



Journal of Testing and Evaluation

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DOI: 10.1520/JTE20240180

Mechanical Evaluation of Asphalt Mixtures Containing Recycled Bituminous Membranes (RBMs)

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S. Raschia, A. Carter, and S. Tattolo, "Mechanical Evaluation of Asphalt Mixtures Containing Recycled Bituminous Membranes (RBMs)," *Journal of Testing and Evaluation*
<https://doi.org/10.1520/JTE20240180>

ABSTRACT

Bituminous membranes (BMs) are mainly composed of a polymer-modified bituminous mastic (with filler addition) and reinforcement. In case one face is exposed to air, the external layer is an antiadhesive layer (covered with mineral chips). Because of aging and deterioration, BMs are removed from roofs or bridge decks and landfilled. Nowadays, only a few membrane producers are equipped with recycling plants to recycle BMs in new products, by reintroducing them in the production process. However, the presence of highly modified bitumen in recycled bituminous membranes (RBMs) makes them an interesting opportunity as a recycled component in asphalt pavement materials. The experimental program evaluated the introduction of RBM in asphalt mixtures to evaluate the effect on mechanical properties. The study involved three types of asphalt materials (i.e., mixtures for surface, binder and base layers), two polymer-modified bitumens typically used in Italy (Performance Grade (PG) 76-22 and PG 82-16) and the addition of RBMs containing atactic polypropylene polymer. The preliminary part of the study investigated the maximum dosage of RBMs in PG 76-22 bitumen, in order to obtain a bituminous blend whose properties can be considered intermediate between PG 76-22 and PG 82-16 binders. This part was conducted in terms of continuous performance grade. Consequently, the maximum RBM dosage was adopted to produce three asphalt materials comparing three bitumens (PG 82-16, PG 76-22, and PG 76-22 with RBMs). Asphalt mixtures were characterized in terms of indirect tensile strength, cracking properties, and complex modulus. Results showed that the use of RBMs in asphalt mixtures allows the reduction of around 10 % of the virgin binder used to produce asphalt materials for base, binder, and surface layers. However, the combined use of RBM and reclaimed asphalt pavement can lead to poor cracking resistance properties.

Manuscript received March 22, 2024; accepted for publication December 11, 2024; published online March 10, 2025.

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Keywords

bituminous membranes, recycling, bitumen, asphalt mixtures, indirect tensile strength, cracking, complex modulus

Introduction

The main purpose of waterproofing systems is to protect from water permeability and improve service life of structural elements, such as bridge decks.^{1,2} Such products can be identified in three main categories: bituminous membranes (BMs), liquid (sprayed) systems, and mastic layers. The common aspect among these three solutions is the presence of polymers and bitumen.³

BMs are the largest tool used as waterproofing system. They are generally sold in the form of ready-to-use rolls, which are 1-m wide and vary in length (between 8 and 12 m) and in weight per unit of area (between 2.5 and 5 kg/m²).¹ The traditional composition of a BM consists in a reinforcement layer (such as glass fiber, polyester, aluminum, etc.) impregnated with a bituminous blend (or compound). In some cases, the BM can have an upper layer to reduce adhesiveness by means of polyethylene foil, sand, talc, granules, etc.⁴ The bituminous blend is usually a highly polymer-modified bitumen with mineral fillers, and the target composition strongly depends on the use to which the final product is intended.⁵

In the past, bituminous blends consisted in oxidized bitumen and mineral fillers (generally limestone). With oxidation, bitumen composition changes drastically, and the polar components concentration increases. The oxidation process causes an increase in the concentration of asphaltenes and resins and a decrease in the concentration of aromatics and saturates. This change globally increases binder adhesion and viscosity. However, the production of oxidized bitumen could lead to the possible generation of toxic chemicals, driving the choice of producing bituminous blends with polymer-modified bitumens. In general, polymers used for this purpose are thermoplastic elastomers or thermoplastics. The most commonly used thermoplastic elastomers are styrene-butadiene-styrene (SBS), whereas, for thermoplastics, atactic polypropylene (APP), a subproduct of the polypropylene industry, is used.⁶

Modified bitumens for BMs production have usually higher polymer concentrations than traditional polymer-modified bitumens for asphalt pavements (i.e., 10 % to 15 % in case of SBS and 15 % to 20 % in case of APP).⁷ SBS polymers have the ability to improve elastic and recovery properties of the base bitumen; hence, its use is preferred in cold regions. On the other hand, APP polymers are suitable for hot climates because of better properties conferred to the bitumen at high service temperature, because of the absence of double bond possibly prone to oxidation.^{8–12}

In terms of BMs disposal, there is no current recycling opportunity approved by the European community, because of materials considered unhealthy and dangerous because of the possible fumes and heavy fines release. Therefore, the most common disposal procedure consists in referring to incinerators. Furthermore, it must be noted that Italian government recently published a first draft regulating the “end-of-waste” processing regarding waste BMs, which is currently under review.¹³

In the United States, more than 11 million tons of BMs are removed every year. About 90 % of them comes from postconsumer (tear-off), whereas the remaining 10 % are from postproduction (manufacturer waste).¹⁴ At the same time, Europe produces about 2 million tons per year of bituminous membranes.¹⁵

However, in a sustainable and ecological perspective, a few BMs production companies have developed internal recycling processes or their products with manufacturing defects or coming from the installation/deconstruction of structures, saving up to 15 % on the dumping costs. At the end of the treatment process, part of the recycled bituminous membranes (RBMs) obtained is incorporated into the formulation of new membranes, thus reducing the use of primary resources, especially bitumen. Results showed that the substitution of 25 % of virgin bitumen by the same amount of RBMs in a binder formulation leads to a decrease of 13 % of the impacts in the global warming potential category.¹⁶ Because of the composition of RBMs (i.e., materials characterized by high dosages of polymer-modified binder), other possibilities for their reuse can be evaluated, especially in terms of bituminous materials, such as hot mix asphalt (HMA).¹⁷

