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Investigation on performances of asphalt mixtures made with Reclaimed Asphalt Pavement: Effects of interaction between virgin and RAP bitumen

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Abstract

According to most recent surveys, the European area produced 265 mil tonnes of asphalt for road applications in 2014. In the same year, the amount of available RAP was more than 50 mil tonnes. The use of RAP in new blended mixes reduces the need of neat bitumen, making RAP recycling economically attractive. Despite the economic and environmental benefits, road authorities tend to limit the use of RAP in asphalt mixes due to uncertainty about field performances. The present study focuses on the interaction between neat and RAP bitumen in asphalt mixes made with different RAP content. The effects of RAP on physical and rheological properties of the final bituminous blend were investigated. This study is part of a wider research, where a specific type of asphalt mixture was produced with different RAP contents being 10%, 20% and 30% by mass of the mix. Bitumen was extracted and recovered from asphalt mixes, then it was subjected to the following laboratory tests: standard characterization, dynamic viscosity and rheological analysis with DSR. Findings showed that the effects of RAP bitumen on the final blend varied in proportion to RAP content. A threshold value of RAP content was found, below which bitumen was not subjected to significant changes in physical and rheological properties. Practical implications on production methods and paving of RAP mixes are also proposed.

Keywords: Reclaimed Asphalt Pavement (RAP); Recycling; Bitumen blending; Bitumen rheology

1. Introduction

Recycling hot mix asphalt results in a reusable mixture of aggregates and aged asphalt binder known as Reclaimed Asphalt Pavement (RAP) [1]. Using the old asphalt bitumen in the newly blended mixtures and, therefore, reducing the required new bitumen content, makes the use of RAP in HMA mixtures economically attractive [2]. It is considered that the most economical use of RAP is in the intermediate and surface layers of flexible pavements because the less expensive RAP binder can replace a portion of the more expensive virgin binder [3]. Hundred per cent of the reclaimed asphalt can be recycled [4] with different methods: hot recycling in asphalt plant, hot in-place recycling, cold in-place recycling and full depth reclamation are the most commonly applied techniques [5].

The percentage of RAP (usually expressed by mass of the mix) that can be incorporated into asphalt mixtures

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depends on production process (plant type, production temperature, mixing time, and discharge temperature), paving technology and permitted emissions as well as RAP source and properties. For instance, RAP obtained from high-trafficked roads (highways or freeways) is likely to contain polymer modified bitumen, which limits bitumen oxidation with beneficial effects on the RAP mix [6]. These factors affect the interaction between RAP and virgin bitumens and consequently impact the performance of asphalt mixtures [7]. The maximum amount of reclaimed asphalt is mainly limited by the production technology [7]. Considering hot in plant recycling, most conventional drum plants can accommodate 50% RAP, whereas the percentage of reusable RAP in batch plant ranges from 10 to 30% [8]. These limitations have been overcome thanks to multiple technologies readily available for production of up to 100% recycled hot mix asphalt [9].

In Italy, RAP availability is 10 million tonnes, but only 20% of the recovered material is used in hot/warm recycling processes [10]. This means that RAP is accumulating in stockpiles, used in low-value [11] and non-bituminous applications (e.g. aggregate in unbound layers), or being dumped. In Germany, France, and The Netherlands, the available quantity of RAP is 11.5, 6.9 and 4.5 million tonnes respectively. The percent of available RAP used in hot/warm recycling is 90% in Germany, 64% in France, and 76% in The Netherlands. The European average is 58%. The European Union released guidelines to favour recycling and re-using of waste or by-products, including RAP. According to Directive 2008/98/EC, Member States of EU shall take measures to promote the re-use of products and preparing for re-use activities [12]. The new circular economy package issued by the European Commission in December 2015 aims at increasing the use of recycled material and RAP in road construction by promoting cradle-to-cradle strategy to save raw materials, reduce carbon footprint of construction process and save money. Nevertheless, re-use and hot/warm asphalt recycling practices struggle in Italy.

Many agencies and public administrations insert restrictions on RAP percentages ranging from 10 to 30% in their regulations due to concerns for pavement performances and production technologies. Uncertainties concern the interaction between RAP binder and virgin binder. Inaccurate assumptions on the effects of interaction might create problems both in mix design and pavement performance [5,7], leading to mixtures that might be subjected to premature failure to cracking, ravelling, moisture damage and rutting. At present, there is no industrial approved standard method to predict the degree of blending in laboratory [3], and tests shall be carried out for evaluating the effects of interaction between RAP binder and virgin binder on mechanical behaviour of RAP mixtures.

2. Experimental plan

2.1. Objectives and research approach

The study aims at investigating the effects of the interaction between virgin and RAP binder on physical and rheological properties of the composite bituminous blend. The objectives of the research are summarized as follows:

- Investigate the effects of the presence of RAP into asphalt mixtures on standard characteristics of bitumen as penetration grade and softening point.
- Determine the effects of RAP binder on rheology of composite blends with neat binder.
- Define threshold values for RAP content above which dynamic characterization tests are needed, in addition to standard characterization tests, in order to evaluate the effects of the interaction between neat and RAP binder.
- Identify practical implication on the use of different RAP percentages into asphalt mixtures.

The present study is part of a wider research on performances and durability of asphalt mixtures made with RAP [13]. The research is divided in two phases: in the first phase, the effects of RAP on asphalt mixtures are investigated. A specific typology of asphalt mixture is produced with different RAP percentages of 10%, 20% and 30% by weight of the mix. Asphalt materials are characterized and compared in terms of resistance to fatigue, stiffness modulus and volumetric properties. The second phase, which is reported in this paper, aims at investigating the effects of RAP on asphalt binder as a composite blend of neat and RAP bitumen. Bituminous samples are recovered from asphalt samples tested in phase 1 and further characterized and compared with standard and dynamic tests.

