New performance indicators for polymer modified binders

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ABSTRACT

In Europe, polymer modified bitumens are specified in accordance with EN 14023. These specifications are based on binder penetration and softening point plus a set of properties including resistance to hardening, cohesion, Fraass breaking point and elastic recovery. The European standard also provides a series of classes for each of these properties and enables the selection of the most suitable class for each polymer modified binder. These properties, however, provide limited information about their effect on the performance of an asphalt mixture in the laboratory or during installation, compaction and in-service. In this paper new binder performance indicators are proposed based on the critical workability temperature of the binder and a suite of tests on a standardised sand mixture. Critical workability temperature was determined from binder viscosity data obtained using a rotational viscometer. Tests on a standardised sand mixture, on the other hand, provided information on the effects of binder properties on stiffness, oxidative ageing, adhesion, resistance to deformation and low temperature cracking. Critical workability temperature was then used to classify the polymer modified binders into five classes, from the most workable to the least workable. Standard binder properties, critical binder workability temperature and binder's properties derived from the sand mixtures were then related to the properties of a dense asphalt concrete mixture. Asphalt mixture properties evaluated in the laboratory included workability, resistance to water damage and, deformation, fatigue and fracture resistance. Finally, performance indicators limits were proposed for each of the binder classes.

Keywords: Compaction, Mechanical Properties, Modified Binders, Viscosity, Workability

1. INTRODUCTION

The use of polymer modified binders (PMBs) in asphalt has increased steadily in Europe and it is now estimated at over 1Mt a year thus more than 7 % of the total bitumen consumption [1]. The main reason for this is that PMBs can significantly improve the performance of asphalt mixtures in terms of rutting, fatigue and thermal cracking and, consequently extend the life of the pavement. However, although the benefits of polymer modification have been widely reported, asphalt mixtures containing PMBs can be more difficult to handle during installation which can result in inadequate compaction leading to early pavement failures.

Traditionally, empirical properties have been used to specify bituminous binders. The current European specifications for PMBs are based on penetration and softening point plus a set of properties including resistance to hardening, cohesion, Fraass breaking point and elastic recovery [2]. The European standard for PMBs provides also a series of classes for each of these properties based on maximum or minimum limiting values. Furthermore, the specification enables the selection of the most suitable class for each polymer modified binder so that the supplier has the choice of selecting the class that better fits a particular binder. These properties, however, provide limited information about the performance of an asphalt mixture during installation, compaction and in-service. Also, although the European specification framework for PMBs includes in its annex several performance related binder tests, these have not been incorporated into the specification.

Compared to the European specifications, the US Performance Grade (PG) binder classification is based on a series of test procedures that measure the material's physical properties that are related to performance. The Dynamic Shear Rheometer is used for instance to determine resistance to deformation and fatigue cracking whereas the Bending Beam Rheometer is used to characterize the low temperature performance of the binder. Results from these tests are then used to classify the binders using two numbers – the first being the average seven-day maximum pavement temperature and the second being the minimum pavement design temperature likely to be experienced. In this specification the physical properties remain constant for all the grades but the temperature at which these properties are achieved varies depending on the climate in which the binder is to be used. The current protocols work well for regular unmodified binders but have been shown to be inadequate for polymer modified binders [3].

In this paper new performance indicators for PMBs are proposed based on binder critical workability temperature and a suite of tests on a standardized sand mixture. Binder critical workability temperature was determined from binder viscosity data obtained using a rotational viscometer. Tests on the standardized sand mixture, on the other hand, provided information on the effect of the binder on stiffness, ageing, adhesion, resistance to deformation and low temperature cracking. Critical workability temperature was used to classify the PMBs into five classes, from the most workable to the least workable. Standard binder properties, critical binder workability temperature and sand mixtures properties were then related to the properties of a dense asphalt concrete mixture. Asphalt mixture properties evaluated included workability, resistance to water damage, deformation, fatigue and fracture resistance. Finally, binder performance indicators limits were proposed for each of the binder classes.

2. BINDER CHARACTERIZATION

2.1 Standard binder properties

The binders used in this study included a 40/60 paving grade bitumen and six different PMBs. The binders evaluated and the properties declared by the bitumen suppliers are presented in Table 1.

Table 1: Standard properties of the binders used in the study

Binder	Grade	Penetration at 25 ^{0}C (dmm)	Softening point (^{0}C)	Force ductility (J/cm^2)	Fraass breaking point (^{0}C)	Elastic recovery at 25 ^{0}C (%)
50pen	40/60	40 - 60	53	-	-	-
PMB1	45-80/45	45-80	45 min	2 (at 5 ^{0}C) min	-12 max	60 min
PMB2	65-105/45	65 - 105	45 min	3 (at 5 ^{0}C) min	-18 max	50 min
PMB3	45-80/50	45-80	50 min	4 (at 5 ^{0}C) min	-12 max	80 min
PMB4	10-40/80	10-40	80 min	2 (at 15 ^{0}C) min	- 7 max	50 min
PMB5	25-55/60	25-55	60 min	3 (at 10 ^{0}C) min	-15 max	70 min
PMB6	25-55/75	25-55	75 min	3 (at 10 ^{0}C) min	-20 max	50 min

2.2 Critical binder workability temperature

During mixing and compaction of asphalt mixtures, binder properties can be considered in terms of viscosity. Viscosity is a measure of the internal friction of a fluid. When a force is applied to a liquid, this force is relieved by the flow of molecules past one another into new positions in the system.

In this work, a rotational viscometer was used to measure binder viscosity at temperatures associated with application conditions of mixing, laying and compaction. Viscosities of selected PMBs were measured at temperatures between 100 and 170 ^{0}C, shear rates varied depending on temperature and type of binder.

Figure 1 shows the change in viscosity with temperature for different binders. It can be seen first that at typical mixing temperatures (170 ^{0}C), the viscosities of all the binders were very similar and grouped together. Furthermore binder viscosities were lower than 500 cP. It has been reported that viscosities of around 200 cP are considered satisfactory for aggregate coating [4]. At this temperature (170 ^{0}C) binder viscosity is low enough to pump into storage and to coat all the aggregates in a relatively short period of time. Typical asphalt mixing times range from 30 to 90 s.

