propensity.

Based on the presented experimental and numerical findings, the indentation test appears to be a viable complementary tool for the viscoelastic characterisation of AC materials and their components, with the potential to be further developed for use in situ. In particular, as the technique is quasi non-destructive, affecting only a small volume of material near the indenter-specimen contact area, the localised nature of the test allows it to be applied for characterisation of thin asphalt layers, such as pavement surface courses. Furthermore, combining the indentation testing with the proposed statistical analysis procedure provides a promising tool to monitor the changes in the AC
binder phase from the measurements performed on AC mixtures.

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