Hindawi
Advances in Materials Science and Engineering
Volume 2020, Article ID 4930646, 9 pages
https://doi.org/10.1155/2020/4930646

Research Article

Mechanical Characterization and Chemical Identification of Clear Binders for Road Surface Courses

Andrea Grilli[1], **Maurizio Bocci**,[2] **Amedeo Virgili**,[2] **and Carla Conti**[2]

[1]*Università degli Studi della Repubblica di San Marino, via Consiglio dei Sessanta, 99-47890 San Marino, San Marino*
[2]*Università Politecnica delle Marche, via Brecce Bianche, 1-60131 Ancona, Italy*

Correspondence should be addressed to Andrea Grilli; andrea.grilli@unirsm.sm

Received 1 September 2019; Revised 8 December 2019; Accepted 28 December 2019; Published 20 January 2020

Academic Editor: María Criado

The development of non-black asphalt mixtures for surface courses may play a significant role to improve functional, aesthetic and environmental issues of road pavements. Nowadays, the development of clear binders as substitutes for traditional bitumen in asphalt mixtures, which combine durability and mechanical properties, exalting the color of pavements for a better integration of road networks in urban and environmentally sensitive areas, is undoubtedly a timing challenge. However, the selection and classification of clear binders are often based only on color and standard requirements referred to traditional bitumen that do not describe consistently the binder behavior. A better understanding on clear binder properties is required to guide the aggregate selection and the mix design for surface layer, merging safety, aesthetical and environmental benefits into long lasting pavement. This paper presents a comprehensive experimental program, including empirical tests, infrared spectrum analysis, and rheological testing over a wide range of temperature and frequency, to determine the overall mechanical behavior of three clear binders. Results highlighted that the selected clear binders differ from traditional bitumen in terms of mechanical behavior. Different composition or origin can induce to completely different performance. Moreover, the combination of several testing procedures allowed suggesting specific application methods and uses for the three clear binders.

1. Introduction

A new awareness on environmental impact and driver safety has risen more and more interest in non-black asphalt pavements since the color of the road pavement helps in achieving numerous advantages. Indeed, the development of non-black asphalt mixtures may play a significant role to improve functional, aesthetical, and environmental issues for road pavements [1, 2].

Currently, non-black asphalt pavements are intended to satisfy specific functional and safety requirements separating different traffic flows through well-evident pedestrian, bus, or bicycle lanes, or identifying distinctive zones such as intersections, roundabouts, or border of residential areas. Moreover, a non-black asphalt pavement facilitates the integration of the road network in a human context, mitigating and giving an additional contribution to the aesthetical perception of the overall surrounding area. For these reasons, non-black asphalt pavements also offer favored solutions in historic center, touristic areas, or pathways [3].

Non-black asphalt pavements can be obtained in several ways such as using colored aggregates and pigments to traditional bitumen or clear binders (or a combination of them) in surface treatments and in asphalt mixtures for surface layer [4]. However, after weathering and wearing, the color of aggregates becomes dominant in influencing the aesthetic and durability of pavement color [2]. Therefore, the most effective and durable method appears to be the selection of aggregates, in terms of both physicochemical properties and color, and translucent binders, or so-called "clear binders."

The transparence of these binders allows the natural color of mineral aggregates to be really exalted over time, along with complying binding and covering performance. An additional paramount potentiality in reducing environmental impact can be obtained when using white aggregate and clear binder. Really, enhanced photometrical characteristics allow energy consumption for lighting to be significantly reduced with the largest advantages in tunnels [5, 6] and the urban heat island phenomenon to be substantially moderated [7, 8].

In the past, clear binders were mainly used in surface layer mixtures only for pedestrian areas. Nowadays, the improvement of the mechanical performance makes clear binders suitable in trafficked road, too.

Clear binders are special formulations with a yellowish aspect that may contain tackifying resin, dispersing oil, materials of vegetal origin, or polymers [9]. Clear binders can be mainly distinguished in low asphaltene content bitumen, natural binder, and synthetic binder [3, 10]. Though different clear binders offer similar aesthetical impact and mimic the mechanical properties of bitumen, origin and production processes influence their mechanical behavior, durability, and ageing [11]. Therefore, a thorough understanding of clear binder properties over a wide range of temperature and frequency must be considered to address the selection of constituent materials and to deal with the mix design, accurately.

2. Objectives

Clear binders are asked to improve the road safety, aesthetic, and environmental impact of pavements, ensuring high mechanical performance to withstand the vehicular traffic. Currently, a lack of standardized methods to classify and to characterize clear binders (they are not polymer modified bitumens, neither paving grade bitumens) makes the selection of clear binders a hazardous and rash procedure, often without matching their specific characteristics with application method and use. A better understanding on clear binder properties is needed to identify specific uses (climatic and traffic conditions) and applications (production, laying and compaction procedures). Future research on a proper mix design method for surface layer mixtures should merge safety aesthetical and environmental benefits into long lasting pavement.

This paper focuses on the chemical identification and mechanical characterization of three clear binders that represent an alternative to traditional bitumen when used in asphalt concrete for surface courses.