As the temperature decreases the binder become more viscous. Also, the change in viscosity with temperature depends on the type of PMB. The US binder specification developed primarily for unmodified bitumen allows for binders with a maximum viscosity of 3000 cP at 135 ^{0}C [5]. Figure 1 shows that at this temperature the viscosity of the binders used in the study were below this maximum value. This suggests that at typical compaction temperatures mixtures produced with these binders will be workable and full compaction could be achieved. When the temperature is reduced further, however, large differences between the viscosity values of the different PMBs start to appear. For instance, at 100 ^{0}C, the viscosity of PMB5 is more than three times that of PMB2. Thus, at this temperature a mixture produced with the low viscosity binder i.e. PMB2, might be still workable whereas the same mixture produced with the high viscosity binder, i.e. PMB5, might be too stiff and difficult to compact resulting in excessive in-situ air voids. Optimum bitumen viscosity range for compaction has been reported between 2000 to 20000 cP [4]. This range is, however, considered two wide particularly when the installation and compaction conditions are critical i.e. cold weather, long haulage, strong winds, thin layer lift, load temperature variation (‘ends of loads’) and others.

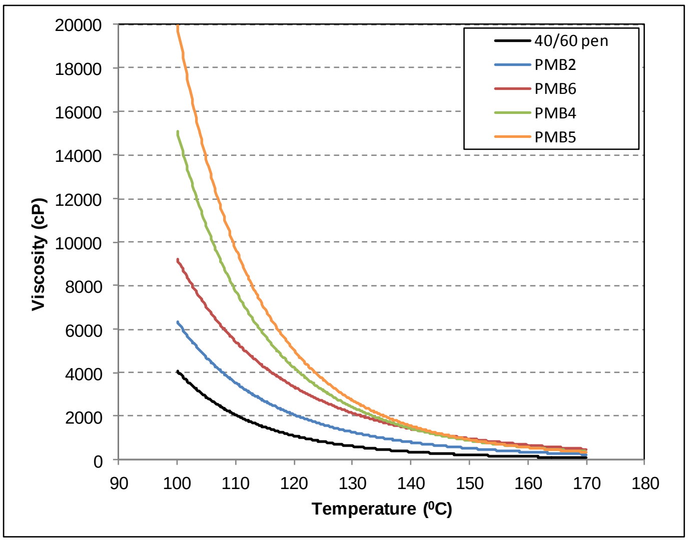

Figure 1: Evolution of binder viscosity with temperature

In this work, the critical workability temperature (T_C) of a PMB has been defined as the temperature at which the viscosity of the binder falls between 4000 cP and 8000 cP (6000 cP ± 2000 cP). This is a typical viscosity range for a 40/60 paving grade bitumen at a temperature of 95 ^{0}C (see Fig. 1). Critical workability temperatures have been determined from viscosity data as shown in Figure 2. It was calculated as the mean temperature between 4000 cP and 8000 cP rounded to the nearest 5 ^{0}C. Critical workability temperatures for the binders used in the study are given in Table 2. PMBs were then classified according to their critical workability temperatures into five classes: Class A (T_C = 100 ^{0}C), Class B (T_C = 105 ^{0}C), Class C (T_C = 110 ^{0}C), Class D (T_C = 115 ^{0}C) and Class E (T_C = 120 ^{0}C). This means that binders with lower T_C will be more workable (less viscous) than those with higher T_C. In other words, the lower the critical workability temperature, the lower the viscosity of the binder.

Table 2: Critical workability temperature T_C and PMB Classes

Binder	Type	Temperature @ 4000 cP (^{0}C)	Temperature @ 8000 cP (^{0}C)	Critical workability temperature T_C (^{0}C)	PMB Class
PMB1	45-80/45	105	95	100	A
PMB2	65-105/45	110	95	100	A
PMB3	45-80/50	110	100	105	B
PMB4	10-40/80	120	110	115	D
PMB5	25-55/60	125	115	120	E
PMB6	25-55/75	115	100	110	C

