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Evaluation of the Performance of a Warm Mix Asphalt (WMA) Considering Aged and Unaged Specimens

Giuseppe Piccone [1,2], Giuseppe Loprencipe [1,*], Arminda Almeida [2,3] and Nicola Fiore [1]

1 Department of Civil, Constructional and Environmental Engineering, Sapienza University, 18 Via Eudossiana, 00184 Rome, Italy; piccone.1251827@studenti.uniroma1.it (G.P.); nicola.fiore@uniroma1.it (N.F.)
2 Departamento de Engenharia Civil, Universidade de Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal; arminda@dec.uc.pt
3 CITTA—Centro de Investigação do Território, Transportes e Ambiente, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
* Correspondence: giuseppe.loprencipe@uniroma1.it; Tel.: +39-06-44585112

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Abstract: In the last decades, all technology production sectors reached a high level of development, without neglecting the attention to environmental aspects and safeguarding energy resources. Moreover, in the sector of pavement industry, some alternatives of bituminous mixtures were proposed to reduce the greenhouse gas emissions. One of these is the warm mix asphalt (WMA), a mixture produced and compacted at lower temperatures compared to traditional hot mix asphalt (HMA) (about 40 °C less), to allow a reduction of emissions into the atmosphere and the costs. Other operative benefits concern the health of workers during the whole road construction process, the reduction of distances to which the mixture can be transported, and therefore also the positioning of the plants. However, it is not all benefits, since reduced production temperatures can bring short- and long-term water sensitivity issues, which could threaten the pavement performance. This paper evaluated the performance (water sensitivity, stiffness, fatigue, and permanent deformation) of a WMA produced using a warm mix fabrication bitumen and compared it with an HMA tested in parallel. In general, except for the resistance to permanent deformation, the WMA presented performances comparable to HMA. Regarding the fatigue behavior of asphalt mixtures, the WMA was less affected by ageing conditions, despite it showing lower performance than HMA.

Keywords: warm mix asphalt; performance; ageing; water sensitivity; permanent deformation; stiffness; fatigue

1. Introduction

The technologies and the methods for the production and spread of traditional bituminous mixtures, classified as hot mix asphalt (HMA), have experienced a remarkable development over the years, passing from manual to modern high-level automated equipment.

During this time, in these production processes, the temperature control is a crucial factor to reach high performances. In fact, the choice of temperature can affect the coating of aggregates by bitumen, the stability of the mixture, the compaction of layers and, finally, can ensure good performance of the long-term pavement road.

For the traditional bituminous mixtures, the control of the temperature, normally in the range 140–170 °C, involves various phases, from the production to the compaction. In case of surpassing the correct temperature, the mixture can overheat and accelerate the binder ageing process; high temperature can also affect long-term performance and determine an increase in fuel and energy consumption, emissions, and harmful fumes, both at the production plant and at the site of interest. On the contrary,

low temperatures applied on traditional bituminous mixtures, even if they reduce oxidative hardening which should reduce susceptibility to cracking by improving pavement flexibility and longevity, can produce low compaction reducing pavement life.

Researchers have carried out studies to reduce the mixing/compaction temperature in the mixtures since the 1970s [1] by utilizing moisture in the aggregate, foaming the binder, and, of course, using emulsified asphalts.

The technology of warm mix asphalt (WMA) and its potential benefits initiated significant interest in the last two decades both in Europe [2] and in other countries interested in economical, environmentally friendly paving materials [3–5].

The benefits deriving from the use of WMA are many, starting from the reduction in energy consumption due to lower temperatures. Considering energy save during mix production, Hasan et al. [6] observed that savings between 23% and 29% can be obtained by using WMA rather than HMA.

HMA, on the other hand, requires heating the binder to high temperatures to ensure that it is fluid enough to be able to completely coat the aggregates, to allow easy workability of the mixture during laying and compaction, and for durability of the road pavement over the years [7]. WMA technologies allow the reduction in manufacturing and compaction temperatures. With the use of WMA, it is therefore possible to reduce emissions, harmful fumes resulting in a lower risk to workers' health. However, reduced manufacturing temperatures can affect the drying process of the aggregates before mixing, and proper aggregates–bitumen adhesion/coating, and consequently it is a WMA issue. Numerous studies have addressed it by quantifying water sensitivity, some use mixture properties [8–11], while others use aggregates–bitumen interface properties [12–14]. There are different methods that can be used to reduce the viscosity of the bitumen at lower temperatures [15]: foamed methods, organic additives and waxes, and chemical additives, and consequently water sensitivity depends on it [16]. In addition, it is important to evaluate the ageing effect on it [17]. In foamed methods, additional additives (such as antistripping agents) are sometimes used to improve coating [18]. The other two methods usually do not require those antistripping agents [16].

In the search for more sustainable pavements, many studies have been developed regarding WMA technologies. For instance, Mallick et al. [19] studied the use of reclaimed asphalt pavement (RAP) in WMA to avoid deterioration of the aged binder. It is known that RAP should not be exposed to relatively high temperatures, so the WMA solution seemed to be a good opportunity. Furthermore, Guo et al. [20] investigated the performance of WMA containing RAP mixtures. The use of other particular components in the mixes has led many researchers to experiment with the application of WMA technology: Ameri et al. [21] proposed the possibility of using electric arc furnace (EAF) steel slag (SS) as a substitution for natural limestone (LS) aggregates. Cheng et al. [22] investigated the size effect of hydrated lime on the moisture susceptibility of WMA mixtures with selected additives. Capitão et al. [23] summarized the main aspects involved in WMA technology, including constituent materials, mix design, and mechanical performance issues, as well as technological specificities. Other research [24] highlighted the reduction of susceptibility to thermal cracking regardless of the WMA additive or process used. The behavior of WMA mixtures with respect to permanent deformations resulting from load repetitions highlights some controversial aspects [25,26]: some studies revealed a quite controversial rutting behavior which cannot be explained considering only the laboratory data [27]. The contribution of ageing regarding the behavior of the mixtures to permanent deformation cannot be neglected. In some research, most aged WMA pavements showed increased "rutting", but in other results lower rut depths could be found in WMA mixtures. As opposed to these results, fatigue and stiffness of aged WMA mixtures samples compared to unaged samples improved significantly. Some attempts to address this behavior regarding the permanent deformation of WMA mixtures were conducted. For example, the use of additives can decrease their susceptibility to rutting [28] or lower the production temperatures of WMA [29].