There are several environmental advantages in recycling BMs as an asphalt material component. These include a reduced demand for bitumen made from virgin mineral oil, less material going to the landfill, and lower CO₂ emissions from incinerators. A preliminary analysis performed in the framework of the “Roof to Road” project indicated that each kilogram of roofing waste used as an ingredient in asphalt mixtures, rather than going to incineration/landfilling, saves 1.677 kg of CO₂.¹⁸ However, it should be highlighted that the process centralization may increase the CO₂ consumption because of the necessity for long-distance transportation of the processed product.¹⁸

The current situation encouraged this study, which aims to evaluate the mechanical properties of asphalt mixtures containing RBMs. The investigation involved two bitumens and three traditional asphalt layer materials (for surface, binder and base layers), which differ in terms of gradation and reclaimed asphalt pavement (RAP) content. The RBM adopted is obtained from the APP-polymer-modified type, which is the most significant in terms of waste amount. The RBM dosage was established on a binder scale investigation, whereas the mechanical evaluation of asphalt mixtures was performed in terms of cracking resistance and complex stiffness modulus.

Materials and Methods

This section contains information about properties of the raw materials used, experimental equipment adopted, and analysis methods used for interpretation of results.

MATERIALS USED AND PROPERTIES

The materials used for the laboratory investigation consist of mineral aggregates and filler, RAP, two polymer-modified bitumens, and one type of RBM.

Aggregates, Filler, and RAP

The asphalt mixtures produced in laboratory are composed of different aggregate sources according to the asphalt layer investigated. Gradations of all materials used are collected in [figure 1](#). The mineral aggregates consist in limestone filler, limestone sand (LS; fraction 0/6), limestone coarse (LC) aggregates (fractions 4/8, 6/12, 12/20, and 20/30), and basaltic (BAS) coarse aggregates (fractions 4/8 and 10/16). [Table 1](#) shows the physical and mechanical properties of the mineral aggregates used. Two fractions of RAP were used, a RAP 0/10 and a RAP 0/20, which are characterized by bitumen content of 4.96 % and 4.45 % by RAP weight, respectively. Both RAP binders were extracted by means of a rotary evaporator, and the master curves of the complex shear modulus and phase angle were investigated ([fig. 2](#)). The superposition of the results in both master curves suggests that the RAP source

FIG. 1

Gradations of aggregates used.

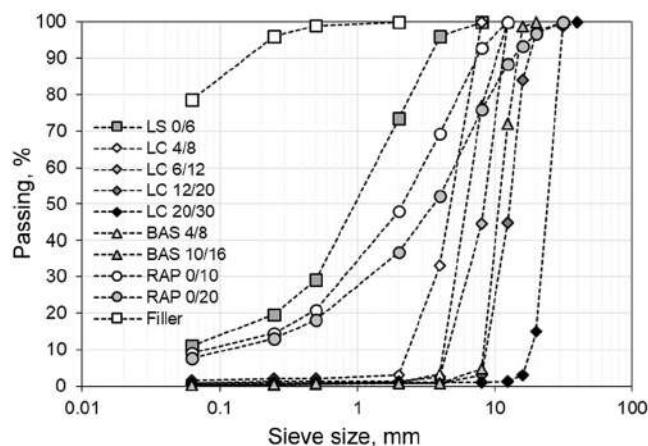
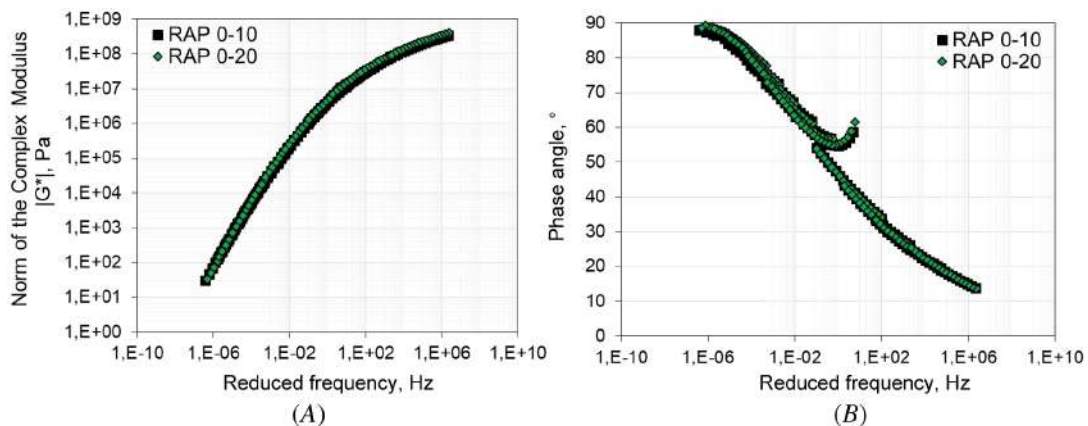


TABLE 1

Properties of virgin aggregates used

Property	Standard	Unit	Result						
			LS 0/6	LC 4/8	LC 6/12	LC 12/20	LC 20/30	BAS 4/8	BAS 10/16
Particle density	BS EN 1097-06:2000 ^{28,a}	mg/m ³	2.668	2.660	2.679	2.662	2.670	2.790	2.750
Particle shape, flakiness index	BS EN 933-3:2012 ^{29,b}	—	—	12	8	9	8	14	13
Resistance to fragmentation, Los Angeles	BS EN 1097-02:2020 - TC ^{30,c}	%	—	21	23	23	22	18	16

Note: ^a Tests for Mechanical and Physical Properties of Aggregates - Determination of Particle Density and Water Absorption; ^b Tests for Geometrical Properties of Aggregates - Determination of Particle Shape, Flakiness Index; ^c Tests for Mechanical and Physical Properties of Aggregates - Methods for the Determination of Resistance to Fragmentation.

FIG. 2 RAP extracted binder master curves ($T_{REF} = 20^{\circ}\text{C}$) of: (A) complex modulus $|G^*|$; (B) phase angle.

employed (0/10 and 0/20) will not have an influence on the rheological properties of the asphalt mixtures produced.