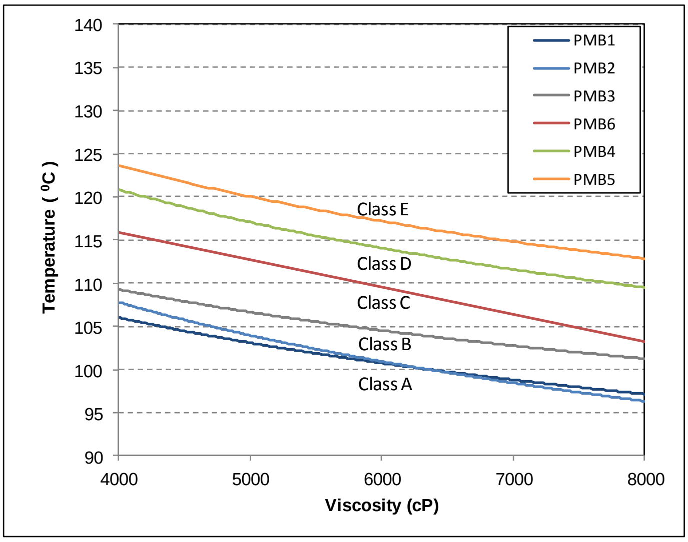

Figure 2: Determination of critical workability temperature T_C

2.2 Sand mixtures

The principle adopted for the characterization of a PMB is based on that used for a different type of binder i.e. cement. The strength of cement is determined in accordance with EN 196-1. In this test, standard sand is used to prepare the specimens for compressive and flexural strength tests. This standard sand is a 0/2 mm, rounded, siliceous sand prepared under a strict quality control process to guarantee quality and consistency. The sand is available from The Societe Nouvelle du Littoral in France and is packaged in polyethylene bags each containing 1350 ± 5 g.
In this work, this standard sand was used to produce mixtures containing sand and bitumen with no addition of filler. The purpose of choosing the standard sand was to remove another variable in the test protocol that may influence the test data. The protocol used to prepare the sand mixtures was as follows. First, the contents of three bags of sand (i.e. 4050 g) were emptied in a bowl and heated for a minimum of 8 h. Temperature of mixing was based on a normalized viscosity defined as the temperature at which the binder had a viscosity of 500 cP, approximately. Then, 258.5 g of binder (6.0 % wt) heated for 4 h was added to the sand and mixed for 2 minutes using a mechanical mixer. After that, 1200 g of the mixture were put into a pre-heated gyratory mould of 100 mm diameter and compacted by applying 40 gyrations to give a specimen air void content of 5.0 ± 1.0 % as measured by the compactor using a maximum density value of 2.284 Mg/m^3. Three specimens per batch and 4 batches were used to produce a total of 12 identical specimens per PMB.
Sand mixture specimens were then tested for stiffness, oxidative ageing, adhesion (water sensitivity), deformation resistance and low temperature cracking resistance.

- Stiffness was determined using the indirect tensile stiffness test. The test was carried out at 20 ^{0}C in accordance with EN 12697-26 Annex C (IT-CY). Six (6) gyratory specimens prepared as before were used and the mean stiffness value was determined.
- Oxidative ageing was evaluated by determining the stiffness ratio after oven ageing. Oven-aged specimens were conditioned in a fan-assisted oven at 85 ^{0}C for 120 h prior to testing. Three (3) gyratory specimens were used. Mean stiffness ratio (before and after ageing) was then determined.
- Adhesion/water sensitivity was evaluated by determining the stiffness ratio after water conditioning. Water conditioning regime followed EN 12697-12 (Method A), i.e. vacuum saturation followed by water conditioning at 40 °C for a period of 70 h. Three (3) gyratory specimens were used and the mean stiffness ratio (before and after water conditioning) was determined.
- Deformation resistance was evaluated using the cyclic compression test. This test is similar to that described in EN 12697-25 Method A. The test conditions were 40 ^{0}C temperature and 50 kPa peak-to-peak axial load. Failure was defined as 10 % axial strain or 10000 cycles. Mean creep rate (microstrain/cycle) of two specimens was calculated.
- Low temperature cracking resistance was evaluated by means of the indirect tensile strength (ITS) test. The test was carried out at 0 ^{0}C in accordance with EN 12697-23. Three (3) gyratory specimens prepared as before were used and the mean indirect tensile strength value was reported.

Results for the sand mixture tests are presented in Table 3. It can be seen first that the stiffness of the sand mixtures depended on the type of binder. Also, the stiffness of the sand mixture with the 40/60 pen was the highest. Oxidation of the sand mixture with the 40/60 pen was, on the other hand, less severe than with the PMBs, as seen from the oxidative ageing ratio. Water sensitivity ratio and ITS values of the sand mixture with the 40/60 pen were lower than those with the PMBs suggesting less resistance to moisture damage and low temperature cracking. Large differences in creep rate values were also observed between the sand mixtures with different PMBs, indicating that resistance to deformation was largely dependent on PMB type.

Table 3: Sand mixtures properties

Binder	Grade	PMB Class	Stiffness (MPa)	Oxidative ageing (Ratio)	Water sensitivity (Ratio)	Deformation resistance (µm/m)	Cracking resistance (kPa)
50pen	40/60	-	1654	1.27	0.63	-	1.6
PMB1	45-80/45	A	1350	1.30	0.85	1150	-
PMB2	65-105/45	A	634	2.25	0.90	355	2.00
PMB3	45-80/50	B	1214	1.51	1.44	156	2.30
PMB4	10-40/80	D	1550	1.40	1.02	50	2.15
PMB5	25-55/60	E	1083	1.82	1.45	31	2.30
PMB6	25-55/75	C	850	2.00	1.05	200	2.25

3. ASPHALT MIXTURES

3.1 Materials

Hardstone aggregate and limestone filler were used to produce a 14 mm Asphalt Concrete (AC) binder course mixture (AC 14 bin). A 40/60 pen bitumen and various PMBs were used to manufacture mixtures with the same composition and grading. Binder content for all the mixtures was 5.5 %.
The asphalt mixtures were prepared by heating the aggregates and bitumen at the recommended mixing temperature. Hot aggregates were mixed for 30 seconds in a mechanical mixer and hot bitumen was then added to the aggregate blend and mixed for a further 2 ½ minutes. The mixtures were then compacted to slabs using a laboratory roller compactor.

3.2 Workability

The gyratory compactor was used to assess the workability of the mixtures. Proportioned aggregates blends and binder were mixed at the recommended temperature and compacted in 100 mm moulds. Three specimens per mixture were compacted. The load (stress) applied by the gyratory compactor was 600 kPa, the angle was 1.25^0 and rotation speed was 30 rpm. Furthermore, the number of gyrations selected was 100. In order to determine air voids of gyratory compacted specimens, the maximum densities of the mixtures were first determined.
Results presented in Table 4 showed that mean air voids at 100 gyrations varied between 3.6 % and 5.0 %. Also, the type of PMB did not have a large effect on the resulting air voids as all the mixtures were compacted at temperatures between 140 and 160 ^{0}C. Air voids were predominantly controlled by the volume of binder, which was the same for all the mixtures.

3.3 Water sensitivity

Resistance to moisture damage was evaluated by means of the water sensitivity test in accordance with EN 12697-12 (Method A). Six cylindrical specimens 100 mm diameter cored from laboratory prepared slabs were used. A dry subset (3 specimens) was maintained at 15 ^{0}C in a temperature controlled cabinet. A wet subset (3 specimens) was conditioned by applying a vacuum residual pressure of 6.7 kPa for 30 minutes followed by water conditioning at 40 °C for a period of 70 h. Indirect tensile strength tests were then carried at 15 ^{0}C and the Indirect Tensile Strength Ratio (ITSR) was then determined. Results presented in Table 4 showed that the ITSR values of all the mixtures were above 80 % which indicates good resistance to moisture damage. ITSR value for the 40/60 pen bitumen was the lowest, suggesting less resistance to moisture damage. Also, the PMB type did not have a large effect on water resistance which appears mainly controlled by the air void content.

