Construction and Building Materials 123 (2016) 712–718

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Aging effects on recycled WMA porous asphalt mixtures

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HIGHLIGHTS

- Aging effect on warm recycled porous asphalt produced using different WMA additives.
- Limited short-term aging for WMA bitumen/mixture due to low production temperatures.
- Extensive long-term aging effects for WMA bitumens/mixtures contrarily to HMA.
- The organic additive tends to increase bitumen and, thus, WMA mixture stiffness.
- Fatigue life is not affected by low production temperature or warm additive type.

ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form 24 June 2016
Accepted 15 July 2016

ABSTRACT

Nowadays, the use of reclaimed asphalt pavements (RAP) is often combined with Warm Mix Asphalt (WMA) technologies with several benefits in terms of environment, cost and mechanical performance. Concerns still exist related to in-service and aging characteristics of warm recycled mixtures since WMA technologies have been developed over the last decade and hence long term performance data are not available yet. The objective of this experimental study is to evaluate the aging effect on recycled porous asphalt (PA) mixtures produced at reduced temperatures using different WMA additives (organic, chemical and zeolite) and including 15% of RAP. In this sense, long term aging was simulated in the laboratory on compacted specimens by means of the Viennese Aging Procedure (VAPro). Rheological properties of the extracted bitumen samples were measured in order to evaluate possible links between bitumen and mixtures performance. As far as mixtures are concerned, stiffness tests were carried out before and after aging, whereas fatigue resistance was evaluated on long term aged mixtures to compare long term performance of HMA and WMA porous asphalt. Mixtures as well as bitumens results showed that the lower aging process that WMA mixtures undergo during production affects mixtures stiffness at the beginning of service life. Only the presence of the organic additive increases the stiffness of WMA bitumens and mixtures due to the crystalline network structure that forms in the bitumen. On the other hand, extensive long term aging effects were measured in case of WMA mixtures. Nonetheless, overall fatigue results showed that long term fatigue performance of WMA mixtures are not significantly affected compared to HMA regardless of WMA additive types.

1. Introduction

Environmental friendly asphalt pavements represent a priority goal for administrators and industries gaining interest from the scientific community. The use of Reclaimed Asphalt Pavement (RAP) as partial replacement of virgin aggregates is a widely recognized sustainable solution since it allows reduction of waste materials and preservation of natural resources as well as savings in construction costs. In addition, lower production temperatures for asphalt mixtures are needed in order to limit emissions and energy consumption as well as ensuring better working environment during construction phases both at asphalt plant and worksite. In this sense, Warm Mix Asphalt (WMA) technologies are recognized as proper solution since they allow significant reductions of mixtures production temperatures without affecting their mechanical performance in the field. Nowadays, the use of RAP is often combined with WMA technologies in order to produce warm recycled mixtures with several benefits in terms of environment, cost and mechanical performance [1–4]. In fact, high production temperatures generally used to produce Hot Mix Asphalt (HMA) mixtures cause additional aging of the already aged bitumen within RAP that

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http://dx.doi.org/10.1016/j.conbuildmat.2016.07.063
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not only compromises its rheological and mechanical behaviour but also generates harmful emissions during production.

Several studies have been carried out to investigate the feasibility of warm recycling in case of porous asphalt mixtures (PA) [5–9]. Wurst and Putman [6] showed that WMA porous asphalt mixtures exhibited greater durability than HMA porous asphalt mixtures after long term aging. Moreover, Goh et al. [5] found beneficial effects of coupling recycled PA with WMA technologies in terms of complex modulus and indirect tensile strength. Concerns still remain related to water susceptibility of warm PA mixtures; it was found that the use of chemical WMA additive tends to limit such a problem with respect to other WMA additives even though it does not guarantee the same performance of PA produced at conventional temperature [8]. Furthermore, short-term and long-term aging effects are two aspects that need careful investigation in case of warm mixtures [10–12]. In fact, during mixing and compaction WMA mixtures are exposed to lower temperatures compared to conventional HMAs so leading to limited short term aging and premature rutting failure. In addition, concerns still exist related to in-service and long term performance since WMA technologies have been developed over the last decade and long term performance data are not available yet. Further investigations are needed in order to fully understand long term behaviour of WMA mixtures, especially in case of PA that are more sensitive to the detrimental effects of climate and traffic that lead to brittleness as well as ravelling [13].

Given this background, the objective of this experimental study is to evaluate aging effects on recycled porous asphalt mixtures produced at reduced temperatures using different WMA additives and including 15% of RAP. In this sense, long term aging was simulated in laboratory by means of an innovative test procedure (Viennese Aging Procedure – VAPro) [14–15]. Mechanical laboratory tests were carried out on mixtures as well as bituminous components in order to evaluate possible links between bitumen and mixtures performance.

