Rheological and performance characterisation of the bitumen recovered from different emulsions for cold mixtures

Original

Rheological and performance characterisation of the bitumen recovered from different emulsions for cold mixtures / Carpani, C.; Bocci, E.; Bocci, M.. - In: ROAD MATERIALS AND PAVEMENT DESIGN. - ISSN 1468-0629. - STAMPA. - 22:1(2021), pp. S214-S231. [10.1080/14680629.2021.1906735]

Published
DOI:10.1080/14680629.2021.1906735

Rheological and performance characterization of the bitumen recovered from different emulsions for cold mixtures

Carlo Carpani[a], E. Bocci[b]* and M. Bocci[a]

[a]*Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Ancona, Italy;* [b]*Faculty of Engineering, eCampus University, Novedrate (CO), Italy*

[*] Edoardo Bocci, PhD, Associate Professor, edoardo.bocci@uniecampus.it, ORCID 0000-0002-8857-0272

Rheological and performance characterization of the bitumen recovered from different emulsions for cold mixtures

In recent years, over-stabilized polymer-modified bitumen emulsions have been widely used to improve the mechanical properties of cold bituminous mixtures for base and subbase layers. However, the effect of the process for the polymer modification of the emulsions on the binder performance have not been investigated. The present paper deals with the analysis of the binders recovered from a reference unmodified bitumen emulsion and two polymer-modified emulsions, respectively including SBR-latex added after bitumen emulsification (post- blending) and SBS added before bitumen emulsification (pre-blending). The investigation included laboratory tests using a dynamic shear rheometer for the linear viscoelastic characterization (frequency sweep) and the evaluation of the resistance to permanent deformations (multiple stress creep and recovery) and damage (linear amplitude sweep). The results showed that the polymer-modified bitumen emulsions have a more pronounced elasticity with respect to the unmodified emulsion, allowing achieving a higher performance against permanent deformations and fatigue. In addition, the SBS modified bitumen emulsion (pre-blending) has better properties than the latex modified emulsion (post-blending), as a consequence of the different chemical structure that the modification process produces.

Keywords: Bitumen emulsion; Blending method; Cold bituminous mixtures; Latex; Polymer modification

Introduction

Nowadays, cold bituminous mixtures (CBM) are taking more and more importance in the context of road construction materials (E. Bocci et al., 2020; Godenzoni et al., 2017; Xiao et al., 2018). This need arises from the fact that, in recent decades, institutions are increasingly looking for eco-sustainability (Al-Merzah, Al-Busaltan, & Nageim, 2019; Dulaimi, Shanbara, & Al-Rifaie, 2020). In particular, these materials allow obtaining several advantages, in economic and environmental terms, with respect to both hot and warm mixtures, due to the reduction of the energy necessary for bitumen and aggregate heating (Godenzoni et al., 2017; Sangiorgi et al., 2017). Moreover, these materials can be produced with a high amount of reclaimed asphalt (RA), reducing the use of the virgin aggregate (M. Bocci et al., 2010; Godenzoni et al., 2017; Stimilli et al., 2013; Xiao et al., 2018). The technical solution to reduce binder viscosity without heating deals with the use of foaming processes or bitumen emulsification (Khan et al., 2016).

Foamed bitumens are obtained through the injection of cold water in hot bitumen (160-180 °C). The heat transfer from bitumen causes the almost instantaneous evaporation of the water and the generated steam determines the immediate expansion of the binder in the form of foam.

Bitumen emulsions (BE) are constituted by two immiscible liquids: the solution of water and emulsifying agent is the "continuous phase" while the bitumen, dispersed in the form of small droplets, is the "internal phase" (Querol et al., 2019). The BE needs to have a dispersion that is stable under storage, mixing, and pumping, but that breaks down (or “sets”, which means that bitumen and water separate from each other) upon contact with aggregates to form a final film of binder (Marasteanu & Clyne, 2006). To improve this storage stability, the emulsifying agents are used, as they decrease the interfacial tension between bitumen droplets and water in order to stabilize the system against coalescence and allow the emulsification (Ronald & Luis, 2016; Tadros, 2013). The production of BE is not a simple task, because for its formulation must take into account a series of different parameters related not only to the manufacturing process, but also to the final properties for which the emulsion has been designed (Querol et al., 2019). There are two different methods of BE production, the conventional method (thought colloid mills) and the high internal phase ratio method, but currently, the most widely used system is the first one (Querol et al., 2019).

The main properties that describe a BE, and that are generally named by the various international standards for their classification, are particle polarity, binder content, breaking index and presence/absence of polymers (D. Lesueur, 2011). BEs can be anionic, cationic or nonionic and can include up to 70% of bitumen (Querol et al., 2019). Currently, cationic emulsions with a residual bitumen content about 60% are most used in the asphalt industry (Marasteanu & Clyne, 2006; Ronald & Luis, 2016). The breaking index represents the breaking speed when the emulsion is put in contact with the aggregates. In particular, an emulsion can be classified in rapid setting (RS), medium setting (MS) and slow setting (SS). The choice depends on the BE application. RS emulsions set quickly in contact with clean aggregates of low-surface area, such as the chippings used in chip seals (surface dressings). MS emulsions set sufficiently less quickly that they can be mixed with aggregates of low surface area, such as those used in open-graded mixes. They can also be used in applications such as tack coat or fog seal. SS emulsions are mixed with reactive aggregates of high surface area and would be used for a dense cold mix which has a high filler content and consequently high reactivity, such as micro-surfacing and slurry seal (Salomon, 2006). In reality, there is a further category, namely the over-stabilized (OS) emulsions, which set more slowly than SS and are typically used in the production of CBM, as they can withstand the contact with Portland cement without breaking, for a certain time (Grilli et al., 2018).

In order to improve some performance characteristics of the residual bitumen, the BEs can be modified with polymers (Lesueur, 2011). Particularly in the case of CBM, the BEs including polymers allow increasing flexibility and plasticity in low-temperature conditions, strength and thermal stability at high temperatures, anti-ageing ability and fatigue resistance (Zhang & He, 2007), extending the whole pavement service life (Shafii et al., 2013). In the past, the CBMs were used only for low-traffic roads or deep pavement layers (subbase and foundation) because of the use of low-performing materials and the lack of a good knowledge on the correct mix design and material internal interaction mechanism (Xiao et al., 2018). Recently, the high properties of the polymer-modified BEs have encouraged the pavement engineers to use CBM not only for subbase and foundation layers but also in place of the hot-mix asphalt base, even in high-trafficked roads (E. Bocci et al., 2020; Buczyński & Iwański, 2017; Sangiorgi et al., 2017; Stimilli et al., 2013).