Table 4: Asphalt mixtures properties

Mixture	Workability	Water sensitivity	Resistance to deformation		Stiffness	Resistance to fatigue	Resistance to cracking
	Voids	ITSR	WTS_{Air}	PRD_{Air}	IT-CY	ε_6	K_{Ic}
	%	%	mm/10^3 cycles	%	MPa	microstain	N/mm$^{3/2}$
AC 14 40/60	3.6	87.7	0.62	28.1	4032	79	32.1
AC 14 PMB1	4.0	107.7	0.62	27.8	2140	120	31.5
AC 14 PMB2	4.9	94.4	0.21	12.1	1659	-	28.9
AC 14 PMB3	5.0	106.6	0.14	9.4	2184	-	31.1
AC 14 PMB4	4.2	99.5	0.05	4.4	4998	140	33.9
AC 14 PMB5	3.9	107.8	0.08	6.2	3336	-	33.4

3.4 Deformation resistance

Deformation resistance was evaluated by means of the wheel tracking test as per EN 12997-22. Wheel tracking tests were carried using a small size device, conditioning in air. Laboratory compacted slabs 300 x 300 x 50 mm^3 were used. Two specimens per mixture were tested. The tests were performed at 60 ^{0}C and the number of load cycles applied was 10,000. Proportional rut depth (PRD_{AIR}) and wheel tracking slope (WTS_{AIR}) were then determined from the tests.
Wheel tracking test results are presented in Table 4. Results showed that the mixture with the 40/60 pen grade binder was less resistant to permanent deformation than the mixtures produced with PMBs. Furthermore, large differences in deformation resistance were obtained for the different grades of PMBs.

3.5 Stiffness

Stiffness modulus was determined using the indirect tensile stiffness test in accordance with EN 12697-26 Annex C (IT-CY). Tests were carried out at 20 ^{0}C and the loading time was 124 ms. Cylindrical specimens 100 mm diameter and 50 mm height cored from slabs were used. Six specimens per mixture were tested.
Results presented in Table 4 showed that the stiffness of the mixtures depended on the type of binder.

3.6 Fatigue resistance

Fatigue resistance was determined using the 4PB fatigue test in accordance with EN 12697-24 Annex D (4PB-PR). Fatigue tests were performed at 20 ^{0}C and 30 Hz. Tests were carried out at different strain (microstrain) levels from 70 to 250 microstrain. Three strain levels were employed. At each strain six specimens were tested.
Fatigue data was used to derive a relationship between the strain (ε) and the number of cycles to failure, defined as the number of cycles to 50 % stiffness reduction (N_{50}). Strains and the corresponding fatigue lives were plotted on logarithmic scales, and a power equation was fitted through the experimental data in order to obtain a relationship between strain and fatigue life of the form $N_{50}=A(1/\varepsilon)^b$, where A and b are regression constants.
Fatigue curves are shown in Figure 3. Regression constants A and b, and R^2 values are presented in Table 5. Fatigue resistance of AC mixtures is given by the microstrain at 10^6 cycles (ε_6). Microstrain at 10^6 cycles values (ε_6) were determined from the plots of the strain vs number of cycles to failure, and are shown in Table 5. The higher the ε_6 value the better the resistance to fatigue.
Results indicated that the fatigue resistance of the AC 14 mixture improved greatly when a PMB was used, as seen by the ε_6 values. Differences between the fatigue resistance of the AC 14 mixtures with PMB1 and PMB4 were also observed.

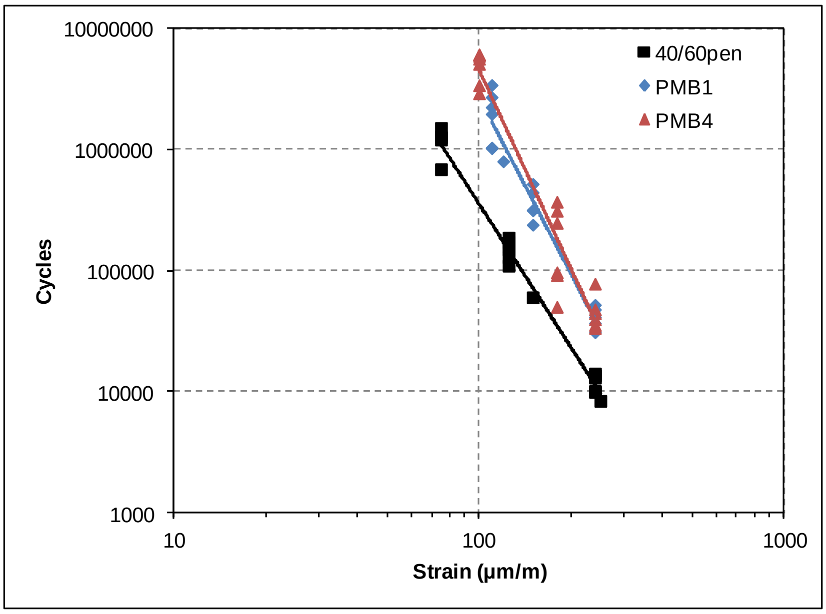

Figure 3: Fatigue lives

Table 5: Fatigue regression constants and microstrain at 10^6 cycles

Mixture	Grade	PMB Class	A	b	R^2	ε_6 (μm/m)
AC14 40/60	40/60	Not applicable	2.57 x 10^{13}	3.93	0.99	79
AC 14 PMB1	45-80/45	A	1.24 x 10^{16}	4.83	0.95	120
AC 14 PMB4	10-40/85	D	3.53 x 10^{17}	5.44	0.94	140

