Construction and Building Materials 172 (2018) 52–62

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

Complex modulus change within the linear viscoelastic region of the mineral-cement mixture with foamed bitumen

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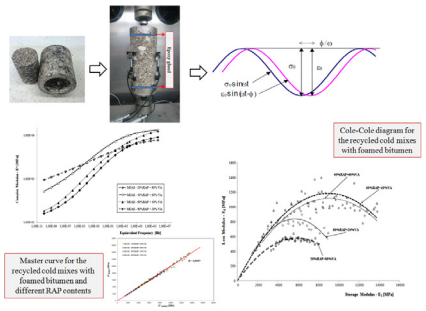
HIGHLIGHTS

- High RAP content in cold-recycled foamed bitumen mixes was assessed.
- High E* at short load times does not ensure the same effect at long load times.
- The lowest sensitivity to E* occurred in the FB-RCM mix with the minimum RAP content.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 November 2017
Received in revised form 7 March 2018
Accepted 21 March 2018

Keywords:
Foamed bitumen
Complex modulus
Phase angle
Recycling
Recycled cold mixture
Reclaimed asphalt pavement
Master curve

ABSTRACT

Deep cold recycling with foamed bitumen (FB-RCM) is currently one of the most widely used road rehabilitation methods. As the percentage of reclaimed asphalt pavement (RAP) in the base mixture may vary with the thickness of recycled bituminous layers, it is vital that the rheological characteristics of the recycled base are evaluated within the linear viscoelastic (LVE) region of response. Calculating complex modulus as a function of loading time and temperature enables the acurate determination of stress and strain distributions for individual conditions. These parameters are of most relevance in the case of a base layer, especially of a recycled base layer, as they provide information needed to determine the limit state in the subgrade and the probability of creep occurring in the recycled base. An increase in the viscous part (E_2) of the complex modulus (E^*) is an indication of a possible creep growth. A higher RAP content in the recycled base layer is likely to increase creep in this layer, thereby reducing the load bearing capacity of the entire pavement layer system.

The primary aim of this study was to assess the effect of RAP quantity on the change of complex modulus (E^*) of the recycled mineral-cement mixture with foamed bitumen (FB-RCM) in terms of the time of loading and temperature. The rheological characteristics of the FB-RCM mixtures can be used for predicting the load bearing capacity in individual cases, depending on RAP availability.

The rheological properties of the FB-RCM mixture were measured within the RAP percentage range 20–80% with a step of 20%. Complex modulus was investigated at five temperatures (−7 °C, 5 °C, 13 °C, 25 °C, and 40 °C) and six loading times (0.1 Hz, 0.3 Hz, 1 Hz, 3 Hz, 10 Hz, and 20 Hz) in the direct tension-compresion test on cylindrical specimens (DTC-CY) according to EN 12697-26. The output variables of the test were the complex modulus (E^*), the phase angle (φ) and complex modulus components (E_1) and (E_2). Results showed that the complex modulus decreased as the the RAP content increased. Irrespective of the mixture type used and the test conditions, the modulus values were from E^* = 1497 MPa to E^* = 13 797 MPa, whereas the phase angle was between 4° and 15°. It was also demonstrated that

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https://doi.org/10.1016/j.conbuildmat.2018.03.214
0950-0618/

the highest complex modulus obtained for the mixtures at short loading times did not quarantee the same values at long loading times. But lead to structural deformations due to a rapid decrease in stiffness modulus at high temperatures and exceeded the limit state in the subgrade. The rapid drop in complex modulus value decreases the durability of the entire pavement layer system.

Contents

1. Introduction

Cold recycling technologies have gained a widespread acceptance in Poland [1,2] and elsewhere [3,4] for the potential they offer, including a wide range of loads and materials within which they can be applied. Cold recycling has been proved effective in base and intermediate pavement layers applications [5,6] with mineral fines from waste materials added at 5–20% [7]. Years of experience in mineral mix design have led to refining two alternative bituminous binders, bitumen emulsion [8] and foamed bitumen [9,10] which, as confirmed by the results reported worldwide, provide high mechanical parameters also in cold and full-depth recycling. Recycling technologies vary depending on the type of materials used in the mineral mix. Mineral materials with a narrow particle size range of 4/12 [11] as well as dense grade aggregate 0/31.5 [12] can be selected to produce the mixes with the required physical and mechanical properties.

The main issue addressed by cold and full-depth recycling technologies is increasing the use of materials recovered from the damaged layers [1,2,5,6] mostly of flexible pavements [5,6,13] (bituminous mixtures and unbound mixtures). The quantity of RAP use in the recycled mixture, usually ranging between 20% and 70%, depends on the thickness of the bituminous layers in the pavement system [5]. Niazi and Jalili [8] evaluated the effect of Portland cement and hydrated lime on recycled cold mixtures using 20% RAP. Chomicz-Kowalska [2] used 50% RAP in the mineral mix for assessing the compaction methods. A study of complex modulus change in terms of RAP contribution (0%, 50% and 70%) in the recycled base layer with foamed bitumen and 0/5 mm, 5/10 mm and 10/14 mm limestone material as additional aggregate was reported by Godenzoni et al. [14].

However, the existing structural layer system determines the percentage content of particular constituents in the recycled base mixture. Thus the recycled base may contain bound materials (improved subgrade) [15], cement concrete [16], granular unbound or bituminous mix layers [13,17]. New aggregate may be needed to correct the existing gradation, thereby raising the construction costs. Therefore investment in good milling and crushing equipment can help increase the RAP use and obtain the required aggregate blend. In some cases RAP constitutes most of the base material and virgin aggregate is only added in a small quantity or no virgin aggregate is used. When the overall thickness of the bituminous layers intended for recycling is 20 cm, and the target thickness of the recycled base layer is also 20 cm, the RAP material will constitute 100% mineral constituents. In cold milling, when 3–4 cm of the existing bituminous layers are removed, the RAP content in the recycled base will still be high, about 80%.

Considering the above, determining the rheological characteristics of the recycled base mixture with foamed bitumen (FB-RCM) and varied contents of RAP seems vital. The RAP material can considerably affect the properties of the base mixture. A higher percentage of RAP in the mixture will increase the bitumen content in the base, changing the mixture properties in terms of temperatures and loading time. The evaluation of complex modulus (E*), phase angle (φ) and complex modulus components (E_1, E_2) at different times of loading and temperatures will provide all necessary data on the recycled base behaviour in the pavement structure under a range of operational conditions. To investigate these properties, dynamic testing – the direct tension–compression test on cylindrical specimens (DTC-CY) for the linear viscoelasticity response was performed in accordance with EN 12697-26 Annex D [18].

2. Purpose and scope of study

The main objective of this study was to determine the viscoelastic (LVE) nature of recycled base mixture with foamed bitumen (FB-RCM) as a function of RAP content in the mix composition. The evaluation of changes in viscoelastic responses of the recycled base course was performed by determining and modelling the complex modulus E^*, while regarding the recycled mixture as being a thermorheologically simple material. Complex modulus testing was performed at five temperatures (−7 °C, 5 °C, 13 °C, 25 °C, 40 °C) and six loading times (0.1 Hz, 0.3 Hz, 1 Hz, 3 Hz, 10 Hz, 20 Hz) in the direct tension–compression test on cylindrical specimens (DTC-CY) in compliance with [18].

Changes in the behaviour of the recycled base mixture with foamed bitumen (FB-RCM) were described using a master curve.