There are three different techniques to produce a polymer-modified BE and the blending method has an important influence on the polymer network distribution, thus on the performance of the final product (Forbes et al., 2001). The polymers can be added through pre-blending method, simultaneous-blending method or post-blending method (Shafii et al., 2011). In the pre-blending method, the polymer is added directly to the bitumen prior to the emulsification process, obtaining a mono-phase emulsion. This method is used for solid polymers and allows obtaining a finer polymer network within the bitumen emulsion, which improves its performance. However, the high temperature for production (up to 180 °C) implies an alteration of the polymer network within the bitumen (as in the typical polymer-modification process of the bitumen for hot mixtures).

In the simultaneous-blending method, the separate streams of bitumen, polymer and emulsifying agent are contemporarily milled together during the BE production whereas in the post-blending method the polymer is added after bitumen emulsification. These latter methods are carried out at lower temperatures (usually below 80-90 °C) and therefore a reduction of energy consumption and of the polymer chain alteration is achieved (Shafii et al., 2013). These techniques are used for liquid polymers and allow producing the so-called “bi-phase” emulsions.

The most common polymers that are used as BE modifiers are latexes of different types, Styrene Butadiene Styrene (SBS) and Ethylene Vinyl Acetate (EVA) (Khadivar & Kavussi, 2013). According to the physical state, each polymer type can be included in a BE through a specific method (pre-, simultaneous- or post-blending). SBS and EVA, in a solid state, are added by pre-blending method. Differently, latex consists of Styrene Butadiene Rubber (SBR) or Natural Rubber (NR) polymers dispersed in a water phase, thus it is incorporated in the BE by simultaneous- or post-blending method (Lesueur, 2011). The result is an emulsion consisting of latex and bitumen particles that are dispersed into the aqueous phase. When BE breaks, the latex particles are spontaneously transformed into a continuous polymer film covering bitumen particles (Takamura & Lubbers, 2000), allowing increasing the bitumen viscosity at high temperatures (thickening) and reducing the thermal cracking at low temperatures (Ruggles (2004)).

In the recent years, many researches have focused on the characterization of polymer-modified BE.

Zhang and He (2007) studied the performance of the BEs modified by a compound of water-epoxy resin emulsion and SBR latex (post-blending) and showed that these materials, in terms of low-temperature cracking and permanent deformation resistance, adhesion and durability, exceed ordinary BE.

Li et al. (2019) also investigated the performance of waterborne epoxy modified BE (manufactured through a particular process, where epoxy was pre-blended with bitumen and curing agent was post-added to the emulsion) as a potential high-performance cold binder and found that this modification allows a higher complex modulus (G^*) and a lower angle phase (δ) to be obtained with respect to the base bitumen, indicating that the epoxy resin raised the elastic features of the binder. Moreover, the multiple stress creep-recovery (MSCR) test results showed that the percent recovery increased and the non-recoverable creep compliance decreased, as the epoxy polymer network strengthened the elastic properties of bitumen. Finally, the linear amplitude sweep (LAS) test results demonstrated that the fatigue life of bitumen emulsion residue was improved by waterborne epoxy resin.

Waterborne epoxy was also used in BE modification by Pan et al. (2019), who compared its effects with those of SBR latex and colloidal silica sol (polymers added by post-blending process). Test results showed that the modifiers allow improving the residual bitumen bonding strength and the rheological properties (increased complex modulus and reduced phase angle at the low frequency region), but the polymer combination and dosage need to be carefully selected.

Khadivar and Kavussi (2013) studied the rheological characteristics of SBR and NR modified BEs (post-blending) at average temperatures, and proved that the addition of these polymers allows increasing the stiffness of the binder residue and reducing its temperature susceptibility, with respect to a traditional BE. Moreover, the SBR modification (but not NR modification) allows decreasing the non-recoverable creep compliance and increasing the elastic recovery.

A research carried out in southern Spain (Carrera et al., 2014; Cuadri et al., 2016) experienced the possibility of using a recycled polyurethane modifier in BE. In terms of applicability, polyurethane-modified bitumens can be emulsified (pre-blending process) at much lower temperatures than in the case of other modifiers. The rheological characterization conducted on the BE residues at 60 °C showed an improved rutting resistance with respect to unmodified recovered bitumen.

Abedini et al., (2017) studied the rheological properties of BE modified (post-blending) with different percentages of nitrile-butadiene rubber (NBR). From dynamic shear rheometer (DSR) analysis it was observed that higher NBR dosages increase complex modulus and decrease phase angle, which determine an increase in the elastic properties. Moreover, increasing NBR polymer content (up to 6%) led to an increase of $G^*/\sin\delta$ and consequently an improvement of rutting resistance. The same research team also investigated the effect of two types of SBR latexes, ordinary linear SBR and carboxyl X-structure SBR (included through post-blending process), as BE modifiers. The results demonstrated that X-SBR, more than ordinary SBR, proved to increase the recovered bitumen stiffness (Abedini et al., 2016) and to reduce the non-recoverable creep compliance and the temperature sensitivity (Abedini et al., 2018).

Jiang et al. (2018) tested three different types of recovered bitumen from polymer-modified BE, respectively including SBR latex (post-blending), Styrene-ethylene-butylene-styrene SEBS copolymer (pre-blending) and Chloroprene rubber CR latex (post-blending). The study mainly focused on the high-temperature performance, investigated in terms of $|G^*|/\sin\delta$ and non-recoverable creep compliance J_{nr}. The results showed that the residues from modified BEs, especially the one including CR latex, have lower high-temperature sensitivity and higher rutting resistance with respect to the other recovered bitumens.

The recalled researches, which are very topical, denote that the characterization of polymer-modified BE is a very felt theme by the scientific community. Even if many studies have been carried out, only few of them seem to investigate the effect of the modification process in the recovered bitumen properties. At the light of this, the objective of the present research was the rheological and performance analysis of the bitumen recovered from different BEs specifically designed for CBM. In particular, the binders recovered from traditional, SBS-modified (pre-blending) and SBR latex-modified (post-blending) BEs were investigated.

Objective

The study focused on the comparison between the bitumens recovered from 3 different types of BEs for CMB: an SBR latex-modified BE produced through post-blending process, an SBS-modified BE produced through pre-blending process and a reference unmodified BE. It is highlighted that the tested polymer-modified BEs are characterized by similar values of ring-and-ball softening point of the residue, as required in the specifications for base-layer CBM by Italian national highways authority (ANAS, 2010).