3.7 Fracture resistance

Fracture resistance was evaluated by means of the semi-circular bending (SCB) test as per EN 12697-44. In this test, a SCB specimen notched at the mid-point is loaded in a three point bending configuration. The maximum load (stress) sustained by the specimen and a geometric factor are then used to determine the fracture toughness (K_{Ic}). Fracture toughness is a measure of the resistance of a material to crack propagation.
SCB specimens were obtained by coring cylindrical specimens of 150 mm diameter (D) and 50 mm height (t) from slabs. These cylinders were cut perpendicular to the axis to obtain the semi-circular specimens, and then notched at the mid-point along the diameter in the direction of the load. Notch depth (a) was 10 mm and span (2s) was 120 mm. Tests were carried out at a displacement rate of 5 mm/min and at a temperature of 0 ^{0}C. Four SCB specimens per mixture were tested.
Results presented in Table 4 showed that fracture toughness values of the AC 14 mixtures with different binders were in general quite similar. Thus, for the test conditions used in the study, fracture toughness is primarily affected by the aggregate structure of the mixtures (grading) and the amount of binder in the mixture. So, for mixtures with similar aggregate skeleton and with a relatively high amount of binder, binder grade and PMB type had a limited effect on fracture toughness.

4. RELATIONSHIP BETWEEN BINDER AND MIXTURE PROPERTIES

4.1 Standard binder properties and asphalt properties

Standard binder properties presented in Table 1 have been correlated to mixture properties given in Table 4 and are shown in Figure 4. It can be seen that the correlation between binder penetration (specification mid-point) and mixture stiffness is very weak (R^2 = 0.25) (Fig. 4a). Similarly, there is a weak correlation between binder penetration and the deformation resistance of the mixture given by the proportional rut depth (PRD) (R^2 = 0.34) (Fig. 4b).
The relationship between binder softening point (minimum value) and mixture stiffness is shown in Fig. 4c. It can be seen that this correlation is quite strong (R^2 = 0.82). There is, however, a weak correlation between binder softening point and the deformation resistance of the mixture (R^2 = 0.29) (Fig. 4d).
Force ductility is a measure of the cohesive strength of a binder. Force ductility values (minimum specified values) of the PMBs used in the study presented in Table 1 were determined at different temperatures, thus, it was difficult to rank the binders according to this parameter or to relate this binder property to any mixture property.
Fraass breaking point temperature has been traditionally related to the low temperature cracking potential of a binder. Binders with low Fraass temperature are in general less brittle at low temperatures and are more suitable for cold weather conditions. Fig. 4e shows the relationship between Fraass temperature of the binder (maximum specified values) and fracture toughness of the mixture. It can be seen that the correlation between these two parameters is quite weak (R^2 = 0.49) (Fig. 4e). Also, the fracture toughness of the mixture measured at 0 ^{0}C increased as the Fraass temperature increased. So, the Fraass breaking point temperature could be interpreted as a measure of the toughness of a binder, the higher the Fraass temperature the higher the toughness of the binder. It should be noted, however, that the differences in the fracture toughness of the mixtures were relatively small. It is believed that, for the type of test and conditions used in the study, the fracture toughness is primarily controlled by the aggregate structure (grading), the volume of binder in the mixture (binder content) and the air voids, and not by the type of binder. However, a relationship may indeed exist between these two parameters when the test conditions are others than those used in the current study
Finally, binder elastic recovery could provide an indication of the fatigue performance of an asphalt mixture. Data presented in Table 4 showed that the AC 14 asphalt mixture with PMB1 had worse fatigue resistance than the same mixture with PMB4, despite PMB1 had higher minimum elastic recovery (60 % min) than PMB4 (50 % min) (Fig. 4f). This suggests that the elastic recovery is not a suitable parameter to rank asphalt mixtures according to their resistance to fatigue damage.

4.2 Critical binder workability temperature and asphalt properties

Figure 5 shows the relationship between binder critical workability temperature (T_C) and mixture properties. It can be seen first that the compacted air voids of the mixtures did not depend on binder critical workability temperature (T_C) as all the mixtures were compacted at temperatures well above the critical workability temperature (Fig. 5a).
It can also be seen that the stiffness of the mixtures increased as the critical binder workability temperature increased (Fig. 5b). Similarly, the mixtures resistance to deformation increased (rut depth decreased) as the critical binder workability temperature increased (Fig. 5c). This might suggest that PMBs with higher viscosities result in higher mixture stiffness and resistance to deformation. It should be noted, however, that the correlations between these parameters were relatively weak, as seen by the R^2 values.
Mixture resistance to moisture damage (water sensitivity) was not related to binder critical workability temperature (T_C) (Fig. 5d) but to binder content and air void content. Limited fatigue data also suggested that mixtures with PMBs with higher binder critical temperature (T_C) might result in enhanced fatigue life (Fig. 5e). As regards low temperature cracking, fracture toughness increased as the binder critical temperature increased (Fig. 5f).