In this context, the objectives of this paper are as follows:

(1) Chemical identification and determination of components in clear binders by Fourier transform infrared spectroscopy (FTIR) testing

(2) Verification of empirical testing to characterize and to classify clear binders

(3) Investigation on the viscoelastic behavior of clear binders by means of rheological characterization in a broad range of temperature and frequency

(4) Recommendation for use/selection of the three clear binders in specific circumstances (traffic loading and climate condition)

3. Experimental Program and Testing Procedures

Three yellowish clear binders (so-called K, R, and C) coming from different production processes were selected as the most representative in the Italian market. The experimental program consisted in three main phases:

(1) Identification and qualitative analysis of binder components by means of FTIR

(2) Empirical characterization to classify clear binders using the well-known framework specification for bituminous binders for a preliminary ranking

(3) Rheological characterization to determine the mechanical properties of clear binders as a function of loading frequency and temperature

In the first phase, FTIR allowed studying the interactions of matter with electromagnetic radiation using electromagnetic waves within a wide, continuous range of frequencies. Fundamental vibrations, mainly stretching and bending of chemical bonds as well as some rotational motions in molecules, were detected in the middle infrared region within the interval of wavenumbers from 4000 to 600 cm^{-1}. The intensity of signal, passing through the probing sample was measured at each specific wavenumber (wavelength or frequency) by a detector resulting in an interferogram which was immediately transformed into an infrared spectrum by the mathematical function Fourier transform. In this case, spectral data were obtained with a PerkinElmer Spectrum GX1 FT-IR, in transmission mode on NaCl plates. The spectral resolution was 4 cm^{-1}. Baseline (two-point linear fit), second derivative, Fourier self deconvolution, and low Gaussian character curve fitting procedures were applied. For data handling, Spectrum v.6.3.1 and Grams AI software packages were used.

For the second phase, the empirical characterization of the binders was based on the EN 14023 with regards to the following:

(i) Penetration value at 25°C complying with EN 1426 to evaluate the consistency of the binders at 25°C

(ii) Softening point by ring and ball testing in accordance with EN 1427 to evaluate the consistency of the binders at high service temperature and the transition temperature from viscoelastic to viscous behavior

(iii) Elastic recovery at 25°C complying with EN 13398 to evaluate the behaviour of binders under large deformation

(iv) Rolling thin film oven test (RTFOT) complying with EN 12607-1 to evaluate the effect of the short-term ageing on the binders in term of mass variation, retained penetration, and increase of softening point

(v) Viscosity at 100, 135, 160, and 180°C in accordance with EN 13302 to evaluate the consistency of binders at the operative temperatures (storage, pumping, mixing, compacting, and other handling operations)

Moreover, the Ancona stripping test (AST) was used to evaluate potential stripping of a binder-aggregate system [12]. The AST was selected for this preliminary study on the affinity between clear binders and aggregate. The past experience helped in the interpretation of results (transparent or yellowish color does not facilitate the assessment of the degree of binder coverage on aggregate particles) and sample preparation method. A sample of binder-covered aggregates (60 g of coarse aggregate, passing 10 mm sieve and retained on 6 mm sieve, mixed with 3 g of binder) was placed in a 600 ml beaker with 200 ml of distilled water. The 600 ml beaker was then placed in a 2000 ml beaker containing 600 ml of boiling water for 45 minutes. At the end of this period, the binder-aggregate system was removed from the beaker and cooled at room temperature, and a visual assessment of the stripping percentage was made by three technicians. In this study, the three clear binders were mixed with a siliceous coarse aggregate at the mixing temperature of the specific binder (T_{mix}) as indicated by viscosity testing. The siliceous coarse aggregate was selected having suitable physical properties (Los Angeles coefficient = 17; water absorption = 1.22%; polished stone value = 50; shape index = 10) and luminance (69.3 cd/m^2) to exalt the aesthetical aspect and photometric characteristics of a surface layer.

In the third phase, the rheological characterization of the clear binders was performed by means of sinusoidal oscillatory tests using a dynamic shear rheometer (DSR). Strain sweep tests were carried out to determine the linear viscoelastic limit and, consequently, a suitable deformation amplitude ($\gamma = 0.5\%$). The frequency sweep with a strain amplitude $\gamma = 0.5\%$ was conducted to measure the complex modulus G^*, storage modulus G', loss modulus G'', and the phase angle δ over a frequency range from 0.159 to 15.9 Hz (0.159, 0.283, 0.503, 0.894, 1.591, 2.833, 5.029, 8.945, and 15,915 Hz), i.e., from 1 to 100 rad/s, and over a temperature range from 82 to 34°C and from 34 to 4°C (6°C intervals) using the 25 mm plate and the 8 mm plate, respectively (EN 14770: 2012). Although clear binders resulted rheological complex materials, the experimental data measured at different temperatures were superposed onto master curves at a reference temperature ($T_r = 20$°C) to extend the investigation over a wide range of loading frequency [13]. The data analysis considered the average values from three repetitions for each test.

The obtained results on clear binders were compared with a 70/100 paving grade bitumen (considered as a typical unmodified bitumen) and a styrene butadiene styrene (SBS) modified bitumen PMB 45/80-70 (considered as a typical modified bitumen).

4. Analysis of Results

4.1. Chemical Identification. When the infrared radiations pass through a sample, some of them are absorbed and others are transmitted. The resulting spectrum represents the molecular absorption or transmission, creating a molecular fingerprint of the sample. Like a fingerprint, no two different molecular structures produce the same infrared spectrum. Figure 1 shows the FTIR spectra for the selected clear binders in comparison with a traditional bitumen (70/100 paving grade bitumen) and a styrene butadiene styrene (SBS) modified bitumen (PMB 45/80-70).