The comparison between the 3 recovered bitumens was carried out in terms of:

- linear viscoelastic (LVE) behaviour, investigated by means of strain sweep and frequency sweep tests with dynamic shear rheometer (DSR) for the construction of the complex modulus and phase angle master curves. In addition, the 2S2P1D model parameters for the 3 bitumens were analysed;
- resistance to permanent deformations, examined through multiple stress creep and recovery (MSCR) test;
- fatigue behaviour, studied through linear amplitude sweep test (LAS).

In order to clearly distinguish between the manufacturing process of the polymer-modified BEs, the residue from SBR latex-modified BE was coded with LMEB (latex-modified emulsified bitumen), as the emulsification was carried out on the unmodified bitumen before polymer addition, while the residue from SBS-modified BE was coded with EPMB (emulsified polymer-modified bitumen), as the emulsification was carried out on the SBS-modified bitumen. Finally, the residue from the unmodified emulsion was coded with EB (emulsified bitumen). Table 1 summarizes the material nomenclature.

Materials

The BEs selected for the present study were commercial products typically marketed in Italy for CBM applications. Table 2 shows the physical properties of the BEs and of the recovered bitumens as declared by the producer. It can be observed that the 3 emulsions have the same characteristics in terms of water content (60%) and breaking index. The latter, in particular, which is equal to 10, identifies the over-stabilized emulsions (EN 13808, 2013), which have a mixing stability with cement lower than 2% according to a specific test procedure (EN 12848, 2009) and thus are suitable to be used in CBM.

On the contrary, some differences can be noticed in the recovered bitumens properties (ring-and-ball softening point and elastic recovery). In fact, the BE producer adjusts the modifier dosage in order to match the acceptability interval defined by Italian standards (ANAS, 2010) for the recovered bitumen softening point (55-75 °C). To this aim, LMEB and EPMB respectively include 3.3% of SBR and 4.0% of SBS by total bitumen weight, resulting in a ring-and-ball softening point value of 62 °C for both. However, the different polymer dosage and blending process determine different elastic recovery values, higher for EPMB, but complying with the specifications (elastic recovery > 55%).

Recovery of the bitumen from the emulsion

The main processes to recover the bitumen from the emulsion, modified or unmodified, are based on three different methods: "distillation and high-temperature evaporation method", "low-temperature evaporation method" and "solvent precipitation method" (Waters et al., 2008). Any national specification has a different indication on the method to be followed for the recovery of BE bitumen and this can influence the rheological properties of the recovered binder. In particular, if the procedure is carried out at high temperatures (over 180 °C), the rheological properties of the bitumen can be somehow influenced (Shafii et al., 2011). This issue is highly important in the case of polymer-modified BE, for which the polymer morphology can be significantly affected by the temperature and the duration of the recovery method (Marasteanu & Clyne, 2006). In particular, the high temperatures required by some of the methods significantly alter or damage the microscopic structure of the emulsion and therefore the residues do not represent the field conditions, where the CBM construction is done at ambient temperature (Takamura & Lubbers, 2000). This is especially true with latex modified emulsions, for which the simultaneous- or post-blending manufacturing process does not entail any polymer swelling or digestion (Lesueur, 2011).

In the present research, the bitumen was recovered from the bitumen emulsion by means of a low-temperature evaporation method, according to EN 13074-1 (2019). The European standard provided the BE conditioning at room temperature for 24 h (approximately 20 °C) followed by 24 h at 50 °C. The recovered bitumens were stored in a cool room (at a temperature of approximately 15 °C) in opaque and sealed containers for at maximum 7 day before testing.

Experimental programme and test procedure

The experimental programme included the analysis of the rheological properties, the resistance to permanent deformations and fatigue behaviour of the recovered bitumens.

The rheological characterization was carried out by means of strain sweep and frequency sweep tests. Strain sweep tests were performed in order to determine the threshold of LVE region γ_{lim}, i.e. the strain value corresponding to a $|G^*|$ deviation equal to 95% of its initial value $|G^*_{in}|$. The test parameters were frequency f = 1.59 Hz, temperature T = 5, 15 and 30 °C, a range of strains γ between 0.005-5% and 2 repetitions for each material. Frequency sweep tests aimed to measure the complex modulus of the bitumens. In particular, these tests were performed at a constant strain $\gamma = 0.2\% < \gamma_{lim}$, over a range of frequencies (from 0.1 to 10 Hz) and temperatures (0, 4, 10, 16, 22, 28, 34, 40, 46, 52, 58 °C). Temperatures > 58 °C were not investigated as CBMs, used for base, subbase or foundation layers, rarely reach this value in their service life.

The strain and frequency sweep tests were carried out through a dynamic shear rheometer (DSR) in plate-plate configuration, applying sinusoidal load curves in control-strain mode. For $T \leq 40$ °C, a diameter of 8 mm and gap of 2 mm were used, while for $T \geq 28$ °C a diameter of 25 mm and gap of 1 mm were adopted. According to EN 14770 (2012), the test protocol provided two repetitions for each test. In case of result dispersion ($|G^*|$ out of the range of 10%), a third repetition was carried out.

The resistance of the recovered bitumens against permanent deformation was investigated through multiple stress creep and recovery (MSCR) test, according to EN 16659 (2016). The test was carried out using a DSR with 25 mm diameter and 1 mm gap. The sample was loaded at constant stress for 1 s, then allowed to recover for 9 s. Ten creep and recovery cycles were run at 0.1 kPa creep stress followed by 10 cycles at 3.2 kPa creep stress. The test was repeated at the temperatures of 28, 34 and 40 °C, which were assumed to be the typical intermediate/high temperatures for CBM in service. The protocol provided 2 repetitions for each temperature. Non-recoverable creep compliance (J_{nr}), and percent recovery (R) were determined.