While many studies have been conducted to demonstrate that some component can be added without significantly affecting the mechanical properties of WMA, many questions and concerns

regarding the environmental benefits they offer have yet to be addressed. Alloza et al. [30] conducted a comprehensive hybrid life cycle assessment of WMA production in order to accurately evaluate and quantify the potential benefits of WMA technology by assessing the environmental impacts of its production associated with energy consumption and greenhouse gas (GHG) emissions.

The main objective of this article is to evaluate the performance of a WMA produced using a warm-mix fabrication bitumen (compacted at 120 °C) and compare it with the results of a HMA tested in parallel (compacted at 160 °C). As temperature reduction might influence aggregates–bitumen adhesion/coating, water sensitivity was quantified as well as other pavement performance properties (stiffness, fatigue resistance, and permanent deformation resistance) considering aged and aged specimens. This research aims to contribute to the understanding of the complex issue of the mixture ageing and water sensitivity by addressing the evaluation of pavement performance.

2. Materials and Methods

This research considers asphalt concrete (AC) mixtures of the type AC 20 bin/reg/base [31]. Two mixtures were considered, a WMA mixture and a typical HMA mixture. The first one was produced with a bitumen designed for warm mix fabrication, while the second one was produced with a conventional bitumen, both with a 35/50 penetration grade. The aggregates blending was the same for the two mixes.

To evaluate the performance of the two mixes and to compare them, several specimens were prepared and then tested to evaluate:

- Water sensitivity—by determining the indirect tensile strength ratio (ITSR);
- permanent deformation—by using the wheel-tracking test (WTT);
- stiffness—by using the four-point bending (4PB) test; and
- resistance to fatigue—by using the four-point bending (4PB) test.

As ageing has a significant effect on performance, each test was conducted on aged and unaged specimens.

2.1. Aggregates

Limestone aggregates were used in this study; more precisely four coarse aggregate fractions where considered to produce an Asphalt Concrete AC 20 bin/reg/base (EN 13108-1) [31]. Table 1 presents the aggregates' properties and Figure 1 depicts the aggregates gradation as well as the upper and lower limits of the grading envelope.

Table 1. Aggregates' properties.

Properties	Standard	Aggregates (mm)			
		11–22	**8–15**	**4/8**	**0/4**
Assessment of fines	EN 933-9 [32]	f_1	f_1	f_3	f_{10}
Methylene blue	EN 933-9 [32]	–	–	–	MB_F10
Density after drying (Mg/m^3)	EN 1097-6 [33]	2.66	2.66	2.65	2.65
Water absorption (%)	EN 1097-6 [33]	0.9	0.9	0.9	0.9
Flakiness index	EN 933-3 [34]	FI_{10}	FI_{15}	–	–
Micro-Deval	EN 1097-1 [35]	$M_{DE}15$	$M_{DE}15$	–	–
Los Angeles	EN 1097-2 [36]	LA_{35}	LA_{35}	–	–

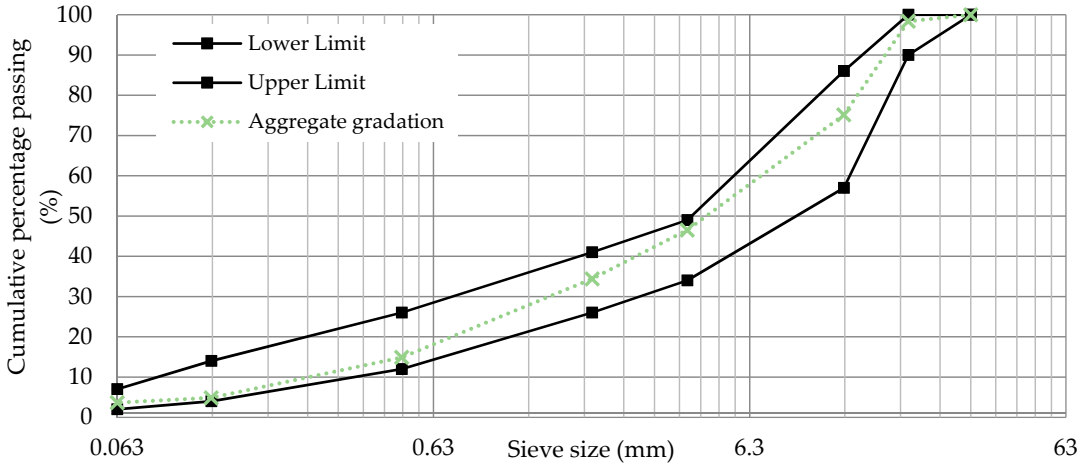


Figure 1. Grading curve of the mixture.

2.2. Asphalt Binder

Two types of asphalt binder were used in this research, namely a "conventional bitumen" for the HMA and a "warm-mix fabrication bitumen" for the WMA. The bitumen used for WMA was an asphalt binder designed for warm mix fabrication. It included waxes for viscosity reduction at high temperatures in order to reduce fabrication temperatures as well as energy consumption and GHG emissions. Table 2 presents its properties. Both asphalt binders consisted of a 35/50 penetration grade binder.

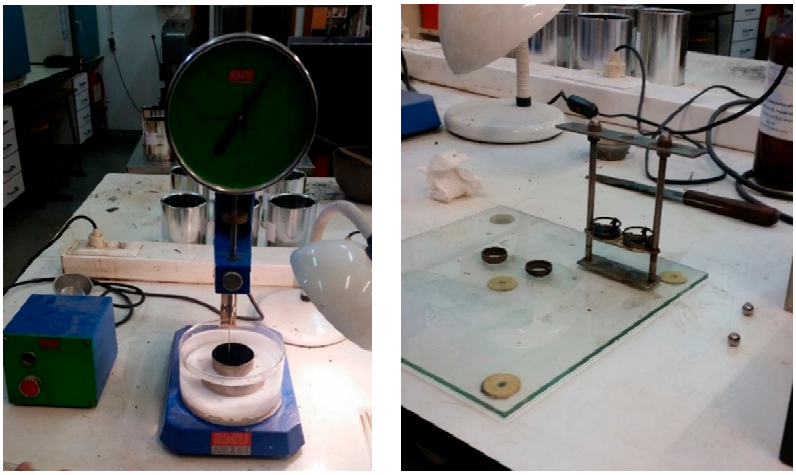
Table 2. Properties of the warm-mix fabrication bitumen.

