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Sample size correction factors for indentation on asphalt bitumens

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HIGHLIGHTS

- Sample size effects for indentation on asphalt bitumens are calculated.
- Results are based on elastic viscoelastic transformations and load superposition.
- Effects are significant for sample sizes commonly used in bitumens' indentation.
- The influence of sample depth is higher than the lateral size effect.
- Sample size correction factors are provided for finite depth and diameter.

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ABSTRACT

Closed form solutions for obtaining fundamental properties of viscoelastic materials through indentation assume a semi-infinite indented media. For real sample sizes, proper material characterization requires determining the effect of finite sample dimensions. Available solutions from the literature were used to obtain correction factors for finite sample depth. Since no solutions were available for laterally confined viscoelastic materials, correction factors were developed in this work, assuming null displacement at the confined lateral edges and applying load superposition. Both correction factors were obtained for axisymmetrical samples indented with conical, cylindrical and spherical geometries. Two asphalt binders commonly used in road paving were tested in indentation with spherical geometry at intermediate temperature. Significant correction factors were needed for sample sizes commonly used in penetration testing of bitumens. The effects of sample dimensions resulted in underestimations of 19% and 22% in the creep compliances of each bitumen. Based on the results, minimum sample sizes required to make the boundary conditions effects' negligible are recommended for common asphalt binders indented at intermediate temperatures.

1. Introduction

Initial studies on contact mechanics date back to Hertz [14], who obtained the elastic solution for two curved surfaces in contact with no adhesion. Further studies [16] incorporated the effect of adhesion between the bodies in the model known as JKR after Johnson, Kendall and Roberts). Later on, Bowden and Tabor [3] studied the influence of friction between both surfaces in contact.

Lee [18] and Lee and Radok [19] developed a solution for linear viscoelastic indentation without adhesion, using Hertz's elastic developments and the method of functional equations. This method allows analyzing time dependent boundary conditions, where the corresponding principle is not applicable. Their method, however, requires the contact area between the indenter tip and the material surface to be continuously increasing with time. Ting's solution [30] overcame the restriction of monotonic increase in the contact area.

All the solutions mentioned above assume a semi-infinite indented media. When the size of the tested samples cannot fulfill this assumption, the indentation needs to be corrected. The effect of the finite sample depth was first determined by Yu et al. [32] for elastic indented media with axisymmetrical indenters. Explicit depth correction factors were provided by Choi et al. [5] for elastic media indented with cylindrical geometry. Han et al. [13] used Yu's solution for correcting nano-indentation with conical geometry in elastic films. Li and Vlassak [20] used Yu's corrections for spherical nano indentation on elastic films. The effect on indentation of finite lateral dimensions is known to be lower than the depth effect and

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it is usually neglected. The effect of boundary conditions on viscoelastic indented media has not been addresses in the literature.

The use of indentation to measure bitumen properties was attempted in SHRP-A-369 [1]. Indentation experiments were also recommended for quality control and as a supplement to the Bending Beam Rheometer (BBR) test by Cominsky et al. [7]. More recently, Ossa et al. [23] have used monotonic and cyclic loading in indentation tests to characterize the mechanical behavior of bitumen. Zofka and Nener-Plante [33] presented a solution for the creep compliance in tension obtained from testing with flat ended cylindrical indenters. All these works used axisymmetrical indenters and assume that the semi-infinite indented media supposition was valid.

In this work, correction factors are developed for viscoelastic media indented with spherical, cylindrical and conical geometries. The corrections are applied to spherical indentation on two asphalt bitumens tested in the lab at intermediate temperature. The corrected indentations are used to determine the creep compliances of the bitumens. Minimum sample sizes are recommended for the semi-infinite media assumption to be valid, when common roads bitumens are tested at intermediate temperatures.

2. Semi-Infinite indented media

Fig. 1 shows a schematic of the indentation on viscoelastic media using spherical, conical and flat-ended cylindrical indenters.

Lee and Radok [19] obtained a solution for rigid spherical indenter on an isotropic linear viscoelastic media assuming surfaces in contact are frictionless. Friction can be neglected if indentations $h(t)$ are smaller than 20% of the indenter radius [5,25]. The solution is presented in Eq. (1).

$$J(t)=\frac{8\sqrt{R}}{3P_0(1-\nu)}h(t)^{3/2} \tag{1}$$

Ian Sneddon [26] developed a general solution for any axisymmetric indenter, from which the creep compliances in shear for conical and cylindrical indentation can be derived. Eqs. (2) and (3) show the solutions for conical [21] and cylindrical [17] geometries, respectively.

$$J(t)=\frac{4}{\pi(1-\nu)\cot(\alpha)P_0}h^2(t) \tag{2}$$

$$J(t)=\frac{4R}{(1-\nu)P_0}h(t) \tag{3}$$

3. Rigidly confined media

3.1. Finite depth

When the indented sample does not satisfy the semi-infinite media assumption, the indentation results need to be corrected for the effect of boundary conditions. Fig. 2 shows the schematics of a sample that has infinite lateral dimensions but finite depth.