The fatigue behaviour was studied by means of linear amplitude sweep (LAS) test, according to AASHTO TP101 (2014). The test was carried out using a DSR with 8 mm diameter and 2 mm gap. The protocol provided a frequency sweep test at a constant strain $\gamma = 0.1\%$ over a range of frequencies from 0.2 to 30 Hz. This preliminary LVE analysis allowed calculating the undamaged material parameter α, which represents the inverse of the slope of the storage modulus vs frequency curve in the log-log plane. Then, an amplitude sweep test was carried out at 5 Hz by continuously increasing the strain from 0.1% to 30% with a constant rate of 0.05% per second (corresponding to a test duration of 3100 cycles, i.e. 620 s). The sample failure was assumed in correspondence of the peak value in the shear stress τ vs shear strain γ curves. Through the application of the ViscoElastic Continuum Damage (VECD) model the normalized complex modulus C vs damage D curve were obtained for each bitumen. In addition, the binder fatigue behaviour was estimated by the following Equation 1:

$$N_f = A \cdot \gamma_{max}^{B} \qquad (1)$$

where γ_{max} was the maximum expected binder strain for a given pavement structure and the coefficients A and B were calculated from the parameters in the C-D curve equation, from the LVE parameter α and from the damage at failure D_f, i.e. the D value in correspondence of the peak in the τ vs γ curve. As suggested by Teymourpour & Bahia (2014), the LAS test (both frequency sweep and amplitude sweep steps) were carried out at a temperature which allowed an initial $|G^*|$ value between 10 and 60 MPa to be achieved, to avoid bulging of adhesive issues in the sample. To comply with this indication, the test temperature was fixed to 15 °C. For each material, 3 test repetitions were carried out.

Result analysis

Identification of LVE region

Table 3 and Figure 1 show the results of the strain sweep tests for the 3 recovered bitumens and allow the threshold of LVE region, γ_{lim}, to be identified. The lowest width of the LVE region was found for LMEB at the temperature of 5 °C, with a γ_{lim} = 0.78%. Therefore, the strain value γ =0.2% (about one third of the minimum γ_{lim} value) was selected for frequency sweep test implementation.

Procedure for LVE analysis and modelling

The measured rheological data were plotted in the Black and Cole-Cole diagrams to evaluate the reliability of the experimental results, assess the time-temperature equivalency and thermo-rheologically simplicity for the tested bitumens, estimate the magnitude of the glassy asymptote and the preponderance of the viscous or elastic behaviour at the different temperatures investigated (Lesueur et al., 1996).

As shown in the following sections, all the recovered bitumens were considered as thermo-rheologically simple and the time-temperature superposition principle (TTSP) was applied to determine complex modulus master curves and shift factor relationships. The rheological data were shifted with respect to time until the isothermal curves merge into a single smooth function at the reference temperature of 34 °C. The estimation of the temperature shift factors was carried out according to the closed form shifting algorithm (Gergesova et al., 2011), based on the minimization of the area between two successive isothermal curves. The 2S2P1D model (Olard & Di Benedetto, 2003) was applied to simulate the rheological behaviour of the binders, while the Williams-Landel-Ferry (WLF) law (Ferry, 1980) was used to model the shift factor trend with temperature. The

2S2P1D model includes a linear dashpot in series with two parabolic elements and with the spring of stiffness G_∞ - G_0 assembled in parallel with a second spring (G_0) (Figure 2).

In detail, according to the 2S2P1D model, the equation for complex modulus is given by Equation (2)

$$G^*(i\omega\tau) = G_0 + \frac{G_\infty - G_0}{1+\delta(i\omega\tau)^{-k}+(i\omega\tau)^{-h}+(i\omega\tau\beta)^{-1}} \quad (2)$$

where G_0 is the static shear modulus when $\omega \to 0$ ($G_0 = 0$ for binders); G_∞ is the glassy shear modulus when $\omega \to \infty$; $\omega = 2\pi f$ is the angular frequency; i is the imaginary unit defined by $i^2 = -1$; τ is the characteristic time; k, h and δ are dimensionless parameters such that $0 < k < h < 1$; β is a function of the dashpot viscosity η such that $\eta = (G_\infty - G_0)\beta\tau$. Based on the TTSP, τ can be determined as in Equation 3:

$$\tau(T) = a_T \cdot \tau_0 \quad (3)$$

where a_T is the shift factor at the temperature T and $\tau_0 = \tau(T_0)$ is determined at the reference temperature T_0. The temperature shift factors can be obtained using the Williams-Landel-Ferry (WFL) equation for bituminous materials (Equation 4):

$$log\frac{a_T(T)}{a_T(T_0)} = -\frac{C_1(T-T_0)}{C_2+(T-T_0)} \quad (4)$$

where a_T is the shift factor at temperature T, T_0 is the reference temperature, C_1 and C_2 are empirical constants.

Rheological behaviour

Figures 3 and 4 depict the rheological data measured through frequency sweep tests in the Black ($|G^*|$ vs ϕ) and Cole-Cole (G_2 vs G_1) diagrams. From the Black diagram, the variability of $|G^*|$ and ϕ can be observed. In particular, $|G^*|$ ranged between 483 Pa and 110.5 MPa for EB, between 955.5 Pa and 80.3 MPa for LMEB, between 3115 Pa and 91.3 MPa for EPMB. The phase angle ϕ ranged between 27.6° and 87.6° for EB, between 28.9° and 80.0° for LMEB, between 24.5° and 64.4° for EPMB.

To assess the validity of the TTSP and thus the thermorheologically simple behaviour, the G^* values measured at different frequencies and temperatures should align on a single smooth curve when plotted in the Black and Cole-Cole diagrams. The results in Figures 3 and 4 confirmed the validity of the TTSP for all the tested bitumens. This is an important finding, especially for LMEB and EPMB, because they are characterized by the presence of polymers.

The Black and Cole-Cole diagrams already highlighted the different rheological behaviour of the tested bitumens. In particular, EB showed the typical trend of a neat bitumen, with G^* uniformly moving from a purely viscous ($|G^*| = 0$, $\phi = 90°$) to a purely elastic ($|G^*| \approx 1$ GPa, $\phi = 0°$) behaviour when decreasing temperature or increasing frequency. Differently, EPMB curves were positioned on the left and below EB curves in the Black and Cole-Cole diagrams, respectively, denoting a higher relevance of elastic component to detriment of the viscous component. The LMEB bitumen showed an intermediate behaviour between EB and EPMB.

Figures 5 and 6 show the master curves of $|G^*|$ and ϕ at the reference temperature of 34 °C. From Figure 5 it can be noted that at low frequencies/high temperatures EPMB gave the highest $|G^*|$, approximately 6 times that of EB and 3 times that of LMEB. Differently, at high frequencies/intermediate-low temperatures the stiffness values were comparable between the different bitumens. In detail, a slightly higher $|G^*|$ was observed for EB with respect for LMEB and EPMB, which provided almost identical values.