Polymer-Modified Bitumens

In this study, two polymer-modified bitumens were used, a PG 76-22 and a PG 82-16, the properties of which are listed in [Table 2](#). Such bitumens are the most used polymer-modified bitumens for road pavements applications in Italy. In fact, a PG 76-22 bitumen is commonly used for road pavements with standard or heavy traffic and containing on average about 20 % RAP, whereas a PG 82-16 bitumen is generally employed for asphalt mixtures intended for airport pavements with lower RAP content (around 15 %). A PG 76-22 bitumen is characterized by the dominant presence of elastomeric polymers (SBS), whereas the PG 82-16 bitumen modification mainly occurs with polymers of plastomeric nature.

For this reason, it can be observed that the PG 82-16 bitumen is characterized by higher performance at high temperatures compared to the PG 76-22 bitumen, but it shows worse resistance to fatigue (according to the linear amplitude sweep test) at intermediate temperatures and thermal cracking at low temperatures.

RBMs

The production process of RBM consists in an accurate industrial line that ensures, on one hand, the separation between different RBM sources (i.e., SBS-polymer-modified and APP polymer-modified membranes) and, on the

TABLE 2

Properties of bitumen used

Property	Standard	Unit	Value	
			PG 76-22	PG 82-16
Penetration	BS EN 1426 - TC ^{31,a}	dmm	48	35
Softening point	BS EN 1427:2015 - TC ^{32,b}	°C	69.0	72.6
Brookfield viscosity at 160°C	BS EN 13302 ^{33,c}	Pa·s	0.490	0.625
Continuous performance grade	ASTM D7643 ³⁴	—	76.4–22.9	85.6–18.5
Multiple stress creep recovery at 58°C	BS EN 16659:2015 ^{35,d}	J _{nr} 0.1 kPa	0.12	0.05
		3.2 kPa	0.15	0.07
		%R 0.1 kPa	61.2	71.9
		3.2 kPa	53.6	66.6
Linear amplitude sweep at 22°C	AASHTO T 391-20 ^{36,e}	N _f (2.5 %)	7.1E+06	4.2E+06
		N _f (5.0 %)	9.7E+04	5.9E+04
		N _f (15%)	1.1E+02	6.9E+01

Note: ^a Bitumen and Bituminous Binders. Determination of Needle Penetration; ^b Bitumen and Bituminous Binders. Determination of the Softening Point. Ring and Ball Method; ^c Bitumen and Bituminous Binders. Determination of Dynamic Viscosity of Bituminous Binder Using a Rotating Spindle Apparatus; ^d Bitumen and Bituminous Binders. Multiple Stress Creep and Recovery Test (MSCRT); ^e Standard Method of Test for Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep.

FIG. 3

RBM with APP polymers used.



other hand, the removal of all kind of contaminating elements, such as wood, steel, concrete, and general waste. More detail cannot be given because of the current patent evaluation.

The present study evaluates the addition of one source of RBM, obtained from the treatment of aged BMs originally composed of APP polymer-modified bitumen. The material appears as a 0–1 mm shredded compound mainly composed of bitumen (**fig. 3**). The RBM investigated was initially analyzed in terms of bitumen content, extracted by means of a hot extractor with wire mesh filter in accordance to the European Standard BS EN 12697-1:2020, *Bituminous mixtures. Test Methods - Soluble Binder Content*.¹⁹ The bitumen content resulted in 48.7 % by RBM mass, whereas the remaining percentage takes into account filler and reinforcing elements.

OPTIMIZATION OF RBM DOSAGE

Bituminous Blends

The study evaluates the addition of RBM containing APP polymers to the polymer-modified binder, PG 76-22, by the wet method, in the form of shredded material containing all the components (**fig. 3**). It is important to remark that RBMs are characterized by highly oxidized binder. The reason why RBM is added to the PG 76-22 bitumen is

to modify its purely elastomeric nature in order to successively compare the mechanical properties obtained with those of the PG 82-16 bitumen, mostly plastomeric. The maximum RBM dosage is the amount that, on the one hand, allows for the recycling of as much bituminous membrane as possible, and, on the other hand, classifies the bituminous blend obtained (PG 76-22 + RBM) as “intermediate” between two typically used bitumens. The RBM dosages studied are 10 % and 20 % by total bituminous blend mass (i.e., PG 76-22 bitumen and RBM). Blending operations were performed by means of a high-shear mixer for bitumen modification and an oil bath used to keep operating temperatures constant at 190°C. The mixing process was carried out for 1 hour, considering the time necessary to obtain an optimal RBM distribution, at a shear speed of 1,800 RPM.

Continuous Performance Grade

The maximum dosage of RBM in the PG 76-22 bitumen is evaluated in terms of high, intermediate, and low continuous performance grade (PG) (ASTM D7643-22, *Standard Practice for Determining the Continuous Grading Temperatures and Continuous Grades for PG Graded Asphalt Binders*). Both virgin binders (PG 76-22 and 82-16), as well as the bituminous blends containing PG 76-22 and RBM, were tested using a dynamic shear rheometer (DSR) and a bending beam rheometer and aged artificially by the rolling thin film oven test and pressure aging vessel procedures. The aim of this step is to achieve continuous PG results contained between those measured on PG 76-22 and PG 82-16 bitumens by maximizing the RBM content.

LABORATORY-PRODUCED ASPHALT MIXTURES

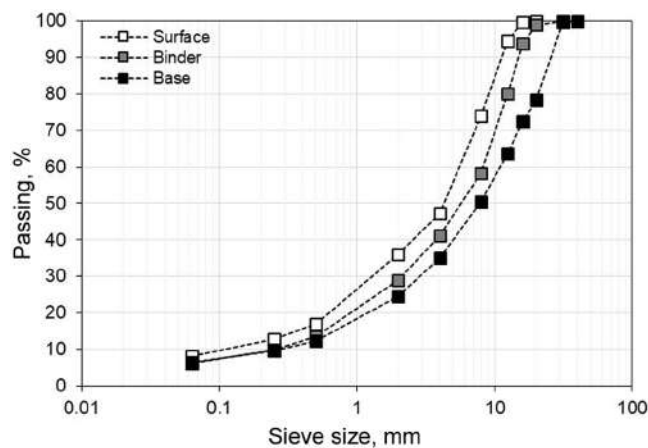
Once the maximum dosage of RBM was determined, nine asphalt mixtures were produced in laboratory divided in three groups according to the asphalt pavement layer (i.e., surface, binder, and base layer). For each layer, PG 76-22 bitumen, PG 82-16 bitumen, and PG 76-22 bitumen with RBM were used as bituminous additions.

