Original Article

New laboratory procedure using a modal approach to obtain vibration attenuation properties of unaged and aged asphalt mixtures

Teresa Real, Laura Montalbán, Claudio Masanet and Julia Real

Institute for Multidisciplinary Mathematics, Polytechnic University of Valencia, Spain

Corresponding author:

Teresa Real, Institute for Multidisciplinary Mathematics, Polytechnic University of Valencia,
Camino de Vera s/n, Valencia 46022, Spain
Email: tereaher@upv.es

Abstract

During asphalt mixture service life, its structural and physical capabilities deteriorate progressively. A modal analysis using impact hammer excitation technique is put forward to measure the damping factor instead of the commonly destructive test described in the standards. Concerning to this modal approach, an aging procedure is presented to obtain and compare the vibration attenuation capacity variation of the mixtures considering aging deterioration. In this research, this new procedure has been applied to asphalt concrete and stone mastic asphalt mixtures with different amounts of Polyethylene Terephthalete. It has been validated using results from four-point bending test. Finally, the results confirmed that asphalt mixtures with 0-2% of Polyethylene Terephthalete present better vibration attenuation capacity than mixtures without it, even when aging appeared.

Keywords

Asphalt mixture; oxidation; Polyethylene Terephthalete; waste material; modal analysis.

Introduction

Asphalt mixture is an important composite construction material which is basically formed by bituminous binder, aggregates and mixture air voids [1,2]. For a long time, these mixtures have been widely used in road paving [3], and, in recent decades in track superstructure design in railroad networks [4,5].

Nowadays, it is well known that physical and chemical properties of asphalt mixtures change during its service life [3]. This situation is produced by asphalt binder aging which produces the pavement deterioration [6, 7].

As stated by Fernandez-Gomez, et al [8], the change of asphalt mixture properties depends on both intrinsic and extrinsic variables. Thus, asphalt aging is subjected to the type of mixture used (content of binder, mixture void content, nature and particle size distribution of the aggregates, etc.), environmental conditions (e.g. temperature, UV irradiation, oxygen) and time [9]. The mixture aging process may be divided in two stages: short-term aging, which is produced during mixing, storage, laying and compactation operations, and long-term aging, which is produced during its service life [10].

In addition, the aging phenomenon consists of two types of deterioration mechanisms classified as reversible or irreversible ones [6]. The reversible mechanism corresponds to the molecular structuring, also called physical hardening, and the second one is characterized by chemical changes (oxidation, volatilization, exudation, UV irradiation) of the binder affecting its rheological properties [8,11].

The current state of knowledge on this topic shows that oxidation is one of the most important environmental factors affecting the durability of the asphalt mixtures [3, 12, 13, 14, 15]. Oxidation is defined as the chemical interaction between the asphalt and the atmospheric oxygen resulting in an irreversible transformation of the asphalt composition, hence changing its chemical and physical properties [14]. The main structural consequences produced by oxidation aging are the hardening and embrittlement of the asphalt [15]. Regarding to the viscosity of the asphalt mixture, the oxidation reduces the phase angle and, consequently, the damping factor therefore decreasing its vibration attenuation capacity [9].

In view of this, previous investigations used different laboratory aging tests to simulate in an accelerated manner the aging of the asphalt during the two stages described above. The aim was to obtain the desired information about the aged mixtures, and compare them with the unaged ones. For instance, Lu and Isacsson [9] used the Thin Film Oven Test (TFOT), the Rolling Thin Film Oven Test (RTFOT) and modified

RTFOT (MRTFOT) to characterize the aging behavior of different types of polymer modified asphalts. As reported by Shenoy [7], RTFOT has been accepted as a reliable aging procedure to simulate the short-term aging. To simulate the long-term aging, Shenoy [7] proposed to apply the Pressure Aging Vessel (PAV) on the RTFOT residue.

At this point, it is important to take into account that previous aging laboratory procedures were used to evaluate the asphalt binders aging [15]. Nevertheless, aging of asphalt mixtures can be quite different than the asphalt binder itself, as reported by Ongel and Hugener [14]. In other words, there is a need to take into account asphalt-aggregate interaction effects on aging since the asphalt molecules interact with aggregates.

The Strategic Highway Research Program [14] considered that the results obtained for an asphalt mixture may be different from the asphalt binder results and, therefore, proposed different aging protocols for them. The most common used have been the short-term oven aging (STOA) and long-term oven aging (LTOA). STOA is applied to asphalt mixtures prior to compactation using a draft oven at 135°C for 4h. In the case of LTOA, the aging of the asphalt mixtures is obtained after introducing compacted samples in the oven at 85°C during almost 120h.

Until now, the introduction of polymers is popularly used to enhance asphalt mixture performance. However, it represents an important drawback since they raise spectacularly the cost of the final product [9, 13, 16]. Currently, a greater environmental concern exists and waste material is used as an additive to improve the asphalt mixture performance. One example of this is the Polyethylene Terephthalete (PET) re-utilization. This material comes from waste plastic bottles and is stored in landfills creating an environmental problem due to its non-biodegradability [17].

Moghaddam et al. [17, 18] studied permanent deformation characteristics of Polyethylene Terephthalate (PET) modified stone mastic asphalt mixtures under static and dynamic loads. Ahmadinia et al. [19] investigated the effects of incorporating waste PET in SMA. The volumetric and mechanical properties of this mixture considering various percentages of PET were calculated and assessed with different laboratory tests. The results contribute to encourage waste material re-use in the pavement industry. PET increased the stiffness level of the mixture improving its resistance level against permanent deformation. Ahmadinia et al [20] concluded that the addition of waste PET into the mixture has a significant positive effect on the properties of SMA such as: mixture's resistance against permanent deformation (rutting), stiffness of the mix and lower binder drain down. Moghaddam, Karim and Syammaun [21] researched SMA mixtures with different amount of PET with the objective to study their stiffness and fatigue resistance. The results obtained from the indirect tensile stiffness modulus test and indirect tensile fatigue test showed that lower amount of PET content increases the stiffness modulus of the mixture, and higher PET amount content makes mixture softer. Additionally, PET reinforced mixtures exhibit significantly higher fatigue lives compared to the ones without it.

However, although there is not sufficient up-to-date information about the application of PET to asphalt mixtures, it is noteworthy to mention that none of the known studies previously conducted have focused on the application of waste PET as an additive to asphalt concrete and stone mastic asphalt focused on the vibration attenuation capacity.

In this research, an alternative procedure using modal approach to study the vibration attenuation capacity of an unaged and aged asphalt mixture is presented. The main goal of this research is to obtain information about the damping factor of an unaged and aged asphalt mixture with PET so as to demonstrate that this waste material plays an important role in its vibration and noise mitigation properties.

Experimental campaign / Methodology

As previously exposed, the aging methods are protocols established to accelerate the deterioration of the asphalt binder or asphalt mixtures simulating short-term or long-term aging. In all cases, additional laboratory test are required to obtain the desired properties of the unaged and aged specimens tested.

The damping factor is a very important material parameter which indicates the vibration energy attenuated during a cycle of vibration [22]. It can be obtained from the four –point bending test on prismatic shaped specimens according with the European Normative EN-12697-24:2004 [23].