The objective of the research is to comprehensively characterize RAP mixtures in terms of performances of asphalt mixtures and bitumens.

2.2. Materials and methods

Five bitumens were investigated. All the bitumens were recovered from specimen of asphalt mixture tested to fatigue in the previous phase of the research. The asphalt mixtures were produced incorporating different percentages of RAP into a traditional asphalt concrete, which was used as reference mixture. Asphalt mixes are classified as Mix0 (control mixture), Mix1 (control + 10% RAP), Mix2 (control + 20% RAP) and Mix3 (control + 30% RAP). A sample of bitumen was recovered from each mixture, respectively B_0 from Mix0, B_1 from Mix1, B_2 from Mix2, B_3 from Mix3 and B_{RAP} from the unprocessed RAP. Bituminous samples B_1, B_2 and B_3 are considered being blends

Table 1
Composition of asphalt mixtures, percentages by mass of aggregates.

MATERIAL	MIX0 (control)	MIX1 (10%RAP)	MIX2 (20%RAP)	MIX3 (30%RAP)
Gravel 10/20 mm	25	26	26	23
Gravel 6/10 mm	16	13	14	15
Gravel 4/6 mm	16	16	14	15
Sand 0/4 mm	40	33	24	15
Filler	3	2	2	2
RAP 0/8 mm	0	5	8	14
RAP 8/12 mm	0	5	12	16
Recovered bitumen from RAP 0/8	0.0	0.3	0.4	0.7
Recovered bitumen from RAP 8/12 mm	0.0	0.3	0.6	0.8
Virgin bitumen Pen Grade 50/70	5.0	4.5	4.0	3.5

because of the presence of both neat and RAP binder. The composition of the asphalt mixtures is given in Table 1.

Asphalt mixtures were manufactured in laboratory with design binder content of 5% by mass of aggregates and design air voids content of 5% by volume of the mix. Aggregates were heated at 180 °C and RAP was dried at 110 °C for 2 h before mixing. Neat binder was incorporated into mixes considering the presence of aged binder into RAP fractions. Significant effort was put forth to achieve similar grading, air voids and binder content in each specimen, ensuring that results of laboratory tests are mainly dependent on the percentage of RAP included.

Asphalt binder was recovered from prismatic specimens and unprocessed RAP using a centrifuge extractor according to the European standard EN 12697-1 annex B.1.5 for cold extractions methods, using dichloromethane CH_2Cl_2 organic solvent. The solution of bitumen and DCM from prior extraction was distilled with rotary evaporator, according to EN 12697-3. The extracted binder content is reported in Table 2.

Recovered binders were tested for determining penetration grade (EN 1426), softening point (EN 1427) and dynamic viscosity at 160 °C (EN 13702-2). Empirically based tests, such as penetration, softening point as well as the more fundamental viscosity, are able to describe the changes in rheological performance of neat and aged bitumen blends [14].

Rotational Viscometer (RV) was used to evaluate the binder viscosity at high temperatures. The RV measures the torque required to rotate a spindle at constant speed while immersed in the simple fluid. Dynamic viscosity is proportional to this measured torque. For all bitumen the dynamic viscosity (η) was calculated at the temperature of 135, 150, 160 and 170 °C. In order to validate the test, the sample was thermo-regulated at 5 °C at intervals of 7 min and 10 °C at intervals of 12 min. Tests were conducted according to EN 13702-2. Viscosity can be considered to be a measurement of purely Newtonian flow and therefore independent of strain rate at test temperatures [14].

The DSR was used to measure the linear viscoelastic properties of bitumens using a sinusoidal loading mode. A temperature sweep (TS) was applied over the range from 0 °C to 90 °C, at a fixed frequency of 10 rad/s with an incremental temperature rate of 0.5 °C/min [15]. The test procedure with 8 mm plane plate and 2 mm gap was studied. In the TS test the complex shear modulus (G^*) and the phase angle (δ) were measured with DSR and studied in terms of master curves.

3. Results

3.1. Standard characterization test results

Results in Table 3 show a decrease in penetration and an increase in softening point as RAP content increases. This indicates a hardening of the composite blend caused by the presence of aged bitumen. Penetration and softening point change in proportion to the RAP content in the mixture.

Parameters measured for B_0, B_1 and B_2 indicate a small hardening of the composite blend due to the presence of RAP binder. The hardening effect of the old bitumen on the composite blend becomes relevant as the RAP binder content is above 20% by weight of the mix.

The Penetration Index (PI) was calculated according to EN 12591 as an indicator of temperature susceptibility of the bitumen. The lower the value of PI, the higher the temperature susceptibility of the binder. PI reported in Table 3 indicates that B_0, B_1 and B_2 have identical temperature susceptibility, with B_3 and B_{RAP} having a higher PI value and, therefore, a lower temperature susceptibility.

3.2. Dynamic viscosity test results

Viscosity values of bituminous blends for each test temperature are shown in Table 4.

Table 2
Soluble binder content extracted and recovered from beams and unprocessed RAP.

Specimen	Recovered binder sample code	Binder content b_c (% on mixture mass)
Mix0	B_0	5.13
Mix1	B_1	4.92
Mix2	B_2	5.01
Mix3	B_3	5.07
Unprocessed RAP	B_{RAP}	4.87

Table 3
Results of standard characterization tests on recovered binders.