The infrared spectrum of K (light blue line), analogously to a 70/100 traditional bitumen (black line), mainly shows hydrocarbon absorptions like CH_2 and CH_3 stretching in the range of 3000–2800 cm^{-1}, CH_2 and CH_3 bending at 1460 and 1376 cm^{-1}, and a weak band at 1600 cm^{-1} due to the presence of aromatic linkages. On the other hand, analogously to a polymer modified bitumen PMB 45/80-70, additional bands at 969 and 699 cm^{-1} due to the presence of aliphatic C=C double bonds (SBS) can be clearly identified. Moreover, bands at 1215 and 753 cm^{-1} attributable to CH_2 out of plane bending deformations can also be highlighted. The data analysis suggests that the origin of K derives from a deasphalted bitumen (low amount of asphaltenes) modified with SBS polymer to perform a satisfactory link with the matrix.

The spectra of C (green line) and R (grey line) can be assigned to hydrocarbon absorptions, like CH_2 and CH_3 stretching in the range of 3000–2800 cm^{-1} and CH_2 and CH_3 bending at 1460 and 1376 cm^{-1}. For both binders, high amount of CH_3 presumes short chains, implying low stiffness at ambient temperature. C and R show a spectrum like an aromatic phthalic polymer (ester, CO stretching in the range of 1740–1720 cm^{-1} and C-O stretching in the range of 1170–1070 cm^{-1}), suggesting a synthetic origin. Moreover, the C spectrum deconvolution highlights a band at 1715 cm^{-1} that would claim the presence of natural waxes [14].

As regards to polymer modification, the percentage of SBS was evaluated by the ratio between the reference bands at 1376 cm^{-1} (CH_3 symmetric band) and the characteristic bands at 969 and 699 cm^{-1} of the unsaturated component [15, 16]. The polymer blend as a modifier for bitumen provides a new route to enhance its rheological properties directly related to service performance. The unsaturation index was calculated as 8.2, 5.0, 4.9, and 2.3 for R, PMB 45/80-70, K, and C, respectively [17].

4.2. Empirical Characterization. The most common empirical tests for bitumen characterization were used to classify the selected binders, although results could not necessarily address the same deductions as for traditional bitumen.

The clear binders showed penetration and softening point values of the same magnitude of bituminous binders (Figure 2); hence, bitumen traditional testing may be considered to determine the clear binder consistency at service temperature (from 25°C to the transition temperature from viscoelastic to viscous behavior).

The selected clear binders are characterized by higher softening point and elastic recovery values than those of paving grade bitumens, due to the contribution of the polymeric modification as highlighted by FTIR.

Binder K showed penetration and elastic recovery values at 25°C similar to PMB 45/80-70, even if the softening point of K is close to the 70/100 paving grade bitumen [4]. In terms of consistency at service temperature, binder K could be considered as a paving grade bitumen with improved elastic recovery.

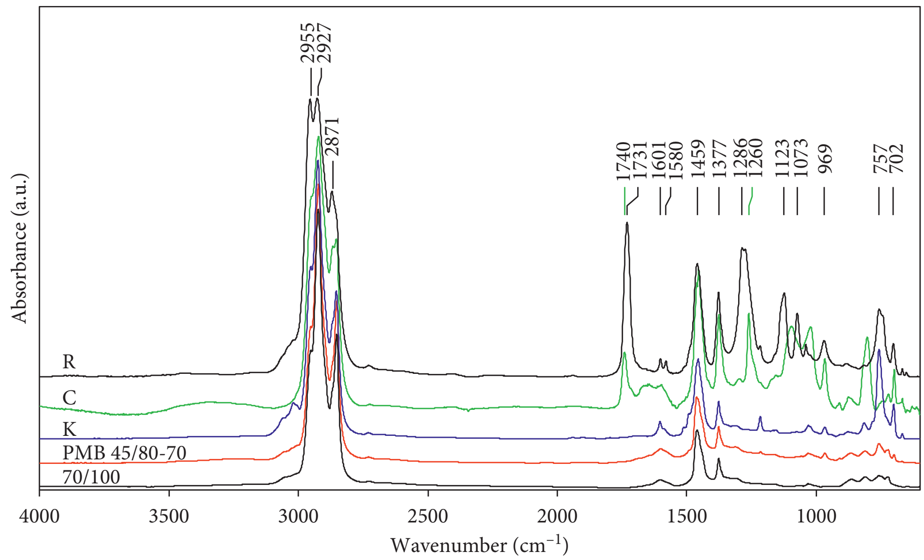


Figure 1: FTIR spectra for the selected binders in the range 4000–600 cm^{-1}.

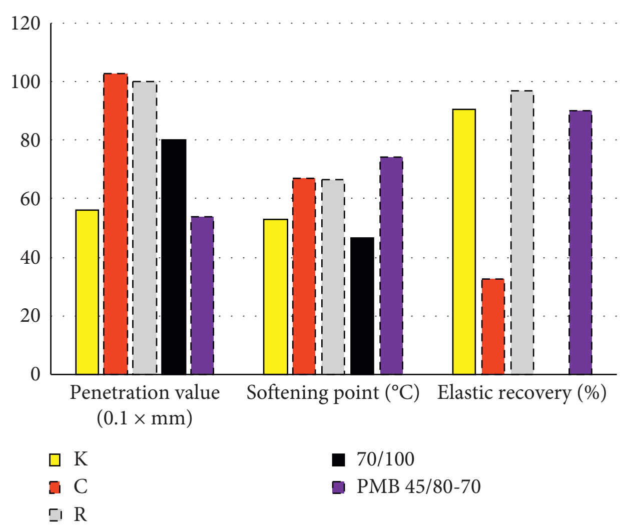


Figure 2: Penetration, softening point, and elastic recovery values of tested binders.

Binders C and R have the highest penetration values at 25°C; thus, in terms of consistency at 25°C, binders C and R could be considered softer than the 70/100 paving grade bitumen but with softening point similar to PMB 45/80-70. Moreover, the elastic recovery of binder R is even higher than PMB 45/80-70 confirming the findings from FTIR.