2. Experimental study

2.1. Materials

Four different porous asphalt mixtures were produced in laboratory using the same mix design that was optimized in previous research studies [16–17] including 15% of selected RAP aggregates from milled porous asphalt surface layers. Basalt aggregates, filler and coarse RAP aggregates (8/16 mm) were combined to obtain the final grading curve showed in Fig. 1.

Moreover, a blend of 70% cellulose and 30% glass fibres dosed at 0.3% by aggregate weight were added to the mixtures. The total bitumen content was set equal to 5.25% by aggregate weight and it includes the aged bitumen within RAP (4.0% by RAP weight). The virgin bitumen (hereafter named "B_H_virgin") used to produce all PA mixtures was a polymer (SBS) modified bitumen (PG 82-16) whose main characteristics are listed in Table 1.

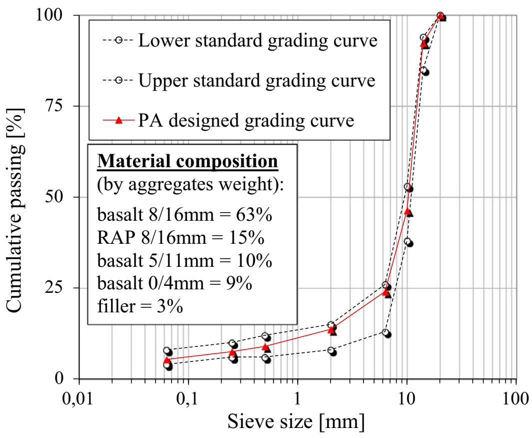


Fig. 1. Aggregates grading curve.

Table 1
Basic characteristics of the SBS modified virgin bitumen.

Bitumen characteristics	Standard	Unit	Value
SBS polymer content by weight	–	%	3.8
Penetration [25 °C; 100 g; 5 s]	EN 1426	0.1 mm	54
Ring and ball softening point	EN 1427	°C	71
Elastic recovery [25 °C; 5 cm/min]	EN 13398	%	89
Dynamic viscosity @ 135 °C	EN 12595	Pa·s	1.24
Mass loss after RTFOT	EN 12607-1	%	0.05
Penetration after RTFOT	EN 1426	0.1 mm	27
Ring and ball softening point after RTFOT	EN 1427	°C	77

One porous asphalt mixture (hereafter named "PA_H") was produced at standard mixing (170 °C) and compaction (160 °C) temperatures as reference HMA for comparison purposes.

Three different WMA porous asphalt mixtures were produced at reduced temperatures equal to 130 °C for mixing and 120 °C for compaction. WMA production temperatures were selected 40 °C lower than conventional temperatures in order to ensure significant emission reductions and cost savings as well as comfortable and healthy working environment for operators [18].

WMA mixtures were prepared using three different WMA additives, representative of the main categories nowadays available in the market, as specified below:

- one mixture (hereafter named PA_WO) was prepared including an organic additive dosed at 3.0% by bitumen weight. The organic wax is a long chain of hydrocarbon molecules that, over its melting point (around 100 °C), ensures a significant reduction of bitumen viscosity allowing mixing and laydown operations at reduced temperatures. Below its melting point, the additive forms a crystalline network structure in the bitumen that increases bitumen stiffness as well as mixture resistance to permanent deformation.
- One mixture (hereafter named PA_WC) was prepared with a chemical additive dosed at 0.5% by bitumen weight. Chemical WMA additives can improve the ability of bitumen to coat aggregate particles by regulating and reducing the slip forces at interface rather than reducing bitumen viscosity. The specific chemical additive selected for this research includes surfactants, emulsifying agents, aggregates coating enhancers and anti-stripping agents. It is produced from ammine substances and it is a viscous liquid at 25 °C with a density of about 1.0 g/cm^3. It is characterized by a viscosity of 450 cP at 15 °C, a pour point of about −8 °C and a flash point higher that 140 °C.
- One mixture (hereafter named PA_WZ) was prepared with a zeolite additive dosed at 0.3% by mixture weight. The zeolite is a water-bearing additive that contains approximately 21% water by mass; during the production process, water is released and vaporizes in contact with hot bitumen. The steam remains encapsulated within bitumen leading to a temporary expansion of bitumen volume with a reduction of its viscosity.

In laboratory, both organic and chemical additives were previously added to hot virgin bitumen (170 °C) and mixed for 15 min right before mixture preparation at 130 °C whereas the zeolite was added directly to asphalt mixture in the mixing chamber at 130 °C, according to producer recommendations.

For both HMA and WMA mixtures, after the mixing phase at 170 °C for HMA and 130 °C for WMAs, short term aging was simulated in laboratory by keeping loose mixtures in a ventilated oven for one hour at the selected compaction temperature [19] (160 °C for HMA and 130 °C for WMAs). Afterwards, compacted and cored specimens were subjected to long term aging process by means of VAPro aiming at simulating the in service age hardening process caused by environmental conditions and traffic loads that continues during the pavement entire life. The VAPro test is described in detail in Section 2.2.