Bituminous sample	Penetration at 25 °C (dmm) EN 1426	Softening point (°C) EN 1427	Penetration Index EN 12591
B_0	27	55	−1.3
B_1	25	56	−1.3
B_2	21	57	−1.3
B_3	16	63	−0.8
B_{RAP}	7	73	−0.5

Table 4
Results of dynamic viscosity test on recovered binders.

Bituminous sample	Dynamic viscosity (Pa·s)			
	135 °C	150 °C	160 °C	170 °C
B_0	1.36	0.46	0.32	0.25
B_1	1.41	0.45	0.33	0.25
B_2	1.51	0.46	0.37	0.28
B_3	1.59	0.75	0.53	0.32
B_{RAP}	1.92	0.96	0.55	0.32

Viscosity of blends increases in proportion to RAP binder content (Fig. 1). The higher the RAP binder, the higher the viscosity of the blend. The presence of the more viscous old binder causes the composite blend to harden, resulting in an increase in viscosity of the mixture. This confirms the results obtained from penetration and softening point tests.

RAP binder has been exposed to ageing processes that have hardened the bitumen. Short term (ST) ageing, which takes place during mixing, transport and laying of bituminous materials, changes the chemical composition of the binder with significant impact on its rheological properties. During ST ageing, bitumen experiences increasing in viscosity caused by oxidation, volatilisation and exudation ([5,16]. During the long term (LT) ageing, bitumen progressively increases viscosity and stiffness due to oxidation, polymerisation, photo-oxidation of surface layers, thixotropy and syneresis [1]. The major part of asphalt ageing occurs during the short term [17]. The increase in viscosity of RAP bitumen is caused by several factors: ratio of resins to asphaltenes [14], increase in number of asphaltenes (between 5 to 20% by weight [18]), increase in molecular weight and polydispersity [16]. Therefore, the presence of RAP binder changes chemistry of the bituminous blend, resulting in a harder and consequently more viscous composite bitumen.

The values of viscosity of RAP blends are greater than typical viscosities of 50/70 bitumens. This is expected since penetration grade and softening point of the neat binder showed deviation from typical values of unmodified 50/70 binders (Table 3), indicating a harder bitumen compared with a traditional 50/70. Measured viscosities exceed recommended values of 0.17 ± 0.02 and 0.23 ± 0.03 Pa·s at 160 °C reported in ASTM D 2493 respectively for optimal mixing and compaction of HMA with unmodified binders. Similar values of viscosity may be found on Polymer Modified Binders (PMB), for which production and working temperatures range from 160 to 180 °C. However, the presence of polymers significantly differentiates the rheological behaviour of modified and unmodified binders, allowing the firsts to be subjected to higher temperatures without experiencing ageing. Lowering the viscosity of RAP blends appears to be crucial to ensure performances and feasibility of RAP asphalt mixtures. An increase in production and working temperatures might cause the composite blend to harden, leading to a further increase in viscosity. Therefore, a softer neat bitumen or additives may be used for lowering the viscosity of RAP blends.

Results indicate no significant differences in viscosity between B_0 and B_1. Therefore, the presence of 10% or less of RAP (low RAP content [17]) into the mixture does not affect the viscosity of the composite blend. Viscosity significantly increases as RAP content exceeds 20% (high RAP content [17]) at temperatures of 150 and 160 °C. This indicates a significant hardening effect on the blend caused by the aged binder as the RAP content is above 20%.

The temperature susceptibility of bituminous blends was represented investigating the trend of viscosity as function of temperature (Fig. 2). Because viscosity measurements are fitted with power-law trend, the x-coefficient of power-law can be used as indicator of temperature susceptibility of bitumens. Results show that the higher the RAP binder content, the higher the temperature susceptibility within the test temperature range. The trend of viscosity of RAP blends is between the trends of neat and RAP binders in proportion to RAP binder content in the blend. When the RAP content is above 20%, the bituminous blend experiences a significant shift towards higher values of viscosity. This indicates a hardening effect of RAP binder present in the mixture.

Viscosity test results can be used to verify the assumption of total blending between neat and RAP binders after being extracted with the procedure previously described. The procedure of extraction and recovery of bituminous blends is expected to produce 100% blending of RAP and virgin binder [5]. The assumption of total blending was verified using the log-additivity rule (LAR). LAR predicts viscosity of homologous polymer blends (HPB), a sub-class of PB with chemically identical polymers differing in molar mass. Viscosity of HPB proportionally depends on mass fraction (percentage by mass) of constituent polymers [19]. LAR is expressed as [20]:

$$\ln \eta_C(T) = \sum_i w_i \ln \eta_i(T)$$

In which η_C is the viscosity of the composite blend at temperature T, w_i and η_i are the mass fraction and the viscosity of the component i at temperature T. Results in Table 4 show that viscosity of bitumen blends increases proportionally with the aged binder content in the composite blend, ranging from recovered neat binder (B_0) viscosity and RAP binder (B_{RAP}) viscosity. Similarly to HPB, the LAR was applied to bitumen blends. Viscosity was calcu-