Clear binders showed resistance to short-term ageing process complying with the EN 12591 requirements for their specific grade as shown in Table 1.

The classification method for paving grade bitumens (EN 12591) has been extended to modified binders for road pavements having improved performances. Using the framework specification for polymer modified bitumens (EN 14023), the characteristics for polymer modified bitumens are classified into range of grades suitable for the manufacture of the materials for road construction and maintenance. Particularly, the designation of polymer modified bitumens comprises the penetration range and the minimum softening point. Following this principle, the nomenclature of K, C, and R should be 45/80-50, 65/105-65, and 65/105-65, respectively.

As far as the elastic recovery is concerned, binder C that showed the lowest elastic recovery value could not be included into a specified class. Note that, as reported by FTIR analysis, binder C had the lowest polymer content.

Dynamic viscosity tests showed that the viscosity values of binder C are similar to those of the 70/100 paving grade bitumen, whereas the other binders showed high viscosity values, closer to those of polymer modified bitumens. As the softening point of binder C is higher than that of a paving grade bitumen, binder C seems to melt quickly from about 60 to 100°C, changing from a modified bitumen-like consistency to a bitumen-like consistency. This behavior appears consistent with the supposition of the presence of natural waxes from FTIR analysis.

Table 2 reports the mixing and compaction temperatures (T_{mix} and T_{comp}, respectively) obtained by analysing the evolution of viscosity η versus temperature T using a power law relationship $\eta = a \cdot T^b$, where a and b are material experimental parameters.

Considering the recommended viscosity ranges for bitumen [4] during mixing and compaction phases of an asphalt concrete (i.e., 170 ± 20 mPa·s and 280 ± 30 mPa·s, respectively), the binder C has a mixing temperature of about 155°C and a compaction temperature of about 140°C, whereas binders K and R required the highest mixing and compaction temperatures probably due to the high concentration of polymers (Figure 3).

As far as binder stripping concerns, the visual inspection of samples established the following coverage percentages: 75% for binder K, 25% for binder C and 30% for binder R (Figure 4). Therefore, binder K showed the highest affinity with the selected siliceous aggregates. The assessment of the

Table 1: Effect of short-term ageing with RTFOT on tested binders.

Binder RTFOT—EN 12607-1	Mass variation	Penetration		Softening point	
	Δm (%)	P (mm × 10^{-1})	Retained P (%)	R&B (°C)	ΔR&B (°C)
K	−0.3	46	82	53.4	0
R	−0.8	97	97	68.2	2
C	−0.8	58	56	67.0	0
70/100	−0.7	41	52	58.0	11
PMB 45/80-70	−0.1	37	69	76.2	2

Table 2: Mixing and compaction temperatures of selected binders.

Material	a	b	T_{mix} (°C)	T_{comp} (°C)
K	$4.0830E+17$	$-6.8072E+00$	182	169
C	$8.0434E+15$	$-6.2605E+00$	153	141
R	$1.2453E+23$	$-9.1289E+00$	193	183
70/100	$2.4879E+18$	$-7.3836E+00$	155	145
PMB 45/80-70	$7.4602E+22$	$-9.1418E+00$	181	172

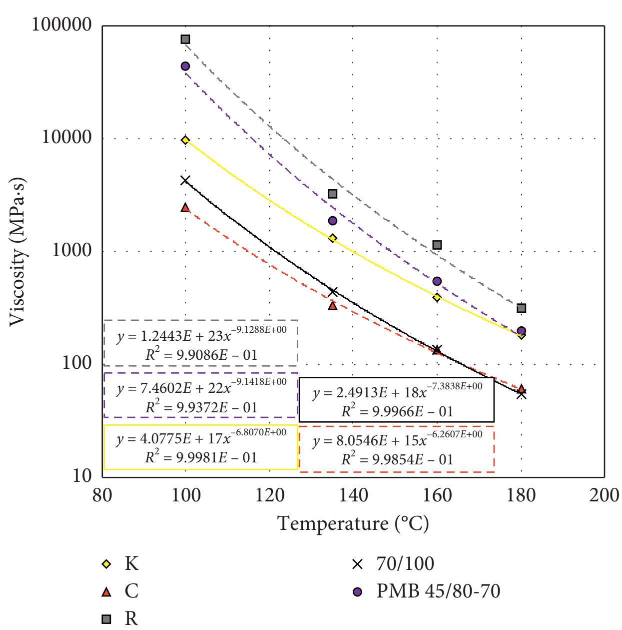


Figure 3: Viscosity values at high temperatures of tested binders.

degree of binder coverage on aggregate particles was carried out by drying the samples at room temperature for one day and using a torch to highlight the reflective portion of particles (portion covered by binder).