The target gradation and the total bitumen content are related to the asphalt layer considered. Figure 4 shows the mix-design gradation of each asphalt layer material, which are obtained with a total RAP content of 15 % in the surface layer, 20 % in the binder layer, and 25 % in the base layer, according to the Italian technical specifications.²⁰

The nine mixtures investigated were produced in laboratory by means of a horizontal-axis heated mixer at a mixing temperature of 170°C. The mineral aggregates, as well as RAP and virgin bitumens, were heated before mixing, whereas RBM shredded material (when needed) was dispersed in the mixer with no additional heating. Different from the bituminous blends produced to assess the maximum RBM dosage, the dry method was adopted in this case. Such a protocol was considered more realistic in terms of how RBM would be employed in the case of a real scale asphalt mixture production. The addition was performed after a first step of

FIG. 4

Gradations of granular blend adopted.



homogenization between mineral aggregates and RAP and right before virgin bitumen. The last component introduced in the mixer was limestone filler.

The total bitumen content of the asphalt mixtures was fixed constant for each layer, considering the amount of RAP binder and the presence of bitumen in the RBM material. As a consequence, asphalt mixtures for surface, binder, and base layers were produced with a total amount of bitumen by mixture mass equal to 5.25 %, 4.47 %, and 4.08 %, respectively. Such dosages were obtained in order to comply with the volumetric requirements contained in the Italian technical specifications.²⁰

Compaction was performed by means of a shear gyratory compactor with a 150-mm-diameter mold, constant pressure of 600 kPa, rotation speed of 30 rpm, and internal angle of 1.25°. All specimens produced were compacted with constant mass at fixed height in order to achieve similar volumetric properties among the mixtures investigated. The air voids content obtained are 3.0 % ± 0.5 % for surface layer materials and 4.5 % ± 1.5 % for binder and base layers materials.

MECHANICAL CHARACTERIZATION

The investigation of the mechanical properties was carried out by performing indirect tensile strength (ITS) tests determining the cracking tolerance index (CT_{Index}) and complex modulus tests.

ITS Test

The ITS tests were carried out according to the BS EN 12697-23:2018, *Bituminous Mixtures. Test Methods - Determination of the Indirect Tensile Strength of Bituminous Specimens*,²¹ using a displacement-speed controlled press with a fixed loading speed of 50 ± 2 mm/min. The test temperature was 25°C, and four repetitions (specimens) for each mixture were tested. The dimensions of the specimens (thickness and diameter) were measured before testing, and the maximum load reached during testing was recorded:

$$ITS = \frac{2P}{\pi \cdot D \cdot t} \quad (1)$$

where P is the maximum load, D is the average diameter (in mm), and t is the average thickness (in mm).

IDEAL-CT Analysis

The cracking resistance of the investigated asphalt mixtures was evaluated following the IDEAL-CT procedure according to the ASTM D8225-19, *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*.²² As for the ITS test, IDEAL-CT analysis was performed at 25°C, and the same testing equipment was used. To evaluate the fracture properties of the mixtures analyzed, the test was stopped when the post-peak load achieved the 10 % of the peak load. The load-displacement curves were recorded, and the CT_{Index} was calculated as follows:

$$CT_{Index} = \frac{t}{62} \cdot \frac{l_{75}}{D} \cdot \frac{G_f}{|m_{75}|} \cdot 10^6 \quad (2)$$

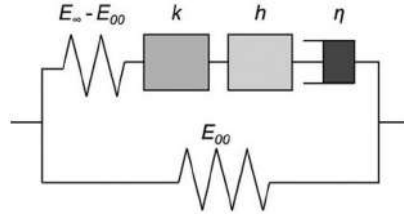
where G_f is the failure energy calculated by dividing the work of failure (area under the load-displacement curve) by the cross-sectional area of the specimen (in kN/mm), $|m_{75}|$ is the absolute value of the post-peak slope m_{75} (kN/mm), and l_{75} is the displacement at 75 % the peak load after the peak (in mm).

Complex Modulus Test

Complex modulus tests were performed in the only-compression configuration on cylindrical specimens (diameter of 100 mm and height of 130 mm), cored and sawed from 150-mm-diameter and 150-mm-high specimens. Tests were carried out by means of a 30 kN servohydraulic press in load control in order to obtain a peak-to-peak strain equal to 50 microstrain. Testing temperatures were 0°C, 10°C, 20°C, 30°C, 40°C, and 50°C, at which the specimen was conditioned for at least 3 hours before testing. A dummy specimen monitored the testing

FIG. 5

2S2P1D model
representation.



temperature with surface and core temperature probes. The testing frequencies were 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, and 10 Hz. The 0.1 Hz frequency was repeated at the end of the sequence to verify the integrity of the tested specimen.

2S2P1D Rheological Model

Complex modulus tests results were analyzed by the 2S2P1D model (fig. 5). The 2S2P1D is a linear viscoelastic (LVE) rheological model commonly used to describe the behavior of HMA mixtures in the LVE domain. It is composed of two springs, two parabolic elements, and one dashpot.²³

The analytical equation of 2S2P1D model is given for a fixed reference temperature (T_{REF}):

$$E^*(\omega) = E_{00} + \frac{E_{\infty} - E_{00}}{1 + \delta(i\omega\tau_E)^{-k} + (i\omega\tau_E)^{-h} + (i\omega\beta\tau_E)^{-1}} \quad (3)$$

where E_{00} is the static modulus when $\omega \rightarrow 0$ (in MPa), E_{∞} is the glassy modulus when $\omega \rightarrow \infty$ (in MPa), δ is a calibration constant, k and h are parabolic exponents (such as $0 < k < h < 1$), ω is the pulsation ($= 2\pi f$), f is the frequency (in Hz), i is the imaginary number ($i^2 = -1$), β is linked to the Newtonian viscosity ($\eta = [E_{\infty} - E_{00}]\beta\tau$), and τ_E is the characteristic time, which is the only value varying with temperature (T), as seen in equation (4):

$$\tau_E(T) = a_T(T) \cdot \tau(T_{REF}) \quad (4)$$

where $a_T(T)$ is the shift factor at the temperature T .

To validate the time-temperature superposition principle, the experimental shift factors $a_T(T)$ can be modeled by the Williams-Landel-Ferry (WLF) model,²⁴ determining the constants C_1 and C_2 by minimizing the error between model and experimental data, as seen in equation (5):

$$\log a_T = \frac{-C_1 \cdot (T - T_{REF})}{C_2 + T - T_{REF}} \quad (5)$$

The 2S2P1D model allows one to describe the LVE behavior of the material studied with the definition of only nine constants (E_{00} , E_{∞} , k , h , δ , β , τ_E , C_1 , and C_2). The reference temperature fixed for modeling is 20°C.

Glover-Rowe Parameter

Complex modulus and phase angle results allow the capturing of cracking properties of the asphalt mixtures by adapting the Glover-Rowe (G-R) parameter generally applied to asphalt binders.²⁵ Initially, the approach evaluated the possibility to assess cracking properties by means of a DSR function in terms of binder ductility with cracking data related to cores obtained from field test sections. A few years later, the G-R parameter was simplified, and, currently, a single DSR measurement of the binder complex shear modulus, $|G^*|$ and phase angle, δ , at 15°C and 0.005 rad/s allows discrimination of different asphalt binders in terms of cracking resistance.²⁶

Further investigations showed that the application of the G-R parameter is possible to assess the cracking properties of asphalt mixtures as well. This approach links the asphalt mixture complex modulus, $|E^*|$, and phase angle, φ , as shown in equation (6)²⁷:

$$G - R_m = \frac{|E^*|(\cos \varphi)^2}{\sin \varphi} \quad (6)$$

where $|E^*|$ is the mixture complex modulus (in MPa) and φ is the mixture phase angle (in degrees).

According to literature, a typical experimental point to determine the cracking resistance of asphalt mixtures is given by a temperature-frequency combination of 20°C and 5 Hz, conditions that were adopted in this study.

Results and Discussion

This section contains the analysis of the results obtained following the experimental program and methods previously described.

OPTIMIZATION OF RBM DOSAGE

Figure 6 shows the results obtained in terms of continuous PG temperatures. In general, PG 76-22 bitumen is characterized by lower PG temperatures than PG 82-16 bitumen, with the highest difference reported for high temperatures, indicating lower rutting resistance and higher fatigue and thermal cracking resistance for the PG 76-22 bitumen. These results are strictly linked to the polymers nature used for binders modification.

The gradual addition of 10 % and 20 % of RBM causes an increase in all the PG temperatures, improving rutting resistance properties and decreasing performance at intermediate and low temperatures. The values obtained from the bituminous blend composed of 80 % of PG 76-22 bitumen and 20 % of RBM are comparable to the results related to the PG 82-16 bitumen; hence, this dosage was adopted for the asphalt mixtures production and testing. According to the results obtained, the composition of the bituminous phase of each asphalt mixture, considering the virgin bitumen, RAP bitumen, and RBM bitumen, is shown in Table 3.

ITS TEST

Figure 7 shows results in terms of ITS and CT_{Index} obtained from the mixtures investigated. The plots show the average values calculated, as well as the error bars representing the parameters variability.

FIG. 6

Continuous PG of the investigated blends.

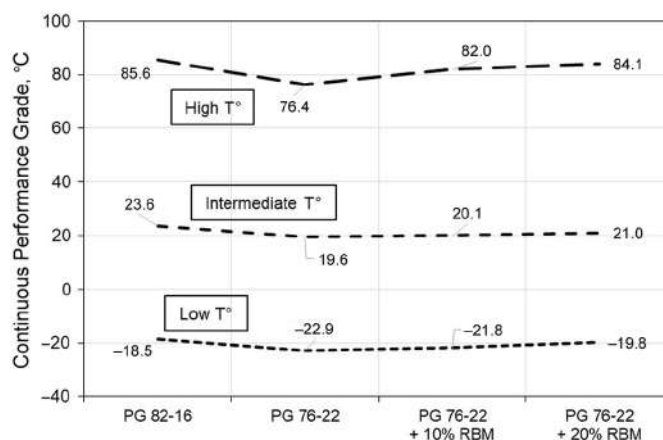
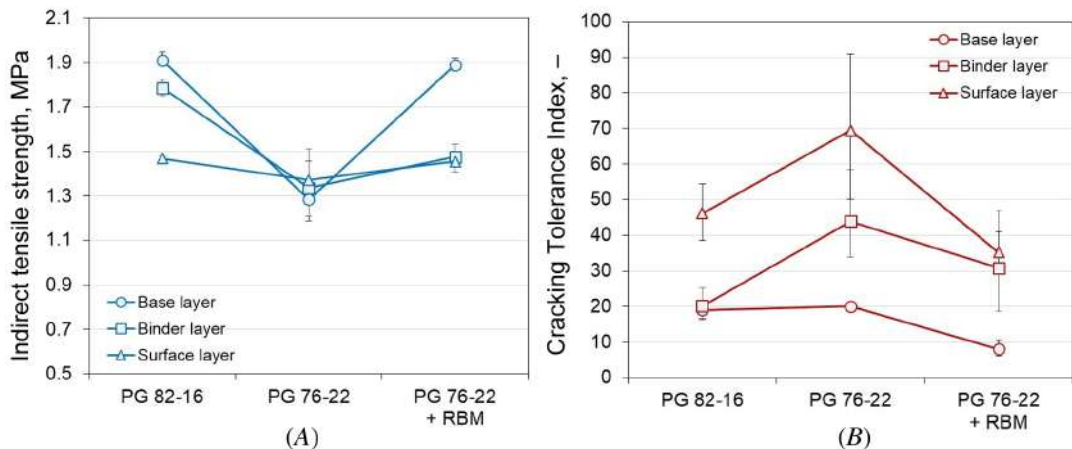