The bituminous phase was then extracted and recovered from all studied PA mixtures, both before and after VAPro specimens aging in order to analyse short and long term aging effects on the rheological behaviour. In this sense, the bitumen that was recovered before VAPro simulates short term aging since the specimen underwent only the oxidation due to mixing and compaction whereas the bitumen that was recovered after VAPro simulates long term aging. The bitumen was extracted according to EN 12697-3 [20] with tetrachloroethylene (C_2Cl_4) as a solvent. The solvent-bitumen solution was distilled according to EN 12697-3 [20] to recover bitumen samples. It is important to underline that extraction and recovery processes may affect the bitumen response due to the possible minimal presence of solvent residual. Nevertheless, since the same processes have been applied to all materials, results can be assumed as a relative index for comparison among the different materials.

Materials identification codes used for mixtures and corresponding bitumens are shown in Fig. 2.

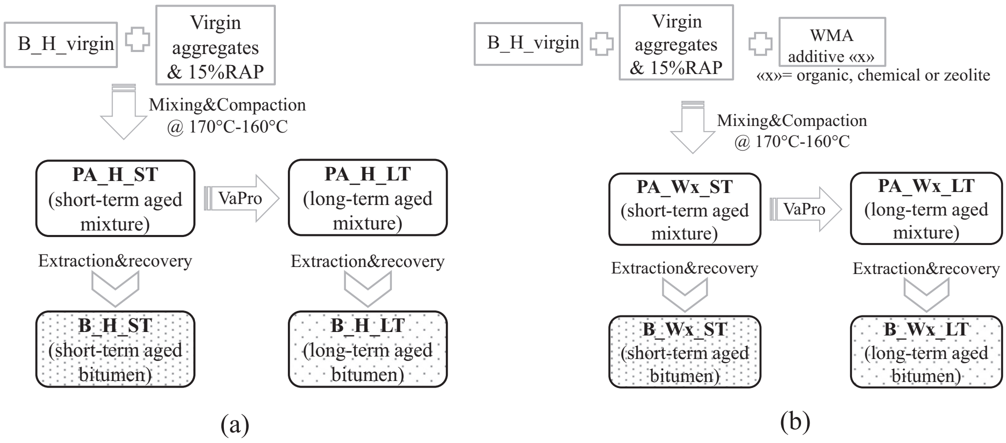


Fig. 2. Investigated materials: HMA (a) and WMAs (b).

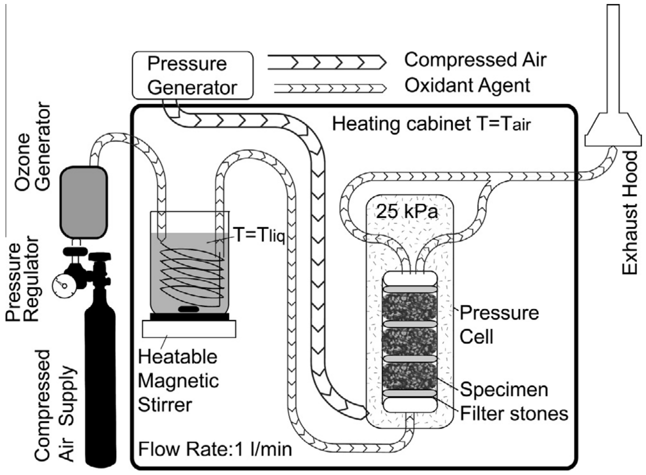


Fig. 3. VAPro Setup [14].

2.2. Aging process – Viennese Aging Procedure (VAPro)

Fig. 3 shows the setup and equipment which was used for VAPro. Compressed air at ambient temperature is supplied from the local laboratory system and passed a pressure regulator, which ensures a constant flow rate (1 L/min) and gas pressure. The subsequent ozone generator, using a dielectric barrier discharge tube [21], enriches the compressed air with ozone and nitrogen oxides. Using compressed air instead of pure oxygen helps to reduce operating costs and to enhance safety of VAPro. Furthermore, the presence nitrogen and nitrogen oxides enables reaction paths for the formation of ozone molecules, and this corresponds better to what happens in the field, respectively [22]. This gas mixture flows through a coiled Cu-Ni tubing, where it is heated up to T_{liq} = +70 °C. Therefore, the coil is placed in a beaker glass, filled with vegetable oil and positioned on a heatable magnetic stirrer. Three HMA specimens are assembled within a triaxial cell between four filter stones and are covered by an elastic membrane. A slight overpressure of 25 kPa was applied in the triaxial cell to force the gas mixture to flow through the specimen instead of passing on the outside. Since an open graded mixture design was used for this paper, the overpressure in triaxial cell was reduced compared to first applications [14]. Concurrently, due to high gas permeability, less flow gas pressure was needed, so that three specimens in series could be aged simultaneous. The triaxial cell and setup for heating up the gas are located in a heating cabinet at temperature T_{air} = 60 °C.