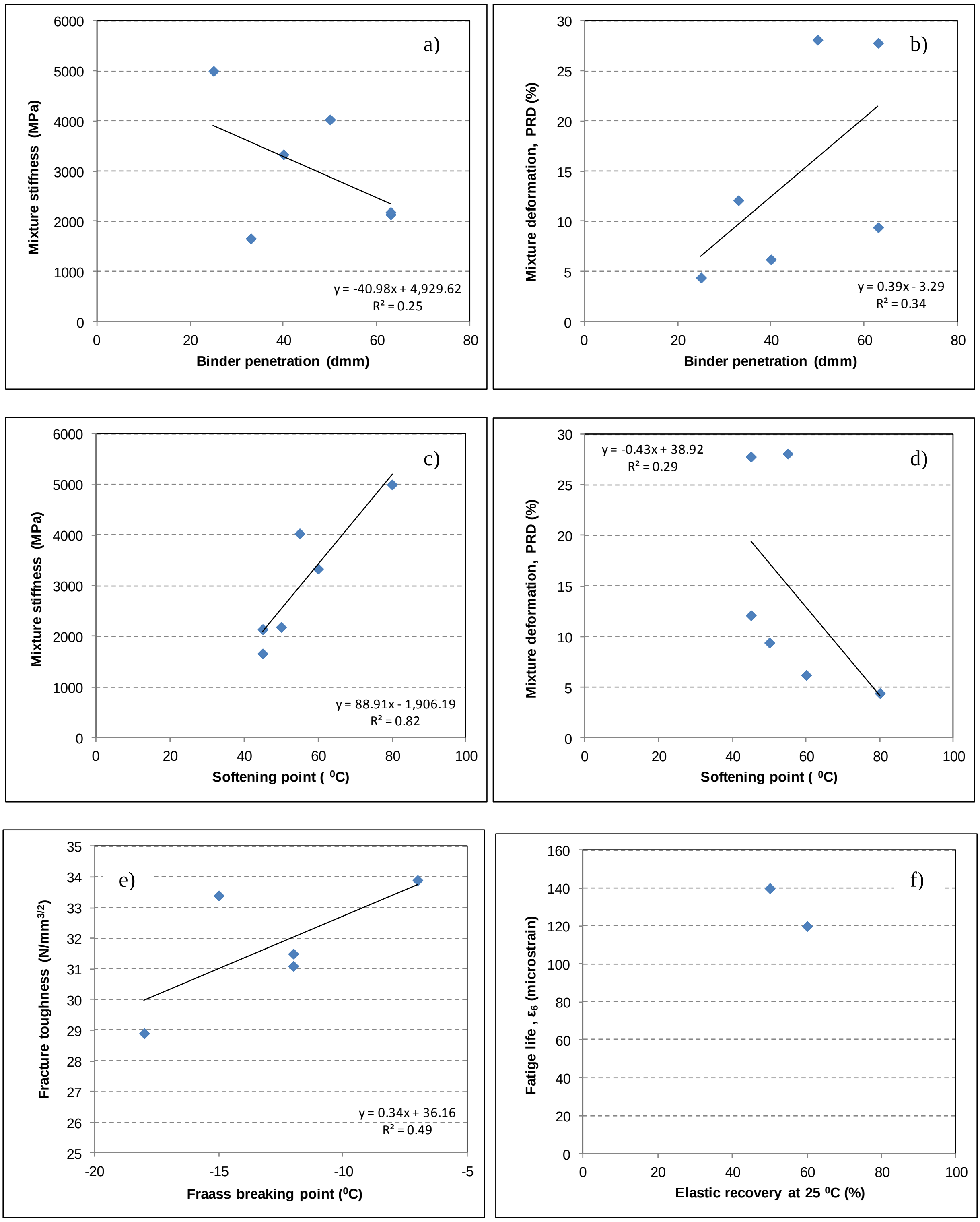

Figure 4: Relationship between standard binder properties and asphalt mixture properties

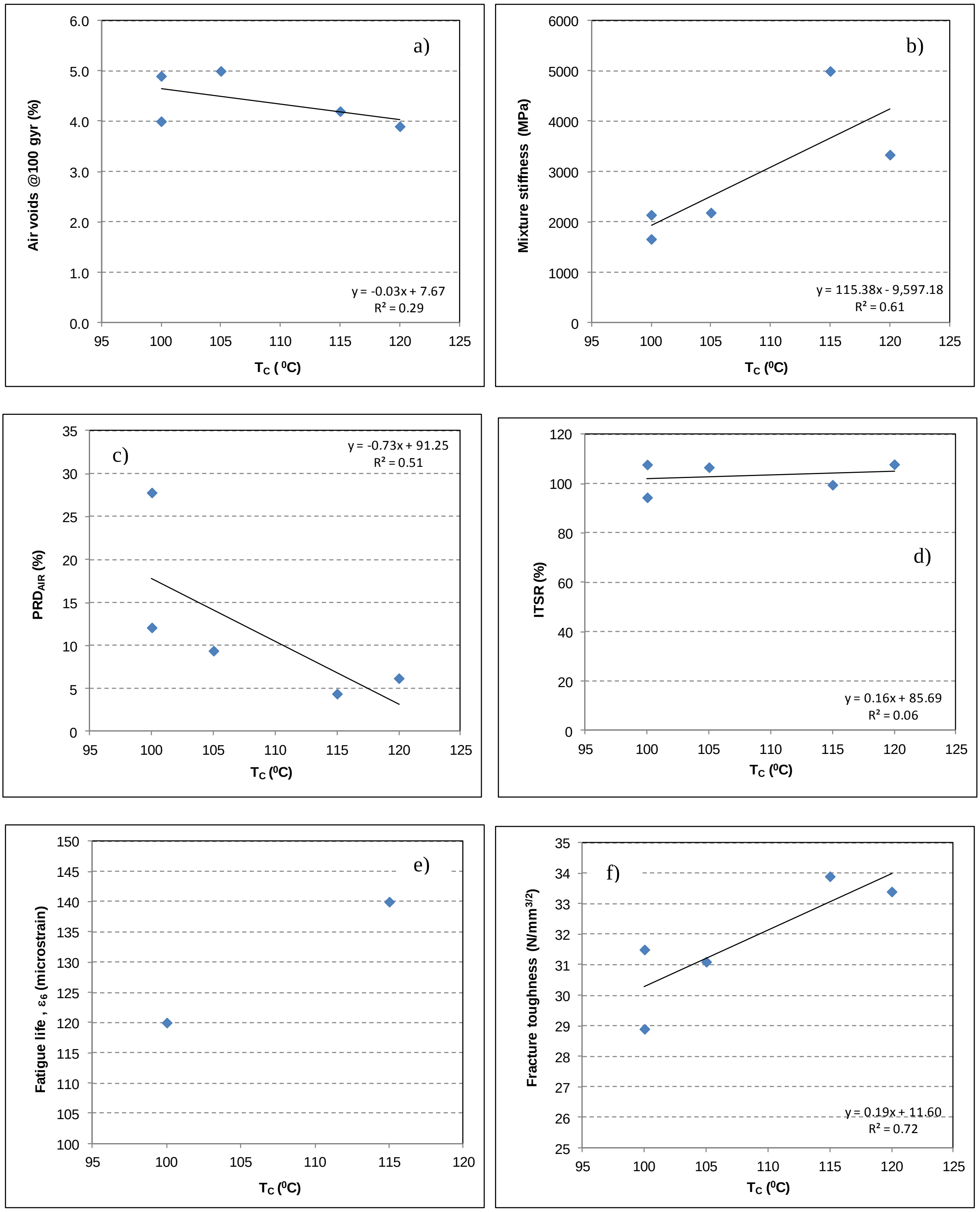

Figure 5: Relationship between binder critical workability temperature and asphalt mixture properties