Properties	Standard	Minimum	Maximum
Penetration 25 °C (0.1 mm)	EN 1426 [37]	35	50
Penetration Index	EN 12591 [38]	−1.5	0.7
Softening point (ring and ball) (°C)	EN 1427 [39]	50	58
Fraass point (°C)	EN 12593 [40]	–	−5
Solubility in xylene (%)	EN 12592 [41]	99.0	–
Flash point (°C)	EN ISO 2592 [42]	240	–
Resistance to hardening 163 °C (EN 12607-1)			
Mass loss (%)	EN 12607-1 [43]	–	0.5
Retained penetration (%)	EN 1426 [37]	53	–
Increase in softening point (Ring and Ball) (°C)	EN 1427 [39]	–	11

To verify the binder characteristics, according to EN 12591 [38], the following two tests were conducted in the laboratory:

- Determination of the needle penetration (EN 1426) [37]—Figure 2a.
- Determination of the softening point—ring and ball method (EN 1427) [39]—Figure 2b.

For each bitumen used, two penetration tests and two "ring and ball" tests were conducted to verify the characteristics of bitumen. Table 3 presents the measures obtained.



(**a**) (**b**)

Figure 2. Test equipment to characterize the bitumen. (**a**) Needle penetration test; (**b**) Softening point test.

Table 3. Results of the bitumen tests.

Property	Standard	Conventional Bitumen		Warm-Mix Fabrication Bitumen		Min	Max
Penetration at 25 °C (0.1 mm)	EN 1426	35	38	39	39	35	50
Softening point (°C) (ring and ball)	EN 1427	53	54	53	54	50	58

2.3. Specimens Preparation

For each test, different specimens were prepared. The content of bitumen used for all specimens was 5%, while the content of aggregates was defined by the grading curve described before (see Figure 1). The HMA and WMA specimens were prepared at different temperatures as depicted in the Table 4.

Table 4. Temperatures for hot mix asphalt (HMA) and warm mix asphalt (WMA) specimens' preparation (in °C).

Mixture	Aggregates	Bitumen	Compaction
HMA	180	160	160
WMA	140	120	120

2.3.1. Water Sensitivity

To determine the water sensitivity of the mixes, a set of eight specimens, four "dry" and four "wet" (immersed in water in according to EN 12697-12 [44]), for each mix (HMA unaged, HMA aged, WMA unaged, and WMA aged) were prepared, making a total of 32 Marshall specimens. All the specimens were compacted with 75 blows of the "impact compactor" in each face, following the standard procedure EN 12697-30 [45].

Once the specimens were prepared, the bulk density of the specimens was determined according to the procedure specified in the standard EN 12697-6 [46], more specifically the procedure B, named "saturated surface dry" (SSD) and used for specimens with a closed surface as in this case. In procedure B, the specimen was saturated preliminary with water, after which the surface was blotted dry with a damp Chamois.

Figure 3 presents average bulk densities of the specimens prepared for the water sensitivity Test considering both aged/unaged and dry/wet conditions.

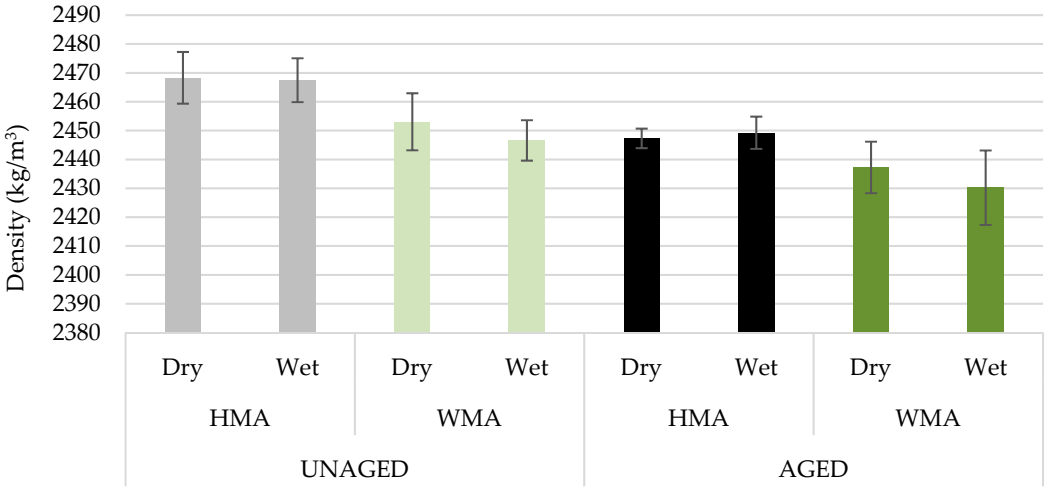


Figure 3. Average bulk densities of water sensitivity tests' specimens.

2.3.2. Permanent Deformation

The second type of specimen considered in this research were the slabs (300 mm × 370 mm × 60 mm), prepared to evaluate the permanent deformation with the "wheel tracking test". The slabs were compacted with the hand driven roller compactor of the Coimbra Institute of Engineering (ISEC) following the standard EN 12697-33 [47]. A total of eight "wheel tracking" slabs were prepared, four for each mix (HMA and WMA) subjected or not to the ageing procedure. Figure 4 presents the average bulk densities of the slabs.

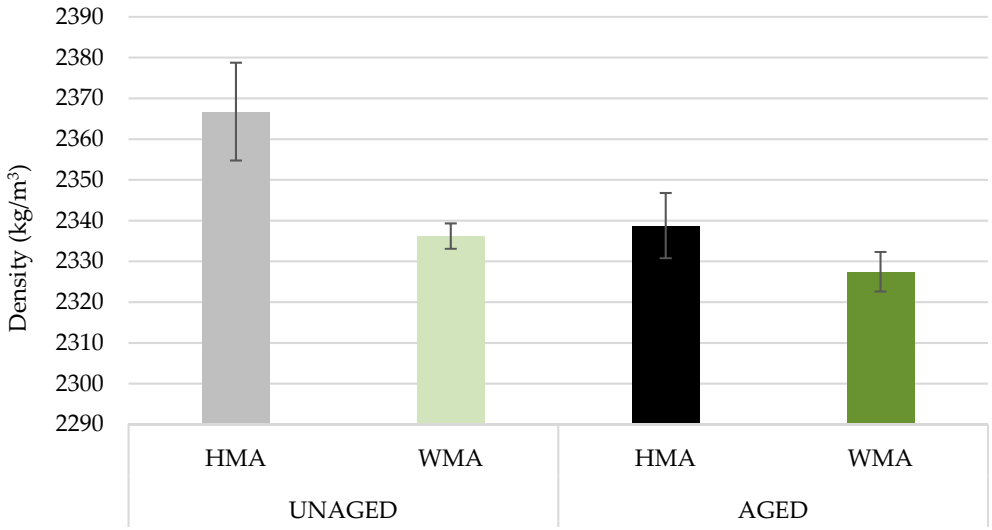


Figure 4. Average bulk densities of wheel tracking slabs.

