Applications of Strain-rate Frequency Superposition for Bituminous Binders

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Received: 18.12.2014, Final version: 11.8.2015

Abstract:
Nonlinear viscoelastic behavior of bitumen has a determinant effect on the performance of asphalt roads suffering permanent deformation due to traffic loads. Up to know, conventional rheological characterization of bituminous binders, such as the time-temperature superposition (TTS) method, only addresses the linear response of this material without considering the application of high strain amplitudes. The strain-rate frequency superposition (SRFS) is an analogous technique that can experimentally determine the flow behavior from nonlinear oscillatory shear experiments. This method was originally applied to soft materials in order to study the slow relaxation process of particular systems by shifting to higher frequencies the behavior usually found at very low frequencies during conventional measurements. In this work, the feasibility of the SRFS method for assessing the rheological properties of bituminous binders has been evaluated. Oscillatory shear measurements accomplished at different constant shear strain amplitude rates ($\dot{\gamma}_o = \omega\gamma_o$) and test temperatures allowed analysing the influence of the nonlinear behavior of unmodified and polymer modified bitumen on their viscoelastic responses. The results showed that displacements in the responses due to different strain rates were not so significant as to extend the frequency range further than in conventional measurements. Differences in responses between both techniques were mainly observed for polymer modified binders, especially to high strain amplitudes which usually involve nonlinear behaviour. In addition, master curves obtained with constant strain rates, i.e. taking into account nonlinear response of the material, showed similar results to those constructed by using conventional methods with constant strain amplitude. From these results, a closer comprehension of the large deformations generated in asphalt pavements can be achieved by studying the nonlinear viscoelastic properties of the bituminous binder.

Key words:
Strain-rate frequency superposition, SRFS method, rheological characterization, time-temperature superposition, bituminous binder, nonlinear viscoelastic behavior

1 INTRODUCTION

The mechanical response obtained in bituminous materials is considered as linear viscoelastic at low stress levels and as nonlinear at high stresses. This performance is reproduced in asphalt mixtures used in road structures subjected to traffic load [1]. The consequences of such non-linearity for the performance of road surface are quite significant since stress level represents axle loading and testing time represents traffic speed and/or volume. This means that if axle loads increase, speed decreases, and/or traffic volume increases, the binder becomes less resistant to permanent deformation.

Different levels of deformations can be attained depending on the composition of the bituminous binder. In fact, the rheological behavior of bitumen is directly related to its chemical composition which may be defined by the so-called SARA fractions. Asphaltenes and resins, i.e. the fractions with higher molecular weights, provide the major part of the elastic behaviour, whereas aromatics and saturates, namely the fractions with low molecular weight and low glass transition temperatures, are related to the viscous behaviour. It has been reported that bitumen viscosity is strongly dependent on the asphaltenes content as well as the maltenes viscosity [2]. Furthermore, several types of polymers have been used as modifiers in order to improve the performance of bitumen by means a toughened binder matrix. As well as composition, temperature is another important factor that defines the mechanical properties of the bitumi-

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were carried out to determine the LVE strain limits for different temperatures and frequencies. The linear domain found for unmodified binders was wider than for polymer modified binders. In general, consequence of the increase of the bitumen stiffness, higher loading frequencies led to wider LVE domains when considering the strain rate effect. The same behavior was observed by analysing the effect of the temperature reduction which showed less influence on the variation of the LVE limits.

The results obtained from the application of the SRFS method to bituminous binders showed that, although displacements to higher frequencies due to different strain rates were obtained when applying high strain rates, in our case, these were not significant enough for extending the frequency range further than in conventional measurements. Moreover, some deviations at high strain amplitudes were found. These deviations were more significant for the storage modulus when the elastic behavior was not dominant (i.e. at low loading frequencies). This effect related to nonlinear responses was mainly observed for polymer modified binders.

In addition, as the complex behavior of the bitumen as viscoelastic material is associated to a nonlinear response at high strain amplitudes and this effect is not considered when TTS method is used with the conventional approach (constant strain amplitude within LVE domain), the application of constant strain rates was evaluated as alternative approach. Standard master curves were built from the single curves at different temperatures and constant strain rate ($\dot{\gamma}_o$ = 0.01 1/s). The resulting master curves showed similar behavior in comparison to those obtained at constant strain amplitude. In this case, the advantage of this new approach by constant strain rates is that higher strain amplitudes related to nonlinear responses are involved in the analysis. Knowing that this effect is an important factor in bituminous binders, which is reproduced at large scale in the asphalt roads, a further study of the application of the constant strain rate approach at higher temperatures is strongly recommended.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. André Studart from the Complex Materials group at ETH-Zurich for his essential recommendations in the initial stage of the experimental study.

REFERENCES

[1] Delgadillo R, Bahia HU: The relationship between nonlinearity of asphalt binders and asphalt mixture permanent deformation, Road Mat. Pavement Des. 11 (2010) 653 – 680.