From Figure 6 it can be observed that EPMB had the lowest phase angle at all frequencies/temperatures, indicating that this bitumen is characterized by the most emphasized elastic features. At low frequencies/high temperatures EPMB and LMEB showed a plateau in the phase angle master curves, indicating that the polymer modification over a certain T (or below a certain f) inhibited the viscous behaviour yielding some elastic features to the binder. By continuing increasing *T*/reducing *f*, ϕ values seemed to tend again towards 90° for both LMEB and EPMB (more slowly for this latter). On the left side of ϕ master curves, LMEB provided an intermediate behaviour between EB (markedly viscous) and EPMB (more elastic), while on the right side (high frequencies/intermediate-low temperatures) LMEB showed a higher viscosity, slightly greater than that of EB. This was maybe related to the physical dispersion of the SBR-latex within the binder matrix. The presence of a continuous film of polymer covering bitumen droplets (Forbes et al., 2001) probably allowed a higher molecule mobility, at low temperatures, than in the case of EB or EPMB, where the continuous phase was constituted by bitumen (or polymer-modified bitumen).

In general, it is interesting to observe that the rheological behaviour of LMEB was closer to that of EB than to that of EPMB, in spite of its polymer content which is slightly lower (3.3% vs 4.0%). This indicates that the complex modulus of the polymer-modified BE depends not only on the content but also on the type of modifier and in particular on the modification process, which entails a different morphology of the bitumen chemical structure (Forbes et al., 2001).

In Figures 5 and 6 the experimental data are superimposed to the curves of 2S2P1D model. According to Di Benedetto et al., (2004), the model was calibrated by minimizing the sum of the squared difference between measured and simulated complex modulus, declined in its storage and loss components (Equation 5).

$$\sum_{i=1}^{N}\left(\left(G_{1,meas}(\omega_i)-G_{1,model}(\omega_i)\right)^2+\left(G_{2,meas}(\omega_i)-G_{2,model}(\omega_i)\right)^2\right) \quad (5)$$

Both the $|G^*|$ and ϕ plots prove that the 2S2P1D model well simulated the experimental data, even the plateau in the phase angle master curves of LMEB and EPMB.

Table 4 shows the parameters of 2S2P1D and WLF models. The graphical comparison between the model parameters is provided in Figure 7. The analysis also included Glower-Rowe parameter, which characterizes the stiffness and relaxation properties of a bitumen (King et al., 2012) and assumes higher values when increasing brittleness. According to Rowe et al., (2014), this parameter can be calculated from DSR data using the following Equation 6:

$$GR = \frac{|G^*| * (\cos \phi)^2}{\sin \phi} \tag{6}$$

where $|G^*|$ and ϕ are the stiffness modulus and phase angle at the temperature of 15 °C and angular frequency of 0.005 rad/s deduced from the 2S2P1D model.

The results showed that the parameters k and h, which represent the order of derivation of the two parabolic elements included in the 2S2P1D model, were comparable between the different recovered bitumens. Likewise, also the characteristic time τ_0 was similar for EB, LMEB and EPMB. Differently, the parameters δ and β increased when moving from EB, to LMEB, to EPMB. The parameter δ is a positive non dimensional coefficient balancing the contribution of the first parabolic element in the global behaviour. The higher values of δ measured for the recovered bitumens from polymer-modified BE reflected the lower height of the pinnacle point of the curves in the Cole-Cole diagram, so denoted higher elastic features, in particular for EPMB. The parameter β is a function of the dashpot viscosity ($\eta = G_\infty \beta \tau$) and was found to be associated with asphaltene (polar molecules) content (Yusoff et al., 2013). The higher values of β obtained for LMEB and EPMB indicated the tendency of $|G^*|$ and ϕ master curves to reach more slowly the equilibrium values of 0 Pa and 90°, i.e. to preserve a stiff and elastic behaviour at high temperatures. The GR parameter resulted higher for the recovered bitumens from polymer-modified BE than for EB. In particular, it was the highest for EPMB. This result was due to the higher |G*| and lower ϕ values and did not indicate a higher brittleness but the predominance of the elasticity over viscosity. In addition, all the *GR* values were far from the limit of 180 kPa, recognized by Rowe et al., (2014) as the threshold over which there can be damage onset. Finally, the WLF parameters C_1 and C_2 slightly increased when passing from EB to LMEB, to EPMB, but the comparable values of the ratio C_2/C_1 denoted a similar temperature sensitivity for the recovered bitumens.

Results of the MSCR tests

Figures 8 and 9 show the results from MSCR tests in terms of average non-recoverable creep compliance (J_{nr}) and average percent recovery (R) at three test temperatures (28, 34 and 40 °C) and two different creep stresses (0.1 and 3.2 kPa).

From the graphs it can be observed that, in the investigated intervals, EB and LMEB were poorly dependant on the creep stress but had different J_{nr} and R as a function of test temperature. On the contrary, EPMB exhibits the same behaviour when varying temperature and creep stress, especially in relation to the J_{nr} parameter.

The EB binder manifested the worst behaviour against permanent deformations, since J_{nr} was higher (i.e. it accumulated a greater deformation with the loading cycles) and R was lower (i.e. the material had a very low recovery during the rest period) with respect to the polymer-modified BE. Instead, the EPMB had very good resistance against permanent deformations and showed a high elasticity, thanks to the low J_{nr} and high R. This material was able to accumulate very little deformation during the loading cycles and also had a very high recovery during unloading. Finally, the rutting resistance of LMEB was intermediate between the other bitumens, since it had lower J_{nr} / higher R compared to EB, but higher J_{nr} / lower R with respect to EPMB.

To summarize, it was possible to draw up a ranking with respect to the behaviour against permanent deformations, where the material that performed best was certainly EPMB, followed by LMEB and finally EB. As in the case of the rheological behaviour, this result was probably due to the higher polymer content in EPMB compared to LMEB, but also to the different blending process. In fact, the slight difference in the modifier dosage (4.0% for EPMB, 3.3% for LMEB) did not reflected on a similarly slight difference in the mechanical behaviour observed during MSCR test, as the measured J_{nr} and R for LMEB were very close to the average of the values measured for EB and EPMB, at all the investigated temperatures and creep stresses.

Damage behaviour of the recovered bitumens

The damage behaviour of the bitumens recovered from BE was investigated by LAS tests. The frequency sweep tests preliminarily carried out on the undamaged bitumen samples showed complex moduli comparable to those measured in the LVE analysis. In particular, $|G^*|$ values of about 15 MPa were determined for all the bitumens at $T = 15$ °C and $f = 5$ Hz (confirming the good choice of the test temperature).