2.3.3. Stiffness and Fatigue Resistance

The third and last type of specimen considered in this research was the beams, obtained by cutting 550 mm × 500 mm × 60 mm asphalt mix slabs. Those slabs were also prepared in laboratory using the hand driven roller compaction following the standard EN 12697-33 [47]. The slabs' borders were removed to take into consideration only the central part of it, taking into account the best conditions of compaction, after which each slab was cut into eight beams of 420 mm × 60 mm × 60 mm. Figure 5 presents the average bulk densities of the tested beams (used in stiffness and fatigue resistance tests).

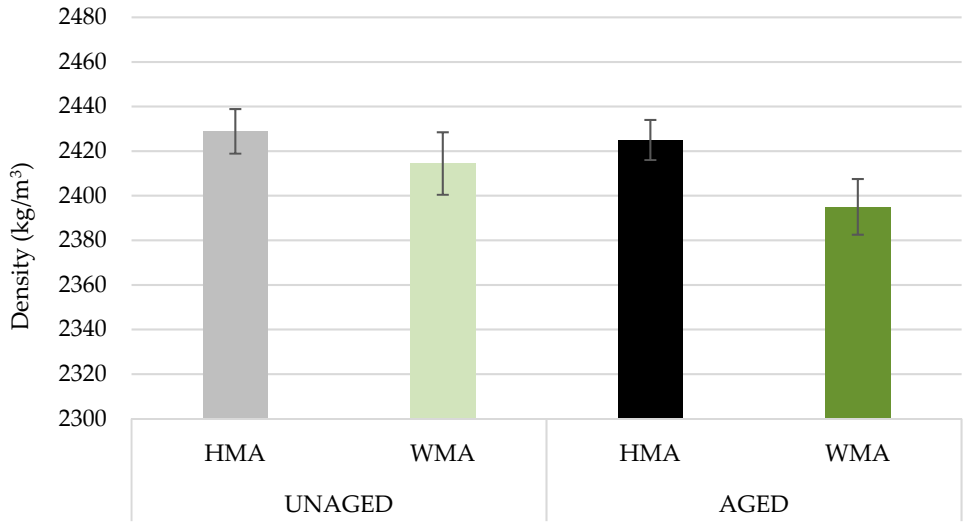


Figure 5. Average bulk densities of the beams.

2.3.4. Ageing Procedure

As ageing influences the properties of AC mixture (both in HMA and WMA [48], half of the specimens were tested after being subjected to a long-term ageing procedure in an oven. For that, the AASHTO R 30-02 test protocol [49], though with certain limitations [50], was selected due to its simplicity and widespread use [51–54]. This protocol establishes that the specimens must be placed in an oven at 85 °C for 120 h (5 days). After that time, the oven is turned off and the door is left open to let the specimens cool down to room temperature.

2.4. Laboratory Tests

2.4.1. Water Sensitivity (ITSR Test)

After having prepared the specimens, the water sensitivity of them were determined. This test method was done to evaluate the effect of saturation and accelerated water conditioning on the indirect tensile strength.

A set of cylindrical test specimens was divided into two equally sized subsets and conditioned. One subset was maintained dry at room temperature while the other subset was saturated and stored in water at elevated conditioning temperature, 40 °C, for 72–88 h.

After conditioning, the indirect tensile strength (ITS) of each of the two subsets was determined in accordance with EN 12697-23 [55] at the specified test temperature. The ratio of the ITS of the water conditioned subset compared to that of the dry subset was determined and expressed in percent (EN 12697-12 [44]). The ITS values (in GPa) were calculated using Equation (1).

$$\mathrm{ITS} = \frac{2P}{\pi \times D \times H} \tag{1}$$

where:

P is the peak load (kN);
D is the diameter of the specimen (mm); and
H is the height of the specimen (mm).

Then, the ITSR values (in %) were calculated using Equation (2).

$$\mathrm{ITSR} = 100 \times \frac{\mathrm{ITS}_w}{\mathrm{ITS}_d} \tag{2}$$

where:

ITS_w is the average ITS of the wet group (kPa); and
ITS_d is the average ITS of the dry group (kPa).

2.4.2. Permanent Deformation (WTT)

This test was conducted according to EN 12697-22 [56]. This European Standard describes test methods for determining the susceptibility of bituminous materials to deform under load. The susceptibility of bituminous materials to deformation is assessed by the rut formed by repeated passes of a loaded wheel at constant temperature of 60 °C (the test temperature specified by the Portuguese Road Administration [57].

In the tests carried out in the laboratory, a small-sized device (Wessex S-867 machine, Wessex Engineering Ltd, Weston-Super-Mare, UK) was used, following procedure B in air. For this case, the minimum number of specimens to test was two. The wheel load, achieved by the use of a weighted cantilever arm, was about 700 N.

The thickness of the specimen was chosen according to the EN 12697-22 [56] and it was a function of the type of device and the upper sieve size of the mixture. In this study (small-sized device and AC 20), a 60 mm thickness was chosen.

The slabs were conditioned in the oven for 4 h at the test temperature (60 °C), as explained in the standard EN 12697-22 [56]. After this, the test began and the vertical position of the wheel was measured. The test ran until 10,000 load cycles were applied or until a rut depth of 20 mm was reached, whichever was the shorter.

The main parameters obtained from this test were the rut depth at the end of test (RD_{air}), the proportional rut depth (PRD_{air}), i.e., the ratio between the RD_{air} and the thickness of the specimen, and the wheel-tracking slope (WTS_{air}) calculated by Equation (3).

$$WTS_{air} = \frac{(d_{10,000} - d_{5000})}{5} \quad (3)$$

where:

WTS_{air} is the wheel-tracking slope (mm per 10^3 load cycles);
$d_{10,000}$, d_{5000} is the rut depth after 10,000 load cycles and 5000 load cycles, in mm.

