Using polymers to improve the rutting resistance of asphalt concrete

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1. Introduction

The permanent deformation (rutting) of asphalt pavements has an important impact on the performance of the pavements during their lifetimes. Rutting not only reduces the useful service life of pavements, but it may affect basic vehicle handling, which can be hazardous to highway users. Rutting develops gradually as the number of load applications increases and appears as longitudinal depressions in the wheel paths and small upheavals to the sides. It is caused by a combination of densification and shear deformation; the main contributing factors are traffic, especially heavy loads, and high temperatures. These depressions or ruts are important because, if the surface is impervious, the ruts trap water causing hydroplaning (particularly for passenger cars), which is extremely dangerous. As the ruts become deeper, steering becomes increasingly difficult, leading to greater safety concerns [1–6]. The stiffness of the binder and its thermal susceptibility are some of the main causes of pavement failure due to rutting. Therefore, the adoption of modified binders is recommended to reduce failures due to rutting.

Modified asphalt involving natural and synthetic polymers was patented as early as 1843 [7]. Test projects were underway in Europe in the 1930s, and neoprene latex was used in North America in the 1950s [8]. In the late 1970s, Europe was ahead of the United States in the use of modified asphalts because European contractors provided warranties, which motivated them to have a greater interest in decreased life cycle costs, even if the initial costs were higher. The high upfront expenses for polymer modified asphalt limited its use in the US [9]. Modified asphalts have the ability to offer improved performance over conventional asphalts, but they are not a solution or panacea for all situations. Thus, a careful balance of asphalt properties and rheological parameters is generally required [10–13]. Examples of problems related to these phenom-ena can be found in most of the reports on modified asphalts [10–18] and are generally linked to the rheology of complex fluids.

Asphalt modification consists of adding an additive with the desired properties to the asphalt to improve it. Since the mid-1980s, polymer-modified asphalt concrete mixtures have been

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widely used to minimize rutting failures of asphalt pavements [4]. Therefore, a careful balance of asphalt properties is generally required to reduce one asphalt mixture distress mode without aggravating other modes, such as the use of a harder asphalt to prevent rutting without aggravating fatigue cracking. Therefore, polymers are mostly used to produce mixtures with longer life and better performance [14–15].

The polymers used for asphalt modification can be classified into two families based on their behaviors once added to the asphalt. Polymers that form a rigid three dimensional network and resist permanent deformation are called plastomers, while those that induce higher elasticity and recovery are called elasto-mers [19]. Some authors suggest an additional nominal class of reactive polymers that have the same properties as plastomers but include functional properties able to bond with asphalt mole-cules [16,20,21].

When a load is applied to the surface of an asphalt pavement, it deforms; however, because the asphalt is a viscoelastic material, as the load is removed, the deformation partially recovers. Therefore, a variable amount of irreversible deformation remains in the asphalt mixtures, resulting in a very small permanent residual strain. Accumulation of millions of these strains due to repeated axle loadings results in surface rutting [22–25]. Because the goal of the analysis in the laboratory is to reproduce the field, many different tests can be used to assess the resistance of asphalt mixtures (e.g., wheel tracking test, dynamic creep test [1]). In particular, dynamic loading systems that use a moving wheel can represent the passage of vehicles along the surface in both dry and soaked conditions at several temperatures.

This study presents an assessment of the rutting resistance of two different types of modified asphalt mixtures containing (i) amorphous polyolefin polymer and (ii) a particular polymer obtained by combining LDPE (low density polyethylene) and EVA (ethyl-vinyl-acetate). Rutting tests were performed by a wheel tracking device to evaluate the rut depth and wheel-tracking slope (WTS), in accordance to EN 12697-22, of the studied asphalt mixtures, which were then compared to three conventional asphalt mixtures produced with different asphalt contents. The additives were used in three different amounts. All mixtures were produced in the laboratory using a kneading compactor in accordance to EN 12697-33. The rutting tests were performed at two different testing temperatures (30 and 60 °C).