2.3. Test program and methods

The experimental program was focused on the evaluation of aging effect and long term performance of WMA bitumens and mixtures compared to HMA.

Rheological properties were measured on extracted bitumen from unaged and aged specimens. A Dynamic Shear Rheometer (DSR) with a plate–plate configuration was used to perform frequency sweep tests over a frequency range from 1 to 10 Hz at 10 tests temperatures from −10 °C to 80 °C. A 25 mm diameter plate and 1 mm gap were selected for high temperatures (from 50 °C to 80 °C) whereas an 8 mm diameter plate and 2 mm gap were selected for low and intermediate temperatures (from −10 °C to 40 °C). Frequency sweep tests were conducted in control strain within the linear viscoelastic range of materials.

As far as PA mixtures are concerned, all specimens were compacted using 150 mm diameter moulds in the gyratory compactor at a fixed height of 155 mm; samples were then cored and cut in such way that three specimens (100 mm diameter and 40 mm height) were obtained from each sample. Target air void content was selected equal to 20% for all mixtures.

Cyclic indirect tensile tests were carried out on specimens before and after long term aging at a temperature of 10 °C by applying a sinusoidal load at three frequencies equal to 1, 5 and 10 Hz, according to EN 12697-26 [23]. From test data, dynamic modulus $|E^*|$ and phase angle φ were determined to examine the viscoelastic behaviour of specimen [24]. A series of pre-tests were carried out in order to determine the upper stress level of the sinusoidal load so that the elastic horizontal strain amplitude of the specimen during testing is between $5 * 10^{-5}$ m/m and $6 * 10^{-5}$ m/m. It was shown that repeated tests on the same specimen are possible with these loading conditions [25]. This is a necessary precondition since all specimens were tested twice, before and after laboratory aging [25]. Moreover, long term performance in terms of fatigue resistance were assessed by testing aged specimens. Fatigue tests were carried out at +10 °C in stress controlled mode using an indirect tensile configuration. According to EN 12697-24 [26], three diametral vertical loads were applied for each mixture in order to ensure horizontal deformation levels between 50 μm/m and 300 μm/m and a number of loading cycles in a range of 10^3 and 10^5. For each stress level, three repetitions were carried out.

3. Results and analysis

3.1. Aging effects on extracted bitumens

Complex modulus values G^* were measured for bitumens extracted and recovered from specimens before (i.e. Short Term aging – ST) and after VAPro aging (i.e. Long Term aging – LT) by means of frequency sweep tests through DSR equipment. Results were used to determine master curves at a reference temperature of 10 °C, considering valid the Time-Temperature Superposition Principle. The modified CAM Model [27] (Christensen Anderson and Marasteanu) was adopted to analyse test data and to represent the relationship between complex modulus norm and reduced frequency (Eq. (1)), following a shift factor variation based on the Williams-Landel-Ferry equation [28].

$$G^* = G_e^* + \frac{G_g^* - G_e^*}{\left[1 + \left(f_c/f'\right)^k\right]^{m_e/k}} \tag{1}$$

where G_e^* is the equilibrium complex modulus ($f \to 0$), equal to zero for bitumen; G_g^* is the glass complex ($f \to \infty$); f_c is the location parameter with the dimension of frequency; f' is the reduced frequency, function of temperature and strain; k and m_e are shape parameters, dimensionless.