2.4.3. Stiffness (4PB Test)

The stiffness of the bituminous mixtures was found according to the standard test EN 12697-26 [58], more precisely using the four-point bending test on prismatic specimens (4PB-PR) under strain-controlled conditions. The amplitude of the load was such that no damage could be generated during the measurements. Experiments with many test methods have shown that for most bituminous mixtures, strains should be kept at a level lower than 50 micro strains to prevent fatigue damage (EN 12697-26 [58]). The range of frequencies is device dependent.

The maximum frequency allowed by the machine is 10 Hz. We decided to choose from the typical set of frequencies proposed by the standard procedure 1, 2, 4, 6, 8, 10, and 1 Hz. If the difference between stiffness on the specimen at the first and last measurements at identical frequency and at the same temperature was greater than 3%, it could be concluded that the specimen was damaged and, therefore, could not be used for further testing. The tests were conducted at 20 °C.

2.4.4. Fatigue Resistance (4PB Test)

Fatigue cracking resistance was also evaluated using the 4PB (four-point bending) test, according to standard EN 12697-24 [59]. The test was carried out under strain-controlled conditions at a test temperature of 20 °C, a temperature that represents the Portuguese conditions [60], on the specimens

primarily subjected to the stiffness determination. The three strain levels applied at a frequency of 10 Hz were 100, 200, and 300 μm/m. The chosen failure criterion was specified in EN 12697-24 [59], i.e., a 50% reduction of the initial stiffness modulus.

The 4PB test results are usually plotted in a log-log scale. Then, a fatigue law is determined by fitting a regression line according to the regression described by Equation (4).

$$\varepsilon = A \times N^B \quad (4)$$

where:

ε is the failure strain in mm/m;
N is the number of load repetitions; and
A and B are regression coefficients.

3. Results and Discussion

3.1. Water Sensitivity (ITSR Test)

Figure 6 presents the indirect tensile strength (ITS) results for both unconditioned (dry) and conditioned (wet) specimens, and unaged and aged specimens. Figure 7 depicts the indirect tensile strength ratio (ITSR).

Figure 6 shows that the WMA presents lower ITS values than the HMA in both dry and wet specimens. Saturation and accelerated water conditioning decreased ITS values of unaged specimens (ITSR values higher than 100%) and contrarily increased ITS values of aged specimens (ITSR values higher than 100%). The values for both mixes were higher than 85%. Thus, it is likely that the reduced manufacturing temperature did not compromise the aggregates-bitumen adhesion/coating. It is noted that the used warm-mix fabrication bitumen was developed to provide cohesion while reducing production temperature.

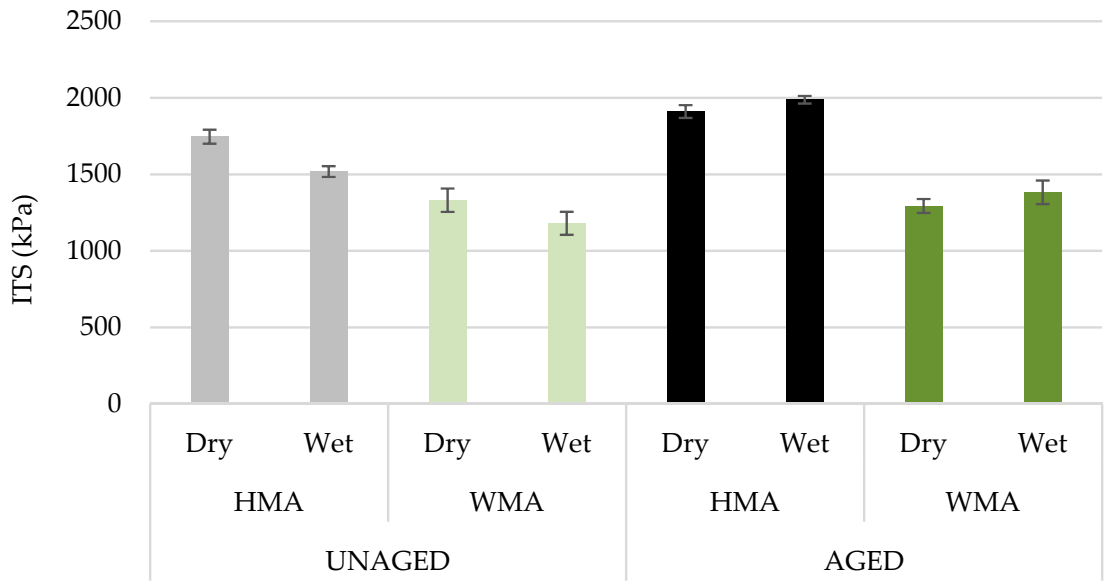


Figure 6. Results of indirect tensile strength.

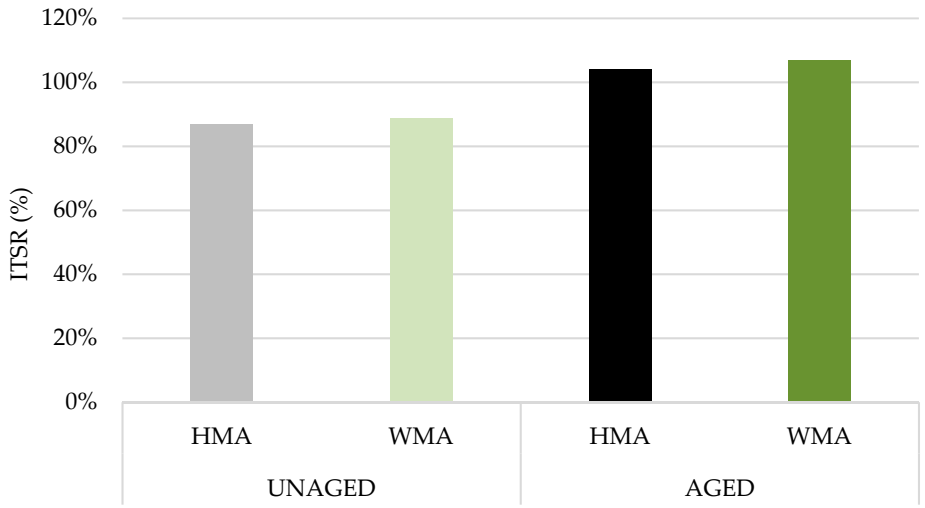


Figure 7. Results of indirect tensile strength ratio (ITSR) values.