Figure 10 shows the shear stress τ measured during LAS test for the different recovered bitumens as a function of the shear strain γ. From the graph it can be noticed that EB had the highest peak of τ but, after sample failure (peak of the τ vs γ curves), the stress necessary to achieve the target strain quickly decreased and tended to 0 Pa. The behaviour of the recovered bitumens from polymer-modified BE was very different. EPMB had slightly lower peaks of τ with respect to EB, but the reduction of the stress after failure was very slow. Even at the end of the test, for $\gamma = 30\%$, rather high shear stresses (approximately 50% of the peak values) were necessary to apply the imposed strain. This indicated that, even after failure, the material had a high reserve of energy to withstand the test stresses. LMEB showed a higher sample-to-sample variability in the output of the test, but the general trend was easily identified as peculiarly different from the others. In fact, the peak value of τ for LMEB was the lowest (less than a half of the average peak value of EB) but, as EPMB, it showed a slow decrease of stress after the peak, denoting a good ability to tolerate further cycles after the sample failure.

Figure 11 shows the damage curves, which depict the reduction of the normalized complex modulus C (ratio of $|G^*|$ at the i-th cycle and $|G^*|$ at the 1st cycle) when increasing the damage intensity D. The C vs D curves determined through VECD model confirmed the indications obtained from τ vs γ curves. For low D values, EB slowly decreased its stiffness when increasing damage, as a consequence of the higher strength (higher peak of τ). However, the curve of EB did not tend to flatten thus, when continuing the sample stressing and damage increasing, C rapidly went to zero. Differently, LMEB and EPMB curves quickly decreased for low D values, but the slope gradually decreased and for high damages the bitumens from polymer-modified BE demonstrated to still have a certain stiffness. Between the two, EPMB seemed to have the best resistance to damage, as the C values were always higher than for LMEB under the same damage and also the slope of the curve was lower, indicating that the higher performance was also enhanced for high damage values.

Figure 12 shows the fatigue parameters calculated from LAS test. In particular, the parameters A and α are considered good indicators of the behaviour of a binder under repeated stresses: according to Hintz et al., (2011), the bitumen with a good resistance to fatigue is characterized by a high value of A (which indicates the fatigue life of the binder at 1% strain amplitude) and a low value of α (which is a measure of strain susceptibility of the binders, i.e., the rate of reduction in fatigue life with increase in strain). From the graph on the left of Figure 12 it can be observed that α was higher for LMEB and EPMB than for EB. However, like for the β value in 2S2P1D model, this result was probably related to the higher elasticity of the material and did not represent a negative issue for the fatigue behaviour. Indeed, a higher value of α in the case of polymer-modified bitumens was noted by Saboo et al., (2018) in similar temperature conditions. Differently, the value of A noticeably increased when moving from EB to LMEB, to EPMB, indicating a significantly higher performance against fatigue. This was confirmed by the graph on the right of Figure 12, which shows the values of N_f calculated through Equation 1 for strains γ_{max} of 2.5% and 5.0%. The simulation suggested that the binders from polymer-modified BE could withstand a noticeably higher number of cycles before failure for both the strain levels. Respectively, N_f for LMEB and EPMB were approximately 2 and 7 times that of EB at γ_{max} = 2.5%, on average. At γ_{max} = 5%, the average N_f for LMEB and EPMB were approximately 1.5 and 4 times that of EB. The fatigue life at γ_{max} = 2.5% has to be considered more significant for these binders, since CMB are used in base or subbase layers and are typically subjected to low strain amplitudes. Since the bitumen stiffness $|G^*|$ at the beginning of the test was comparable, this result was not related to how the sample was tested and, thus, to how the binder will operate in its service life (control-stress or control-strain), but highlighted how the presence of elastic polymers in the binder allowed achieving a greater resistance to fatigue. The better performance of EMPB with respect to LMEB indicated that this effect was enhanced in the case of higher polymer content and pre-blending processing.

Conclusions

The present study aimed at comparing the binders recovered from different bitumen emulsions for cold mixtures: a reference over-stabilized BE and two polymer-modified emulsions, including SBR-latex (post-blending) and SBS (pre-blending), analogous according to Italian national standards. The investigation included the analysis of the rheological behaviour, the LVE modelling and the evaluation of the resistance to permanent deformation and damage.

On the basis of the results shown in the main body of the paper, the following conclusions can be drawn:

- All the recovered bitumens showed a thermorheologically simple behaviour, which could be well simulated through 2S2P1D model.
- At low frequencies/high temperatures, EPMB had the highest $|G^*|$ and lowest ϕ values, denoting a higher elasticity, while LMEB had intermediate properties between EPMB and EB. At high frequencies/intermediate-low temperatures, the $|G^*|$ values were comparable between the different bitumens, while ϕ was lower for EPMB than for EB and LMEB, which presented similar viscous features.
- In general, the complex modulus of LMEB was closer to that of EB than to that of EPMB, in spite of its polymer content which was slightly lower (3.3% vs 4.0%). This was probably a consequence of the different modification process, which entails a different morphology of the bitumen chemical structure.
- The parameters k, h and τ_0 of the 2S2P1D model were comparable between the different recovered bitumens, while δ and β increased when moving from EB, to LMEB, to EPMB, reflecting an increase in the elastic features over the viscous ones. Likewise, also the GR parameter resulted higher for the recovered bitumens from polymer-modified emulsions than for EB, due to the predominance of the elasticity over viscosity.
- The MSCR tests showed that EPMB had the best performance against permanent deformation, followed by LMEB and finally EB. As in the case of the rheological behaviour, this result was probably due to the higher polymer content in EPMB compared to LMEB, but also to the different blending process, since the measured

J_{nr} and R for LMEB were very close to the average of the values measured for EB and EPMB, at all the investigated temperatures and creep stresses.

- The LAS test results showed different properties of the recovered bitumens against damage. From the τ vs γ curves it was observed that EPMB and LMEB had a reserve of energy against the imposed strain after the sample failure, while the curves of EB quickly decreased and tended to 0 Pa after overtaking the peak. The C vs D curves showed that EB had a higher performance for low damage levels whereas, when increasing damage, EPMB and LMEB had a better behaviour. The analysis of the fatigue parameters indicated that LMEB and especially EPMB, thanks to their elasticity, had a higher resistance against repeated cycles than EB.

The previously described findings confirm that the polymer-modified bitumen emulsions for CMB allow achieving a better performance than unmodified emulsions in terms of rheological behaviour and resistance to permanent deformation and damage. In addition, the results show that, even if the two commercial products are equivalent according to Italian national standards, the bitumen emulsion modified with SBS through pre-blending process has better properties against rutting and fatigue. Future developments of the research will focus on evaluating the characteristics of these binders after ageing and validating the performance at mastic and mixture level.

References

AASHTO TP 101-14. (2014). *Standard Method of Test for Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep*.

Abedini, H., Naimi, S., & Abedini, M. (2017). Rheological properties of bitumen emulsion modified with NBR latex. *Petroleum Science and Technology*, *35*(15), 1576–1582. https://doi.org/10.1080/10916466.2017.1319386

Abedini, M., Hassani, A., Kaymanesh, M. R., & Yousefi, A. A. (2016). The rheological properties of a bitumen emulsion modified with two types of SBR latex. *Petroleum Science and Technology*, *34*(17–18), 1589–1594. https://doi.org/10.1080/10916466.2016.1214600

Abedini, M., Hassani, A., Kaymanesh, M. R., Yousefi, A. A., & Abedini, H. (2020). Multiple Stress Creep and Recovery Behavior of SBR-Modified Bitumen Emulsions. *Journal of Testing and Evaluation*, *48*(4), 20180031. https://doi.org/10.1520/jte20180031

Al-Merzah, S., Al-Busaltan, S., & Nageim, H. A. (2019). Characterizing Cold Bituminous Emulsion Mixtures Comprised of Palm Leaf Ash. *Journal of Materials in Civil Engineering*, *31*(6). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002714

Bocci, E., Graziani, A., & Bocci, M. (2020). Cold In-place Recycling for a Base Layer of an Italian High-Traffic Highway. In *Lecture Notes in Civil Engineering* (Vol. 48). https://doi.org/10.1007/978-3-030-29779-4_31

Bocci, M., Canestrari, F., Grilli, A., Pasquini, E., & Lioi, D. (2010). Recycling Techniques and Environmental Issues Relating to the Widening of an High Traffic Volume Italian Motorway. *International Journal of Pavement Research and Technology*, *3*(4), 171–177. https://doi.org/10.1017/CBO9781107415324.004

Buczyński, P., & Iwański, M. (2017). Fatigue Life Comparison of Recycled Cold Mixes with Foamed Bitumen and with Bitumen Emulsion. *Procedia Engineering*, *172*, 135–142. https://doi.org/10.1016/j.proeng.2017.02.035

Carrera, V., Cuadri, A. A., García-Morales, M., & Partal, P. (2014). The development of polyurethane modified bitumen emulsions for cold mix applications. *Materials* *and Structures/Materiaux et Constructions*, *48*(10), 3407–3414. https://doi.org/10.1617/s11527-014-0408-2

Cuadri, A. A., Roman, C., García-Morales, M., Guisado, F., Moreno, E., & Partal, P. (2016). Formulation and processing of recycled-low-density-polyethylene-modified bitumen emulsions for reduced-temperature asphalt technologies. *Chemical Engineering Science*, *156*, 197–205. https://doi.org/10.1016/j.ces.2016.09.018

Delmar R. Salomon. (2006). Asphalt Emulsion Technology. *TRANSPORTATION RESEARCH CIRCULAR E-C102, August*. https://doi.org/10.17226/23246

Di Benedetto, H., Sauzéat, C., Delaporte, B., & Olard, F. (2004). Linear viscoelastic behaviour of bituminous materials: From binders to mixes. *Road Materials and Pavement Design*, *5*(December 2014), 163–202. https://doi.org/10.1080/14680629.2004.9689992

Dulaimi, A., Shanbara, H. K., & Al-Rifaie, A. (2020). The mechanical evaluation of cold asphalt emulsion mixtures using a new cementitious material comprising ground-granulated blast-furnace slag and a calcium carbide residue. *Construction and Building Materials*, *250*. https://doi.org/10.1016/j.conbuildmat.2020.118808

EN 12848. (2009). *Bitumen and bituminous binders - Determination of mixing stability with cement of bitumen emulsions*.

EN 13074-1. (2019). *Bitumen and bituminous binders - Recovery of binder from bituminous emulsion or cut-back or fluxed bituminous binders. Part 1: Recovery by evaporation*.

EN 13808. (2013). *Bitumen and bituminous binders - Framework for specifying cationic bituminous emulsions*.

EN 14770. (2012). *Bitumen and bituminous binders - Determination of complex shear* *modulus and phase angle - Dynamic Shear Rheometer (DSR)*.

EN 16659. (2016). *Bitumen and Bituminous Binders - Multiple Stress Creep and Recovery Test (MSCRT)*.

Ferry, J. D. (1980). *Viscoelastic Properties of Polymers, 3rd Edition*.

Forbes, A., Haverkamp, R. G., Robertson, T., Bryant, J., & Bearsley, S. (2001). Studies of the microstructure of polymer-modified bitumen emulsions using confocal laser scanning microscopy. *Journal of Microscopy*, *204*(3), 252–257. https://doi.org/10.1046/j.1365-2818.2001.00955.x

Gergesova, M., Zupančič, B., Saprunov, I., & Emri, I. (2011). The closed form t-T-P shifting (CFS) algorithm. *Journal of Rheology*, *55*(1), 1–16. https://doi.org/10.1122/1.3503529

Godenzoni, C., Bocci, M., & Graziani, A. (2017). Rheological characterization of cold bituminous mastics produced with different mineral additions. *Transport Infrastructure and Systems - Proceedings of the AIIT International Congress on Transport Infrastructure and Systems, TIS 2017*, (2015), 185–191. https://doi.org/10.1201/9781315281896-26

Grilli, A., Cardone, F., & Bocci, E. (2018). Mechanical behaviour of cement-bitumen treated materials containing different amounts of reclaimed asphalt. *European Journal of Environmental and Civil Engineering*, *22*(7), 836–851. https://doi.org/10.1080/19648189.2016.1219972

Hintz, C., Velasquez, R., Johnson, C., & Bahia, H. (2011). Modification and validation of linear amplitude sweep test for binder fatigue specification. *Transportation Research Record*, (2207), 99–106. https://doi.org/10.3141/2207-13

Jiang, J., Ni, F., Zheng, J., Han, Y., & Zhao, X. (2018). Improving the high-temperature performance of cold recycled mixtures by polymer-modified asphalt emulsion.