Stiffness and fatigue tests were carried out to compare the performance of the modified asphalt mixtures to reference mixtures. The stiffness of the studied asphalt mixtures was evaluated by testing prismatic specimens in four-point bending at different temperatures and frequencies to develop the master curves of each mixture. The fatigue life was assessed by testing the previous specimens at 20 °C and 10 Hz. A comparison between the mixtures was conducted for a single strain level (300 μ).

The rutting results were fit in the model proposed by the NCHRP 1-37A project to verify the applicability of using wheel tracking results to predict the pavement performance.

2. Materials and testing procedures

2.1. Materials

Two polymers were used in the modification of the asphalt. The first is made of amorphous polyolefin with a low molecular weight and low fusion point and belongs to the family of EVA polymers. The second is composed of LDPE and EVA and other polymers with a low molecular weight and medium fusion point. The polymers were small pellets and were workable at room temperature so they could be easily stored or added directly into the hot asphalt. Fig. 1 shows the flexible semi-soft granules at room temperature. Table 1 reports the physical properties of both polymers.

Three different types of asphalt mixtures were evaluated containing: (i) no additive, (ii) amorphous polyolefin polymer and (iii) a particular polymer obtained by combining LDPE and EVA.

The asphalt mixtures design were designed according to the Italian specifications for a binder course and included conventional asphalt (85 mm/10 penetration, 44 °C softening point) and virgin aggregates. The amorphous polyolefin polymer modified asphalt presented the following penetrations: 67, 51, and 42, respectively for 3, 6 and 9 polymer content. In terms of softening point, the values are 50, 58 and 52 °C, respectively for 3, 6 and 9 polymer content.

The aggregate gradation for all the asphalt mixtures is reported in Table 2 and correspond to a 20 mm nominal maximum aggregate size. The determination of the binder content was carried out to obtain 4.0% air void content as defined in the Italian Standard. Thus, the optimum asphalt content was 4.1% of the weight of aggregate.

Polymers pellets were directly added into the asphalt mixture just before the hot asphalt.

Three dosages per additive were used: 3%, 6% and 9% of the asphalt weight. Three asphalt contents were considered for the reference mixture.

The labels used for all 9 mixtures studied in this work, as well as the asphalt content, air-void content, voids in mineral aggregate (VMA), voids filled with asphalt (VFA) and the maximum specific gravity are provided in Table 3.

After designing the mixtures, they were produced and compacted in slabs of 500 × 260 × 50 mm (Fig. 2: left) using a roller compactor to obtain 4 ± 1.0% air-voids. Mixtures containing amorphous polyolefin polymer were blended and com-pacted at 140 °C. Mixtures with LDPE + EVA polymer were mixed at 175 °C and compacted at 140 °C. The compaction equipment included a prismatic mold and a series of metal plates that were set on top of the mixture (kneading compactor)(Fig. 2: center). The compaction energy was transferred through two twin metal wheels (Fig. 2: right) that moved horizontally on the plates.

2.2. Testing procedures

The rutting resistance of mixtures was assessed by wheel tracking tests according to the European Standard EN 12697-22 using the "small device procedure B" (in air). A minimum of two slabs per mixture were compacted and tested up to 10,000 load cycles. Each slab was poured into the metal mold (Fig. 2: left) and tested in load control. The device's wheel applied a load of 700 N, while its speed was set to 26.5 passes per minute corresponding to 0.44 Hz.

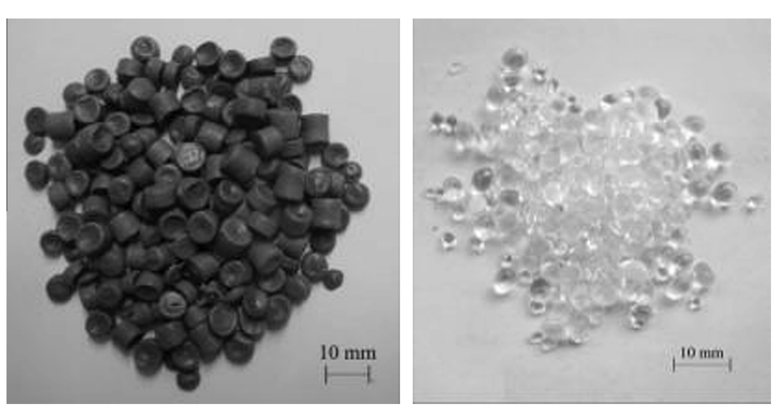

Fig. 1. Polymer pellets at room temperature: (left) LDPE, (right) EVA.