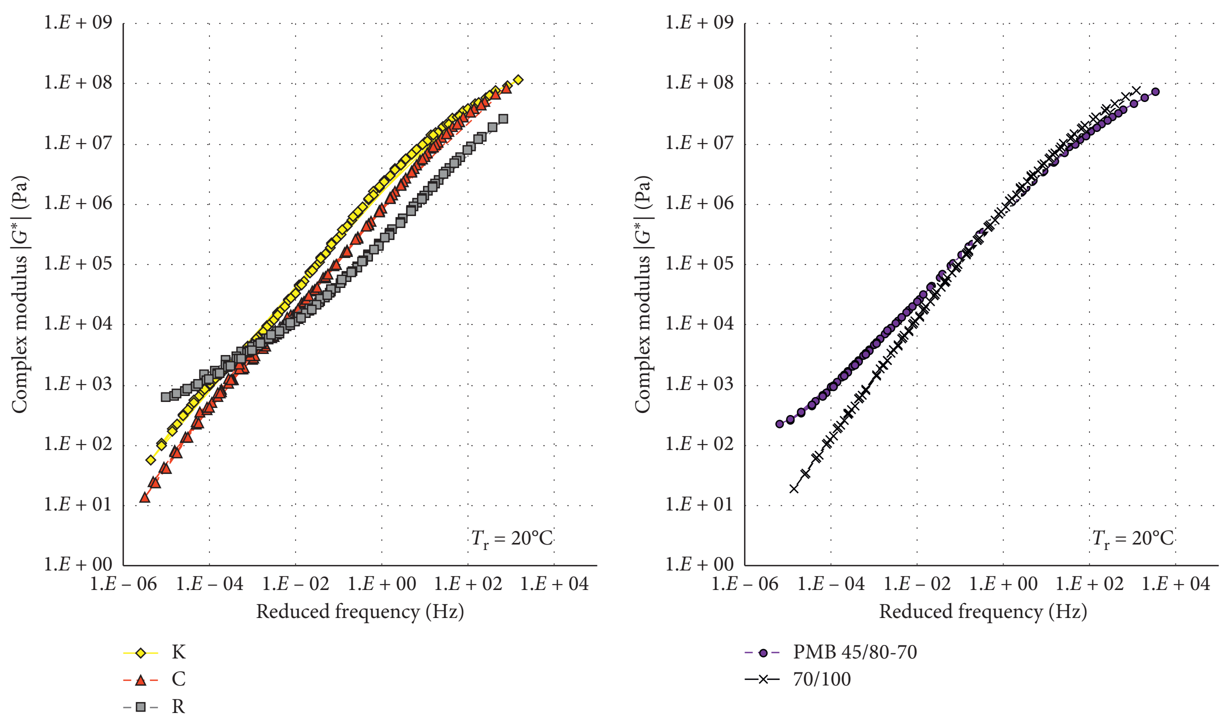
4.3. Rheological Characterization. Master curves of dynamic properties extend the rheological analysis to time and temperature domains. The frequency-temperature superposition principle (FTSP) was applied to allow the identification of continuous rheological master curves in terms of G^*, δ, G', and G'' [18, 19], in the entire investigated domain of reduced frequencies (from Figures 5–7). The complex modulus master curve at the reference temperature ($T_r = 20$°C) was modelled fitting the experimental data through the equation proposed in NCHRP Report 459 [20] and Williams–Landel–Ferry (WLF) formulation [21]. The shift factors and master curve parameters were simultaneously calculated by a solver, minimizing the sum of squares of differences.

Binder K shows the asymptotical behaviors typical of a paving grade bitumen [22] (Figure 5). At high reduced frequencies, the complex modulus $|G^*|$ individuates a trend in the logarithmic plot (Figure 5) towards the glassy state limit with the decrease of the phase angle δ down to about 30°. At low reduced frequencies, $|G^*|$ master curve shows a constant slope and the phase angle δ approaches the limit value of 90° achieving the pure viscous flow (Figure 6). However, the intermediate behavior internal to the two asymptotes is mainly characterized by an inflection, between 10^{-2} and 10^{-4} Hz, in complex modulus master curve (Figure 5). In this frequency range, the K behavior deviates if compared to the common trend of a paving grade bitumen [23], showing a simultaneous phase angle (minimum phase angle equal to 65°) and complex modulus decrease with the decrease in reduced frequency (or the increase of temperature). The local minimum of δ master curve characterizes bitumens modified by SBS copolymers and binders including the same copolymer [10], identifying the presence of polymer elastic networks or entanglements in the modified binders [23] (Figure 6). The phase angle minimum can be attributed to a hard/soft relaxation for polymer-modified binders [9]. The polymer modification gives an enhanced consistence at high service temperature with higher resistance to non-reversible deformation. Confirming the FTIR results, the continuous development of rheological parameters highlights the good compatibility between the polymer and the binder matrix due to the characteristic absence of asphaltene micelles in binder K, which are traditionally considered as detrimental for bitumen/polymer compatibility [9].

On the contrary, the viscoelastic behavior of binder C and binder R is more complex than a bituminous binder, and it cannot be explained by the uniform transition from elastic response (high reduced frequencies) to viscous response (low reduced frequencies) reducing frequency as for the conventional bitumen [19]. The values of δ measured at different temperatures do not overlap to form a unique master curve, implying a thermo-rheologically complex behavior (Figure 6). Therefore, the FTSP could not be used due to the viscous component of the C and R binder response. C and R do not show a unique relaxation mechanism.

(a) (b) (c)

Figure 4: Siliceous aggregate and binder systems after AST.



(a) (b)

Figure 5: $|G^*|$ master curves for the selected binders in comparison with bituminous binders.

Binder C reaches the pure viscous flow at low reduced frequencies and approaches to the glassy state limit at high reduced frequencies as a paving grade bitumen (Figure 5). Nevertheless, the rheological behavior of the binder C is characterized by an inflection on the $|G^*|$ master curve and the presence of a discontinuity on δ master curve between 10^{-3} and 10^{-4} Hz. In this case, the assumption of thermo-rheological simplicity cannot be properly considered and the FTSP does not apply on the entire time-temperature domain [24]. Specifically, the δ master curve can be divided into three regions (Figure 6) [24]. From the highest reduced frequencies to 1 Hz, the rheological properties of binder C follows the common trend of a paving grade bitumen: the phase angle continuously increases, and the complex modulus decreases as the reduced frequency decreases (or temperature increases). Between 1 Hz and 10^{-4} Hz, the phase angle decays from 80 to 50° and $|G^*|$ shows a rubbery plateau, highlighting a solid-like behavior or a structured physical network (crystals) into the binder that offers stiffness to the binder. However, the transition to a rubbery state is inhibited by the melting of wax-like materials. Stiffness and elasticity are instantaneously lost when the material turns into a liquid state. Indeed, decreasing frequencies (or increasing temperature) below the discontinuity, the phase angle rises to the limit value of 90°, confirming a liquid state.

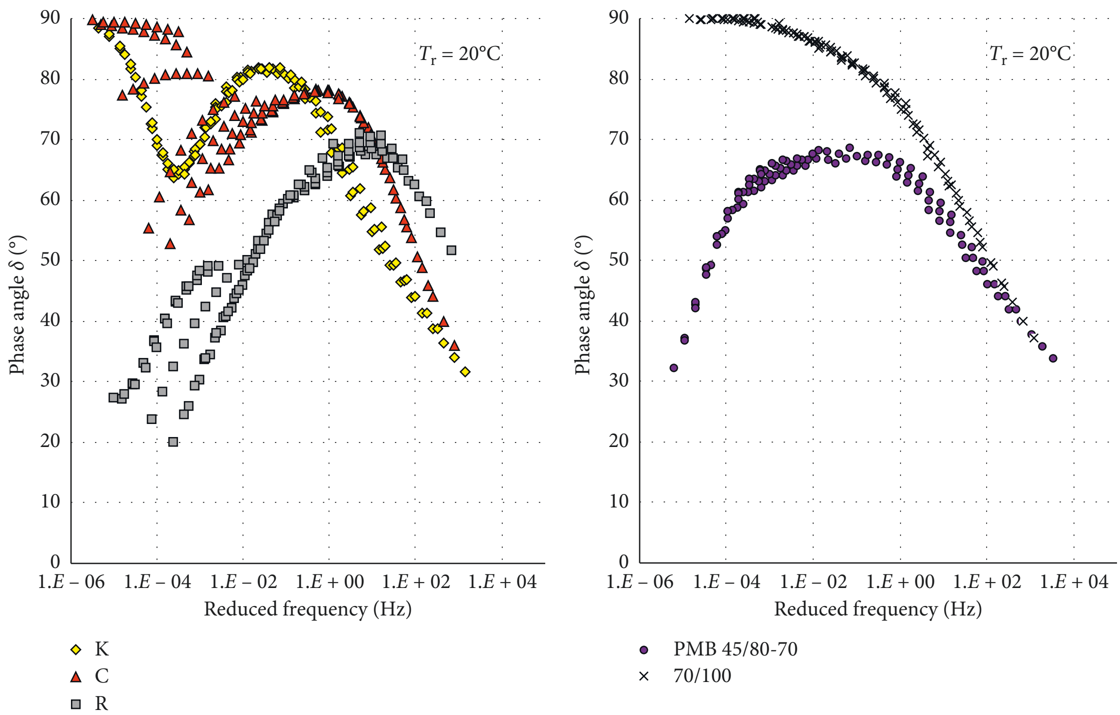


Figure 6: δ master curves for the selected binders in comparison with bituminous binders.

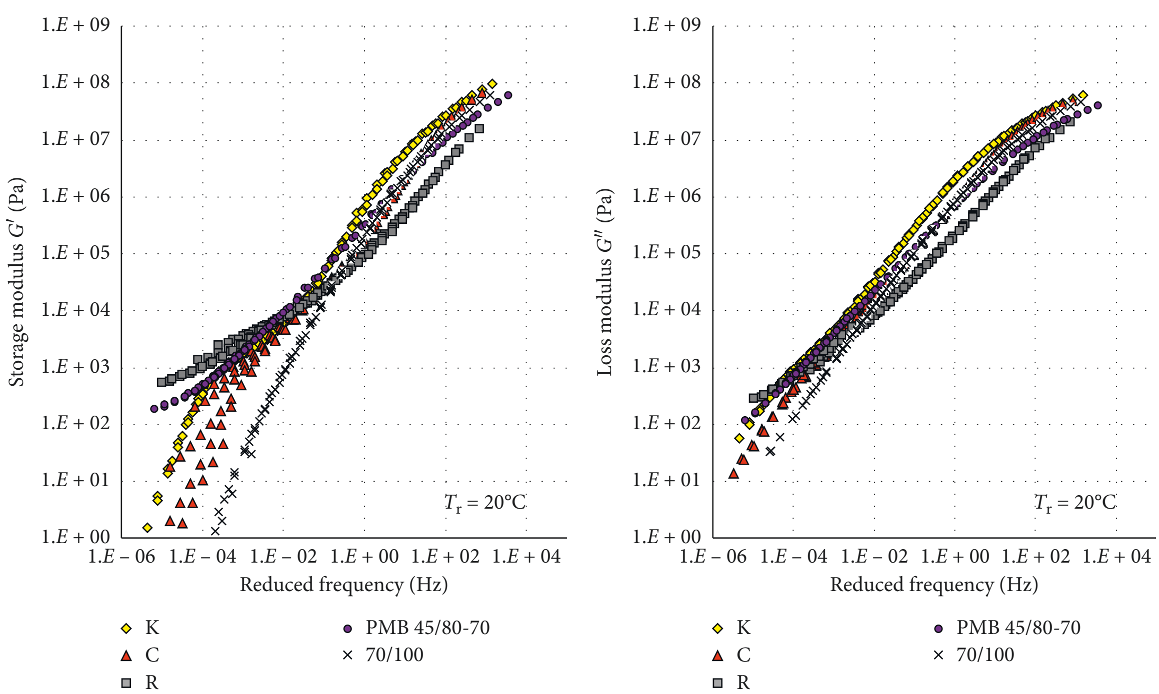


Figure 7: G' and G'' master curves for the selected binders.

Binder R shows an inflection on the $|G^*|$ master curve and the presence of a discontinuity on δ master curve between 10^{-2} and 10^{-4} Hz. At low reduced frequency, $|G^*|$ master curve tends to a horizontal asymptote with a rubbery plateau, while δ evolves in distinctive branches, highlighting the presence of different solid-like components. Consequently, the FTSP cannot be valid in that frequency range.

Observing the relationship between G' (storage modulus) and G" (loss modulus) in Figure 7, it can be asserted that at low frequencies, binder R shows G' values higher than G'' values. This highlights a high polymer content confirming the FTIR analysis, while binder K reaches the highest storage and loss moduli values at high frequencies, representing a significant resin concentration [13, 18]. At high frequencies, K and C seem to converge at similar glassy modulus values, whereas R keeps the lowest stiffness values.

Considering Figure 7, significant differences among binders occur at intermediate and low frequencies, where the nature of the polymer network is dependent on the properties of the base bitumen (maltenes composition), polymer type and content, and the compatibility of the system [23]. At intermediate frequencies, binder K shows a continuous development of rheological parameters that highlights the good compatibility between the polymer and the binder matrix, whilst binder C shows the melting of wax-like materials with instantaneous decrease in stiffness and elasticity which inhibits the transition to a rubbery state. At low frequencies, binders C and K approach the pure viscous flow, while binder R shows a horizontal asymptote identifying a rubbery plateau. Moreover, binder R appears less susceptible to temperature variations since the master curves evolve in a narrow range in the domain of reduced frequencies.

5. Conclusions

Surface courses using clear binder can improve several functional and safety requirements, highlighting specific lanes or areas, harmonizing the integration of the road network in a human context, and mitigating environmental impact. Nevertheless, clear binders have specific properties that differ from straight-run bitumens, significantly. For this reason, the selection and characterization of clear binders must be based on their overall behavior and not only on empirical testing for bitumen characterization.

This paper focuses on the chemical identification and mechanical characterization of three clear binders that can represent an alternative to traditional bitumen. The following conclusions can be drawn:

(1) FTIR testing suggested different binder origins and important remarks on binder components which resulted consistent to the results from mechanical testing. Particularly, the FTIR analysis pointed out that the origin of K derives from a deasphalted bitumen (low amount of asphaltenes) modified with SBS polymer with effective link between matrix and SBS, whereas C and R show a spectrum like an aromatic phthalic polymer suggesting a synthetic origin. Moreover, the C spectrum deconvolution suggested the presence of waxes.

(2) Bitumen traditional testing may be considered to determine the clear binder consistency at service temperature (from 25°C to the transition temperature from viscoelastic to viscous behavior) but rheological testing imposed that no prediction can be done at other temperature ranges since the experience on traditional bitumen can address wrong suppositions.

(3) From empirical testing, it can be asserted that the clear binders could be considered as a paving grade bitumen with improved elastic recovery and softening point. All clear binders comply with the technical requirements on short-term ageing for their specific grade. Dynamic viscosity tests showed that the viscosity values of binder C are close to those of a paving grade bitumen, whereas the other binders showed far higher viscosity values.

(4) The three tested clear binders are thermo-rheologically complex materials, and the analysis of their behavior needs a specific investigation as testing conditions change.

(5) Binder K showed the asymptotical behaviors to the glassy state limit or the pure viscous flow and a continuous development of rheological parameters. The local minimum of δ master curve identified the presence of polymer elastic networks with good compatibility between the polymer and the binder matrix. On the other hand, C and R binder response in terms of δ values highlighted a thermo-rheologically complex behavior. Particularly, C is characterized by the presence of a discontinuity on δ master curve at intermediate frequencies due to the melting of wax-like materials and R showed a complex behavior strongly influenced by the presence of different solid-like components which generate a rubbery plateau and a δ evolution in distinctive branches at low reduced frequency.

(6) The obtained results can address specific technical recommendations. Binder K can be considered suitable in a wide range of conditions, while binders C and R appeared rather soft at the service temperatures. C can compromise the durability of pavements under quasistatic traffic loading or in hot and wet weather conditions, whereas binder R showed the best performance at the highest and lowest temperatures.

(7) The operative temperatures for production and laying of binder C do not change if compared with a paving grade bitumen, whereas binders K and R require higher operative temperatures. Considering the remarkable cost of these binders (about 10 times of a paving grade bitumen), the correct application allows a more sustainable investment.

6. List of Standards

EN 1426: determination of needle penetration (2007).

EN 1427: bitumen and bituminous binders; determination of the softening point; ring and ball method (2007).

EN 12591: bitumen and bituminous binders; specifications for paving grade bitumens (2009).

EN 12607-1: bitumen and bituminous binders; determination of the resistance to hardening under the influence of heat and air; part 1: RTFOT method (2007).

EN 13302: bitumen and bituminous binders; determination of dynamic viscosity of bituminous binder using a rotating spindle apparatus (2010).

EN 13398: bitumen and bituminous binders; specifications for paving grade bitumens (2010).

EN 14023: bitumen and bituminous binders; framework specification for polymer modified bitumens (2010).

EN 14770: bitumen and bituminous binders; determination of complex shear modulus and phase angle; dynamic shear rheometer (DSR) (2012).