International Journal of Pavement Engineering, *21*(1), 41–48. https://doi.org/10.1080/10298436.2018.1435882

Khadivar, A., & Kavussi, A. (2013). Rheological characteristics of SBR and NR polymer modified bitumen emulsions at average pavement temperatures. *Construction and Building Materials*, *47*, 1099–1105. https://doi.org/10.1016/j.conbuildmat.2013.05.093

Khan, A., Redelius, P., & Kringos, N. (2016). Toward a new experimental method for measuring coalescence in bitumen emulsions: A study of two bitumen droplets. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *494*, 228–240. https://doi.org/10.1016/j.colsurfa.2016.01.045

King, G., Anderson, M., Hanson, D., & Blankenship, P. (2012). Using black space diagrams to predict Age-induced cracking. *RILEM Bookseries*, *4*, 453–463. https://doi.org/10.1007/978-94-007-4566-7_44

Lesueur, D. (2011). Polymer modified bitumen emulsions (PMBEs). In *Polymer Modified Bitumen*. https://doi.org/10.1016/B978-0-85709-048-5.50002-X

Lesueur, Didier, Gerard, J., Claudy, P., Letoffe, J., Planche, J., & Martin, D. (1996). A structure-related model to describe asphalt linear viscoelasticity. *Journal of Rheology*, *40*(5), 813–836. https://doi.org/10.1122/1.550764

Li, R., Leng, Z., Zhang, Y., & Ma, X. (2019). Preparation and characterization of waterborne epoxy modified bitumen emulsion as a potential high-performance cold binder. *Journal of Cleaner Production*, *235*, 1265–1275. https://doi.org/10.1016/j.jclepro.2019.06.267

Marasteanu, M. O., & Clyne, T. R. (2006). Rheological characterization of asphalt emulsions residues. *Journal of Materials in Civil Engineering*, *18*(3), 398–407. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:3(398)

Olard, F., & Di Benedetto, H. (2003). General “2S2P1D” Model and Relation Between the Linear Viscoelastic Behaviours of Bituminous Binders and Mixes. *Road Materials and Pavement Design*, *4*(2), 185–224. https://doi.org/10.1080/14680629.2003.9689946

Pan, C., Liang, D., Mo, L., Riara, M., & Lin, J. (2019). Influence of different modifiers on bonding strength and rheological performance of bitumen emulsion. *Materials*, *12*(15). https://doi.org/10.3390/ma12152414

Querol, N., Barreneche, C., & Cabeza, L. F. (2019). Asphalt emulsion formulation: State of the art of formulation, properties and results of HIPR emulsions. *Construction and Building Materials*, *212*, 19–26. https://doi.org/10.1016/j.conbuildmat.2019.03.301

Ronald, M., & Luis, F. P. (2016). Asphalt emulsions formulation: State-of-the-art and dependency of formulation on emulsions properties. *Construction and Building Materials*, *123*, 162–173. https://doi.org/10.1016/j.conbuildmat.2016.06.129

Rowe, G. M., King, G., & Anderson, M. (2014). The Influence of Binder Rheology on the Cracking of Asphalt Mixes in Airport and Highway Projects. *Journal of Testing and Evaluation*, *42*(5), 20130245. https://doi.org/10.1520/jte20130245

Ruggles, C. S. (2004). The efficient use of environmentally-friendly natural rubber latex in road construction–Past, present and future. *Rubber in Transport*, 9–12.

Saboo, N., Kumar, R., Kumar, P., & Gupta, A. (2018). Ranking the rheological response of SBS- and EVA-modified bitumen using MSCR and LAS tests. *Journal of Materials in Civil Engineering*, *30*(8). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002367

Sangiorgi, C., Tataranni, P., Simone, A., Vignali, V., Lantieri, C., & Dondi, G. (2017). A laboratory and filed evaluation of Cold Recycled Mixture for base layer entirely made with Reclaimed Asphalt Pavement. *Construction and Building Materials, 138*, 232–239. https://doi.org/10.1016/j.conbuildmat.2017.02.004

Shafii, M., Abdul Rahman, M., & Ahmad, J. (2011). Polymer modified asphalt Emulsion. *International Journal of Civil & Environmental Engineering*, *11*(6).

Shafii, M., Ahmad, J., & Shaffie, E. (2013). Physical properties of asphalt emulsion modified with natural rubber latex. *World Journal of Engineering*, *10*(2), 159–164. https://doi.org/10.1260/1708-5284.10.2.159

Stimilli, A., Ferrotti, G., Graziani, A., & Canestrari, F. (2013). Road Materials and Pavement Design Performance evaluation of a cold-recycled mixture containing high percentage of reclaimed asphalt Performance evaluation of a cold-recycled mixture containing high percentage of reclaimed asphalt. *Road Materials and Pavement Design*, *14*(S1), 149–161. https://doi.org/10.1080/14680629.2013.774752

Tadros, T. F. (2013). Emulsion Formation, Stability, and Rheology. *Emulsion Formation and Stability*, 1–75. https://doi.org/10.1002/9783527647941.ch1

Takamura, K., & Lubbers, C. (2000). Comparison of Emulsion Residues Recovered by Forced Airflow and RTFO Drying. *2000 ISSA/AEMA Proceedings*, 1–17.

Teymourpour, P., & Bahia, H. (2014). Linear Amplitude Sweep Test: Binder Grading Specification and Field Validation. *Binder Expert Task Group Meeting*.

Waters, J. C., Bosma, G. M., & Herrington, P. R. (2008). *Residual Binder Extraction from Emulsions for Quality Assurance Testing*.

Xiao, F., Yao, S., Wang, J., Li, X., & Amirkhanian, S. (2018). A literature review on cold recycling technology of asphalt pavement. *Construction and Building Materials*, *180*, 579–604. https://doi.org/10.1016/j.conbuildmat.2018.06.006

Yusoff, N. I. M., Mounier, D., Marc-Stéphane, G., Rosli Hainin, M., Airey, G. D., & Di

Benedetto, H. (2013). Modelling the rheological properties of bituminous binders using the 2S2P1D Model. *Construction and Building Materials*, *38*, 395–406. https://doi.org/10.1016/j.conbuildmat.2012.08.038

Zhang, R., & HE, Y. (2007). An Asphalt Emulsion Modified by Compound of Epoxy Resin and Styrene-Butadiene Rubber Emulsion. *Test*, *1*(4), 292–298.