Table 1
Basics physical properties of the polymers.

	Appearance	Softening Point [°C]	Fusion Point [°C]	Melt Index
LDPE	Black/gray granules	150	160	1 ÷ 5
EVA	Neutral granules	100	120	<10

Table 2
Aggregate gradation for all the asphalt mixtures.

Sieve size (mm)	Passing (%)	Lower–upper limits (%)
31.5	100	100
20	98	98–100
12.5	73.5	44–86
4	42	33–55
2	29	25–40
0.5	13	10–22
0.125	7	5–12
0.065	4	3–9

The main parameters obtained from the wheel tracking test were the wheel tracking slope in air (WTS_{AIR}) and the rut depth at 10,000 cycles. Based on the historical weather condition in northern Italy during the summer and spring periods, 30 and 60 °C were selected as representative temperatures for the rutting tests. All slabs were thermally conditioned in an oven before testing. Then, two thermocouples were set inside the mixture during testing to ensure the temperature.

To assess the stiffness and fatigue resistance, at least six four-point bending tests were carried out using prismatic specimens (380 × 50 × 50 mm) cut from the slabs compacted by the kneading compactor. Prismatic specimens were conditioned in a controlled temperature chamber prior to testing and then tested at the following conditions for the assessment of the stiffness modulus:

- Temperatures: −5, 10, 20, 30 °C.
- Load frequency: 0.1, 0.2, 0.5, 1, 2, 4, 6, 8, 10 Hz.

After the stiffness evaluation, each prismatic specimen was subjected to fatigue testing at a frequency of 10 Hz and a testing temperature of 20 °C. The fatigue resistance was defined as the number of cycles at a 50% reduction in stiffness.

For the stiffness and fatigue tests, the bending was realized by the movement of the two centre load points (Fig. 3) in vertical direction perpendicular to the longitudinal axis of the specimen, while the vertical positions of the two end points remained fixed. The clamping device was air controlled and allowed to fix equally the four points. Displacements and deformations were measured by means of LVDTs. Three LVDTs positioned respectively at the centre and at L/3 from the end points were used. The applied periodic displacement was symmetrical about the zero, and sinusoidal, and the displacement amplitude was a constant as a function of time (according to EN 12697-26).

3. Results

3.1. Rut resistance

The results of the rutting tests are expressed in terms of the wheel tracking slope (WTS) and rut depth. The WTS is computed as the ratio of the difference between the rut depth after 5000 load cycles and 10,000 load cycles, in accordance to EN 12697-2. The rut depth was measured at 10,000 load cycles. The results of all 9 mixtures and two test temperature (30 and 60 ° C) are presented in Figs. 4 and 5 for the rut depth and WTS, respectively.

The addition of both amorphous polyolefin polymer and LDPE + EVA polymers induced a significant reduction in the rut depth and a quantifiably lower value of WTS. Therefore, wheel tracking results demonstrated that the addition of these modifiers enhanced the resistance to permanent deformation at both moder-ate (30 °C) and high temperatures (60 ° C). Mixtures with amor-phous polyolefin polymer and LDPE + EVA polymer were compared to REF4.1 because they had the same asphalt content.

Independent of the mixture and temperature, the rut depth and the slope of the rut-cycle curve decreased as the additive content increased even though the final deformation was higher than the reference unmodified mixture. The results of the rutting tests confirmed that modification with polymers increased the resistance to permanent deformation. In addition, by increasing the additive content, the slope of the curve deformation-cycle (which can be represented by the WTS value) decreased. In particular at 30 ° C, mixtures with amorphous polyolefin polymer showed the lowest value of WTS; the WTS was one order of magnitude lower than other mixtures. This result suggests that no deformation will occur in these mixtures.