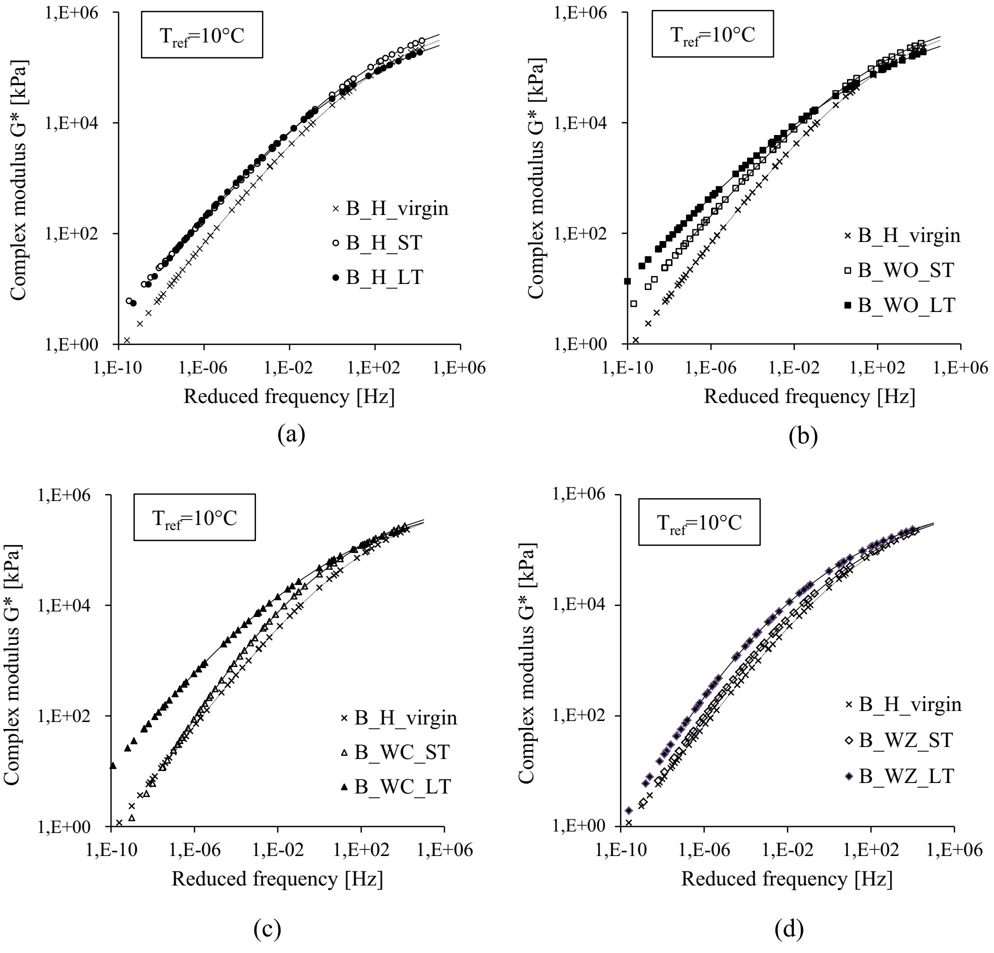
Shifted experimental data as well as master curves are reported in Fig. 4 for all materials. Moreover, the virgin bitumen used to produce all mixtures was tested and analysed likewise and its results are reported in the graphs (B_virgin) for comparison purposes since it represents the unaged condition (before short and long term aging).

As regards to short term aging process, aging effects can be deducted by comparing master curves of the virgin bitumen with the bitumens extracted from the specimens before VAPro aging (ST). The bitumen extracted from the HMA mixture is highly influenced by short term aging process as stiffness of B_H results significantly higher than the B_virgin (Fig. 4a). Such a result can be attributed to the high standard production temperatures that were used to mix and compact HMA mixture specimens. In fact, during mixing time, the bitumen is in very thin films and it is exposed to air at 170 °C; such a process tends to highly stiffen the bitumen due to both air oxidation and loss of more volatile components. Afterwards, the age hardening of bituminous component continues during the transportation and laydown phase, although at a much slower rate [29]; as mentioned before, such a stage was properly simulated during laboratory operations by keeping the loose material in a ventilated oven at the selected compaction temperature before being compacted. As far as WMA bitumens are concerned, short term aging process leads to less pronounced increase in complex modulus when compared to HMA bitumen due to the reduced production temperatures used for WMA mixtures (Fig. 4b, c and d). The short term aging stiffening effect results more remarkable in case of organic additive whereas lower complex moduli characterize bitumens including chemical additive and zeolite. The higher complex modulus measured for the WMA bitumen including organic additive can be attributed to the crystalline network structure that organic wax forms in the bitumen below its melting point so increasing bitumen stiffness [30].

As far as long term aging process is concerned, it is possible to notice a clear difference in behaviour between HMA and WMA bitumens. HMA bitumen rheological properties are not affected by VAPro process since comparable G* values were measured for B_H_ST and B_H_LT whereas all WMA bitumens become significantly stiffer due to long term aging process. Such a result can be related to the different mixture production technologies (HMA and WMA) and, in particular, to the lower initial stiffness of WMA bitumens that make them more susceptible to aging effects.