TABLE 3

Bituminous phase composition of the asphalt mixtures investigated

Layer	Mixture	Bitumen Dosage by Mixture Mass, %			Total
		Virgin	RAP Binder	RBM Binder	
Base	PG 76-22	2.93	1.15	—	4.08
	PG 82-16				
Binder	PG 76-22 and RBM	2.57		0.36	
	PG 76-22	3.53	0.94	—	4.47
	PG 82-16				
	PG 76-22 and RBM	3.10		0.43	
Surface	PG 76-22	4.53	0.72	—	5.25
	PG 82-16				
	PG 76-22 and RBM	3.98		0.55	

FIG. 7 (A) ITS results and (B) CT_{Index} 

In terms of ITS results, the higher average value obtained with the PG 82-16 bitumen, if compared with the PG 76-22 for the same asphalt mixture, is highlighted. Furthermore, for PG 82-16 bitumen, the average ITS value calculated for the base asphalt mixture is the highest, whereas the average ITS value calculated for the surface asphalt mixture is the lowest, following the decreasing RAP content. Grading distribution and RAP content are significant variables among the three asphalt mixture types, and both aspects caused the difference in the results obtained. When considering mixtures produced with PG 76-22, the results obtained in terms of ITS are not significantly different among the three asphalt materials.

Mixtures produced with PG 76-22 bitumen and RBM globally show higher ITS values if compared to mixtures with PG 76-22, confirming the stiffening effect conferred by the RBM oxidized residual bitumen at intermediate temperatures. Base and surface layers materials containing RBM are characterized by similar resistance values compared to those produced with PG 82-16, contrary to what was found for binder asphalt materials.

In terms of the CT_{Index} , asphalt mixtures produced with PG 76-22 bitumen showed better cracking resistance than mixtures produced with PG 82-16 bitumen. In addition, higher values were recorded for surface layer materials, followed by binder layer materials and base layer materials, regardless the bituminous phase. As previously considered for ITS results, the difference in CT_{Index} values among the different layer materials analyzed can be

attributed to the different gradations and RAP content. The addition of RBM to PG 76-22 bitumen in surface and binder layers causes a decrease in the value of CT_{Index} , conferring similar cracking resistance values to mixtures with PG 82-16 bitumen. The use of RBM in a base layer material combined with 25 % of RAP causes a significant loss in cracking resistance values.

COMPLEX MODULUS TEST

Figures 8 and 9 show experimental data related to complex modulus tests. Figure 8 illustrates the results in terms of Cole-Cole plans, whereas figure 9 depicts master curves of the norm of the complex modulus, $|E^*|$. Figure 8 confirms the applicability of the time-temperature superposition principle; hence, the master curves were built by experimental shift factors related to each mixture and modeled by the WLF equation. The shift factors adopted allowed to analyze the experimental data in a reduced frequency range of $(194 \div 0.0018)$ Hz for surface layer materials, $(118 \div 0.0016)$ Hz for binder layer materials, and $(360 \div 0.0006)$ Hz for base layer materials.

The Cole-Cole plans show the experimental data for each asphalt layer material, highlighting the contribution conferred by each bitumen introduced. It can be observed that the viscoelastic behavior of the two virgin binders (PG 76-22 and PG 82-16) is similar for the three asphalt materials because the experimental data describe comparable trends between the storage modulus (E_1) and the loss modulus (E_2). On contrary, the introduction of RBM leads to a lower contribution of the viscous part (E_2) to the norm of the complex modulus because of the oxidized bitumen contained in the recycled material. This result is valid for the three asphalt materials, and it is less remarked as the RAP content increases (15 % in surface layer materials, 20 % in binder layer materials, and 25 % in base layer materials). This highlights the fact that, with a lower amount of RAP, the effect of the aged RBM

FIG. 8 Cole-Cole plans of the asphalt mixtures: (A) surface layer materials; (B) binder layer materials; (C) base layer materials.

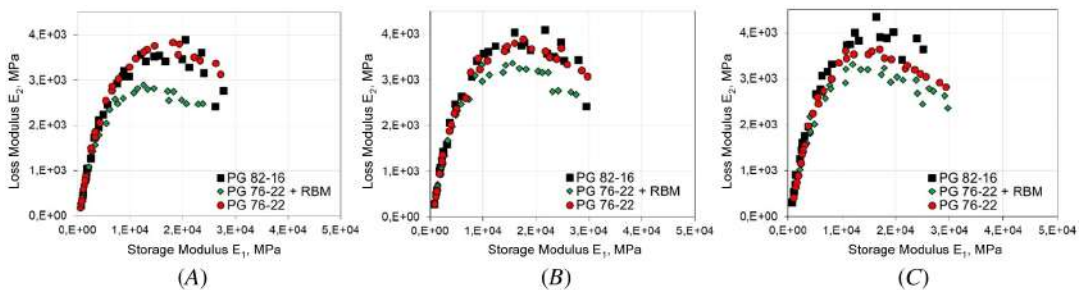


FIG. 9 Master curves of the norm of the complex modulus ($T_{REF} = 20^\circ\text{C}$): (A) surface layer materials; (B) binder layer materials; (C) base layer materials.