Table 3
Asphalt mixtures composition and volumetric parameters.

Mixture ID	Additive		Asphalt content	Air voids	VMA	VFA	Maximum specific gravity
	Name	(%)	(%)	(%)	(%)	(%)	(g/cm^3)
REF3.6	Without additive	–	3.6	3.1	11.7	73.2	2564
REF4.1		–	4.1	4.6	15.2	69.6	2514
REF4.6		–	4.6	3.7	15.0	75.2	2507
APP3	Amorphous polyolefin polymer	3	4.1	4.6	15.0	69.8	2516
APP6		6		4.8	15.2	68.6	2517
APP9		9		3.9	14.9	74.0	2502
LEP3	LDPE + EVA polymer	3	4.1	4.9	15.7	69.1	2504
LEP6		6		4.8	15.7	69.6	2503
LEP9		9		4.7	15.7	69.8	2501

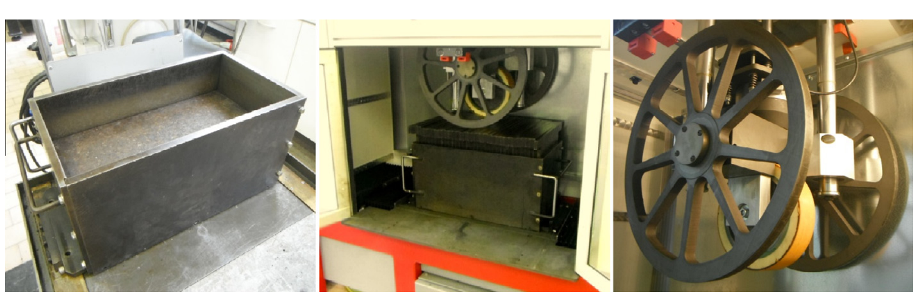

Fig. 2. Metal mold (left), sliding plates on top of the metallic mold (center), wheel tracking device: detail of loading metal wheels and rutting wheel (right).

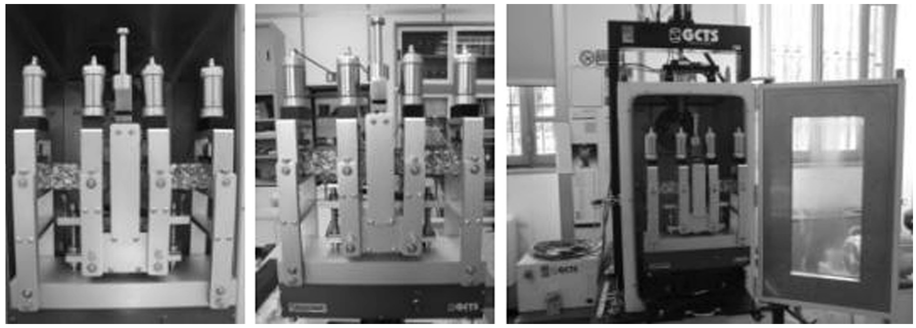

Fig. 3. Four point bending fatigue apparatus.

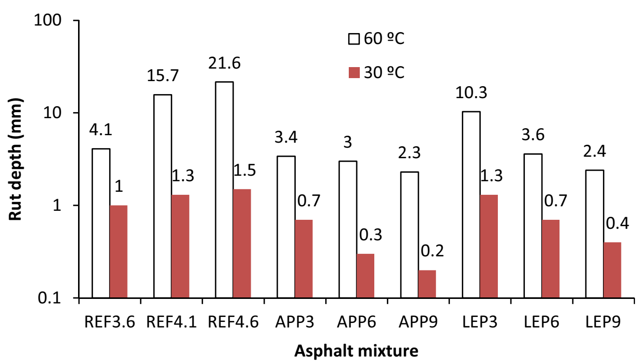

Fig. 4. Rut depths for all the asphalt mixtures.