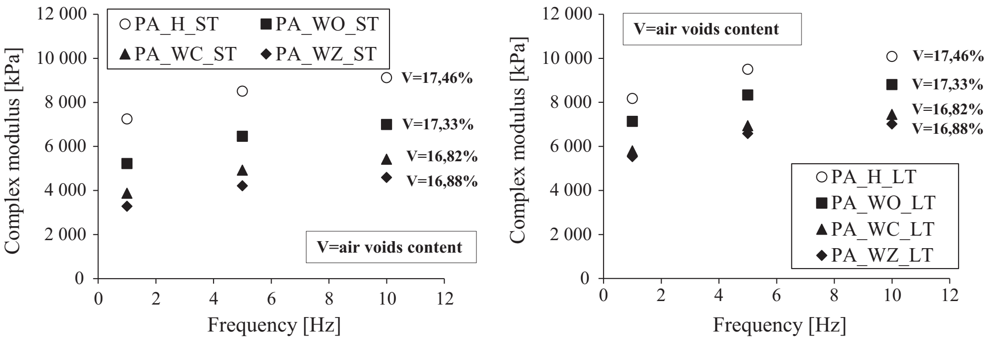
3.2. Mixtures stiffness

Indirect tensile modulus results obtained at 10 °C are reported in Fig. 5 as average of 9 repetitions; tests were carried out at three different load frequencies equal to 1 Hz, 5 Hz and 10 Hz. Stiffness values were measured before and after VAPro aging in order to evaluate the effect of short (ST) and long term (LT) aging on WMA mixtures. Stiffness values before VAPro aging (Fig. 5a) are indicative of the behaviour of short term aged mixtures since the materials were subjected only to mixing and compaction procedures. At the same time, the oxidation that affects upper pavements layers during in-service life is simulated in the laboratory by means of VAPro procedure; thus, stiffness results for aged materials (Fig. 5b) are representative of long term mixture properties.



(a) (b) (c) (d)

Fig. 4. Master curves at reference temperature of 10 °C of extracted bitumens before and after aging: B_H (a), B_WO (b), B_WC (c) and B_WZ (d).



(a) (b)

Fig. 5. Mean stiffness results at 10 °C of HMA and WMA mixtures before (a) and after (b) aging by means of VAPro procedure.

Table 2
ANOVA test: influence of production temperature and additive type on mixtures moduli after short (left) and long (right) term aging.

Short term aging			Long term aging		
	p-Value	significant?		p-Value	significant?
PA_H/PA_WO	1,1E−04	No	PA_H/PA_WO	9,0E−03	No
PA_H/PA_WC	3,6E−06	No	PA_H/PA_WC	1,4E−04	No
PA_H/PA_WZ	8,4E−09	No	PA_H/PA_WZ	8,4E−07	No
PA_WO/PA_WC	0,009	No	PA_WO/PA_WC	0,019	No
PA_WO/PA_WZ	1,3E−05	No	PA_WO/PA_WZ	5,8E−04	No
PA_WC/PA_WZ	0,2	Yes	PA_WC/PA_WZ	0,6	Yes

Moreover, the average air voids content of each mixture is reported in Fig. 5.

Results show that the stiffness of asphalt mixtures is highly dependent on load frequency as expected; in particular, the stiffness increases as the frequency increases for all mixtures studied. Such a trend is not affected by production temperatures or aging status.

Short-term aged results show that all WMA mixtures are characterized by lower stiffness values than the HMA mixture suggesting that the reduced production temperature could affect stiffness properties of warm mixtures due to the lower temperature-induced oxidation during the production phase. The presence of organic WMA additive partially compensates this stiffness gap; the higher stiffness of the WMA mixture prepared with organic additive with respect to the other WMA mixtures can be attributed to the higher bitumen stiffness, consistently with previous outcomes (§3.1). As a matter of fact, other researches [31] found that asphalt mixtures prepared with organic WMA technology measured higher stiffness and improved fatigue cracking resistance than those prepared with other WMA technologies.

Long-term aged results show that, even after VAPro procedure, WMA mixtures do not achieve the same stiffness properties of HMA mixture. The effect of long-term aging is evident for all WMA mixtures but it is not sufficient to compensate the initial stiffness gap respect to HMA due to the reduced production temperatures. The only exception is represented by the WMA mixture including organic additive that show higher stiffness values with respect to the other WMAs, resulting in long term stiffness similar to the HMA mixture. As previously mentioned, the presence of organic additive demonstrate a higher initial stiffness both for bitumen and mixture due to the additive nature that tends to form a crystalline network within bituminous phase. However, it is important to note that such a behaviour similar to HMA is not desirable in terms of durability since excessive long term stiffness can lead to premature fatigue and thermal cracking failure.

Moreover, a one-way ANOVA analysis at 95% confidence level is performed to verify statistical significance of results: the p-values are reported in Table 2 for short and long term aged mixtures. ANOVA tests confirm a significant difference in stiffness moduli in case of short and long term aged mixtures. In particular, all WMA mixtures are characterized by a significant lower stiffness than HMA and PA_WO demonstrates significant higher stiffness values than all the other WMA mixtures. On the other hand, no statistical significance can be detected between results of WMA mixtures including chemical and zeolite, regardless the aging processes.

In order to evaluate and quantify long-term aging effect on HMA and WMA mixtures, the stiffness increase (ΔE*) due to VAPro aging procedure was calculated as follows:

$$\Delta E^* = \frac{E^*_{LT} - E^*_{ST}}{E^*_{ST}} \times 100 \qquad (2)$$

where E^*_{LT} is the complex modulus of long term aged specimens after VAPro aging and E^*_{ST} is the complex modulus of short term aged specimens before VAPro aging.