The regular procedure to obtain this information would be as follows: different specimens are manufactured and divided in two sets. The first set of specimens is tested with the four-point bending test in accordance with the European Normative [23]. This laboratory test provides information about the damping factor of the unaged mixtures. Then, the aging method (LTOA) is applied to the second specimens set. The LTOA residues are tested applying the four-point bending test [23]. In this case, the information obtained is the damping factor for the aged asphalt mixtures. Once damping factors information of the unaged and aged mixtures is obtained, the effect of aging on the vibration attenuation capacity is known.

This common resistance to fatigue test used to obtain vibration attenuation properties of asphalt mixtures is a destructive laboratory method. Thus, it means higher costs since different specimens are needed to characterize mixtures before and after the aging procedure.

In this way, this research aims to offer a new non-destructive test procedure in which the same specimen may be tested to characterize both unaged and aged mixtures. A modal analysis using impact hammer excitation technique was elected to substitute the four-point bending test due to is one of the widely used non-destructive techniques to examine the vibration characteristics of materials [24, 25, 26]. In addition, impact hammer excitation technique is the simplest method for modal testing with low costs and time [27].

The new aging procedure conducted in this research is explained afterwards. Firstly, different asphalt mixtures (asphalt concrete and stone mastic asphalt) with different PET percentages were manufactured using dry process. Secondly, these asphalt mixtures were tested using the experimental modal analysis proposed and the four-point bending test on prismatic shaped specimen at 20°C. Then, the damping factors obtained were compared so as to assess the proper functioning of the impact hammer test used herein.

Once the correct working of the new test was confirmed, a long-term oven aging procedure (LTOA) was carried out in order to simulate in an accelerate manner the service life aging of the mixture. Finally, the LTOA residues were tested again with the impact hammer technique test proposed within 24 hours. The damping factor of the unaged and aged mixtures were obtained and thus, information about the vibration attenuation capacity of the asphalt mixtures during their service life.

Materials

Material manufacturing

A test campaign was carried out on different asphalt mixtures with different amounts of post-consumer PET so as to characterize unaged and aged asphalt mixture behavior in terms of vibration attenuation capacity. For this purpose, asphalt concrete mixture and stone mastic asphalt mixture were developed considering different PET percentages. These percentages were adopted considering the literature [19, 20] and then, adapted to present study. The mixture combinations considered for this study are exposed in Table 1.

Table 1. Different asphalt mixtures analyzed.

MIXTURE	**TYPE OF MIXTURE**	**PET % wt**	**ASPHALT BINDER % wt**	**AGGREGATES % wt**	**FILLER % wt**
0 %	AC	0	4	91	5
0.5%	AC	0.5	4	90.5	5
1%	AC	1	4	90	5
1.5%	AC	1.5	4	89.5	5
2%	AC	2	4	89	5
4%	AC	4	4	87	5
0 %	SMA	0	5	86.8	8.2
0.5%	SMA	0.5	5	86.3	8.2
1%	SMA	1	5	85.8	8.2
1.5%	SMA	1.5	5	85.3	8.2
2%	SMA	2	5	84.8	8.2
4%	SMA	4	5	82.8	8.2

Prismatic shaped specimens were fabricated to conduct the laboratory tests proposed. The prismatic shaped specimens presented a length of 400mm, width of 60 mm and height of 60mm. All specimens were prepared using an impact compactor with 75 impacts according to EN 12697-30 Standard [28]. For each mixture exposed in Table 1, five specimens were made. Four of them were used in the four-point bending test on prismatic shaped specimens so as to allow comparison analyses with statistically representative results. The other one was used to implement the new aging procedure presented. Only one specimen of each mixture was necessary for the impact hammer method since it is a non-destructive test, thus the specimen may be tested repeatedly.

Figure 1 exhibits the specimens used in the new test method.

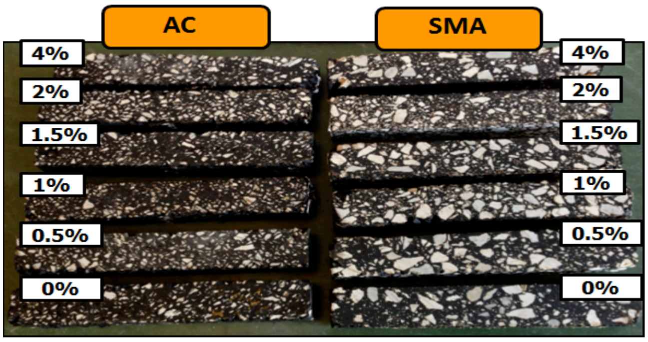

Figure 1. Specimens for the new test method.

Aggregates and filler.

For the design and production of the mixtures tested, limestone aggregates and filler have been used. Different aggregate gradations are considered depending on the mixture type analyzed (asphalt concrete or stone mastic asphalt).

Table 2 shows the aggregate gradation for the AC and SMA mixtures.

Table 2. Adopted Aggregate Gradation for AC and SMA mixtures.

NOMINAL SIZE OF AGGREGATE (mm)	PERCENT PASSING IN AC MIXTURE (%)	PERCENT PASSING IN SMA MIXTURE (%)
31.500	100.00	100,00
22.400	99.00	100.00
16.000	79.00	99.00
8.000	58.00	58.00
4.000	42.00	38.00
2.000	31.00	24.00
0.500	15.00	21.00
0.250	10.00	15.00
0.063	5.00	8.50

Asphalt binder.

Binder used in this research is B 50/70, according to the Spanish specifications [29]. The mechanic characteristics are shown in Table :

Table 3. B50/70 Characteristics [29].

CHARACTERISTICS		**NORMATIVE**	**UNIT**	**B 50/70**
Penetration (25 °C)		1426	0.1 mm	50-70
Softening point		1427	°C	46-54
Aging resistance	Mass change	12607-1	%	≤ 0.5
	Restrained penetration	1426	%	≥ 50
	Softening point increment	1427	°C	≤ 11
Penetration index		12591 13924 Appendix A	-	Range -1.5 to +0.7
Flash point		ISO 2592	°C	>230
Solubility		12592	%	≥99.0

Plastic waste material.

PET from waste plastic bottles has been used in this research. This material is considered as polyester material since it is a semi-crystalline thermoplastic polymer [18]. This material has been studied for SMA mixtures in previous researches [21]. In this research, PET has been incorporated to SMA and to AC mixtures. The specific gravity of PET is 1.39 g/cm^3, as stated by Ahmadina, et al. [20]. The gradation of the Polyethylene Terephthalate (PET) is shown in Table 4. This gradation of PET was obtained as indicated in [18].

Table 4. PET gradation. [19].

SIEVE SIZE	**PERCENT PASSING (%)**
1.18 mm	100
425 µm	0

Tests conducted

Four-point bending test

The four-point bending test on prismatic shaped specimens was conducted in accordance with the European Normative EN-12697-24:2004 [23]. This test was conducted to validate the impact hammer test proposed herein by comparison of the results.

This test was performed in laboratory at 20°C obtaining results for the complex modulus E* and the phase angle at the same time. As indicated in EN-12697-26:2012, the complex modulus E* is defined as the sum of the imaginary modulus (E’’) and real modulus (E’). They represent the viscous and elastic behavior, respectively. Equation 1 shows the relation between them.

$$E^{*} = E' + E'' \tag{1}$$

The phase angle (φ) is provided by the test as indicated in equation 2.

$$\tan(\varphi) = E'' / E' \tag{2}$$

Thus, a phase angle reduction means that the energy attenuation capacity decreases in a cyclic deformation [30].