3.2. Permanent Deformation (WTT)

Aside from low-temperature and fatigue cracking, permanent deformation is another major distress of asphalt pavements. Figure 8 presents the evolution of rut depth against the number of loading cycles and Table 5 summarizes the results of all the parameters calculated.

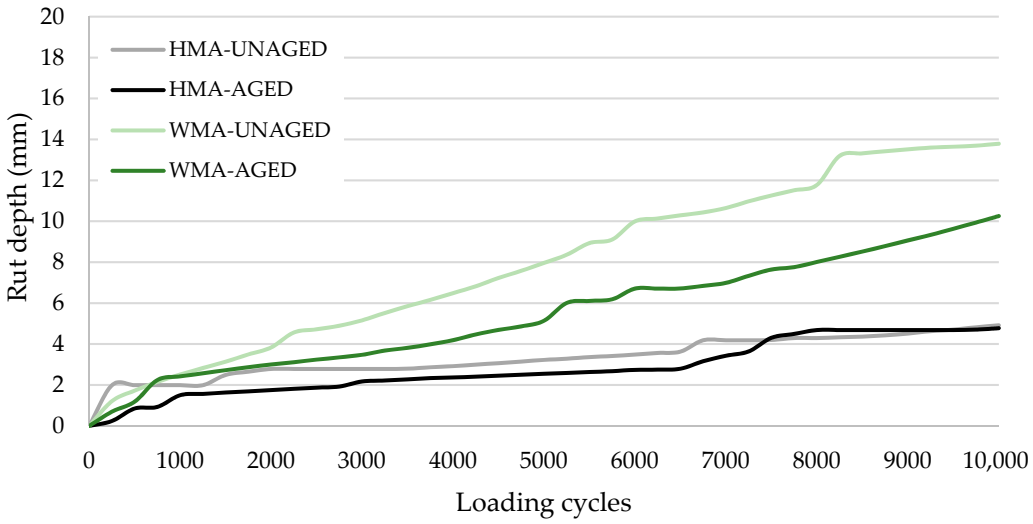


Figure 8. Results of permanent deformation for aged and unaged specimens.

Table 5. Wheel tracking test parameters.

Mixture		RD_{air} (mm)	PRD_{air} (%)	WTS_{air} (mm/10^3 Load Cycles)
HMA	Unaged	4.9	8.1	0.338
	Aged	4.8	7.9	0.446
WMA	Unaged	13.8	22.7	1.165
	Aged	10.3	16.7	1.023

The resistance to permanent deformation (wheel tracking test) of the WMA slabs was not as good as the HMA slabs. The WMA aged slabs show better behavior than the unaged. Nevertheless, the values of the WMA slabs were not so bad (rut depth lower than 15 mm), as the tests did not stop before 10,000 cycles, even at 60 °C. The results highlight the benefits of ageing. When the asphalt is aged, it gets stronger because aggregates and bitumen increase their bond, due to bitumen hardening.

3.3. Stiffness (4PB Test)

Stiffness modulus established with samples prepared in the laboratory and by 4PB tests are usually used as a reference for behavior/quality control analysis of the samples coming from the construction site. Figure 9 presents the variation of stiffness with frequency.

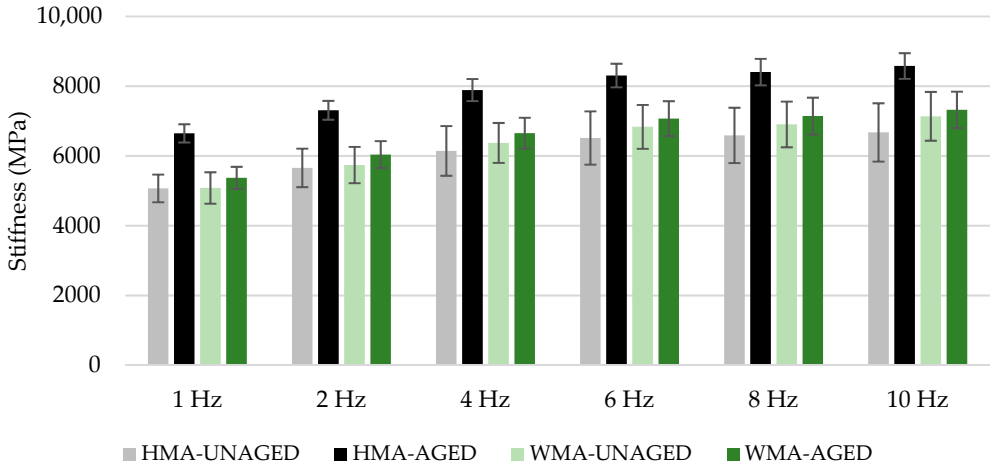


Figure 9. Results of stiffness.

From Figure 9, it is possible to conclude that for the unaged beams, stiffness is almost the same for low load frequency, and it does not differ a lot for higher frequencies. The aged beams presented a higher stiffness compared to the unaged ones, because of bitumen hardening. In addition, in this case, the performance of WMA, although smaller, was comparable to those of HMA. All the values were higher than 5000 MPa, which is a reasonable value for low-to-high volume roads.

3.4. Fatigue Resistance (4PB Test)

To complete the characterization of the mechanical performance of the mixtures studied, the four-point fatigue bending beam (4PB) test method was conducted at 20 °C using a loading frequency of 10 Hz, according to EN 12697-24 [59]. Figure 10 presents the 4PB test results and the corresponding fitting fatigue laws (in a bi-logarithmic scale), whose parameters of Equation (4) are presented in Table 6.

Thus, it can be seen in Figure 10 that, for the strain–fatigue levels tested, all the mixes showed not comparable fatigue slopes, suggesting that they did not have an equivalent sensitivity to strain in terms of fatigue life. In detail, it is possible to see, for great strain level (300 μm/m), comparable values of cycles both WMA and HMA, and higher values of the unaged beams compared to the aged (differences unaged/aged less than 10,000 cycles). For small strain level (100 μm/m), HMA presented higher values of cycles than WMA. This means that the slope of the fatigue lines for WMA were higher than HMA, which suggests that the mixtures with warm-mix fabrication bitumen are more sensitive to change of strain level. Through the equations of each curve, it is possible to obtain the strain level at which the asphalt reaches 50% of the resistance after 1 million cycles. Table 7 presents the classical strain level value, ε_6, which indicates the strain failure at one million cycles.

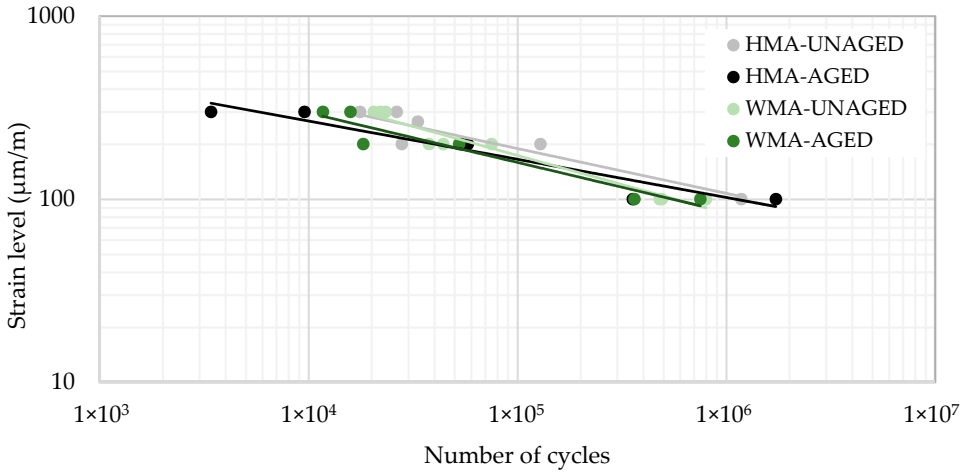


Figure 10. Results of fatigue test.

Table 6. Fitting fatigue laws' parameters.

Mixture		*A*	*B*	Adjusted R^2 (%)
HMA	Unaged	3175.6	−0.245	87.2
	Aged	1826.8	−0.209	92.1
WMA	Unaged	6636.7	−0.317	95.9
	Aged	3579.1	−0.271	92.1

A: *y*-intercept of regression line; *B*: slope of regression line; *R*: coefficient of determination.

Table 7. Strains at one million cycles (ε_6 in μm/m).

HMA		WMA	
Unaged Specimens	**Aged Specimens**	**Unaged Specimens**	**Aged Specimens**
107.6	101.8	83.2	84.7

Table 7 highlights how, for HMA, the levels of strain deformation were higher than WMA. The ageing procedure brought improvements for WMA beams in terms of fatigue despite HMA traditional asphalt.

Further investigation of the results can be made by considering, for the two mixtures (HMA and WMA), the differences between the number of cycles in the unaged and aged conditions.

In Figure 11, the differences in the number of cycles between unaged and aged conditions are plotted in the range of strain-level considered. For 300 μm/m, these differences were comparable for HMA and WMA. In the range considered, the unaged-aged WMA difference was quite constant with respect to the analogous curve calculated for HMA, which increased from 300 to 100 μm/m. In consequence, for a 100 μm/m strain level, the HMA difference was about 15 times higher than the WMA difference. From these results, it seems that WMA, despite having lower fatigue resistance than HMA, was less affected by ageing conditions.

Another interesting result can be highlighted considering the differences in terms of strain level between the HMA and WMA (unaged-aged). Figure 12 shows these differences after varying numbers of cycles.

It can be noted that ageing produces a different effect on HMA and WMA resulting in a greater unaged-aged difference for HMA compared to WMA. This could lead to the conclusion that, in addition to the evidently known better behavior with respect to fatigue of HMA, the WMA tends to have a lower performance in terms of fatigue, but also a confirmed lower sensitivity by ageing.

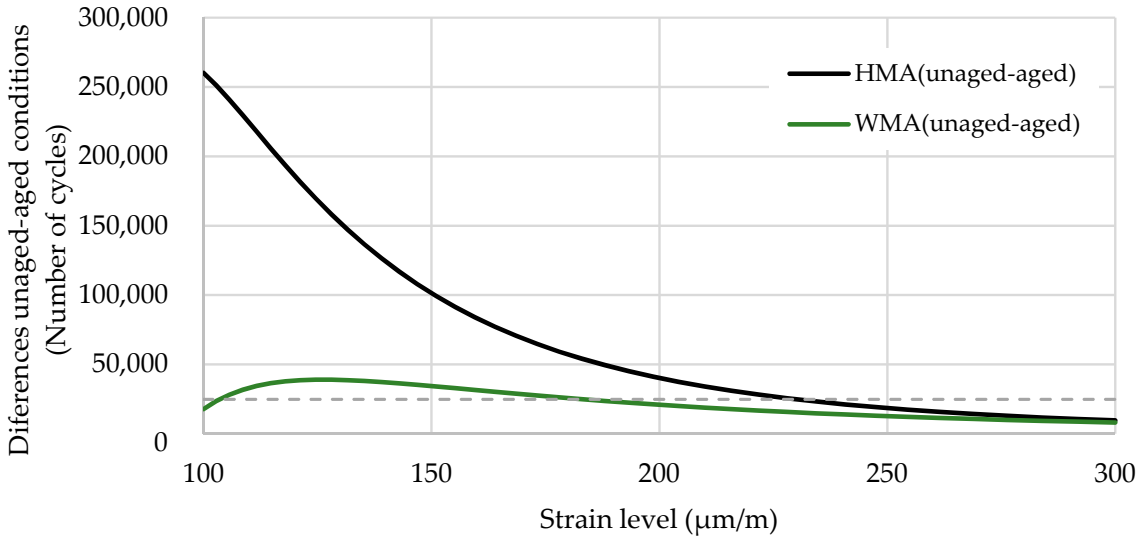


Figure 11. HMA and WMA sensitivity to aged condition varying strain level.