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] M. Saint-Jacques and Y. Brosseaudki, "Coloured bituminous wearing courses in France—overview of uses," in *Proceedings of the 10th International Conference on Asphalt Pavements*, vol. 1, pp. 12–17, ISBN: 978-1-61782-084-7, Quebec City, Canada, August 2006.

[2] A. Destrée, N. Piérard, and A. Vanelstraete, "Development of a test method to determine the colour durability of coloured bituminous mixtures," *Road Materials and Pavement Design*, vol. 16, no. sup1, pp. 170–186, 2015.

[3] N. Piérard, J. De Visscher, S. Vansteenkiste, and A. Vanelstraete, "Coloured asphalt pavements: mix design and laboratory performance testing," in *8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials. RILEM Bookseries*, F. Canestrari and M. Partl, Eds., vol. 11, pp. 283–294, Springer, Dordrecht, Netherlands, 2016.

[4] J. Read and D. Whiteoak, *Shell Bitumen Handbook*, Thomas Telford Publishing, London, UK, 5th edition, 2003.

[5] M. Bocci, A. Grilli, F. Cardone, and A. Virgili, "Clear asphalt mixture for wearing course in tunnels: experimental application in the Province of Bolzano," *Procedia—Social and Behavioral Sciences*, vol. 53, pp. 115–124, 2012.

[6] E. Bocci and M. Bocci, "Clear asphalt concrete for energy saving in road tunnels," in *Proceedings of the 12th International Conference on Asphalt Pavements (ISAP)*, vol. 2, pp. 1817–1825, Raleigh, NC, USA, June 2014.

[7] M. Santamouris, "Using cool pavements as a mitigation strategy to fight urban heat island—a review of the actual developments," *Renewable and Sustainable Energy Reviews*, vol. 26, pp. 224–240, 2013.

[8] V. Di Maria, M. Rahman, P. Collins, G. Dondi, and C. Sangiorgi, "Urban heat island effect: thermal response of different types of exposed paved surfaces," *International Journal of Pavement Research and Technology*, vol. 6, no. 4, pp. 414–422, 2013.

[9] D. Lesueur, "The colloidal structure of bitumen: consequences on the rheology and on the mechanisms of bitumen modification," *Advances in Colloid and Interface Science*, vol. 145, no. 1-2, pp. 42–82, 2009.

[10] F. Merusi and F. Giuliani, "Chromatic and rheological characteristics of clear road binders," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2293, no. 1, pp. 114–122, 2012.

[11] K. Plug and A. de Bondt, "Required mechanical properties of a clear binder for coloured asphalt concrete," in *Proceedings of the 16th Asphalt Pavement Engineering and Infrastructure Conference*, Liverpool, UK, February 2017.

[12] M. Bocci and S. Colagrande, "The adhesiveness of modified road bitumens," in *Proceedings of the 5th Eurobitume Congress*, vol. 1A, Stockholm, Sweden, June 1993.

[13] F. J. Navarro, P. Partal, F. Martínez-Boza, and C. Gallegos, "Effect of composition and processing on the linear viscoelasticity of synthetic binders," *European Polymer Journal*, vol. 41, no. 6, pp. 1429–1438, 2005.

[14] H. F. Shurvel, "Spectra-Structure correlation in the mid- and far-infrared," in *Handbook of Vibrational Spectroscopy*, Wiley, Hoboken, NJ, USA, 2006.

[15] A. Stimilli, G. Ferrotti, C. Conti, G. Tosi, and F. Canestrari, "Chemical and rheological analysis of modified bitumens blended with artificial reclaimed bitumen," *Construction and Building Materials*, vol. 63, pp. 1–10, 2014.

[16] F. S. Coquet and E. J. Ista, "The detemination of SBS, EVA and APP polymers in modified bitumens," in *Polymer Modified Asphalt Binders*, American Society for Testing and Materials, Philadelphia, PA, USA, 1st edition, 1992.

[17] J. Xu, T. Xia, L. Zhao, B. Yin, and M. Yang, "Correlation between phase separation and rheological behaviour in bitumen/SBS/PE blends," *RSC Advances*, vol. 8, no. 73, pp. 41713–41721, 2018.

[18] P. Partal, F. Martínez-Boza, B. Conde, and C. Gallegos, "Rheological characterisation of synthetic binders and unmodified bitumens," *Fuel*, vol. 78, no. 1, pp. 1–10, 1999.

[19] G. D. Airey, M. H. Mohammed, and C. Fichter, "Rheological characteristics of synthetic road binders," *Fuel*, vol. 87, no. 10-11, pp. 1763–1775, 2008.

[20] H. U. Bahia, D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and R. M. Anderson, "Characterization of modified asphalt binders in superpave mix design," vol. 459, NCHRP Report National Academy Press, Washington, DC, USA, 2001.

[21] M. L. Williams, R. F. Landel, and J. D. Ferry, "The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids," *Journal of the American Chemical Society*, vol. 77, no. 14, pp. 3701–3707, 1955.

[22] D. A. Anderson, H. U. Bahia, and D. W. Cristensen, "Binder characterization and evaluation—volume 3: physical properties," in *Strategic Highways Research Program. Report Number SHRP-A-369*, National Research Council, Washington, DC, USA, 1st edition, 1994.

[23] G. D. Airey, "Rheological properties of styrene butadiene styrene polymer modified road bitumens," *Fuel*, vol. 82, no. 14, pp. 1709–1719, 2003.

[24] M. Pasetto, A. Baliello, G. Giacomello, and E. Pasquini, "Aesthetic and mechanical suitability of a clear synthetic resin as a unconventional binder for road pavements," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 8643608, 15 pages, 2019.