Once the phase angle is obtained, the damping factor is calculated using the relation indicated in equation 3 as stated by Rutherford et al. [31].

$$\xi = \tan(\varphi) / 2 \tag{3}$$

Where ξ is the damping factor.

Impact hammer test

This method is based on dynamic excitation of the specimens characterizing its vibratory response by accelerometers. In this way, vibration attenuation capacity of each mixture could be obtained analyzing the attenuation of the vibration signal induced.

Test device and test procedure. The test device is shown in Figure 2.

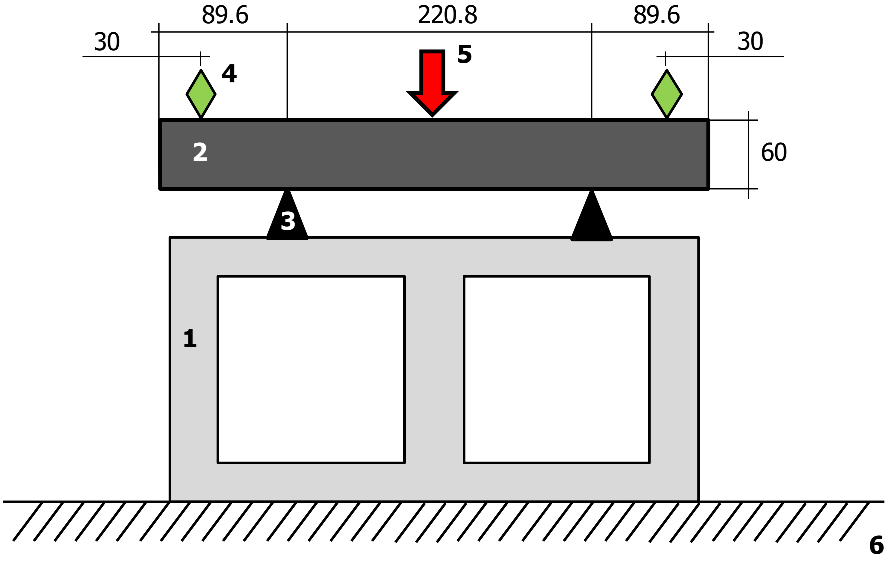

Figure 2. Schematic diagram of the test system (Measurements in millimeters).

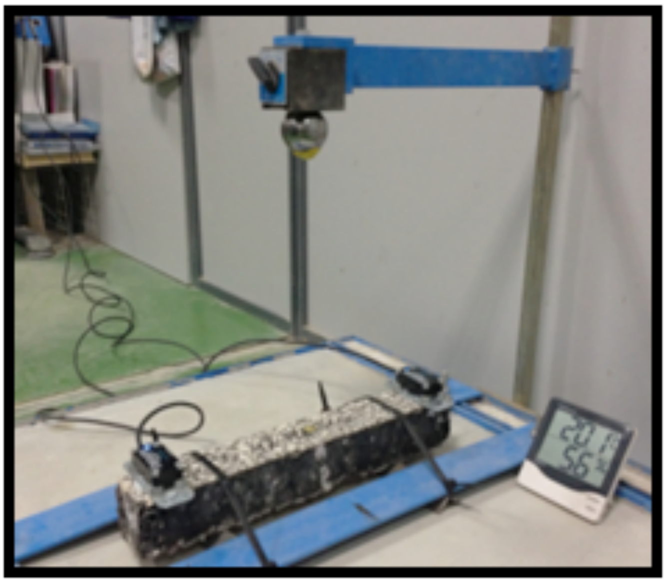

Figure 3. Impact hammer test preparation.

As illustrated in Figure 2, a standard concrete block (1) was located on a flat, horizontal and stable surface (6) which is mainly located on the floor. The specimens (2) were supported by two points using two steel bars (3). The correct location of the specimen must be done with special care since the acceleration depends on the support distances and boundary conditions. Bars were located on the nodal positions of the theoretical mode shapes in order to simulate adequately the free boundary condition in laboratory. Elastic fasteners were used in order to maintain the bars in a fixed position (Figure 3). These elastic fasteners were located also in the nodal points to not affect adversely the vibration of the specimen.

Therefore, previously to the disposition shown in Figure 2, a modal analysis of each specimen was conducted using finite element methods by ANSYS software package (Figure 4). Nodes were selected points where the amplitude of the different vibration modes was zero. In this way, the supports were located at the theoretical nodal points of the fundamental first bending mode of the specimens [27]. FEM results showed that the position of the nodes corresponding to the first bending mode for each specimen varied insignificantly. Thus, the support positions were selected as the medium points of each specimen nodes.

A triangular cross-section was chosen for the bars to obtain a support point of contact with nodes. In this situation, the specimens were tested without vibration constrains, and therefore, their damping factor could be obtained.

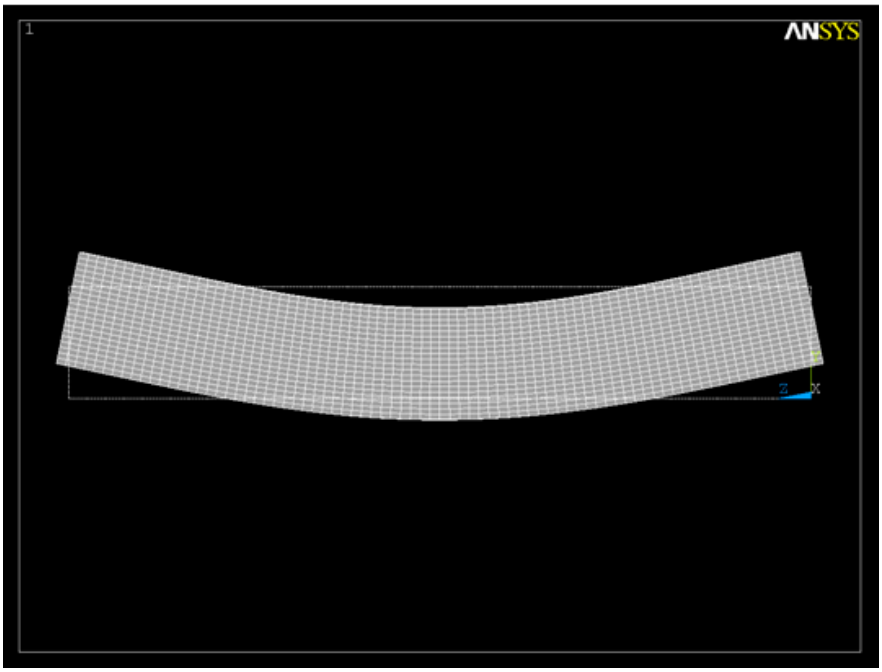

Figure 4. Example of the deformation of AC with 0% PET regarding first bending mode of vibration.

Once the specimen model deformations were obtained for the first bending mode of vibration, the measurement and impact point locations were decided. Triaxial accelerometers (4) were located at both ends of the specimen as indicated in Figure 2. This decision was made taking into account two main principles: maximum distance between them and first bending mode must be registration. Impact hammer excitation technique was used to produce a transient impulsive force excitation in the middle of the specimens (5). The load was applied in the vertical direction coinciding with the longitudinal beam axis to excite vertical bending modes only. The aim of this test is to obtain the damping factor in a fast and low cost way.

It is important to take into account that damping factor depends on the inertia, stiffness and damping of the system, but it does not depend on the applied load [32]. Thus, an uncontrolled load was considered in this research. Eight impacts were done on each specimen checked to obtain statistically representative results.

In this research, only damping factor of the first bending mode was the parameter of interest considered regarding the following two reasons. Firstly, it is important to keep in mind that near the natural frequency of a mode, the overall vibration shape will tend to be dominated by the mode shape of the resonance. Thus, only the first bending mode was needed to be studied since the frequencies of the four-point bending test were under the natural frequency of this mode. Secondly, damping of the material depends on the bending mode analyzed as indicates the literature [27, 33]. In this way, only the damping factors considering the first bending mode were studied since the main objective of this investigation is to study the vibration attenuation capacity of the asphalt mixtures with PET during its service life, and not to obtain the damping factor of the all bending modes of the specimens.

Test principle. Results obtained for the test are accelerations in the time domain for each specimen analyzed. Therefore, a post-processing of measured data is necessary to obtain definitely the damping factor of each mixture.

Regarding to a damped vibratory system with a single degree of freedom, the characteristic equation of the movement is defined in equation 4 as stated by Biligiri [30].

$$x(t) = Ae^{-\xi \omega_1 t} \sin(\omega_n t + \rho) \tag{4}$$

Where x is the displacement, A is the maximum amplitude of vibration in case of a perfect elastic solid, ω_1 is the undamped natural frequency, ω_n is the damped natural frequency, t is the time, ξ is the damping factor and ρ the phase angle or lag.

Figure 5 is a representation of the fundamental theoretical vibration model taken into account.

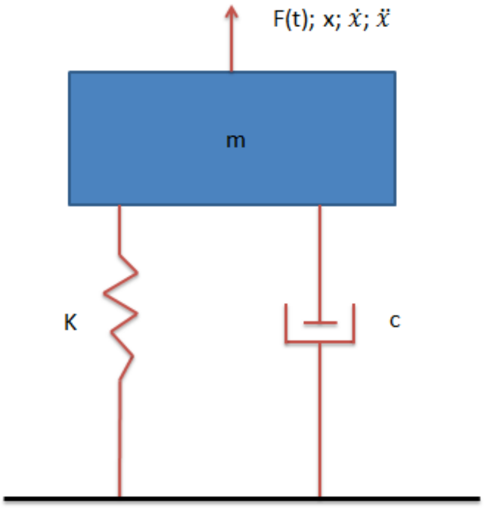

Figure 5. Representation of the fundamental theoretical vibration model.

In this case, the positive and negative envelope of accelerations can be obtained as indicated by equation 5.

$$x(t) = \pm A e^{-\xi \omega_1 t} \tag{5}$$

Figure 6 illustrates an example of the oscillation movement of a damped vibration system with one degree of freedom, and the envelope of the accelerations obtained with equation 5.

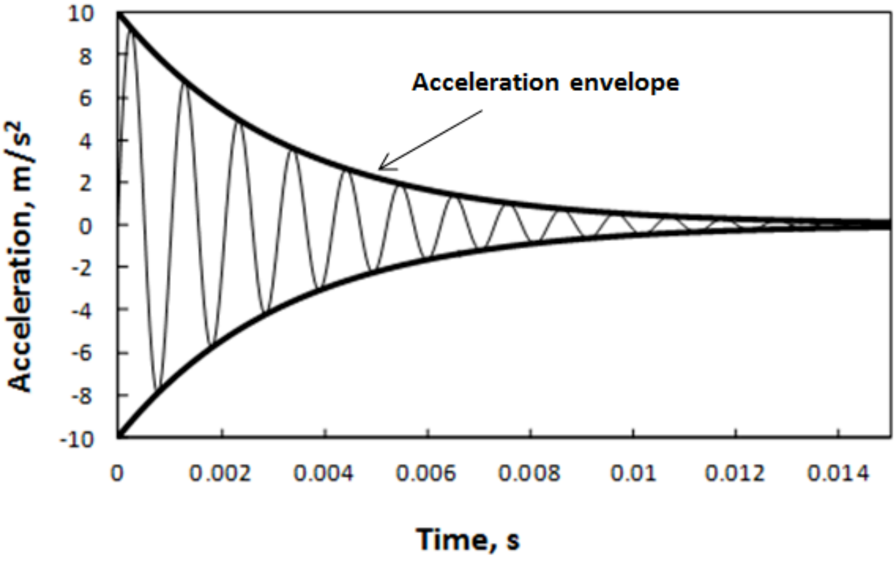

Figure 6. Oscillation movement of a damped vibration system after a transient excitation load.

Therefore, the experimental data can be adjusted obtaining the envelope of accelerations and obtaining the damping factor as indicated in following lines.

Figure 7 shows an example of the results obtained with the new test method for one particular case and, moreover, the acceleration envelope adjustment. In this research, the acceleration envelope curve adjustment was made using the method of least squares.

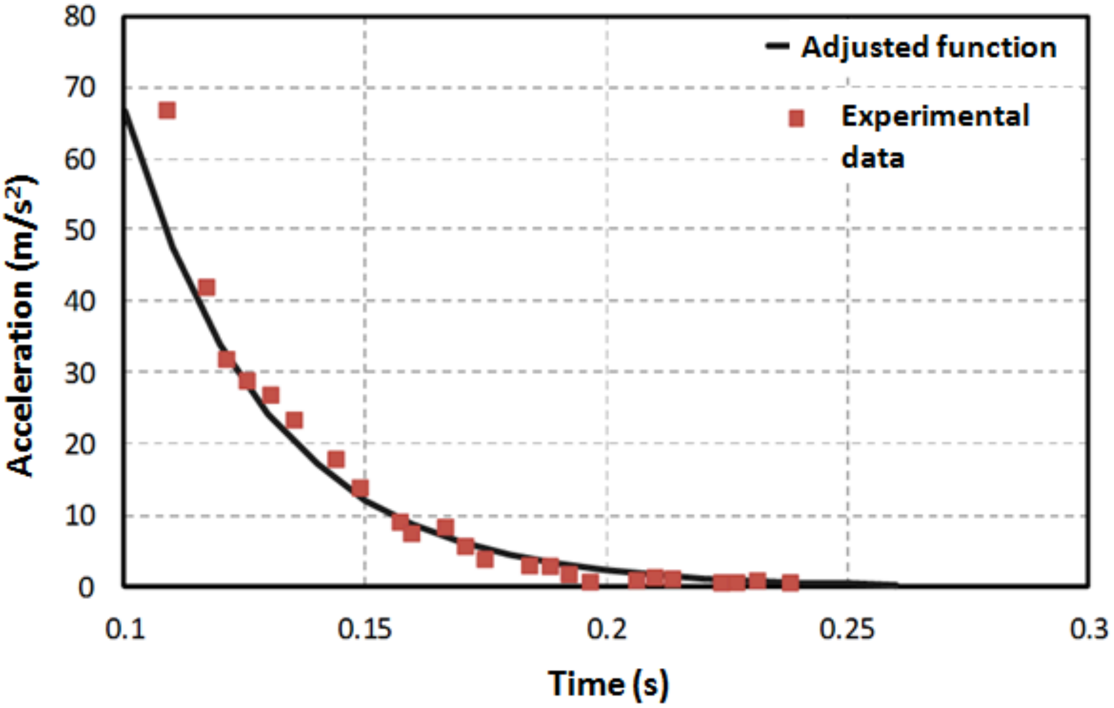

Figure 7. Example of the results obtained and curvature adjustment using the method of least squares.