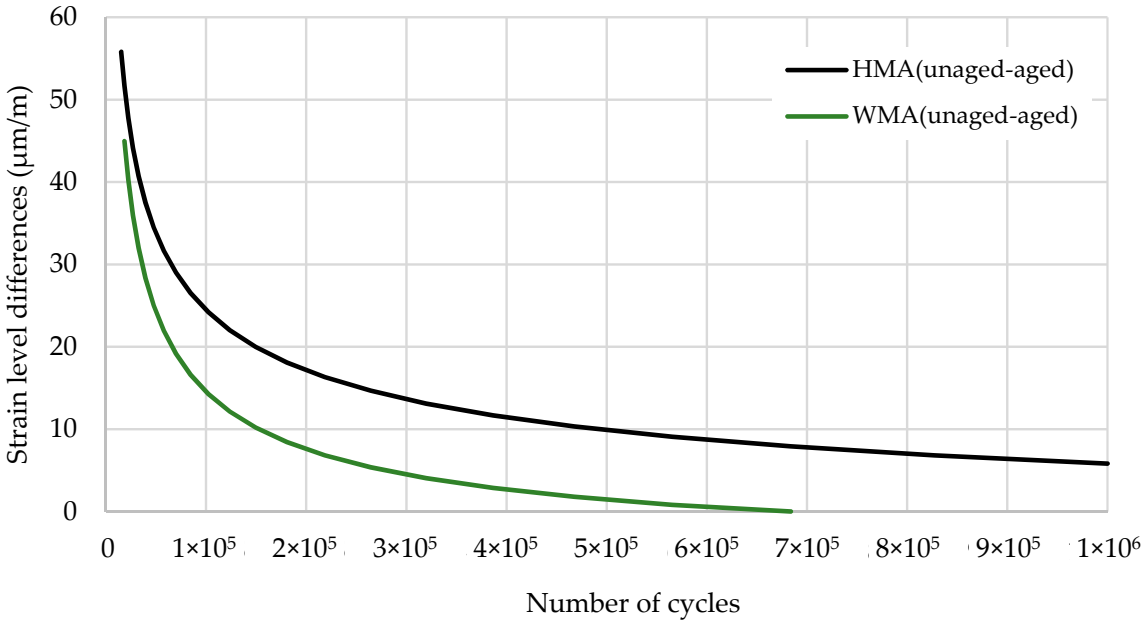


Figure 12. HMA and WMA sensitivity to aged condition varying number of cycles.

Beyond 70,000 cycles, the WMA differences (unaged-aged) assumed values very close to 0. This result would show that for WMA, beyond a certain value of load cycles, there are no differences in behavior between unaged and aged specimens in terms of strain level.

To complete the comparisons in terms of fatigue laws, Figure 13 shows the differences in terms of strain level between (HMA-WMA) in unaged and aged conditions.

It was observed that the difference in terms of fatigue between a HMA and a WMA always determines better performance for HMAs with a trend that shows, for low numbers of load cycles, a smaller difference in terms of strain (HMA-WMA). This difference stands at a constant-asymptotic value over a certain number of cycles (over 500,000 cycles for unaged conditions).

Similar behavior is also found for aged specimens with minor differences compared to the unaged situation.

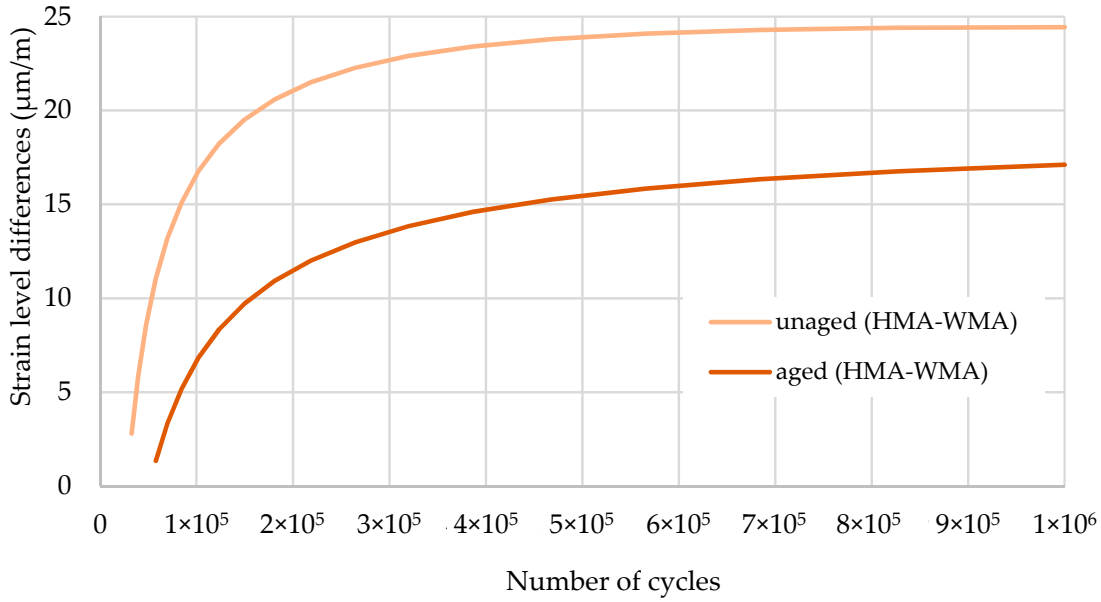


Figure 13. Comparison between HMA and WMA considering aged condition.

4. Conclusions

In the present study, the performance of WMA and HMA were compared in terms of water sensitivity, permanent deformation, stiffness, fatigue, and ageing effects. WMA showed lower indirect tensile strength values than HMA but similar water sensitivity. Ageing resulted in higher ITS values and these ITS increases were higher in the water conditioned specimens, which resulted in ITSR values higher than 100%. It could lead to the conclusion that the reduced manufacturing temperature did not compromise the aggregates-bitumen adhesion/coating.

In what concerns the other evaluated pavement performance characteristics, ageing also increased dynamic modulus, but this is not an improvement as both WMA and HMA aged mixtures showed lower fatigue resistance than unaged ones. From the comparisons between the fatigue laws, it emerged that WMA, despite having lower performance than HMA, was less affected by ageing conditions; the strain level that caused the failure at 10^6 cycles for WMA unaged was similar to WMA aged, while it was 5.7% higher for unaged HMA than aged ones. HMA showed higher resistance to permanent deformation and more sensitivity to ageing than WMA.

Overall, these results suggest that WMA can be a valid alternative to HMA because it allows significant energy and environmental advantage, evaluated preliminarily by appropriate laboratory tests of the pavement performance regarding traffic, climatic condition, and service life.

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