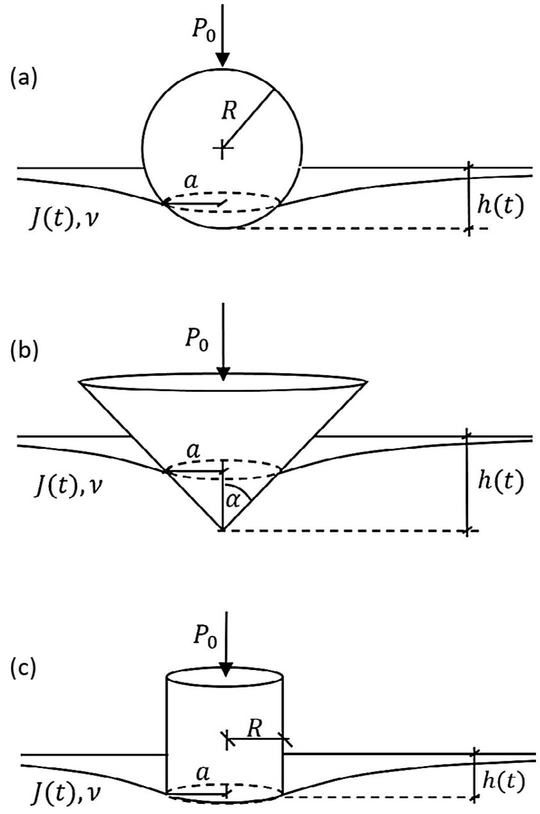

Fig. 1. Indentation on viscoelastic media with spherical (a), conical (b) and cylindrical (c) indenters. P_0 : applied constant load, R: radius of the spherical or cylindrical indenter, a : opening angle of conical indenter, $J(t)$: creep compliance in shear of the indented media (bitumen), ν: Poisson's ratio of the indented media (bitumen), a : contact radius, $h(t)$: indentation depth (measured from the original surface level).

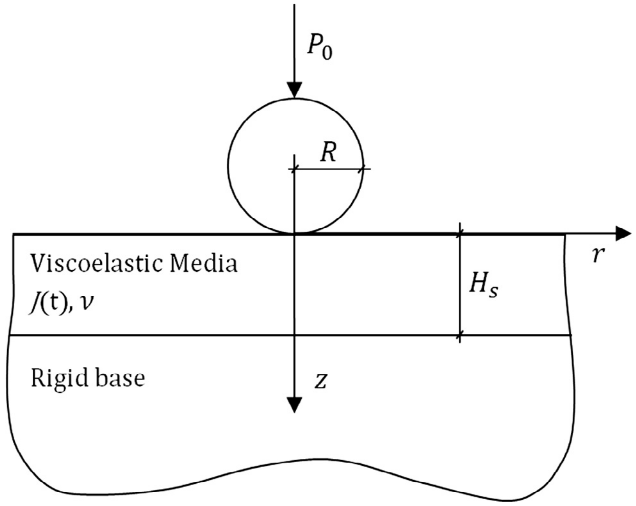

Fig. 2. Spherical indenter on a viscoelastic media of finite depth H_s.

The axial symmetry of the problem allows carrying out a two dimensional analysis using radial (r) and vertical (z) coordinates. The boundary conditions at the surface of the indented media are:

$$\begin{aligned} &w(0,0)=h \\ &\sigma_{zz}(r,0)=0 \qquad r>a \\ &\sigma_{rz}(r,0)=0 \qquad r\geqslant 0 \end{aligned} \tag{4}$$

were $w(r,z)$ is the vertical displacement field, σ_{zz} is the vertical stress, σ_{rz} is the shear stress and a is the contact radius defined previously. The boundary conditions at the interface between the indented media and the rigid base are:

$$u(r,H_s)=w(r,H_s)=0 \quad r\geqslant 0 \tag{5}$$

were $u(r,z)$ is the horizontal displacement field. The solution can be mathematically reduced to a second type of Fredholm integral equation [32]. For a spherical indenter of radius R [20]: