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Effect of foaming technique and mixing temperature on the rheological characteristics of fine RAP-foamed bitumen mixtures

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Effect of foaming technique and mixing temperature on the rheological characteristics of fine RAP-Foamed Bitumen Mixtures

This paper evaluates and compares the differences in the rheological characteristics of the fine aggregate matrix (FAM) portion of plant produced Foamed Bitumen Mixtures (FBMs) by means of a mechanical foaming process, and by the incorporation of zeolites in combination with Reclaimed Asphalt Pavement (RAP) material. This evaluation explores, for the first time, the impact of plant production variations for half-warm, warm and hot processes (i.e. mixing temperatures around 90, 120 and 160ºC, respectively) on their rheological response. A fine Virgin-HMA, a fine HMA-RAP –no foaming technique -, and a 100% fine RAP mixture were also produced for comparison purposes. Dynamic Mechanical Analysis (DMA) tests were conducted on all evaluated FAM mixtures to determine their linear viscoelastic properties. Results indicate that the rheological response of the fine RAP-FBMs is influenced primarily by the contribution of the RAP binder in the total bitumen blend, and ageing of the fine RAP material, which were a function of the foaming technology and the production temperature of the materials.

Keywords: reclaimed asphalt pavement; foaming technologies; fine aggregate matrix; dynamic mechanic analysis; viscoelastic properties

Word count: 7630

Introduction

The use of foamed bitumen and its potential applications in road infrastructure projects dates back to the mid-1950s. The initial process developed by Csanyi (1957) was mainly used for soil and base stabilization processes and it consisted of foaming hot liquid bitumen with steam. Later, in 1968, Mobil Oil Australia acquired Csanyi's patent and modified the original foaming process. In the new process, the hot liquid bitumen was foamed by combining it with a controlled flow of cold water (rather than steam) in an expansion chamber and was delivered through a nozzle onto the aggregate mass, a process known as mechanical foaming. Foamed bitumen has lower viscosity than the same bitumen in its liquid state and an expanded volume up to 20 times its original volume, making it suitable for mixing with cold (and often damp) aggregates (Csanyi, 1957). Following the lapse in these patent rights, the use of foamed bitumen gained more acceptance by road authorities across the world, which helped spread its application (Jenkins et al., 2000). For instance, this technique has been used in the stabilization of a variety of materials (e.g. sand, gravel and crushed stone aggregates) which also include Reclaimed Asphalt Pavement (RAP) material (i.e. cold recycling), and can be applied in the construction of surface and base courses for low and heavily trafficked roads. In addition, foam bitumen has also been mixed with aggregates pre-heated at different temperatures, obtaining improved coatability and workability conditions (Bowering and Martin, 1976, Newcomb et al., 2015). The use of foamed bitumen in road construction using this technique can be applied in-place or can be accomplished in a central plant.

More recent developments in foaming technologies include the incorporation of zeolites (i.e. mineral additives that contain around 18-20% of water in their internal structure) (Corrigan, 2008). Unlike the traditional mechanical foaming technique where the foaming effect is generated by direct water injection into the bitumen, in this process water is introduced indirectly through these foaming additives to generate the foam. When the zeolites contact the heated bitumen, they release the water gradually in the form of steam, producing bubbles on the bitumen's surface (Perkins, 2009), with lower expanded volume than that produced by means of the mechanical foaming technique. This condition decreases the binder's viscosity and enhances the workability of the asphalt mixture allowing production of mixtures for warm applications (i.e. mixing temperatures 20-30^{o}C lower than typical HMA) (PQ Corporation, 2012). Zeolites can be introduced into the bitumen or in the mixing zone of a drum plant as the bitumen and aggregate are being combined.

Thus, both foaming techniques employ different mechanisms to reduce the binder’s viscosity allowing lower mixing and compaction temperatures to be used in comparison to those required for conventional Hot Mix Asphalt (HMA) materials, providing environmental and paving benefits.

This paper uses these foaming technologies, which are focused on plant-produced processes, with virgin and RAP materials. RAP material, generally obtained from milling existing distressed flexible pavements, has been regularly used as part of new or rehabilitated road structures as a means to reduce the amount of virgin bitumen and aggregates added to the final mixtures. Thus, the use of RAP is associated with lessening environmental impact and with paving cost reductions. However, concerns over the use of high amounts (i.e. more than 20-30% by mass) of this reclaimed material in new mixtures still exist due to the characteristics of the RAP bitumen. The ageing process that the RAP binder experiences during its service life can stiffen the final recycled asphalt mixture, which can lead to premature fatigue and low temperature cracking (Shah et al., 2007, West et al., 2013, Daniel et al., 2010).

Mixture modifications to account for the properties of the hardened RAP bitumen in the final mixture include the use of soft (high penetration grade) binders or the incorporation of rejuvenators. These materials aim to restore the performance properties that the aged RAP binder had before its service life by reducing its viscosity and stiffness, and increasing its ductility (Karlsson & Isacsson, 2006, Tran et al. 2012, Zaumanis et al. 2013). Nevertheless, the use of foaming techniques with these materials, will aid in compaction and workability of the recycled mixtures as well, and may reduce further oxidation of the RAP binder since lower production temperatures can be used, allowing higher percentages of RAP material to be incorporated.

In this regard, in order to select the adequate virgin bitumen grade to account for the hard RAP binder in the recycled mixtures, the European Standard EN 13108-8:2005 for reclaimed asphalt states that if the RAP content is higher than 10% of the total material used in the fabrication of new hot mixtures for surface layers, and higher than 20% for mixtures used in base layers, a logarithmic blending law for penetration and a linear blending law for softening point should be used. In this design procedure, it is assumed that all the aged bitumen present in the RAP material is available in the hot mixture, and would effectively contribute to the final blend. This fact is important because the amount of blending occurring within the mixtures containing RAP, which is affected by numerous factors such as mixing temperature, mixing time, storage, transportation and placement of the asphalt mixtures (Howard et al., 2009, Mogawer et al. 2012, Jacques et al., 2016, Karlsson and Isacsoon, 2003 and Kriz et al., 2014), influences the properties of the final mixtures and, therefore, their performance in the field.

In this sense, although the characteristics of Foamed Bitumen Mixtures (FBMs) and RAP have been widely studied, and the combination of these technologies has a great sustainable value, limited work to date has been attempted to evaluate how the particular requirements brought from the different available foaming techniques (e.g. mixing temperature, mix processing and plant design) may impact the mechanical response of the recycled mixtures. Within this context, this study aims at characterising and comparing the rheological behaviour of the fine aggregate matrix (FAM) portion of plant produced FBMs in combination with 50% fine RAP, employing the traditional mechanical foaming technique, and the incorporation of zeolite minerals. Although both foaming techniques are generally regarded as warm processes (with mechanical foaming being also widely applied in cold recycling), extended fabrication conditions in both foaming techniques for half-warm, warm and hot processes (i.e. mixing temperatures around 90, 120 and 160°C respectively) is an important unexplored variable that can influence their mechanical response. In addition, the rheological behaviour of the fine RAP-FBMs was also compared to that of a fine Virgin-HMA, a fine HMA with 50% fine RAP –no foaming technique -, and a 100% fine RAP mixture.

FAM materials are herein defined as the combination of bitumen, the fine portion of the aggregates (e.g. particles below 1mm) and air voids, which are found within the full HMA. Characterising bituminous materials at this level is important since the fine matrix is responsible for holding the structure together under loading of the asphalt mixture, and because it has been recognised that several fracture processes initiate and propagate through this matrix (Montepara et al., 2011). In addition, a main advantage of FAM materials in comparison with the full mixtures is that they have a more uniform internal structure, which contributes to the control of the experimental variability associated with the heterogeneity of the mixtures (Masad et al., 2008, Caro et al., 2008)

It is noteworthy to mention that limited studies related to RAP mixtures have been conducted by testing these FAM materials (He et al., 2016, Sánchez et al., 2017b), and only one study has evaluated fine mixtures with FBM and RAP materials (Sánchez et al., 2017a). Thus, the evaluation of RAP-FBMs at this scale is useful to obtain novel information about the effect of different foaming techniques in combination with RAP material and plant production variations, such as different mixing temperatures, on their rheological response.

FAM design and characteristics of the fine RAP-FBMs

The initial step in the design of the FAM mixtures consisted in selecting the design of the full HMA mixture which was a 0/14mm size close graded surface course based on the British Standard BS 4987-1:2005, containing 5% by mass of bitumen. A 70/100-penetration grade virgin bitumen was used. This bitumen was characterised following the BS 2000-49:2007, BS 2000-58:2007, BS 2000-505:2010, and BS 2000-80:2007 standards. According to these tests, the properties of this bitumen were 73 dmm penetration at 25°C, softening point of 46°C, rotational viscosity at 150°C of 140 mPa s, and a Fraass breaking point of −12°C, respectively.

Then, the FAM gradation was designed following the methodology proposed by Masad, et al (2006). The initial step in this method consists in normalising the full HMA gradation to the percentage passing the 1mm sieve. Figure 1 presents the gradations of the full HMA mixture and of the corresponding FAM material. To estimate the bitumen content, a theoretical approach based on the volumetric properties of the full asphalt mixture was used to determine the volume of bitumen required to coat the fine aggregate particles. The results showed that the bitumen content for the FAM materials was 10.7% by mass of the total FAM mixture. Due to the higher specific surface areas of the finer particles, this result is expected since the amount of bitumen present in FAM materials is always higher than that of the full-asphalt mixtures.

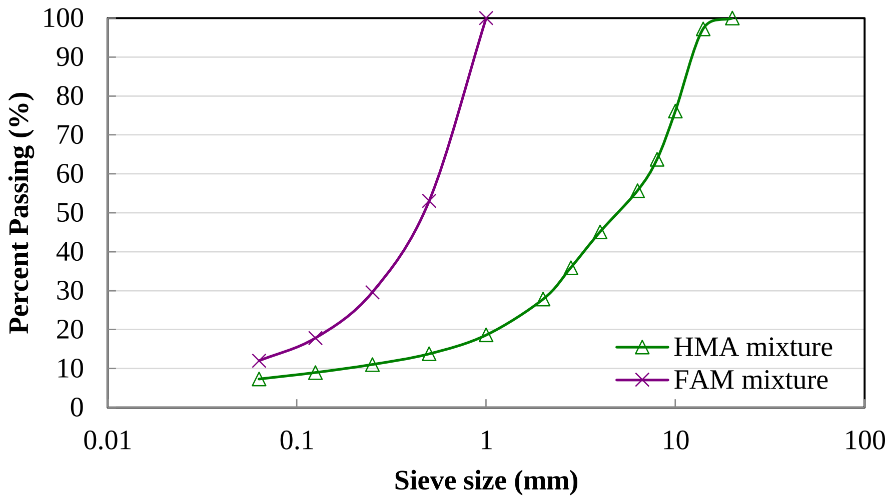


Figure 1. Gradation of the HMA mixture and the FAM materials.

As was described previously, the foamed bitumen present in the fine RAP-FBMs was produced in the laboratory by means of two foaming techniques, which include: 1) mechanical foaming, and 2) the incorporation of zeolites. In the first method, foamed bitumen was produced using the Wirtgen WLB 10 laboratory foaming plant, by adding 3% water content by mass of the asphalt binder and pressurised air to hot liquid bitumen at 160^{o}C. In the second method, zeolites were added to the bitumen in a dosage rate of 5% of zeolites by total mass of the asphalt binder, following the manufacturer's recommendation (PQ Corporation, 2012).

In both foaming techniques, the foamed bitumen was combined with fine virgin aggregates and fine RAP material that were previously subjected to three different heating conditions, and that, consequently, changed the temperature of the mixture at the end of the mixing stage to produce half-warm (i.e. fine aggregates at 90°C), warm (i.e. fine aggregates at 120°C), and hot (i.e. fine aggregates at 160^{o}C) processes.

The fine RAP material used in this study was produced in the laboratory with the aim of controlling the characteristics of its components (i.e. RAP aggregate gradation, bitumen grade, etc.), and also to reduce issues related with the variability of their properties. The laboratory procedure for fine-RAP production consisted of subjecting a loose sample of a fine Virgin-HMA mixture to a controlled artificial long-term ageing protocol in the laboratory. Initially, a virgin FAM mixture was manufactured with a mixing temperature of 160°C, with the same gradation and bitumen content described previously in this section. Then, the FAM loose mixture was subjected to an ageing protocol which consisted of exposing the FAM loose mixture to heat in the oven for 32h at 105°C, as suggested by Oke (2011), who conducted a comprehensive study that demonstrated the feasibility of this method to reproduce RAP material in the laboratory. Once the fine RAP material was produced, the bitumen was recovered by distillation following the BS EN 12697-4:2005 and it was characterised following the same tests as for the bitumen present in the fine Virgin-HMA mixture. According to these tests, the properties of the bitumen extracted from the RAP were 38 dmm penetration at 25°C, softening point of 53°C, rotational viscosity at 150°C of 217 mPa s, and a Fraass breaking point of −5°C.

Thus, a total of nine fine mixtures were manufactured in the laboratory including three fine FBMs produced by the mechanical foaming technique plus fine RAP material (Mechanical foamed-RAP), three fine FBMs containing zeolites plus fine RAP material (Zeolite-RAP), and three fine control mixtures which include: 1) a fine HMA mixture containing 50% fine RAP material, with no foaming technology labelled as 'HMA-RAP', 2) a FAM mixture made with 100% fine RAP material labelled as '100%-RAP', and 3) a virgin FAM mixture - no RAP material, no foaming technology, labelled as 'Virgin-HMA'. All control fine mixtures were manufactured at 160°C. The control Virgin-HMA fine mixture was fabricated using a 70/100-penetration grade bitumen, with the properties described previously in this section.

For the Mechanical foamed-RAP fine mixtures, the bitumen was heated at 160°C in all cases for foaming purposes, while the fine virgin aggregates and fine RAP material were heated 20ºC above the mixing temperature in order to achieve the targeted mixing temperatures (i.e. 90, 120 and 160ºC). For the Zeolite-RAP fine mixtures, the virgin bitumen, the fine virgin aggregates and the fine RAP material were heated up to 90, 120 and 160ºC to achieve these target final temperatures in the final fine mixtures. For the fine mixtures containing 50%RAP, half of the components (i.e. bitumen and aggregates) of the Virgin-HMA FAM design were replaced by RAP material. Thus, the fine RAP mixtures contain the same amount of bitumen (i.e. 10.7%) and the same aggregate gradation as the fine Virgin-HMA. Based on the information presented previously, Table 1 summarizes the temperatures of the constituent materials of all fine mixtures evaluated. The amount of fine RAP material required for the 50%RAP fine mixtures was heated up to the corresponding temperature for 6 hours prior its incorporation with the virgin material. Also, in order to account for the stiffened RAP bitumen present in the fine mixtures containing RAP, a soft virgin bitumen was used in these mixtures, whose properties were determined using a bitumen blending design, as explained in the next section.

Table 1. Temperature of the constituent materials for each FAM mixture.

Mixture Type	**Temperature of the Materials (ºC)**			**Mixing T (ºC)**	**Compaction T (ºC)**	**Foaming technology**
	Bitumen	**Aggregates**	**RAP**			
Virgin-HMA	160	160	-	160	140	None
HMA-RAP	160	160	160	160	140	
100% RAP	160	-	160	160	140	
Mechanical foamed-RAP-90C	160	110	110	90	80	Mechanical foaming
Mechanical foamed-RAP-120C	160	140	140	120	110	
Mechanical foamed-RAP-160C	160	180	180	160	140	
Zeolite-RAP-90C	90	90	90	90	80	Zeolites
Zeolite-RAP-120C	120	120	120	120	110	
Zeolite-RAP-160C	160	160	160	160	140	

Thus, it is worth recalling that in order to compare the impact of the foaming technique and mixing temperature on the mechanical properties of the fine RAP-FBMs, all the evaluated fine mixtures followed the same mixture design (i.e. fine gradation and binder content).

Bitumen blend design

For the fine mixtures containing 50% fine RAP, the European Standard for reclaimed asphalt (EN 13108-8:2005) was used to predict the required properties (i.e. penetration grade and softening point) of the virgin bitumen used to obtain a final fine mixture of 70/100 pen when combined with the fine RAP material. This final target penetration of the mixture (i.e. 70/100) was selected with the expectation of obtaining mixtures with equivalent penetration to the fine Virgin-HMA, so this mixture could be used as a reference mixture. In this way, the estimated penetration of the virgin bitumen was calculated by:

$$a logpen_1 + b logpen_2 = (a + b) logpen_{blend} \qquad (1)$$

where pen_1 is the penetration of the recovered bitumen from RAP; pen_2 is the penetration of the virgin bitumen, pen_{blend} is the penetration of the final bitumen blend in the mixture containing RAP, and *a* and *b* are the ratios by mass of the bitumen from the RAP and of the virgin bitumen respectively ($a + b = 1$). Similarly, the softening point of the virgin and RAP blended bitumen can be computed as:

$$T_{R\&B_{blend}} = aT_{R\&B_1} + bT_{R\&B_2} \qquad (2)$$

where $T_{R\&B_{blend}}$ is the softening point in the final bitumen blend, $T_{R\&B_1}$ is the softening point of the recovered bitumen from RAP and $T_{R\&B_2}$ is the softening point of the virgin bitumen, *a* and *b* represent the same ratios as in equation (1). Table 2 shows the properties of each component of the final bitumen blend.

Table 2. Bitumen blend design for FAM mixtures with 50% RAP content.

Bitumen	Penetration at 25ºC (dmm)	Softening point (ºC)
Virgin bitumen	141	39
Recovered bitumen from RAP	38	53
Final bitumen blend	73	46

Based on these results, a virgin bitumen of 145 dmm penetration at 25°C, softening point of 41°C, and Fraass breaking point of −13°C, was used for the soft virgin bitumen in all the fine mixtures containing 50% RAP material. Based on the previous calculations, it is expected that this virgin bitumen will be blended at a certain level with the RAP bitumen to produce a final effective binder with an equivalent 70/100 penetration.

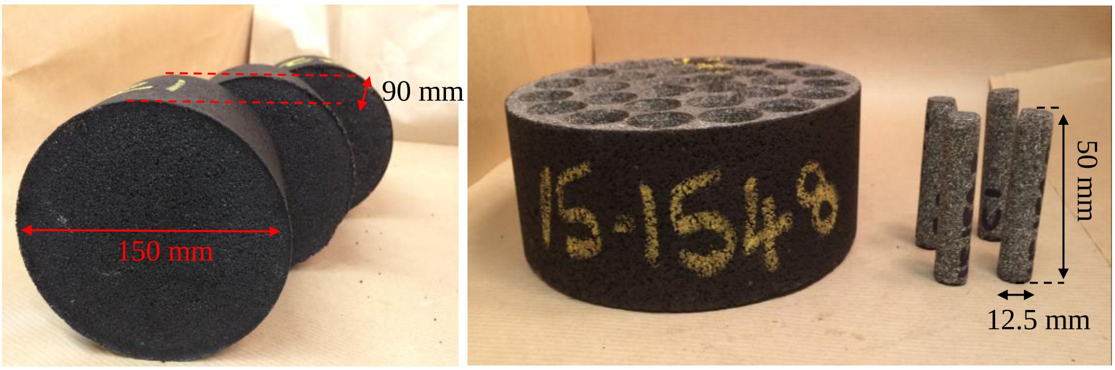
FAM mixtures mixing

For the Mechanical foamed-RAP fine mixtures, a heated mechanical mixer was adapted to the foaming unit of the Wirtgen WLB 10, as suggested in previous studies (Sunarjono, 2008, Newcomb et al., 2015), with the objective of maintaining the temperature of the fine virgin aggregates and fine RAP material (i.e. to achieve mixing temperatures of 90, 120 and 160ºC) at the time that the foamed bitumen was sprayed out from the nozzle for further mixing. Furthermore, with this foaming technique, a dynamic mixing process (i.e. aggregates spinning while foamed bitumen was squirted from the nozzle) was used in order to take advantage of the increased volume of the bitumen while in its foamed state, which lasts only a few seconds. Mixing was carried out for a duration of three minutes.

In the case of the Zeolite-RAP fine mixtures, zeolites were added at room temperature to the bitumen pre-heated at the mixing temperature (i.e. 90, 120 and 160°C), prior to its incorporation with the fine virgin heated aggregates and fine RAP material which were pre-heated at the same temperatures as the bitumen as was described previously. In this case, and for the fine Virgin-HMA, the fine HMA-50%RAP, and the fine 100% RAP mixture, hand mixing was performed for three minutes, until the fine aggregates were fully coated.

Experimental setup and sample preparation

Cylindrical specimens of 150 mm in diameter and 90 mm in height for each FAM mixture were prepared following the method proposed by Masad et al. (2006). The cylindrical FAM specimens were compacted using the Superpave Gyratory Compactor (SGC) (Figure 2a), and after compaction, the top and bottom parts of these specimens were trimmed and a coring barrel was used to extract cylindrical samples of 50 mm in height by 12.5 mm in diameter (Figure 2b). For this study, the SGC specimens were compacted following the BS EN 12697-31:2007, targeting a density of 2056 kg/m^3. It should be noted that all the fine mixtures reached the targeted values, and were workable at the various production temperatures used.



a) b)

Figure 2. Procedure for the fabrication of FAM testing specimens: a) SGC specimens 150mm in diameter, and b) FAM testing specimens' dimensions.

Since the SGC process results in different air void distribution radially along the sample, the resultant cylindrical samples contain different air void contents as well. Therefore, the specimens to be tested were carefully selected to have similar air void contents, in order to compare the impact of the components of the mixtures on their mechanical properties. Two specimens for each FAM mixture with an air void content around 8.3% were selected for testing, with differences between the two specimens of the same mixture, and among all the fine mixtures of less than 0.5, which are considered acceptable levels of variability for the purpose of this study.

The Dynamic Mechanical Analyser (DMA) testing procedure was then performed on the prepared cylindrical FAM specimens for each mixture to determine their linear viscoelastic properties. DMA is a non-standardised method that has been previously used by various researchers to characterise linear and nonlinear viscoelastic properties, and deterioration processes of these materials (Masad et al., 2006, 2008; Caro et al., 2008, 2012, Sánchez et al., 2017b). The experimental procedure consists of using a rheometer with a solid geometry to conduct frequency and temperature sweep tests using a sinusoidal strain-control torsional loading scheme to measure the corresponding shear stress response. In this way, the rheological viscoelastic properties of the mixtures can be determined. A constant strain amplitude of $6.5x10^{-3}$% was applied, a value commonly recommended in the literature to test FAM materials in their linear viscoelastic range (Caro et al., 2008, 2015; Castelo Branco, 2008; Masad et al., 2008, Sánchez et al., 2017), using loading frequencies that varied from 0.5 Hz to 15.85 Hz, and varying temperatures from 15 to 65^{o}C, with 10^{o}C increments. In this work, the tests were performed using the solid fixture configuration of a Kinexus DSR rheometer after gluing the small cylindrical specimens to some special metallic holders that permitted to set the samples in the rheometer, as shown in Figure 3.

a) b) c)

Figure 3. DMA testing configuration for FAM materials: a) FAM sample with metallic holders, upper and lower geometries ready to be slotted in the cylindrical container, b) FAM sample mounting, and c) testing.

Tests results and analysis processes

The frequency and temperature sweep test results were used to obtain the master curves of the complex shear modulus, $|G^*|$, of the materials. In addition, the effects of production temperature on the two fine RAP-FBMs groups were quantified through the shape parameters that describe the $|G^*|$ master curves following the approach described by Mensching et al. (2017). In this approach, the authors show that with an increase in RAP content or as asphalt materials age, the $|G^*|$ master curves exhibit a characteristic flattening effect which can be quantified by the slope of the master curve (γ parameter) and the inflection point position of the flattening effect (controlled by $10^{-\beta/\gamma}$), with higher values of both parameters (lower absolute values) indicating an increase in the hardness of the mixtures (Mensching et al., 2017). Thus, as the $|G^*|$ master curves for FAM materials exhibit a sigmoidal shape similar to those of the full-asphalt mixtures, the shape parameters (β and γ), were determined after fitting the $|G^*|$ master curves for both fine RAP-FBMs groups by means of the standard sigmoidal function shown below (ARA Inc., 2004):

$$\log|G^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log(\omega_r)}} \qquad (3)$$

where ω_r is the reduced frequency, and α, β, δ and γ are the fitting coefficients: δ is the lower asymptote, α is the difference between the upper and lower asymptote values, and β and γ define the shape of master curve; γ is the width of relaxation, and β the location of inflection point (the frequency of inflection point = $10^{-\beta/\gamma}$) (Rowe et al., 2009).

The following sections present the test results among the different fine mixtures that were evaluated, and analyse the impact of foaming technique and production temperature on their linear viscoelastic properties.

Rheological characteristics

The $|G^*|$ master curves in this section correspond to the average $|G^*|$ values of two replicates per mixture. Only two replicates were tested after observing low variability among the results, as also reported in previous research (Caro et al. 2015, Sánchez et al. 2017). Indeed, the difference in the $|G^*|$ values between the two replicates varied between 5.0 and 9.0%, for high frequencies (low temperatures) and low frequencies (high temperatures), respectively, which are considered accepted levels of variability following previous works conducted on FAM materials (Caro et al. 2015, Sánchez et al. 2017). Initially, Figure 4 presents the $|G^*|$ master curves at a reference temperature of 25°C for the three fine control mixtures (i.e. fine Virgin-HMA, fine HMA-RAP (no foaming technology), and fine100%RAP mixtures).

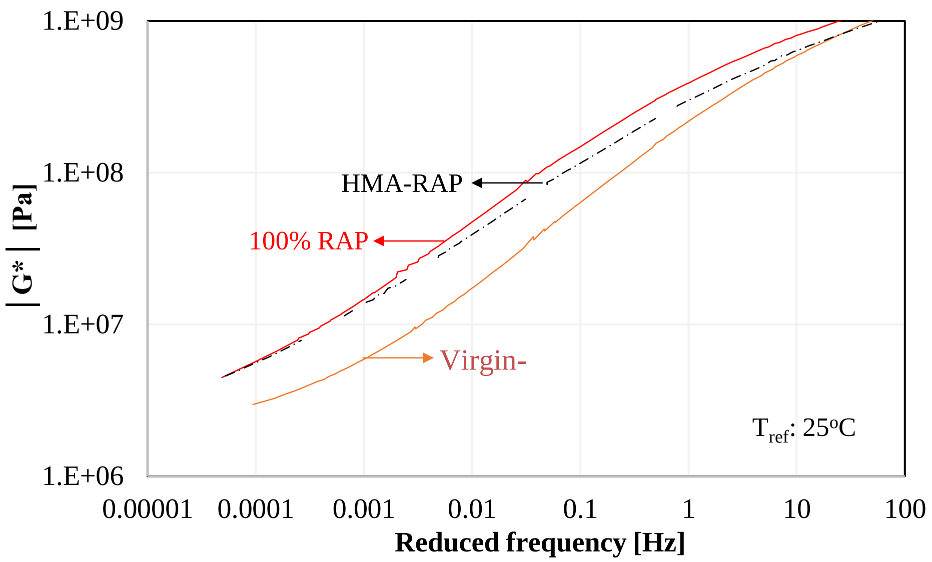
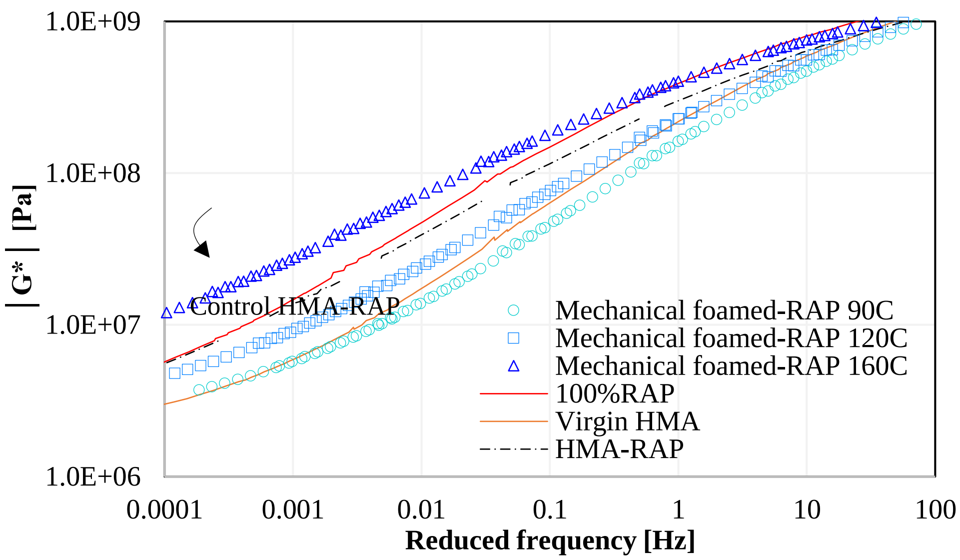


Figure 4. Evaluation of blending between RAP and virgin binders.

Figure 4 shows that the |*G**| master curve of the fine HMA-RAP mixture exhibits a closer resemblance to that of the fine 100% RAP mixture than to that of the fine Virgin-HMA, and that it exhibits a flattening effect which ends up overlapping with the fine 100%RAP master curve at low frequencies (high temperatures), and with the fine Virgin-HMA master curve at high frequencies (low temperatures). This behaviour of the fine HMA-RAP mixture suggests that complete blending between the virgin and RAP bitumen did not occur. If complete blending would have occurred, the combination of the soft virgin bitumen used for the preparation of the fine HMA-RAP mixture, and the RAP bitumen would produce a fine mixture with similar properties to that of the fine Virgin-HMA (i.e. soft virgin bitumen would have mitigated the stiffening effect of the hard RAP bitumen). However, this result shows that the behaviour of the fine HMA-RAP mixture was mostly dominated by the hard RAP bitumen and little interaction with the virgin bitumen was obtained, generating an overall increase in its stiffness. Although the fine HMA-RAP mixture (no foaming technique) did not achieve the equivalent final penetration of the blended RAP plus virgin bitumen of 70/100 pen, the study has still been able to assess the effect of foaming technique and mixing temperature on the mixtures containing RAP as explained next.

It is now important to compare the behaviour of the fine control mixtures in Figure 4, with those of the two fine RAP-FBMs groups to evaluate the effect of foaming technology and mixing temperature on their mechanical properties. These results are presented in Figure 5 with the three fine control mixtures included as lines rather than symbols.

a)



b)

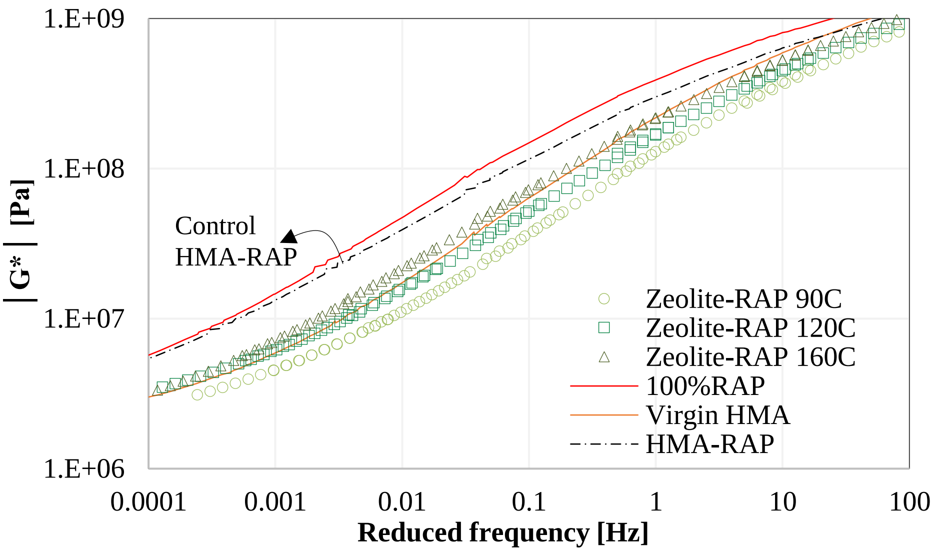


Figure 5. |G*| master curve at a reference temperature of 25°C for: a) Mechanical foamed-RAP fine mixtures, and b) Zeolite-RAP fine mixtures.

Two initial observations can be made from Figure 5: 1) both fine RAP-FBMs groups exhibit higher |G*| values with production temperature, over the range of reduced frequencies, and 2) each fine RAP-FBM exhibits an increase or decrease in the magnitude of the |G*| values with respect to those of the HMA-RAP fine mixture. Thus, the changes in the magnitude of the |G*| values were a function of the mixing temperature and foaming technology used. With the objective of better quantifying the actual effect of mixing temperature on the |G*| values of both fine RAP-FBMs groups, an example of the |G*| values for both fine RAP-FBMs groups is presented in Figure 6, at a low reduced frequency of 0.001Hz, at the reference temperature (25°C). Only the HMA-RAP fine mixture is included here, in order to evaluate the impact of foaming technique in the fine mixtures containing 50% RAP.

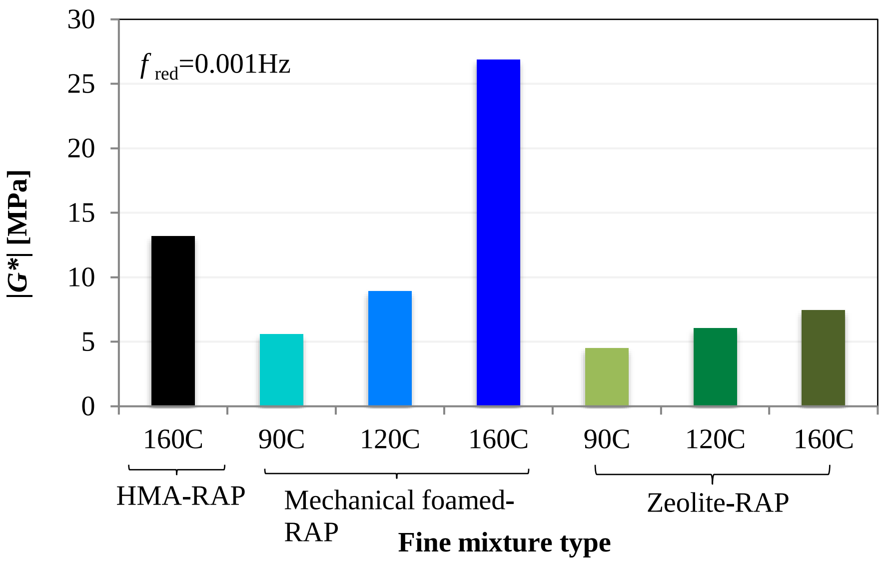


Figure 6. |G*| values for both fine RAP-FBMs groups at 0.001Hz and 25°C

Figure 6 corroborates that the |*G**| values of both fine RAP-FBMs groups increased with temperature, although the Mechanical foamed-RAP fine mixtures exhibit higher increase in their |*G**| values with temperature than the Zeolite-RAP fine mixtures. For instance, at 0.001Hz, the |*G**| values for the Mechanical foamed-RAP fine mixtures produced at of 120 and 160^{o}C increased by 60 and 381% with respect to those of the Mechanical foamed-RAP fine mixture produced at 90^{o}C. On the other hand, the |*G**| values for the Zeolite-RAP fine mixtures produced at 120 and 160^{o}C increased by 34 and 65% with respect to those of the Zeolite-RAP fine mixture produced at 90^{o}C. In all cases the |G*| values for the Mechanical foamed-RAP fine mixtures are higher than those of the Zeolite-RAP fine mixtures at the same mixing temperatures. In addition, Figure 6 shows that the Mechanical foamed-RAP fine mixture manufactured at 160^{o}C exhibits an increase in the magnitude of the |G*| values by 104% with respect to those of the fine HMA-RAP mixture. All other fine RAP-FBMs, exhibit lower |*G**| values compared to those of the HMA-RAP fine mixture.

This behaviour of the |*G**| values in the two fine RAP-FBMs groups suggests that increasing the mixing temperature affects their |*G**| values in two ways (same direction ways): (1) higher mixing temperature might have led to higher contribution of the RAP binder in the total binder and consequently |*G**| increased, and (2) the RAP binder experienced further ageing with production temperature contributing also to the increase in the stiffness of the fine mixtures.

For instance, at low mixing temperatures of 90^{o}C, only part of the RAP bitumen is likely to contribute to the total binder blend due to its high viscosity, being mainly the soft virgin bitumen which dominates the overall response of the fine mixture. At higher mixing temperatures of 120 and 160^{o}C, on the other hand, the RAP binder has undergone more ageing, and there might be higher contribution of the RAP binder in the total binder blend due to its higher viscosity, and thus higher |*G**| values. These results are in good agreement with previous studies conducted on full-asphalt mixtures that have investigated the effect of production temperature on the degree of blending of RAP and virgin binders (e.g. Howard et al. 2009, Mogawer et al. 2012, Johnson et al. 2013). Thus, it can be theorised that there is a three-component system present in these fine RAP-FBMs, and that the volumetric proportion of these components change with the mixing temperature and foaming technology used. These components consist of: 1) the soft virgin bitumen, 2) part of the hard bitumen from the RAP and, 3) the actual bitumen blend, composed of a combination of the previous two. Figure 7 shows a schematic representation to illustrate this concept.

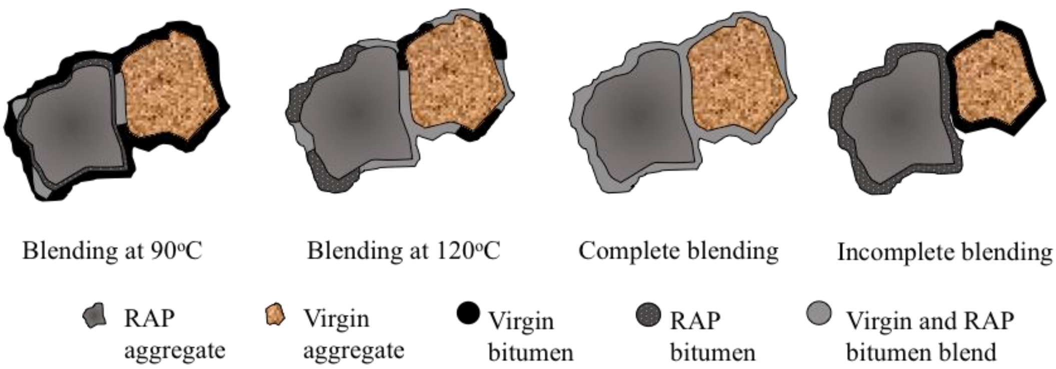


Figure 7. Schematic representation of blending between RAP-virgin binders with temperature.

Furthermore, the higher rise in the |*G**| values for the Mechanical foamed-RAP mixtures compared to those of the Zeolite-RAP fine mixtures manufactured at the same mixing temperature could be explained by further ageing of the RAP material present in the former mixtures due to the particular plant production conditions. For instance, in order to achieve the same final mixing temperatures of 90, 120 and 160°C in the two fine RAP-FBMs groups, the fine RAP material present in the Mechanical foamed-RAP fine mixtures was pre-heated at higher temperatures (110, 140 and 180°C, respectively) than that present in the Zeolite-RAP fine mixtures (i.e. fine RAP material was pre-heated at 90, 120 and 160ºC, respectively) – Table 1 –, which generates higher increase in the |*G**| values of the former fine mixtures. Similar results have been reported in previous studies conducted on full-asphalt mixtures containing 50%RAP, which found that over-heating of RAP at temperatures greater than 120ºC leads to further ageing of the bitumen present in the RAP (Yu et al., 2016). Furthermore, short term ageing in the soft virgin binder of the Zeolite-RAP fine mixtures might be occurring (i.e. soft virgin bitumen was heated at 90, 120 and 160ºC, while in the Mechanical foamed-RAP fine mixtures soft virgin bitumen was always at 160ºC despite mixing temperatures).

The increase in the |*G**| values on the two fine RAP-FBMs groups was further studied by the shape parameters (γ and -β/γ) of the corresponding |*G**| master curves, which have been plotted against each other in Figure 8. This figure also includes the shape parameters of the fine Virgin-HMA, the fine HMA-RAP and the fine 100% RAP mixtures for reference purposes.

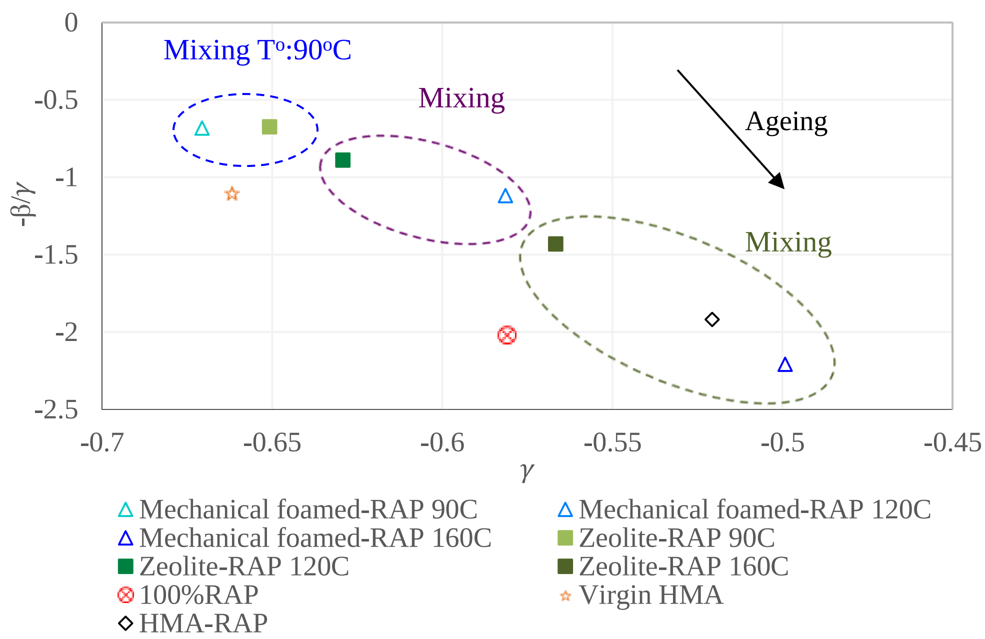


Figure 8. Changes in the shape parameters of the |*G**| master curves for both fine RAP-FBMs groups with production temperature.

According to Mensching et al. (2017), a point in this plot moves towards the lower right of the plot (lower values of both parameters) with ageing, as the mixture becomes stiffer and loses relaxation capability. This trend is clearly noticeable in both fine RAP-FBMs groups, with the Mechanical foamed-RAP fine mixtures exhibiting greater changes in both parameters with mixing temperature. The relative position of each fine RAP-FBMs is an effect of the combination of the degree of blending between RAP and virgin binders with production temperature, and ageing of the RAP material due to the particular requirements in each foaming technique to target the desired mixing temperatures as explained before. Indeed, as mixing temperature increases, the behaviour of both groups of fine RAP-FBMs mixtures and that of the fine HMA-RAP, approaches to that of the 100%RAP fine mixture, suggesting higher contribution of the RAP binder into the final blend and thus higher stiffness. Conversely, at mixing temperatures of 90^{o}C the Mechanical foamed-RAP and Zeolite-RAP fine mixtures are within the same area of the fine Virgin HMA (i.e. no RAP material), suggesting low interaction with the RAP binder at this reduced temperature and thus lower stiffness.

In an attempt to understand the influence that ageing could have in the expected cracking performance of the two fine RAP-FBMs, the rheological data was used to calculate the Glover-Rowe (*G-R*) parameter following the approach developed by Glover et al. (2005) and by Mensching et al. (2016). The basis of this parameter was initially developed by Glover et al. (2005) as a mean to identify ageing and assess fatigue-cracking potential of asphalt binders. The *G-R* parameter is calculated by means of Equation 4 at a temperature-frequency combination of 15^{o}C and 0.005rad/s.

$$G - R = \frac{|G^{*}|(cos^{2}\delta)}{sin\delta} \qquad (4)$$

Mensching et al. (2016) developed a mixture-based parameter, with the same format as the *G-R* for asphalt binders, employing stiffness and relaxation of the mixture (|E*| and δ) instead of complex modulus and phase angle of the binder. The parameter suggested by the authors is calculated by means of Equation 4 at a frequency matching that of the *G-R* low-temperature for binders (1.666×10^{-2} rad/s) and temperature 10ºC warmer than the PG low temperature grade of the binder.

At this stage, since FAM materials represent an intermediate scale between the binder and the full asphalt mixture, an example of the *G-R* parameter for the two fine RAP-FBMs groups was calculated by means of Equation 4 at a temperature-frequency combination of 15ºC and 1.666×10^{-2} rad/s, and is presented in Figure 9 in the form of Black space (i.e. plot of |*G**| vs. δ). The same results (i.e. cracking susceptibility of the fine mixtures) were obtained at other frequency values.

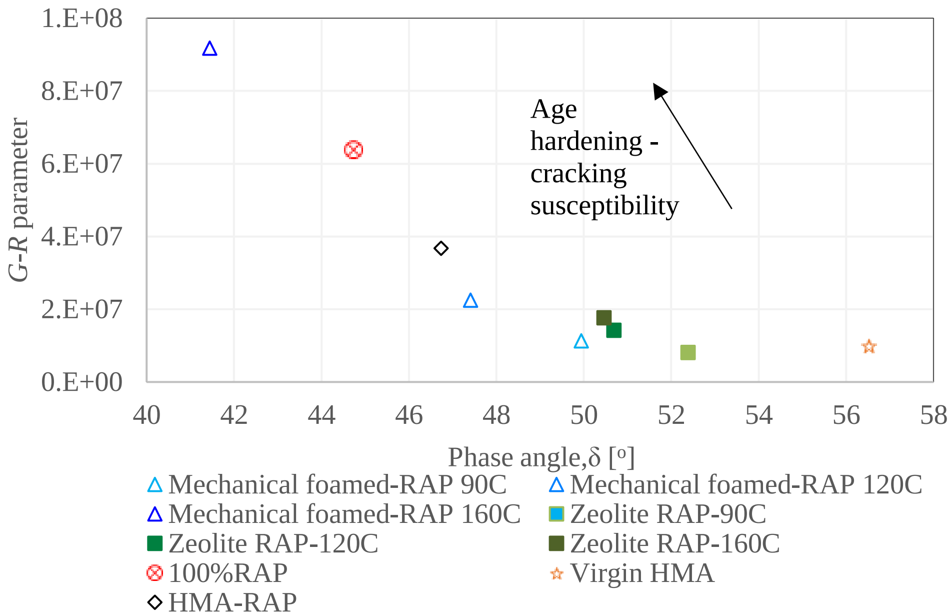


Figure 9. Effect of foaming technology and production temperature. Glover-Rowe analysis for fine RAP-FBMs at 15ºC and 1.666×10^{-2} rad/s.

In this plot, the materials that move towards the upper left of the plot experience age hardening, and have higher cracking susceptibility. Indeed, all fine RAP-FBMs exhibit this shift as mixing temperature increases. However, this analysis shows that each fine RAP-FBM exhibits different changes in their rheological response with temperature. For example, the *G-R* value at a mixing temperature of 160^{o}C is 8 times and 2 times higher than that at a mixing temperature of 90^{o}C for the Mechanical foamed-RAP and Zeolite-RAP fine mixtures, respectively. This means that the changes in mixing temperature do not lead to the same age hardening effects and cracking susceptibility in the fine RAP-FBMs groups. These differences are due to their different rheological characteristics as was described previously from the $|G^*|$ master curves. The relative position of the Mechanical foamed-RAP fine mixture at 160^{o}C – showing the highest *G-R* and lowest δ values, among the rest of the fine RAP-FBMs and also with respect of the HMA-RAP and 100%RAP fine mixture (manufactured at the same mixing temperature) –, indicates that the overall increase in the hardness of this mixture may lead to a poor long-term performance in terms of thermal cracking resistance. All other fine RAP-FBMs exhibit higher δ and lower *G-R* values with respect to this mixture and also to the HMA-RAP and 100%RAP fine mixtures, suggesting that their overall expected performance in terms of thermal cracking is superior and less likely to be compromised.

Conclusions

This study evaluated and compared the rheological response of the fine aggregate portion of asphalt mixtures produced by means of the traditional mechanical foaming technique and by the addition of zeolites (focusing on plant processes) with 50% fine RAP content. Although the former foaming technique has intended to be used mainly for warm mix processes or cold recycling, mainly on in-situ projects and the latter is commonly used for warm mix asphalt production, the study also included the evaluation of plant production variations in both foaming techniques for half-warm, warm and hot processes (i.e. mixing temperatures of 90, 120 and 160°C).

The results showed that both fine RAP-FBMs groups exhibited higher $|G^*|$ values with production temperature, as expected, likely due to higher contribution of the RAP binder in the total bitumen blend, and ageing of the RAP material. The Mechanical foamed-RAP fine mixtures exhibited higher rise in their $|G^*|$ values and higher cracking susceptibility compared to the Zeolite-RAP fine mixtures manufactured at the same mixing temperatures. Thus the foaming technique and mixing temperature have different effects on the rheological response of the produced fine mixtures and, consequently, in their long-term performance, therefore it is important to consider these plant production variations in the design of high-RAP content mixtures.

In particular, pre-heating the fine RAP material to produce Mechanical foamed-RAP fine mixtures for half-warm and warm processes (bitumen was heated at 160°C in all cases) were shown to be good approaches to produce competent mixtures at lower temperatures than those used for HMA, lowering further ageing of the RAP material, and reducing cracking susceptibility. When RAP material is pre-heated at temperatures above 160°C, for hot processes, although there is a higher contribution of the RAP binder in the total binder blend, which is beneficial to reduce the amount of virgin binder added in the fine mixture, further ageing of the RAP material may lead to cracking issues.

In terms of the Zeolite-RAP fine mixtures, it was observed that although the mechanical capacity of the mixtures increased with production temperature, the increase in the magnitude of the $|G^*|$ values for hot processes, with respect to warm processes (which constitutes the main application of this technique), was not significant (increase in $|G^*|$ by 20% at 0.001Hz and 25°C). Thus, unless the application of hot processes brings further advantages that compensate the environmental and economic costs of increasing the temperature, it is still better to maintain the common practice in warm applications. An economic study that provides a fair comparison between these two options is recommended. Conversely, although it was possible to incorporate high RAP content with zeolite foaming technique for half-warm applications, the mechanical capacity of the mixture might be compromised ($|G^*|$ decreased by 26% at 0.001Hz and 25°C), reinforcing the conclusion and actual practice that warm processes might be the best approach for this foaming technique.

Finally, it is worth mentioning that in this study the properties of the RAP material were controlled; however, in practice the properties of the RAP material might be unknown and the variability of its properties restrains the possibility of providing generalised conclusions on the overall rheological response of foamed mixtures containing RAP materials.

Disclosure statement

No conflict of interest.

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