The parameter ΔE^* is represented in Fig. 6 for all frequencies and mixtures. Results show that all WMA mixtures are more affected by long term aging than the HMA mixture. It is well known that age hardening that takes place during the entire pavement service life is highly influenced by the bitumen film thickness around aggregate particles and by the air void content which provides different entry of air, water and light [29]. In the present study, both parameters can be considered constant since mix design and target air void content were the same for all studied mixtures. Thus, the different long term aging level can be only attributed to mixtures production technologies (HMA and WMA) and, in particular, to the lower initial stiffness of WMA mixtures

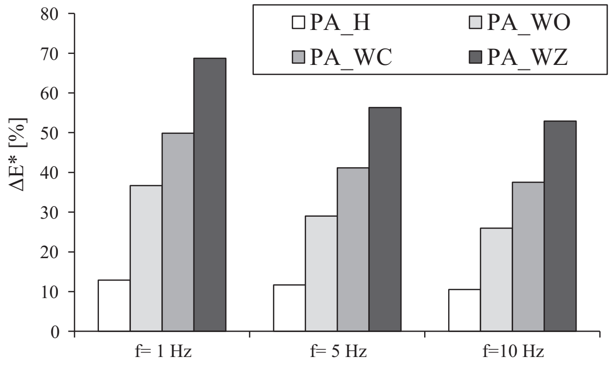


Fig. 6. Aging effect on stiffness properties for HMA and WMA mixtures.

that makes them more susceptible to aging effects. As a matter of fact, the effect of aging is found to be more pronounced for WMA mixtures including zeolite and chemical additive since they are characterized by lower stiffness before aging.

Such outcomes are consistent with the results obtained for bitumens as all WMA bitumens demonstrate to stiffen significantly more than HMA bitumen due to long term aging process. Thus, the extensive stiffening effect that characterize all aged WMA mixtures can be mainly attributed to the corresponding stiffening of bituminous components. In fact, long term aging effect of WMA bitumens including chemical additive and zeolite result more pronounced with respect to the bitumen including organic additive consistently with the recorded WMA mixtures stiffness increase (Fig. 6).