4.3 Sand mixtures properties and asphalt properties

Binder properties derived from sand mixtures have been correlated to mixture properties and are shown in Figure 5. It can be seen that the correlation between binder stiffness and mixture stiffness is relatively good (R^2 = 0.53) (Fig. 6a). There is also a strong correlation between binder deformation (creep rate) and the deformation resistance of the mixture given by the proportional rut depth (PRD) (R^2 = 0.99) (Fig. 6b). There is also relatively good correlation between binder adhesion (moisture sensitivity ratio) and mixture resistance to moisture damage as measured by the ITSR (R^2 = 0.55) (Fig. 5c). It has also been found that the indirect tensile strength (ITS) at 0 ^{0}C of the sand mixtures was not related to the fracture toughness of the asphalt measured at the same temperature. It should be noted, however, that the fracture toughness values of the asphalt mixtures were in general very close. No clear trends were found between sand mixture properties like stiffness and ITS, and mixture fatigue properties as seen in Figs. 6e and 6f. This suggested that none of the tests on the sand mixtures were able to depict the fatigue behaviour of the asphalt mixtures with different PMBs.

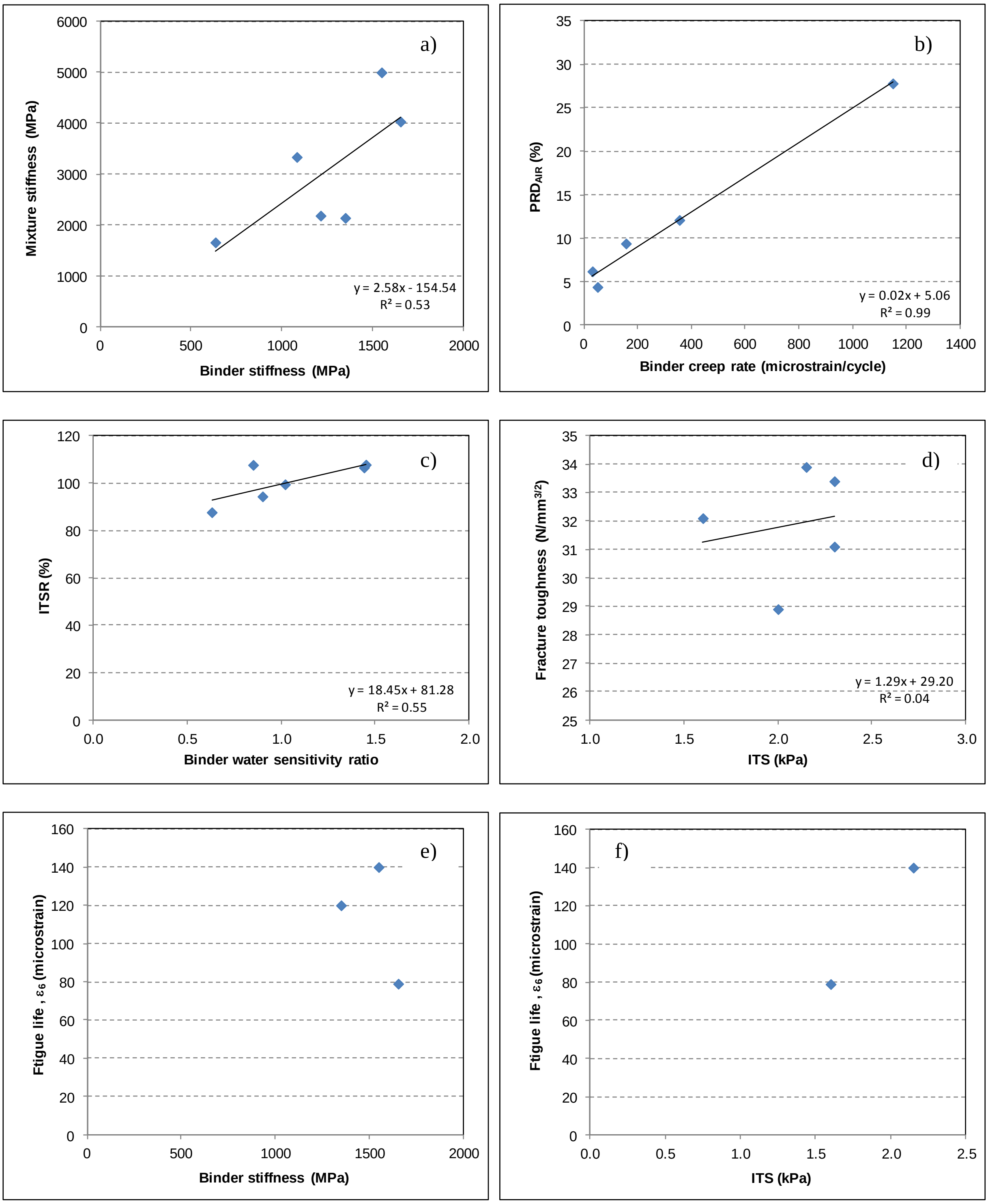

Figure 6: Relationship between sand mixture properties and asphalt mixture properties

5. DISCUSSIONS

The aim of this work was to develop a protocol for the selection of PMBs which relied on a binder parameter that could be related to the workability and therefore compactability of an asphalt mixture during installation. Polymer modified binders are in general more viscous than conventional bitumen particularly at rolling and compaction temperatures. Thus, under certain conditions, asphalt mixtures containing PMBs can be difficult to compact which can lead to excessive in-situ air voids. This, in turn, can result in reduced durability due to the acceleration of oxidation (ageing) and water ingress (moisture damage). If the mixture produced with the PMB is not fully compacted, its performance might be worse than that of a properly compacted non polymer modified conventional mixture. More importantly, the service life of a poorly compacted mixture can be considerable reduced and the material might need to be replaced within the first few years of installation.

The critical binder workability temperature (T_C) of a PMB defined as the temperature at which the viscosity of the binder falls between 4000 cP and 8000 cP has been used to classify the binders into five classes from the less viscous or most workable (Class A) to the most viscous or least workable (Class E). This criteria can be used for instance when selecting binders for different climatic conditions or for different seasons, winter and summer. For instance, depending on the application Class A and Class B PMBs could be used in cold regions whereas Class C and Class D might be only allowed in mild or hot regions. Similarly, Class A or Class B binders could be used during summer and winter periods whereas the use of Class C and Class D PMBs might be restricted to the summer months. Other possible applications could be haulage time, for instance maximum haulage times for Classes A and B could be limited to 4 h, 3 h for Classes C and D and 2 h for Class E. The binder selection could also be influenced by the intended mixture layer thickness and likely cooling rates.

Test on the standardized sand mixtures have been used to establish threshold values for the different properties measured. Table 6 shows an example of the proposed limiting values for different PMB Classes. These tests can be used as a quality control measure for PMBs. They can also be used to assess new PMBs or new polymers. Furthermore, the tests on the sand mixtures are relatively simple and can be carried out by both the bitumen and the asphalt suppliers as the equipment required to perform these tests is commonly available in most asphalt laboratories. Also, the full characterization of a PMB can be carried out in a relatively short period of time (5 days) compared to a full evaluation of a polymer modified asphalt mixture, which could take much longer (1 month). For product declaration and CE marking purposes, however, the asphalt mixture will have to be tested following standard procedures. Once the PMB is characterized using this protocol it can then be used in different types of asphalt mixtures without the need of performing the full set of asphalt tests.

Table 6: PMB performance indicators

<table>
<tr><th>PMB Class</th><th>Critical workability temperature T_C (^{0}C)</th><th>Stiffness (MPa)</th><th>Oxidative ageing (Ratio)</th><th>Water sensitivity (Ratio)</th><th>Deformation resistance (μm/m)</th><th>Cracking resistance (kPa)</th></tr>
<tr><td>A</td><td>100</td><td rowspan="5">Declared value</td><td rowspan="5">≤ 2.5</td><td rowspan="5">≥ 0.80</td><td>≤ 2000</td><td rowspan="5">≥ 2.0</td></tr>
<tr><td>B</td><td>105</td><td>≤ 500</td></tr>
<tr><td>C</td><td>110</td><td>≤ 500</td></tr>
<tr><td>D</td><td>115</td><td>≤ 100</td></tr>
<tr><td>E</td><td>120</td><td>≤ 100</td></tr>
</table>

6. CONCLUSIONS

Based on the laboratory work to characterize polymer modified binders the following conclusions can be drawn:

- Viscosity data showed that at typical installation temperatures of 135 ^{0}C the viscosities of all the PMBs were similar and below 3000 cP but when the temperature was reduced large differences in viscosities started to appear. Thus, although an asphalt mixture with a low viscosity binder might be still workable at this temperature, the same mixture with a high viscosity binder might be too stiff and difficult to compact.
- The critical workability temperature of a PMB (T_C), defined as the temperature at which the viscosity of a binder falls between 4000 cP and 8000 cP, was introduced to classify the binders into five classes from the most workable (Class A) to the less workable (Class E). This classification can be use when selecting binders for different climatic conditions (hot or cold), or different seasons (summer or winter), or to limit haulage time depending on the type of binder used.
- A standardized sand mixture was used to derive PMB properties including stiffness, oxidative ageing, adhesion (water sensitivity), deformation resistance and low temperature cracking resistance. Differences in these properties were observed between sand mixtures with 40/60 pen grade bitumen and the PMBs, and between different types of PMBs.
- Fatigue resistance of the AC 14 dense asphalt mixture improved greatly when a PMB was used instead of paving grade bitumen. Better fatigue was also observed for PMB4 (Class D) than for PMB1 (Class A). Similarly, asphalt resistance to deformation improved when PMBs were used but the extent of this depended on PMB grade. Also, asphalt mixtures with PMBs showed better resistance to water damage compared to that with conventional bitumen.

- Relationships were established between the properties of PMBs and those of a dense asphalt mixture produced with the same binders. Good correlations were obtained between softening point and mixture stiffness (R^2 = 0.82), critical workability temperature of the binder (T_C) and fracture toughness of the asphalt mixture (R^2 = 0.72) and sand mixture resistance to deformation (creep rate) and asphalt mixture resistance to deformation (rut depth) (R^2 = 0.99).
- PMBs performance indicators based on the critical workability temperature (T_C) and on the properties of the standardized sand mixture were proposed. These set of properties and limits can be used as a quality control measure for PMBs. They can also be used to assess new PMBs from a new supplier or new polymers.

REFERENCES

[1] Eurobitume. European Bitumen Consumption 2013. Brussels, Belgium. http://www.eurobitume.eu/system/files/EuropeanBitumenConsumption2013.pdf.

[2] Comité Européen de Normalisation (CEN), EN 14023: 2010 Bitumen and bituminous binders – Specification framework for polymer modified bitumen.

[3] Superpave protocols for modified asphalt binders, H. U. Bahia, D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and M. R. Anderson, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Project NCHRP 9-10, Final Rep., 2000.

[4] The Shell Bitumen Handbook (6th Ed.), R. Hunter, A. Self and J. Read, Shell International Petroleum Company Ltd, ICI Publishing, London, 2015.

[5] Development of SHRP binder specification, D. A. Anderson and T. W. Kennedy, Journal of the Association of Asphalt Paving Technologists, Vol. 62, pp. 481 – 507, 1993.