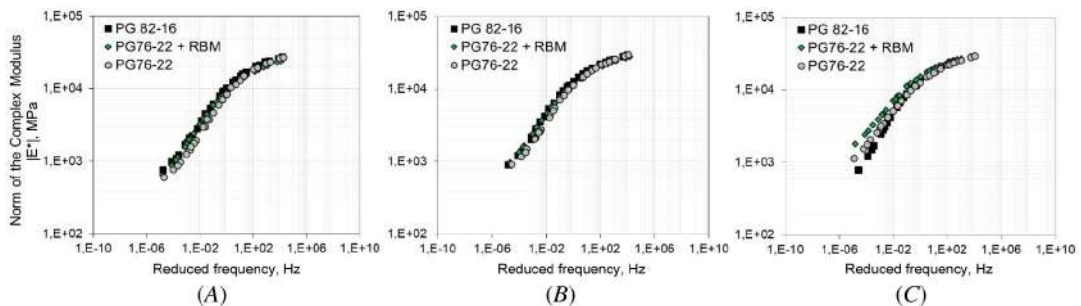


TABLE 4

2S2P1D and WLF models parameters

Layer	Bituminous Phase	E_{00} (MPa)	E_{∞} (MPa)	$k(-)$	$h(-)$	$\delta(-)$	τ (T_{REF})(s)	$\beta(-)$	$C_1(-)$	$C_2(^{\circ}\text{C})$
Surface layer	PG 76-22	550	37,000	0.21	0.52	2.85	0.17	400	22	153
	PG 82-16	600	37,000	0.20	0.50	2.85	0.47		29	204
	PG 76-22 + RBM	550	38,000	0.16	0.47	2.50	0.18		32	229
Binder layer	PG 76-22	750	35,500	0.22	0.48	1.90	0.34		27	194
	PG 82-16	750	37,500	0.20	0.53	2.45	0.95		43	312
	PG 76-22 + RBM	750	37,000	0.19	0.50	2.70	0.85		33	240
Base layer	PG 76-22	750	34,000	0.19	0.49	2.60	2.50		24	153
	PG 82-16	550	37,000	0.21	0.58	2.20	1.10		30	242
	PG 76-22 + RBM	700	35,000	0.20	0.48	4.50	64.00		57	378

binder is predominant (surface layer materials), whereas, for high RAP content (base layer materials), the introduction of RBM is less influent.

In terms of complex modulus $|E^*|$, the results highlight similar master curves among the three binders used (PG 82-16, PG 76-22, and PG 76-22 + RBM) for surface and binder layers materials. However, from a deeper analysis, mixtures produced with PG 82-16 bitumen show higher complex modulus values at high temperatures (or low frequencies) than mixtures containing PG 76-22 + RBM and PG 76-22, respectively. In case of base layers materials, the combination of PG 76-22 with RBM confers the highest complex modulus values at high temperatures (or low frequencies), followed by mixtures with PG 76-22 and PG 82-16. This finding is linked to the contemporary presence of RBM and high RAP content.

Table 4 lists parameters for 2S2P1D and WLF models for the asphalt mixtures investigated, whereas figure 10 shows the experimental master curves of the norm of the complex modulus modeled with the 2S2P1D model. Figure 11 shows the experimental shift factors modeled with the WLF model.

The asymptotic static modulus E_{00} generally ranges between 550 and 750 MPa, although a significant difference cannot be highlighted in surface layer and binder layer materials in accordance with the binder used. However, binder layer and base layer materials show higher E_{00} values than surface layer materials because of the higher presence of RAP. The lower value observed for the base layer material containing PG 82-16 bitumen could be caused by a difference in the air voids content. The asymptotic glassy modulus E_{∞} values vary between 34,000 and 38,000 MPa among all mixtures, and the difference represents the difference in air voids content. The use of RBM with PG 76-22 bitumen is not influential at high temperatures (low frequencies), whereas it causes an increase in the glassy modulus E_{∞} at low temperatures (high frequencies) if compared to the mixtures produced with PG 76-22 bitumen only.

FIG. 10 2S2P1D model of master curves of the norm of the complex modulus ($T_{REF} = 20^{\circ}\text{C}$): (A) surface layer materials; (B) binder layer materials; (C) base layer materials.

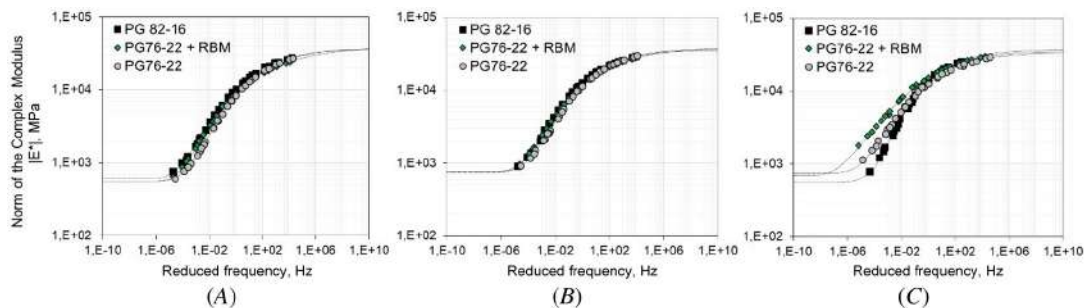


FIG. 11 Experimental shift factors and WLF model of the mixtures investigated ($T_{REF} = 20^\circ\text{C}$): (A) surface layer materials; (B) binder layer materials; (C) base layer materials.