Once the adjustment of the curve is made, the expression obtained for the adjustment by the method of least squares is defined as indicated the equation 6:

$$y = e^{m+nt} \tag{6}$$

Where y is the vertical acceleration, t is the time and m, n are constants of the curve.

Regarding to both equations 5 and 6, the relations indicated in equations 7 and 8 can be drawn:

$$A = e^{m} \tag{7}$$

$$n = -\xi\omega_1 \tag{8}$$

From these two equations, the damping factor can be obtained as indicated in equation 9:

$$\xi = -\frac{n}{\omega_1} \tag{9}$$

As shown eq. 9, n and ω_1 must be known to calculate the damping factor. n is obtained from the acceleration envelope adjustment and ω_1 was obtained from the numerical model for each specimen. Modal analysis was used to calculate the first eigenfrequencies of each specimen. After obtaining these results, ω_1 could be determined using equation 10 [32].

$$\omega_1 = \sqrt{\frac{K}{m}} = 2\pi f_n \tag{10}$$

Where k is the stiffness, m is the mass and f_n is the eigenfrequency, in this case, the first eigenfrequency.

The results obtained are indicated in Table 5.

Table 5. Eigenfrequency of the first vibration mode and natural vibration frequency for each mixture.

MIXTURE	**f (Hz)**	**ω_1 (rad/s)**
AC 0%	888.47	5582.42
AC 0.5%	740.82	4654.71
AC 1%	886.04	5567.15
AC 1.5%	915.29	5750.94
AC 2%	719.93	4523.45
AC 4%	949.09	5963.31
SMA 0%	725.30	4557.19
SMA 0.5%	845.02	5309.42
SMA 1%	732.42	4601.93
SMA 1.5%	725.46	4558.20
SMA 2%	784.88	4931.55
SMA 4%	715.05	4492.79

Finally, the damping ratio can be obtained for each mixture using the equation 9.

Aging procedure

LTOA protocol is used as an aging procedure in this research. In this way, compacted asphalt mixture specimens were introduced inside an oven and heated at 85 °C during 5 days.

Results and discussion

In this section, the damping factor obtained with the four-point bending test on prismatic shaped specimens and with the impact hammer test are exposed. The unaged mixture results are used for the validation of the procedure proposed by comparison between them. Once the validation of the method is done, unaged and aged mixture results are shown and compared.

Four-point bending test

The results obtained from four-point bending test are indicated in Figure 8 for both types of asphalt mixture tested.

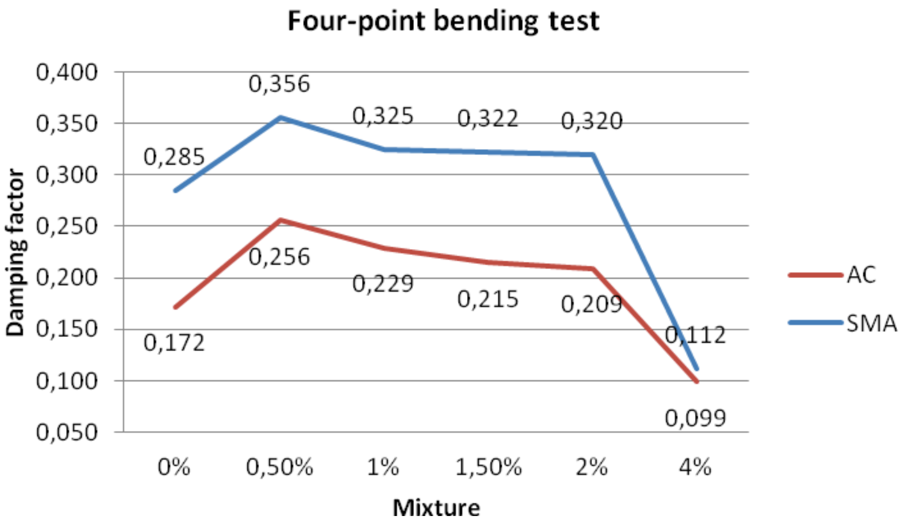

Figure 8. Damping factor obtained with the four-point bending test.

As it can be seen in Figure 8, SMA mixtures present higher damping factors than the AC mixtures independently of PET content. This can be explained considering that SMA mixtures present discontinuous aggregate gradation and higher asphalt binder content, thus more viscous behavior with better vibration attenuation capacity.

Additionally, Figure 8 shows that the same trend is followed by both asphalt mixtures. The results of the damping ratio indicate that the vibration attenuation capacity is higher in all mixtures with 0-2%wt PET content. Then, higher PET content is not fruitful since the mixtures present worse behavior than the expected with PET-less mixtures. The damping factor remains nearly unchanged between 1-2% of waste PET. Nevertheless, damping factor experiments a sharp increase with 0.5% of PET in both mixtures analyzed.

This situation evidences clearly that waste PET material is a eco-friendly additive able to improve the vibration attenuation capacity of an asphalt mixture when a proper quantity is mixed (0-2%).

Impact hammer test

Damping factor results obtained with the impact hammer test can be observed in Figure 9.

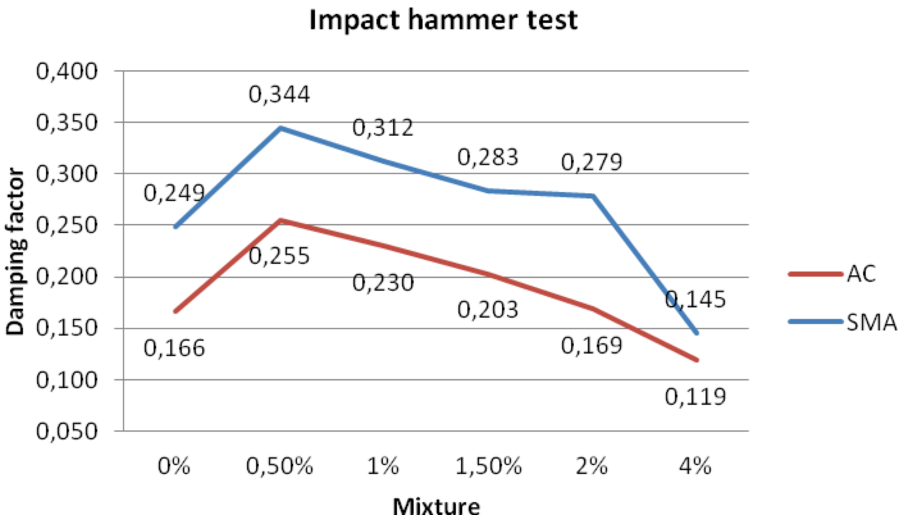

Figure 9. Damping factor obtained with the impact hammer test.

As it can be seen in Figure 9, damping factor increases between 0 and 0.5% and then decreases as PET content rises. The trend showed in Figure 9 is not the same for asphalt concrete and stone mastic asphalt. Only in the case of stone mastic asphalt, a stabilization of the damping factor appears between 1.5 and 2% of PET content. In the case of asphalt concrete, an increase of PET content produces a decrease of the damping factor almost linearly.

In this case, the largest damping factor value appears with 0.5% of waste PET in both asphalt concrete and stone mastic asphalt mixtures. Moreover, PET content between 0-2% produces a damping ratio higher than the asphalt mixture without PET in both mixture types. Additionally, PET amounts higher than 2% worsen the ability to attenuate vibrations.

Validation of the impact hammer test

With the objective to validate the method proposed, a comparison between the damping factor obtained with the four-point bending test and the obtained with the impact hammer test have been carried out as indicated in Figures 10 and 11.

Figure 10 illustrates the results obtained for each test method in the case of asphalt concrete.

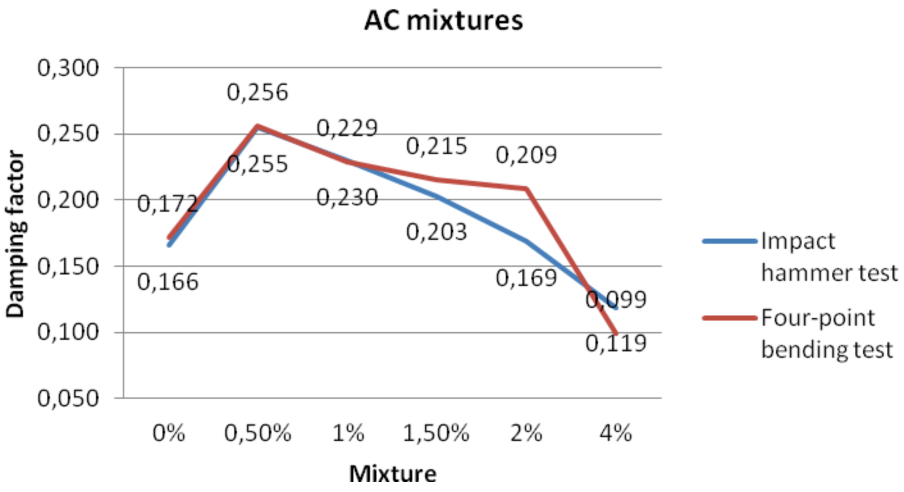

Figure 10. Damping factor comparison**.**

Figure 11 shows the results for each test method used to characterize the damping factor of the stone mastic asphalt.

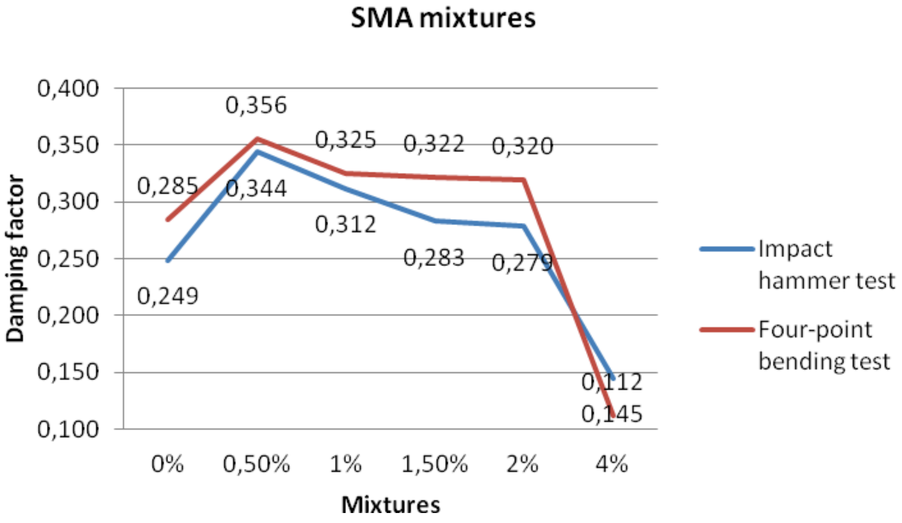

Figure 11. Damping factor comparison.

As it can be seen in Figure 10 and 11, the results obtained with the impact hammer test are generally similar to that obtained for the four-point bending test.

On one hand, asphalt concrete presents practically equal damping factor values for PET content between 0-1%. However, damping factor differs for asphalt concrete mixture with higher PET amount

On the other hand, stone mastic asphalt results obtained with the hammer method are slightly lower than the obtained with the four-point bending test except at 4% of PET.

Nevertheless the same trend is obtained with both procedures. As it can be seen in Figures 10 and 11, the damping factor increases with 0-0.5% PET content and decreases with higher amounts of PET. Additionally, stone mastic asphalt presents higher damping factor than the asphalt concrete, and thus, higher capacity to mitigate vibrations.

It is important to take into account that a small-scale vertical axis has been defined to appreciate the differences between both test results. Once these differences have been discussed before, the average error obtained in each mixture measurement is analyzed in order to assess the accuracy of the hammer test. The damping factor for each mixture obtained with each test and the average error can be observed in Tables 6 and 7.

Table 6. Comparison of the AC results obtained with both impact hammer and four-point bending tests.

Mixtures	Impact hammer test	Four-point bending test	Average error (%)
0%	0.166	0.172	7.640
0.50%	0.255	0.256	
1%	0.230	0.229	
1.50%	0.203	0.215	
2%	0.169	0.209	
4%	0.119	0.099	

Table 7. Comparison of the SMA results obtained with both impact hammer and four-point bending tests.

Mixtures	Impact hammer test	Four-point bending test	Average error (%)
0%	0.249	0.285	11.281
0.50%	0.344	0.356	
1%	0.312	0.325	
1.50%	0.283	0.322	
2%	0.279	0.32	
4%	0.145	0.112	

On that basis, the validation of this hammer method is confirmed since proper damping factor trends have been obtained. Additionally, the average errors calculated in the measurements are smaller than the accepted in the literature to validate methods for estimating dynamic parameters (frequencies, damping factors and mode shapes) [34]. It can be conclude that the impact hammer test proposed can estimate the damping factor with reasonable accuracy compared to the four-point bending test and, therefore it is considered as a validated method.

Aging results

Once the validation of the hammer test has been made, the LTOA protocol has been applied to force the aging of the asphalt mixtures. After obtaining the aged specimens, the impact hammer test has been applied. In this way, damping factors of aged asphalt mixtures are obtained, as can be observed in Figure 12.

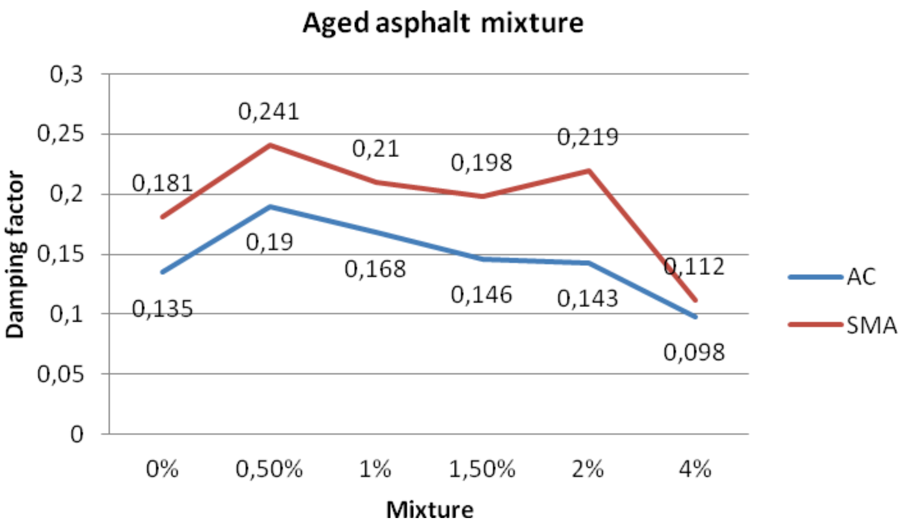

Figure 12. Damping factor of aged mixtures.

Figure 12 shows the results of the damping factor for each asphalt concrete and stone mastic asphalt analyzed. These results shown the same trend obtained with the unaged specimens with the exception of the stone mastic asphalt with 2% of waste PET material. In this case, the damping factor experiments a slight upturn.

It is important to highlight that aggregate gradation plays an important role in asphalt mixtures. Thus, damping factor of the aged stone mastic asphalt is still larger than the obtained for aged asphalt concrete.

The differences experimented by the damping factor can be observed in Figure 13 and Figure 14 for asphalt concrete and stone mastic asphalt respectively.

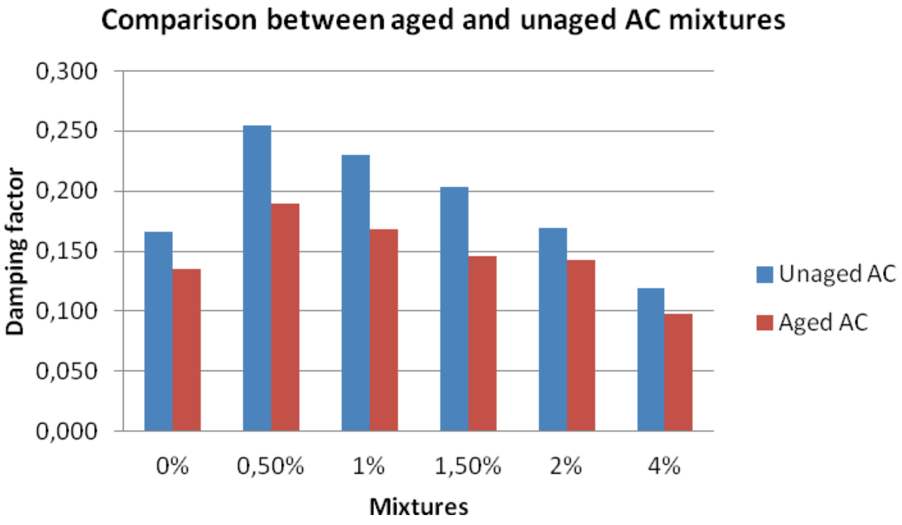

Figure 13. Damping factor of the unaged and aged asphalt concrete mixtures.

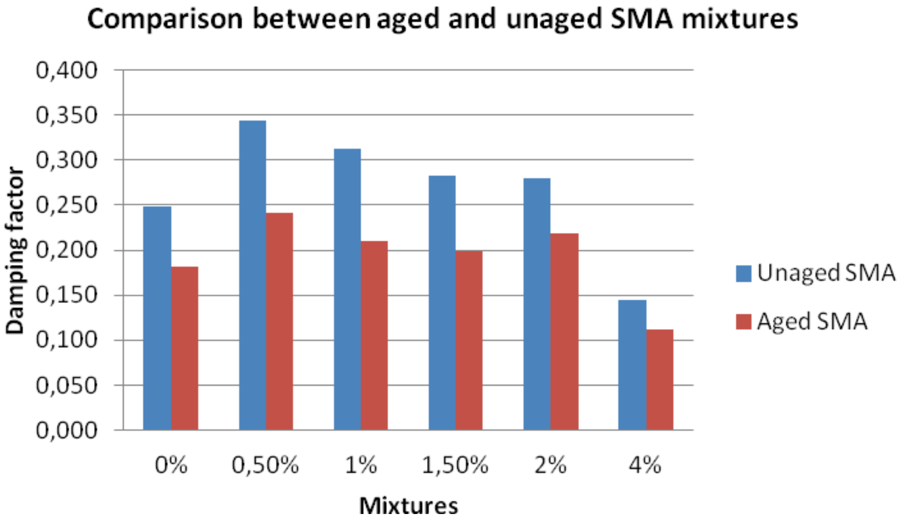

Figure 14. Damping factor of the unaged and aged stone mastic asphalt mixtures.

As illustrated by Figure 13 and Figure 14, the damping factor of each mixture decreases with the asphalt aging. This means that less energy can be dissipated by the asphalt mixture and thus, they experiment less vibration attenuation capacity, in accordance with Zhong, Zheng and Rose [22]. This situation agrees with previous researches about asphalt aging in which asphalt binder aging produces a reduction of phase angle and therefore, a decrement of the viscous behavior of the binder [6].

In Figure 15, the differences of the damping factor of unaged and aged asphalt mixtures are shown in percentage form.

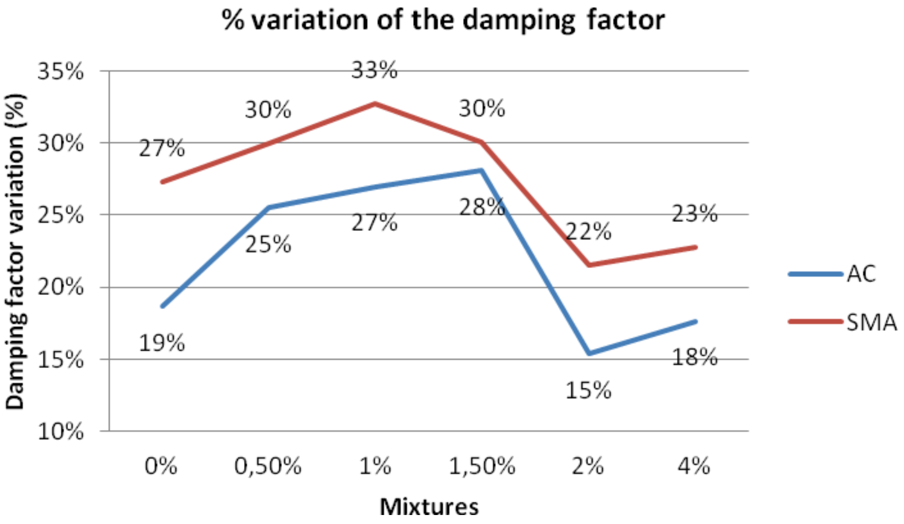

Figure 15. Damping factor percentage of variation.

As shown in Figure 15, stone mastic asphalt mixtures experiment higher decrement of the damping factor, thus higher aging procedure than the asphalt concrete mixtures is achieved. It is explained because asphalt concrete mixtures are more compacted mixtures than stone mastic asphalt. Thus, more oxygen molecules are available in the stone mastic asphalt, hence strong oxidation may appear explaining the results achieved. This is supported by previous researches which established that void content and void connectivity had a significant influence on the change of the mechanical properties of oxidized mixtures [2].

Conclusions

In this research, a new aging procedure has been proposed using an experimental modal analysis with the impact hammer excitation technique as an alternative to the four-point bending test. The main objective of this test procedure is to obtain information about the damping factor of both unaged and aged mixtures. The LTOA is the protocol selected to force the aging of the asphalt mixtures. In this way, the vibration attenuation properties of the asphalt mixtures with post-consumer PET has been analyzed and, moreover, their variation after their service life.

The main conclusions obtained with this study can be drawn as follows:

- A non-destructive test procedure has been presented and assessed as an alternative test for the four-point bending test from the point of view of vibration attenuation properties.
- The results evidence that vibration attenuation properties of each mixture change depending on the time and moreover, on the type of asphalt mixture. In this situation, different vibration attenuation capacity is obtained for each mixture considering the same asphalt binder, thus, it is demonstrated that aggregate gradation and its interaction between binder molecules plays an important role in the aging procedure.

- The comparison between unaged and aged results demonstrates that oxidation causes a decrement of the damping factor, and therefore reduces the capacity of the mixture to mitigate vibrations.
- Asphalt mixtures with waste PET content within 0-2% improve the asphalt mixture vibration attenuation capacity. Higher contents of PET are not beneficial for the vibration properties since worse damping factor than the PET-less mixture is achieved.
- Regarding to the vibration attenuation capacity, asphalt mixtures with 0.5% of waste PET present the best behavior. Concerning that SMA mixtures present better vibration attenuation capacity than the AC mixtures, a SMA mixture with 0.5% waste PET can be proposed as the best mixture.
- Finally, the study of this test procedure regarding different asphalt mixtures and different aging procedures are recommended for improving and validating this procedure in a wider range of application.

References

1. Whiteoak D. *The Shell Bitumen Handbook*. 4th ed. Shell Bitumen UK, Chertsey, 1990.

2. Caro S, et al. A micromechanical model to evaluate the impact of air void content and connectivity in the oxidation of asphalt mixtures. Constr. Build. Mater. 2014; 61:181-190.

3. Pan T. A first-principles based chemophysical environment for studying lignins as an asphalt antioxidant. Constr. Build. Mater. 2012; 36:654-664.

4. EAPA: European Asphalt Pavement Association. Asphalt in Railway Tracks. Breukelen, The Netherlands. 2003.

5. Rose J, Fonseca P and Ridgway N. Utilization of asphalt/bituminous layers and coatings in railway trackbeds – a compendium of international applications, in: ASME 2010 Joint Rail Conference, Univ Illinois Urbana Champaign, Urbana, IL, APR 27-29, 2010. 2010 Joint Rail Conference. 1 pp. 239-255.

6. Lu X and Isacsson U. Effect of ageing on bitumen chemistry and rheology. Constr. Build. Mater. 2002; 16(1):15-22.

7. Shenoy A. Prediction of high temperature rheological properties of aged asphalts from the flow data of the original unaged samples. Constr. Build. Mater. 2002; 16 (8):509-517.

8. Fernandez-Gomez WD, et al. The effects of environmental aging on Colombian asphalts. Fuel.2014; 115:321-328.

9. Lu X and Isacsson U. Artificial aging of polymer modified bitumens. J. Appl. Polym. Sci. 2000; 76(12):1811-1824.

10. Naskar M, et al. Effect of ageing on different modified bituminous binders: comparison between RTFOT and radiation ageing. Mater. Struct. 2013;46(7):1227-1241.

11. Feng ZG, et al. Effect of ultraviolet aging on rheology, chemistry and morphology of ultraviolet absorber modified bitumen. Mater. Struct. 2013;46(7):1123-1132.

12. Siddiqui MN and Ali MF. Studies on the aging behavior of the Arabian asphalts. Fuel. 1999;78 (9):1005-1015.

13. Bulatovic VO, Rek V and Markovic J. Rheological properties of bitumen modified with ethylene butylacrylate glycidylmethacrylate. Polym. Eng. Sci.. 2014;54 (5):1056-1065.

14. Ongel A and Hugener M. Aging of bituminous mixes for rap simulation. Constr. Build. Mater. 2014; 638:49-54.

15. Yut I and Zofka A. Correlation between rheology and chemical composition of aged polymer-modified asphalts. Constr. Build. Mater. 2014; 62:109-117.

16. Biligiri KP and Kaloush KE. Effect of specimen geometries on asphalt mixtures' phase angle characteristics. Constr. Build. Mater. 2014; 67:249-257.

17. Moghaddam TB, Soltani M and Karim MR. Experimental characterization of rutting performance of Polyethylene Terephthalate modified asphalt mixtures under static and dynamic loads. Constr. Build. Mater. 2014; 65: 487-494.

18. Moghaddam TB, Soltani M and Karim, MR. Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test. Mater. Des. 2014; 53:317-324.

19. Ahmadinia E, et al. Using waste plastic bottles as additive for stone mastic asphalt. Mater. Des. 2011; 32(10):4844-4849.

20. Ahmadinia E, et al. Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt. Constr. Build. Mater. 2012; 36:984-969.

21.Moghaddam TB, Karim MR and Syammaun T. Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. Constr. Build. Mater. 2012; 34:236-242.

22. Zhong XG, Zeng X and Rose JG. Shear modulus and damping ratio of rubber-modified asphalt mixes and unsaturated subgrade soils. J. Mater. Civ. Eng. 2002; 14 (6):496-502.

23. EN 12697-24:2012. Bituminous mixtures. Test methods for hot mix asphalt. Part 24: Resistance to fatigue.

24. Remennikow A and Kaewunruen S. Experimental investigation on dynamic railway sleeper/ballast interaction. Exp. Mech. 2006; 46 (1):57-66.

25. Gonilha JA, et al. Modal identification of a GFRP-concrete hybrid footbridge prototype: Experimental tests and analytical and numerical simulations. Compos. Struct. 2013; 106:724-733.

26. Hatifi MM, Firdaus MH and Razlan AY. Modal analysis of dissimilar plate metal joining with different thicknesses using MIG welding. International Journal of Automotive and Mechanical Engineering. 2014; 9 (1):1723-1733.

27. Ndambi JM, et al. Comparison of techniques for modal analysis of concrete structures. Eng. Struct. 2000; 22 (9):1159-1166.

28. EN 12697-30:2013. Bituminous mixtures. Test methods for hot mix asphalt. Part 30: Specimen preparation by impact compactor.

29. PG-3. Pliego de prescripciones técnicas generales para obras de carretera y puentes (PG3). Centro de Publicaciones Secretaría General de Carreteras. Ministerio de Fomento. Madrid. Spain. 2011.

30. Biligiri KP. Effect of pavement materials' damping properties on tyre/road noise characteristics. Constr. Build. Mater. 2013; 49:223-232.

31. Rutherford T, et al. Laboratory investigation into mechanical properties of cement emulsified asphalt mortar. Constr. Build. Mater. 2014; 65:76-83.

32. Balachandran B and Magrab E. Vibraciones. Thomson Learning. Madrid. Spain. 2006.

33. Real J, et al. Experimental modal analysis of railway concrete sleepers with cracks. Structural engineering and mechanics. 2012; 44 (1):51-60.

34. Sarparast H, et al. Estimation of modal parameters for structurally damped systems using wavelet transform. Eur. J. of Mech. A. Solids. 2014; 47:82-91.