[2] Lesueur D: The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification, Adv. Colloid Interface Sci. 145 (2009) 42 – 82

[3] Van Der Poel C: A general system describing the viscoelastic properties of bitumen and its relation to routine test data, J. App. Chem. 4 (1954) 221 – 236

[4] Vijay R, Deshpande AP, Varughese S: Nonlinear rheological modeling of asphalt using White-Metzner model with structural parameter variation based asphaltene structural build-up and breakage, Appl. Rheol. 18 (2008) 23214.

[5] Atul Narayan SP, Venkata Nag KA, Murali Krishnan J, Desphande AP, Rajagopal K: Nonlinear viscoelastic response of asphalt binders in transient test, Road Mater. Pavement Des. 13 (2012) 191 – 202.

[6] Stastna J, Jorshari K, Zanzotto L: Nonlinear dynamic moduli in asphalt, Mater. Struct. 35 (2002) 59 – 63.

[7] Hintz C, Velasquez R, Johnson C, Bahia HU: Modification and validation of the linear amplitude sweep test for binder fatigue specification, Transp. Res. Rec. 2207 (2011) 99 – 106.

[8] Ossa EA, Desphande VS, Cebon, D: Phenomenological model for monotonic and cyclic behavior of pure bitumen, J. Mat. Civil Eng. 17 (2005) 188 – 197

[9] Ewoldt RH, Hossoi AE, McKinley GH: New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear, J. Rheol. 52 (2008) 1427 – 1458.

[10] Yu W, Du Y, Zhou C: A geometric average interpretation on the nonlinear oscillatory shear, J. Rheol. 57 (2013) 1147 – 1175.

[11] Wyss HM, Miyazaki K, Mattsson J, Hu ZB, Reichman DR, Weitz DA: Strain-rate frequency superposition: A rheological probe of structural relaxation in soft materials, Phys. Rev. Lett. 98 (2007) 238303.

[12] Sollich P, Lequeux F, Hébraud P, Cates ME: Rheology of soft glassy materials, Phys. Rev. Lett. 78 (1997) 2020 – 2023.

[13] Mohan PH, Bandyopadhyay R: Phase behavior and dynamics of a micelle-forming triblock copolymer system, Phys. Rev. E 77 (2008) 041803.

[14] Erwin BM, Rogers SA, Cloitre M, Vlassopoulos D: Examining the validity of strain-rate frequency superposition when measuring the linear viscoelastic properties of soft materials, J. Rheol. 54 (2010) 187 – 195.

[15] Kowalczyk A, Hochstein B, Stähle P, Willenbacher N: Characterization of complex fluids at very low frequency: Experimental verification of the strain rate-frequency superposition (SRFS) method, Appl. Rheol. 20 (2010) 52340.

[16] Ferry J: Viscoelastic properties of polymers, John Wiley and Sons, New York (1980).

[17] Attané P, Soucemarianandin A, Turrel G, Prud'Homme JB: Nonlinear behaviour of asphalts in steady and transient shear flow, Rheol. Acta. 23 (1984) 297 – 301.

[18] Sayir MB, Hochuli A, Partl MN: Measuring the complex

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http://www.appliedrheology.org

viscosity of bitumen in the kHz range with a new resonance rheometer. Proceedings of the Eurobitume workshop on performance related properties for bituminous binders, Luxemburg (1999).
[19] Polacco G, Vacin OJ, Biondi D, Stastna J, Zanzotto L: Dynamic master curves of polymer modified asphalt from three different geometries, Appl. Rheol. 13 (2003) 118–124.
[20] Airey GD, Rahimzadeh B, Collop AC: Linear rheological of bituminous paving materials, J. Mater. Civ. Eng. 16 (2004) 212–220.
[21] Sybilski D, Soenen H, Gajewski M, Chailleux E, Bankowski W: Binder testing, In: Advances in interlaboratory testing and evaluation of bituminous materials, RILEM State-of-the-Art Report 9 (2013).
[22] Atul Narayan SP, Venkata Nag KA, Murali Krishnan J, Deshpande AP, Rajagopal K: Nonlinear viscoelastic response of asphalt binders in transient test, Road Mat. Pavement Des. 13 (2012) 191–202.
[23] Reddy KS, Umakanthan S, Krishnan JM: Constant strain rate experiments and constitutive modeling for a class of bitumen, Mech. Time-Depend. Mater. 16 (2012) 362–274.
[24] Airey GD, Rahimzadeh B: Combined bituminous and mixture linear rheological properties, Constr. Build. Mater. 18 (2004) 535–548.
[25] Cheung CY, Cebon D: Experimental study of pure bitumens in tension, compression and shear, J. Rheol. 123 (1997) 45–73.
[26] Bahia HU, Hislop WP, Zhai H, Rangel A: Classification of asphalt binders into simple and complex binders, J. Assoc. Asphalt Paving Technol. 67 (1998) 1–41.
[27] Schwartz CW, Gibson N, Schapery RA: Time-Temperature Superposition for asphalt concrete at large compressive strains, Transp. Res. Rec. 1789 (2002) 101–112.

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