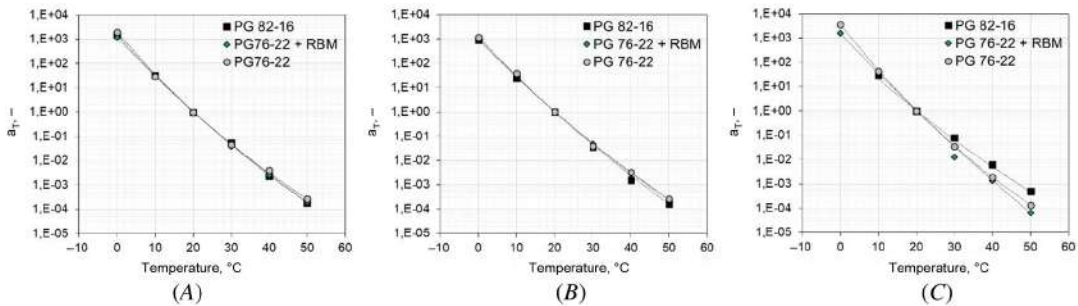
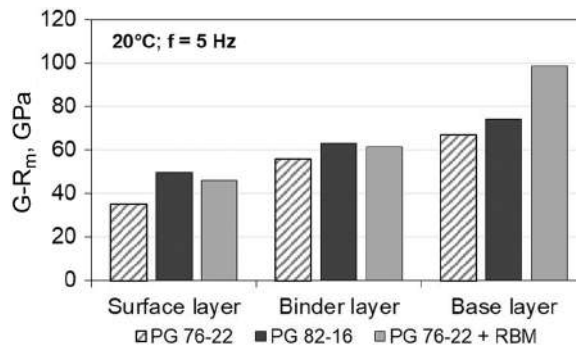


FIG. 12

Glover-Rowe mixture parameter of the mixtures analyzed.



Viscous parameters k and h are similar if the same bitumen is considered for the production of the asphalt mixtures, meaning that the increasing RAP content from the surface layer to the base layer does not have an influence. Furthermore, the introduction of RBM in mixtures with the PG 76-22 bitumen have a significant effect only in case of surface layer materials, characterized by lower values if RBM is used.

The shape parameter δ and characteristic time τ (T_{REF}) are strictly linked to the bitumen aging condition of the mixture analyzed. In general terms, higher values of δ and τ (T_{REF}) correspond to a bituminous material characterized by a higher aging level. Shape parameter δ values are not significantly different in case of surface layer materials, whereas binder and base layers materials show δ values higher if RBM is employed, with the maximum value attributed to the base layer asphalt mixture.

The characteristic time τ (T_{REF}) values of the model globally ranges between 0.17 s and 2.50 s for all mixtures, except for the base layer material containing PG 76-22 binder and RBM, characterized by a higher value, which means a higher aging level due to the presence of both RAP (25 %) and RBM.

Figure 12 shows the $G-R_m$ parameter values calculated from the experimental data of complex modulus tests of the asphalt mixtures analyzed. It has to be noted that PG 82-16 bitumen is characterized by higher values than PG 76-22 bitumen for the three asphalt mixtures, highlighting a worse resistance to cracking caused by the different nature of the polymers used for modification. At the same time, $G-R_m$ values referred to the same bitumen (PG 76-22, PG 82-16, or PG 76-22 + RBM) tend to increase from surface layer to base layer materials. This effect is attributed to the incremental dosage of RAP, from 15 % in surface layers to 20 % in binder layers and to 25 % in base layers.

The use of RBM with PG 76-22 bitumen penalizes cracking resistance properties by increasing the $G-R_m$ values if compared to the base bitumen PG 76-22. However, in surface and binder layer materials, the $G-R_m$ values

obtained in mixtures with RBM are lower than the results obtained from that with PG 82-16 bitumen, indicating that the cracking resistance can be considered acceptable as it is contained between two traditionally bitumens used. On the other hand, for base layer materials, the use of RBM causes a significant increase in the $G-R_m$ value, conferring to the material lower cracking resistance. Such a result can be attributed to the combined effect of the higher RAP content and use of RBM.

Conclusions

This study evaluated the effect of RBM on the mechanical properties of asphalt mixtures usually produced for the three main pavement layers: surface, binder, and base layers, respectively. The purpose of the study was to blend RBM with a PG 76-22 virgin bitumen in order to reach mechanical properties that could fall in between a PG 76-22 and a PG 82-16 virgin bitumen. The dosage of recycled membrane was assessed analyzing the continuous high, medium, and low performance grades of the two binders (PG 82-16 and PG 76-22) and two blends of PG 76-22 bitumen and RBM (10 % and 20 % by total bituminous blend mass). With this approach, a dosage of 20 % of RBM was fixed. The mechanical properties investigation of the asphalt mixtures produced employing the three bitumens allowed us to obtain the following findings:

- The ITS resistance of mixtures containing PG 82-16 bitumen and PG 76-22 bitumen with RBM can be considered similar with good approximation. Resistance values conferred by the use of PG 76-22 are globally lower, and the introduction of RBMs causes an increase in resistance values because of the presence of aged and oxidized binder.
- The highest cracking resistance (in terms of CT_{Index} values) was obtained for mixtures containing PG 76-22 bitumen and for surface layer materials above binder and base layer materials because of the lower RAP content. Asphalt mixtures with PG 82-16 bitumen and PG 76-22 bitumen with RBM are characterized by similar but worse cracking tolerance properties.
- In terms of stiffness complex modulus, the different binder used (PG 82-16, PG 76-22, and PG 76-22 with RBM) resulted in different complex behavior, especially at high and intermediate temperatures. At high temperatures, PG 82-16 bitumen and PG 76-22 bitumen with RBM confer higher values of stiffness compared to that of the PG 76-22 bitumen. Furthermore, at intermediate temperatures, the Cole-Cole plans highlighted that the combined presence of aged binders from RAP and RBM leads to a difference in the viscoelastic behavior of the mixes containing RBM, characterized by lower values of the viscous part of the complex modulus (E_2). This analysis, combined with the results in terms of $G-R_m$ parameter and characteristic time τ (T_{REF}) from the 2S2P1D model, highlights the high level of aging and oxidation of the binder resulting from the RBM and RAP blending. This aspect is more critical in the analyzed mixtures with 25 % RAP, which could be more prone to premature cracking.
- The evaluation of the mechanical properties of the mixtures analyzed and the results obtained highlighted the possibility to introduce RBMs in asphalt mixtures. Further investigations and studies are certainly needed in order to capture the global effect of this resource to asphalt materials in terms of chemical, mechanical, and production properties (especially in terms of compactability). In this manner, a significant percentage of virgin binder introduced for mixtures production could be saved and substituted with an alternative otherwise landfilled.

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