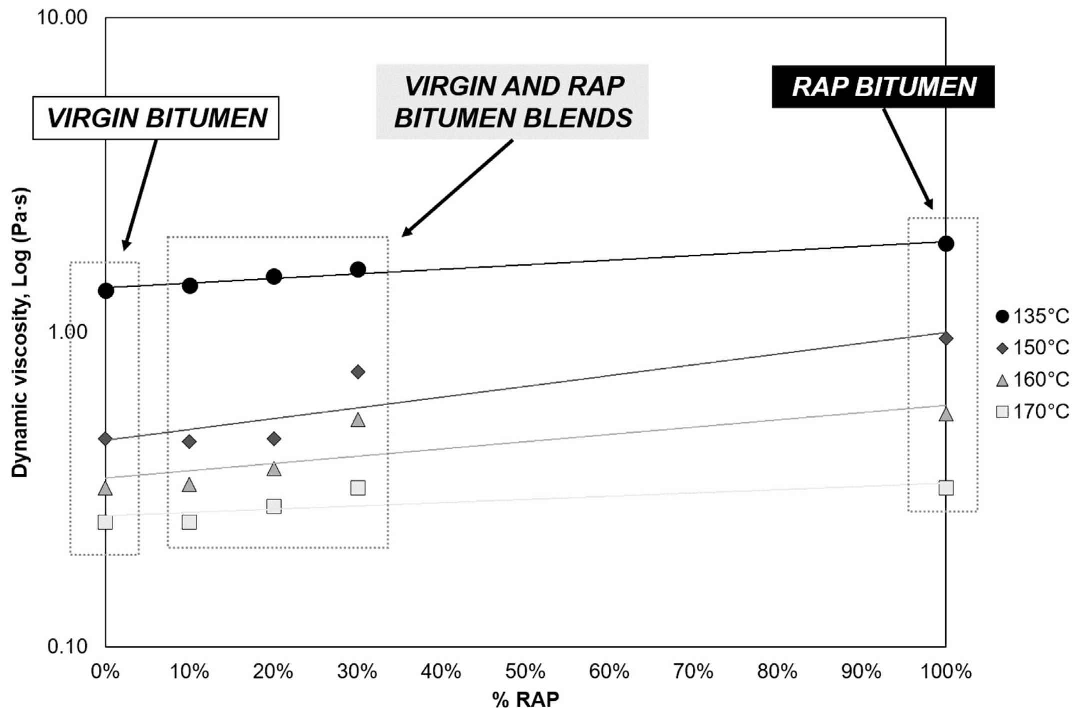

Fig. 1. Dynamic viscosity as function of aged binder content.

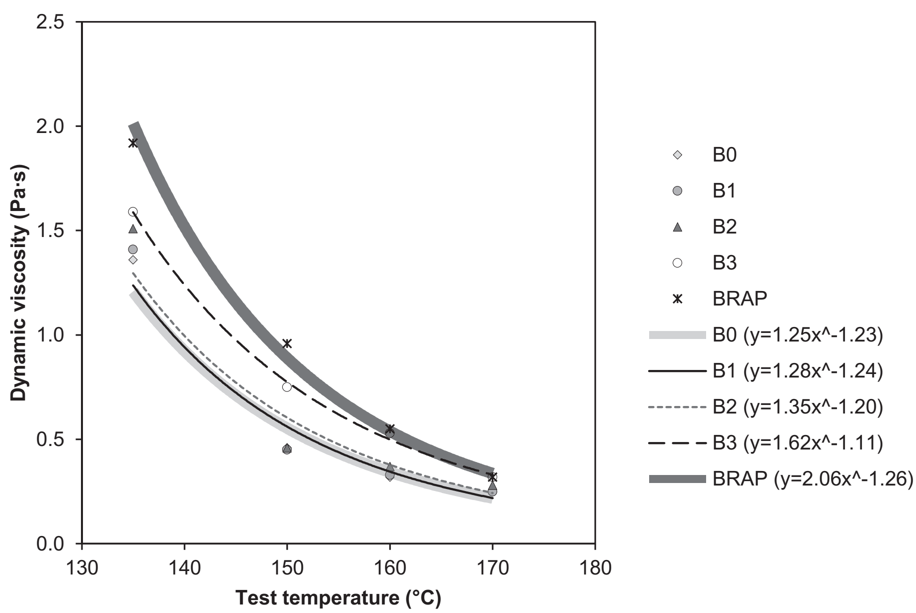

Fig. 2. Temperature susceptibility of bituminous samples measured through viscosity tests.

lated with LAR for B_1, B_2 and B_3, then predicted and measured values were compared. Results are reported in Table 5.

A strong correlation was found between measured and calculated viscosities, as indicated by the linear relationship between $\ln(\eta_M)$ and $\ln(\eta_C)$ with slope of 0.99 and $R^2 = 0.99$ (Fig. 3). The viscosity of bitumen blend is proportionally affected by the content of RAP binder in the composite mix, showing a viscosity-concentration dependence in relation to the LAR. Investigated bituminous blends can be considered as homologous blends, validating the assumption of total blending between neat and RAP binders for the recovered bitumens.

3.3. Dynamic mechanical analysis with dynamic shear rheometer

3.3.1. Complex modulus isochronal plots (master curves)

An isochronal plot is a curve on a graph representing the behaviour of a system at a constant frequency or loading

Table 5
Comparison between viscosity values of bituminous blends measured in laboratory and values calculated with LAR (viscosity is expressed in natural log values).

Bituminous sample	Dynamic viscosity at 135 °C		Dynamic viscosity at 150 °C		Dynamic viscosity at 160 °C		Dynamic viscosity at 170 °C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
B_0	0.307	0.307	−0.777	−0.777	−1.139	−1.139	−1.386	−1.386
B_1	0.344	0.348	−0.799	−0.799	−1.109	−1.109	−1.386	−1.386
B_2	0.412	0.387	−0.777	−0.777	−0.994	−0.994	−1.273	−1.273
B_3	0.464	0.424	−0.288	−0.288	−0.635	−0.635	−1.139	−1.139
B_{RAP}	0.652	0.652	−0.041	−0.041	−0.598	−0.598	−1.139	−1.139

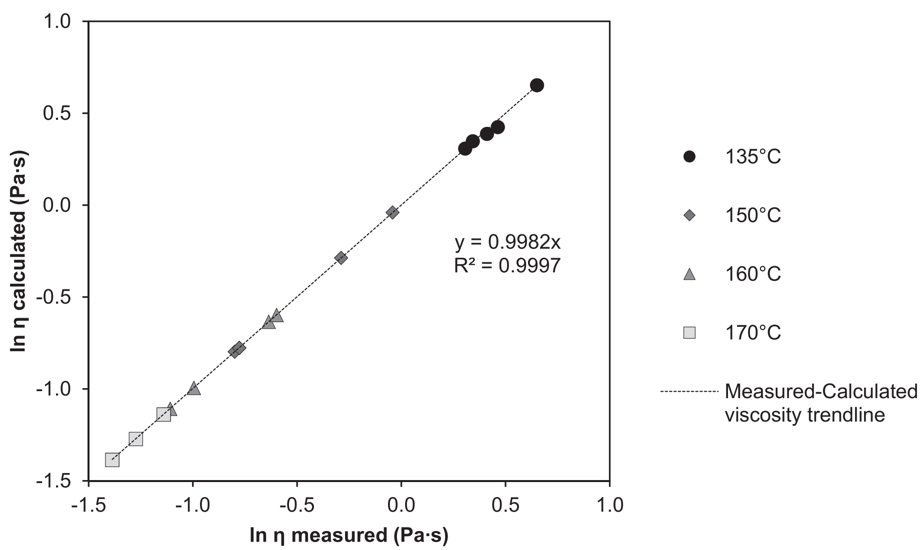

Fig. 3. Relationship between measured and LAR calculated viscosity of bituminous samples.

time. Curves of the complex modulus G^* versus temperature are isochrones [21].

Master curves of complex modulus G^* are reported in Fig. 4. Values of complex modulus (Table 6) increase in proportion to RAP content over the test temperature range, resulting in a vertical shift of G^* curves. The increase in complex modulus indicates a hardening of the bitumen caused by the presence of the aged binder.

The hardening effect of aged binder on the composite blend is proportional to the RAP binder content in the mixture. When RAP content is equal or below 10%, the vertical shift is almost negligible. For RAP percentage equal or above 20%, the influence of recovered binder becomes more relevant, resulting in a significant vertical shift of G^* curves. Therefore, adding small amounts of reclaimed asphalt into the mixture has very limited effects on binder stiffness.

The effects of the aged binder on the complex modulus vary over the test temperature range. At temperatures from 0 °C to 20 °C, curves of G^* for B_0, B_1, B_2 and B_3 show the same trend and similar values, indicating a limited stiffening effect of the aged binder. This might suggest that the presence of even high percentages (greater than 20%) of RAP binder into the mixtures has small effect on the low-temperature cracking susceptibility of the blends. As temperature exceeds 20 °C, isochrones of B_1, B_2 and B_3 deviate from the reference curve of B_0 and shift towards higher values of G^* (with a magnitude in proportion to the RAP binder content). The stiffening effect of the RAP binder on the complex modulus of the blends becomes more relevant when temperature exceed 20 °C, becoming constant at a temperature of approximately 50 °C.

3.3.2. Phase angle isochronal plots

The phase angle δ is plotted in Fig. 5 as tgδ versus temperature. Values of δ are reported in Table 7. Tgδ is defined as the ratio between loss (G'') and storage (G') components of the complex modulus, therefore it can be considered as an indicator of the viscoelastic balance of the mixture.

Results show that the phase angle decreases in proportion to RAP content in the mixture over the temperature range. Since tgδ is defined as G''/G', the decrease in the phase angle corresponds to an increase in the elastic behaviour of the bitumen caused by the presence of aged binder.

As observed for complex modulus isochrones, the magnitude of the decrease in tgδ and hence the increased elastic

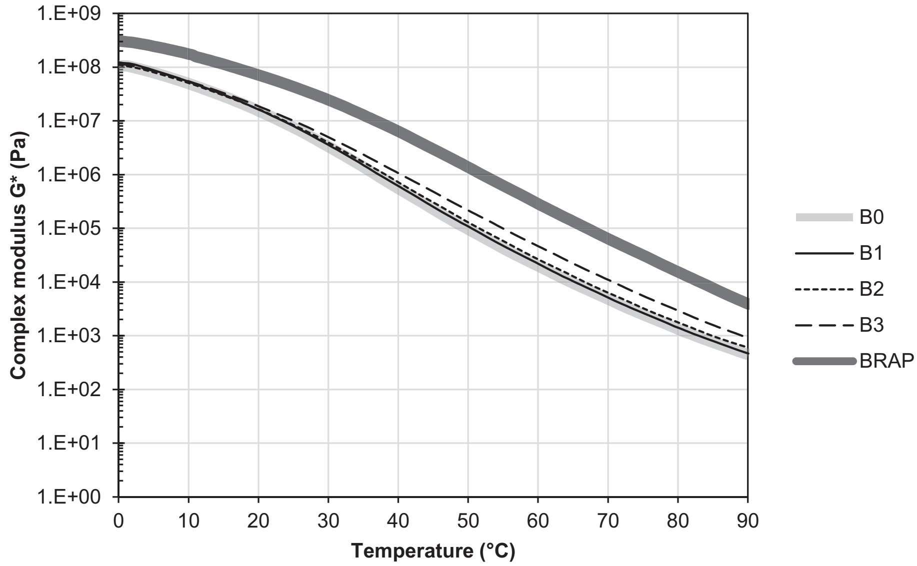

Fig. 4. Isochronal curves of complex modulus G* of investigated mixtures.

Table 6
Complex modulus values measured with DSR for each bitumen, reported at temperature steps of 10 °C.

Temperature (°C)	Complex Modulus |G*| (kPa)				
	B_0	B_1	B_2	B_3	B_{RAP}
0	104000	123000	110000	114000	308000
10	51600	56400	52800	56600	182000
20	16200	17200	17300	19600	74500
30	3550	3830	4200	5250	25900
40	592	658	772	1130	6790
50	103	116	138	229	1460
60	21.1	23.4	28.1	49.2	305.0
70	5.1	5.5	6.7	11.6	67.7
80	1.4	1.5	1.9	3.1	16.3
90	0.5	0.5	0.6	1.0	4.1

Table 7
Phase angle values measured with DSR for each bitumen, reported at temperature steps of 10 °C.

Temperature (°C)	Phase angle δ (°)				
	B_0	B_1	B_2	B_3	B_{RAP}
0	29	28	26	26	18
10	38	38	35	34	23
20	50	49	46	44	31
30	62	61	57	54	41
40	72	71	67	63	52
50	78	77	75	70	62
60	83	82	80	76	70
70	85	84	82	80	76
80	83	83	79	81	81
90	72	74	66	73	80

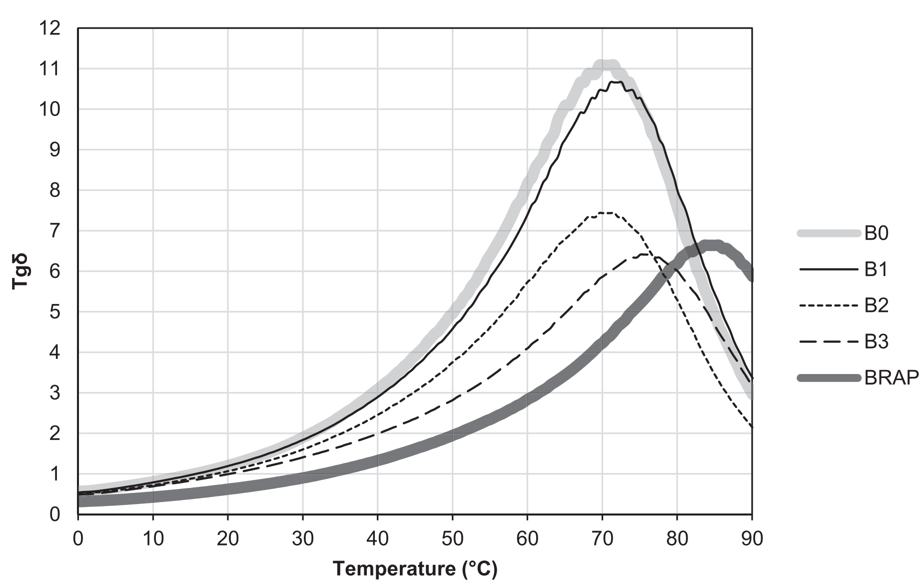

Fig. 5. Plot of phase angle represented as tgδ versus test temperature.

behaviour of the mixture is proportional to the aged binder content. When the aged binder content is equal or below 10%, there is a limited influence of the aged binder on rheological properties of the final blend. The effects of the presence of aged binder into the composite blend become more relevant as the RAP content raises to or exceeds 20%. The curves of tgδ for B_2 and B_3 shift towards the B_{RAP} curve and lower values of tgδ, indicating a more elastic behaviour of the blends.

G′ describes the amount of energy stored and elastically released during each oscillation of the DSR, while G″ describes the energy dissipation associated with viscous effects [22]. When the stored energy equals the dissipated energy, the mixture experiences a viscoelastic transition to a predominantly elastic or viscous behaviour. The equality of G′ and G″ occurs as tgδ = 1 at the cross-over temperature. The cross over temperature allows to determine the temperature range where the mechanical response of the bituminous blend is predominantly elastic or viscous. The calculated cross-over temperatures are reported in Table 8.

Results indicate that the cross-over temperature increases as the content of RAP binder into the blends increases. Therefore, an increase in the aged binder content leads to a widening of the temperature range where the mechanical response of the bitumen is predominantly elastic.

On the basis of the previous considerations, the plot of tgδ (Fig. 5) can be divided into three regions. A first region (low temperatures), corresponding to a temperature range of 0 °C to cross-over temperature, is where the mechanical response of bitumens is predominantly elastic. A second region (intermediate temperatures), from the cross-over temperature to approximately 70/80 °C depending on RAP binder content, is where the mechanical response is predominantly viscous and tends to become more viscous as temperature increases. A third region (high temperatures), corresponding to a temperature range of 70/80 °C to 90 °C (end of test), is where the mechanical response is predominantly viscous but tends to become more elastic.

This behaviour at high temperatures can be also observed plotting the isochronal curves of storage and loss modulus, reported in Figs. 6 and 7. The curves of the storage modulus change trend at high temperatures, with tendency of G′ to be horizontal, whereas the curves of the loss modulus continue decreasing over the entire temperature range. The plot of G′ and G″ versus temperature indicates an increased elastic behaviour of the bitumen at high temperatures, as results from the trend of tgδ at high temperatures.

Table 8
Results of cross-over temperatures and corresponding complex moduli G* of investigated mixtures.

Bituminous sample	Cross-over temperature (°C)	G* at cross-over temperature (MPa)
B_0	15.6	26.7
B_1	16.1	27.1
B_2	18.6	19.6
B_3	20.3	18.4
B_{RAP}	33.1	16.6

3.3.3. Black diagram

A Black diagram is a graph of the norm of the complex modulus G^* versus the phase angle δ [21]. Data can be presented in one plot, without any manipulation of raw data with Time-Temperature Superposition Principle (TTSP).

Results in Fig. 8 show a shift of the curves towards lower values of the phase angle with the increase of the RAP binder content into the bituminous blends. This is caused by the dual effects of the increase in complex mod-

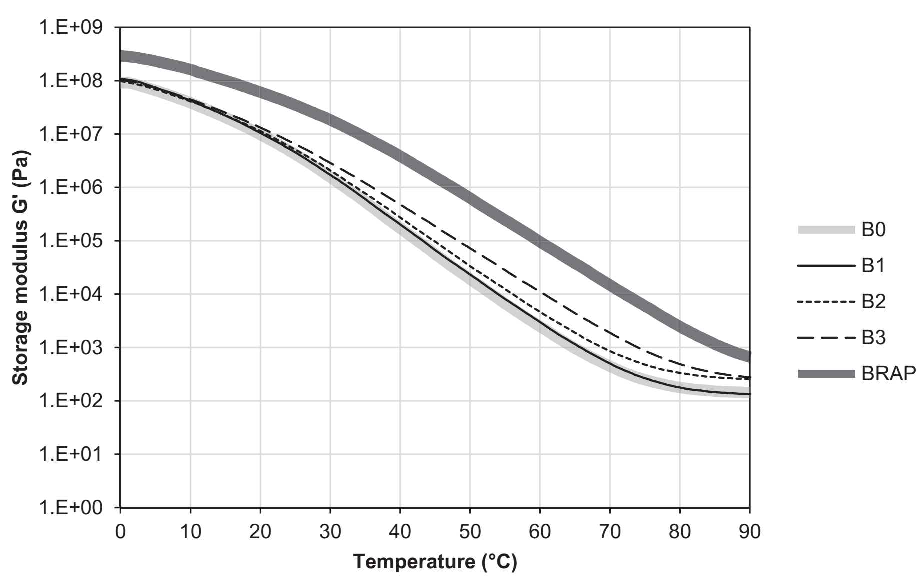

Fig. 6. Isochronal curves of storage component of complex modulus G′.

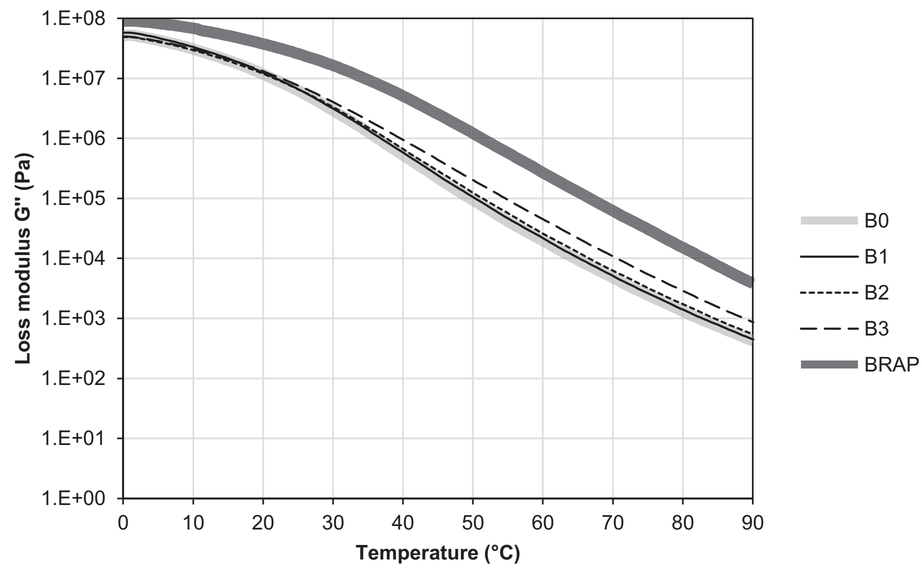

Fig. 7. Isochronal curves of loss component of complex modulus G″.

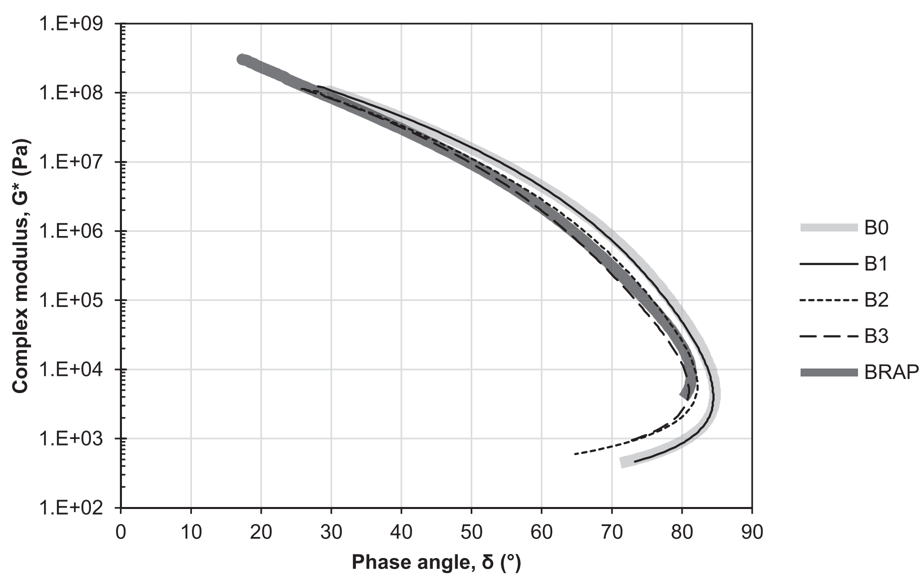

Fig. 8. Black diagram for investigated bitumens.

ulus and the decrease in phase angle. The first indicates a hardening of the bitumen, the second indicates an increase in the elastic response of the mixtures as RAP binder content increases.

The aged bitumen has little influence on the rheology of the final blend when the RAP content in the asphalt mixture is equal or below 10%, as can be noted from B_0 and B_1curves. The effect of RAP binder becomes relevant when the RAP content is equal or above 20%, as results from the shift of B_2 and B_3 curves on the Black space.

As previously observed referring to the plot of tgδ, the turning inward of the Black diagram curves reveals an increased elastic response of the bitumens at high temperatures. This is specific to B_0, B_1, B_2 and B_3. Therefore, this behaviour can be attributed to the rheology of the neat binder.

3.3.4. Cole-Cole diagram

The Cole-Cole diagram is a plot of the loss modulus G″ as a function of the storage modulus G′. The graph provides a means of representing the viscoelastic balance of the bitumen [14]. As for the Black diagram, the Cole-Cole diagram does not require any information about test temperature or frequency.

When the RAP binder content increases, the curves reported on the Cole-Cole diagram (Fig. 9) shift towards the lower right-hand corner of the plot, with a larger increase in storage modulus than loss modulus at a given

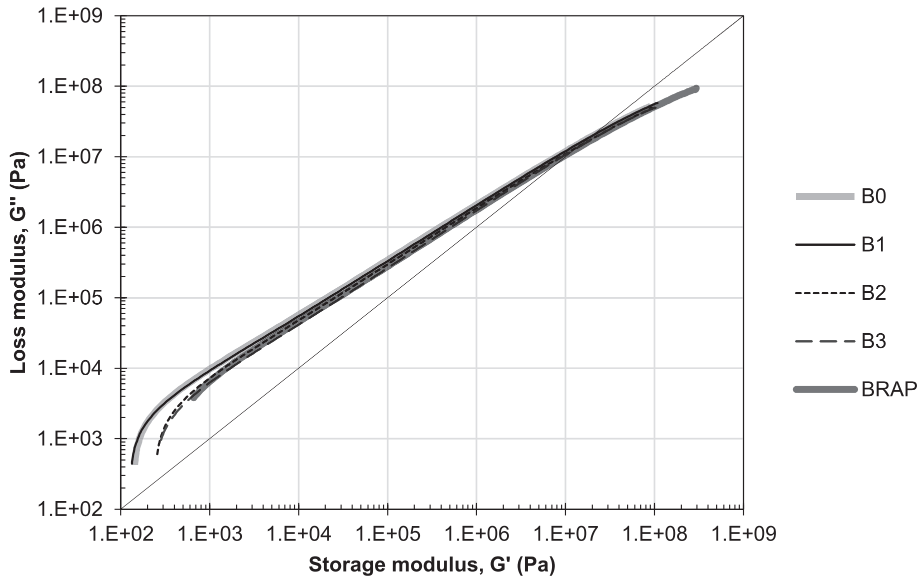

Fig. 9. Cole–Cole diagram for investigated bitumens.

temperature. Increasing the RAP binder content leads to a more elastic, less viscous and stiffer rheological behaviour of the mixes.

4. Conclusions

4.1. Summary of results

Findings from laboratory tests indicate that the aged binder influences physical and rheological properties of the final blend due to an interaction with the virgin binder.

Results of standard characterization tests show an increase in softening point and viscosity at 160 °C and a decrease in penetration grade as the RAP content in the mixtures increases. This indicates a hardening of the composite blend caused by the presence of aged binder.

The dynamic viscosity of bitumens was investigated as a function of RAP content and temperature. Results show that viscosity increases in proportion to the RAP binder content. The RAP binder changes the chemistry of the bituminous blends, resulting in a more viscous and consequently harder composite bitumen. The presence of 10% (by mass of the mix) or less of RAP binder into the mixture does not affect the viscosity of the blend, whereas a RAP binder content of 20% or higher causes a significant increase in viscosity. The trend of viscosity with temperature shows an increased temperature susceptibility as the RAP content increases.

The rheology of bituminous samples was investigated with the DSR analysing the complex modulus and phase angle isochrones, the Black space and the Cole-Cole diagram. Results show a hardening and an increased elastic behaviour of bitumens caused by the presence of RAP binder into the bituminous blends. The effects on the final blend are in proportion to the aged binder content. The aged bitumen has little influence on the rheology final blend when the RAP content in the asphalt mixture is equal or below 10%. The effects of RAP binder are significant when the RAP content is equal or above 20%. In addition, the increase in the cross-over temperature with RAP content indicates a widening of the temperature range where the mechanical response of the bitumen is predominantly elastic.

4.2. Practical implications

The use of RAP into asphalt mixtures increases bitumen viscosity in proportion to the RAP content in the mix. Lowering bitumen viscosity may be required to achieve adequate RAP mixes workability. An increase in production and working temperatures may reduce bitumen viscosity and increase mix workability, but might also cause the composite blend to harden, with an undesirable stiffening effect on the bitumen and negative consequences on performances of asphalt mixtures (brittleness). Using a softer and hence less viscous neat binder is recommended, if needed, when the RAP percentage incorporated in the mix is equal or above 20% (by weight of the mix). Viscosity blending charts can be used to determine the penetration grade of the neat bitumen for reaching the desired viscosity.

The effects of RAP binder on the bituminous blend depend on the percentage of RAP incorporated in the mixture. Results from laboratory tests show that RAP can be incorporated into the investigated mixture at percentages up to 10% with no significant effects on properties of bitumen. In this case, RAP can be added without the need to perform any additional laboratory test on recovered binder. As the RAP content is equal or above 20%, it's highly recommended to perform laboratory investigations on the recovered binder as per the procedure presented in this study.

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