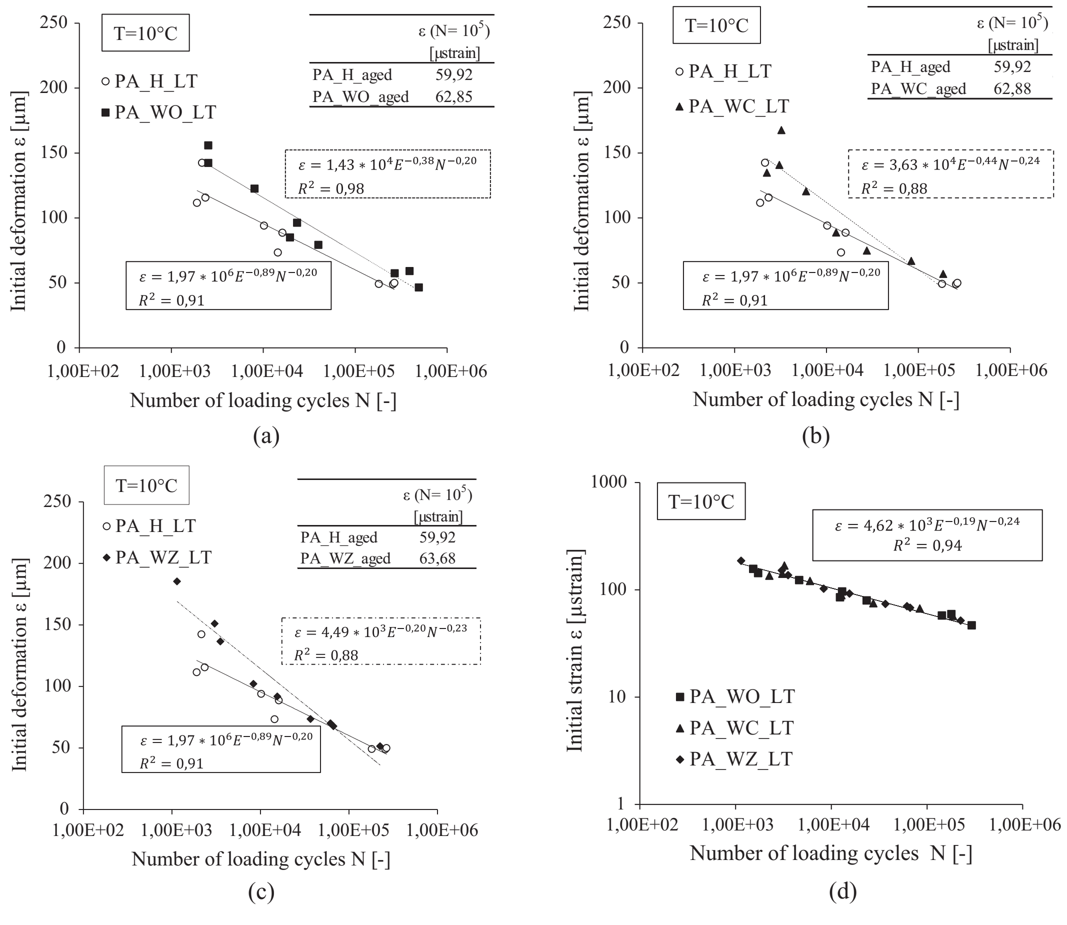
3.3. Fatigue resistance

Fatigue results for long-term aged mixtures are shown in Fig. 7 in terms of initial maximum horizontal strain as a function of number of cycles until failure. The fatigue failure of each specimen is determined as number of cycles to reach 50% of initial stiffness. Moreover, fatigue curves are expressed as a generalized relationship incorporating horizontal strain (ε), number of cycles at failure (N) and initial mixture stiffness (E). Many researchers, in fact, had shown that critical horizontal strain is highly influenced by the material stiffness that, as consequence, needs to be incorporated in the fatigue life prediction curve [32,33].

The fatigue curve obtained for each WMA mixture, directly compared to reference HMA mixture results, is depicted in Fig. 7a, b and c along with the corresponding regression coefficient (R^2). Results show that the WMA mixture including organic additive performs similarly to the HMA mixture in terms of fatigue resistance since they are characterized by the same slope parameter (Fig. 7a). On the other hand, fatigue behaviour of WMA mixtures including chemical additive (Fig. 7b) and zeolite (Fig. 7c) is slightly different than the HMA mixture as the fatigue curves are characterized by higher slope parameters.

In order to directly compare mixtures fatigue behaviour, the horizontal deformation value related to a target number of cycles of 10^5 (selected as target fatigue life) is calculated as considered representative of the predicted deformation after an extensive traffic level. Such deformation parameters, reported in Fig. 7a, b and c, show a full comparability of the studied mixtures as results obtained for all WMA mixtures and the reference HMA mixture were very similar. Thus, the lower stiffness of long term aged WMA mixtures compared to the mixture produced at standard temperature do not provide any benefits in terms of overall fatigue resistance. At the same time, lower production temperatures do not imply any detrimental effects in terms of long term fatigue performance.

Finally, all experimental data obtained for WMA mixtures are reported in the same graph in Fig. 7d for an overall comparison. It is possible to notice that there is not clear distinction between data which can actually be fitted by a unique regression line. As a matter of fact, considering all test data as representative of a unique material a good regression coefficient is obtained, demonstrating that all mixtures are characterized by very similar fatigue behaviour. Such a result suggests that the fatigue behaviour is more influenced by production temperatures rather than WMA additive type.



(a) (b)

(c) (d)

Fig. 7. Fatigue curves of the HMA and WMA mixtures including organic additive (a), chemical additive (b) and zeolite (c). Fatigue results of all WMA studied mixtures (d).

4. Conclusions

Based on the results obtained during the experimental program, the following conclusions can be drawn:

- WMA bitumen and WMA mixtures are characterized by lower stiffness values than the HMA suggesting that reduced production temperature could affect stiffness properties of warm mixtures due to the lower temperature-induced oxidation during the production phase;
- extensive long term aging effects are measured in case of WMA bitumens and mixtures contrarily to HMA materials that are not significantly affected by VAPro process;
- stiffness values of WMA mixtures results lower than HMA mixture even after long term aging due to the initial stiffness gap; the presence of organic additive tends to increase bitumen stiffness and, as a consequence, mixtures stiffness;
- WMA mixture including organic additive performs similarly to HMA in terms of fatigue slope whereas the presence of chemical additive and zeolite leads to a slightly higher fatigue slope parameters.
- Overall fatigue results show that long term fatigue performance of WMA mixtures are not significantly affected by low production temperatures or WMA additive type; similar results are found despite the different stiffness values of WMA and HMA mixtures.

Overall experimental results underline the different aging behaviour of WMA and HMA mixtures and the direct correlation with bituminous phase; despite differences in aging effects, long term performance in terms of fatigue resistance are not affected by production temperatures or WMA additive type.

The understanding of temperatures productions and aging effects on PA mixtures performance is a fundamental starting point in order to better interpret and analyse the overall properties of open graded WMA mixtures. However, the present experimental program does not presume to cover the entire PA pavements characterization since premature failure of porous asphalt mixtures is often related to water susceptibility as well as ravelling failure rather than stiffness issues or fatigue cracking.

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