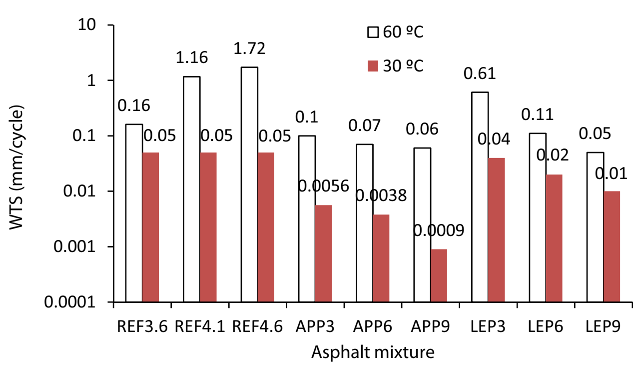

Fig. 5. WTS for all the asphalt mixtures.

3.2. Stiffness

The bending stiffness test results were fit using the sigmoidal model proposed in the AASHTO TP-62 standard for the reference temperature of 20 °C. All curves were plotted in a half space together with the reference curve so a direct comparison with the unmodified mixture can be made (Fig. 6). Points represent the experimental data while lines represent the master curves.

For the base mixtures, the increase in the asphalt content caused a vertical shift of stiffness values but no changes in the shape. Looking into the details, it appeared that curves REF3.6 and REF4.1 were very close for reduced frequencies above 10 Hz. REF4.1 is below REF3.6 which is reasonable assuming that the theoretical REF4.1 should pass between REF3.6 and REF4.6, if the volumetrics of both mixtures are identical.

Both APP and LEP mixtures had a strong effect on the stiffness modulus. The thermal susceptibility of the modified asphalt was reduced by the addition of the polymers. This effect was evident in the slopes of the master curves. A lower slope represents a lower thermal sensitivity because the modulus varies less over a set range of values. At low frequency values, the master curves of the APP mixtures were higher than the reference mixtures and conversely at high frequencies. This behavior underlines the positive effect of adding EVA to the mixture. It reduced the stiffness in the low temperature regime (high frequency domain) and increased it at high temperatures (low frequencies).

The behavior of the LEP mixtures was similar to the APP mixtures, even if the increase of the stiffness modulus was generally higher. In other words, the increase of the stiffness modulus due to LDPE was much more significant than that with EVA even though they were both above the reference values. This considerable increase is observed in the high frequencies where the LDPE-modified mixtures show stiffnesses slightly higher than the unmodified mixture. Master curves of the LDPE mixtures maintained the sigmoidal shape and they are shifted vertically compared to REF4.1.

3.3. Fatigue resistance

The fatigue life of the asphalt mixtures was assessed by developing fatigue curves for each mixture. To compare the asphalt mixtures, the fatigue resistance at the 300 μ was computed and presented in Fig. 7. Mixtures with LDPE (LEP) have identical fatigue resistance to the reference mixture (REF4.1) for 3% and 6% polymers. For 9% polymer, the fatigue life is slightly greater. The APP mixtures have better fatigue behavior at all polymers content.

The joint analysis of permanent deformation and fatigue resistance presents evidence that the ranking of the mixtures is identical for both tests. The APP mixtures have better performance in permanent deformation and fatigue. LEP mixtures have the worst performance.

4. Application of rutting results in the NCHRP model

The key elements that govern permanent strain accumulation for a given asphalt mixture are temperature and stress level [26]. Both of these parameters influence the elastic (resilient) strains as well as the permanent strains. Normalizing the permanent strains by the elastic strains should therefore capture most of the temperature and stress effects [26]. This theory is the basis for the asphalt rutting model implemented in the NCHRP Project 1-37A mechanistic–empirical design methodology [27]. This model has been used by many authors [28,29], and its general form is the following equation:

$$\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = B_\sigma[a_1\beta_1 + a_2\beta_2\log(T) + a_3\beta_3\log(N)] \qquad (1)$$

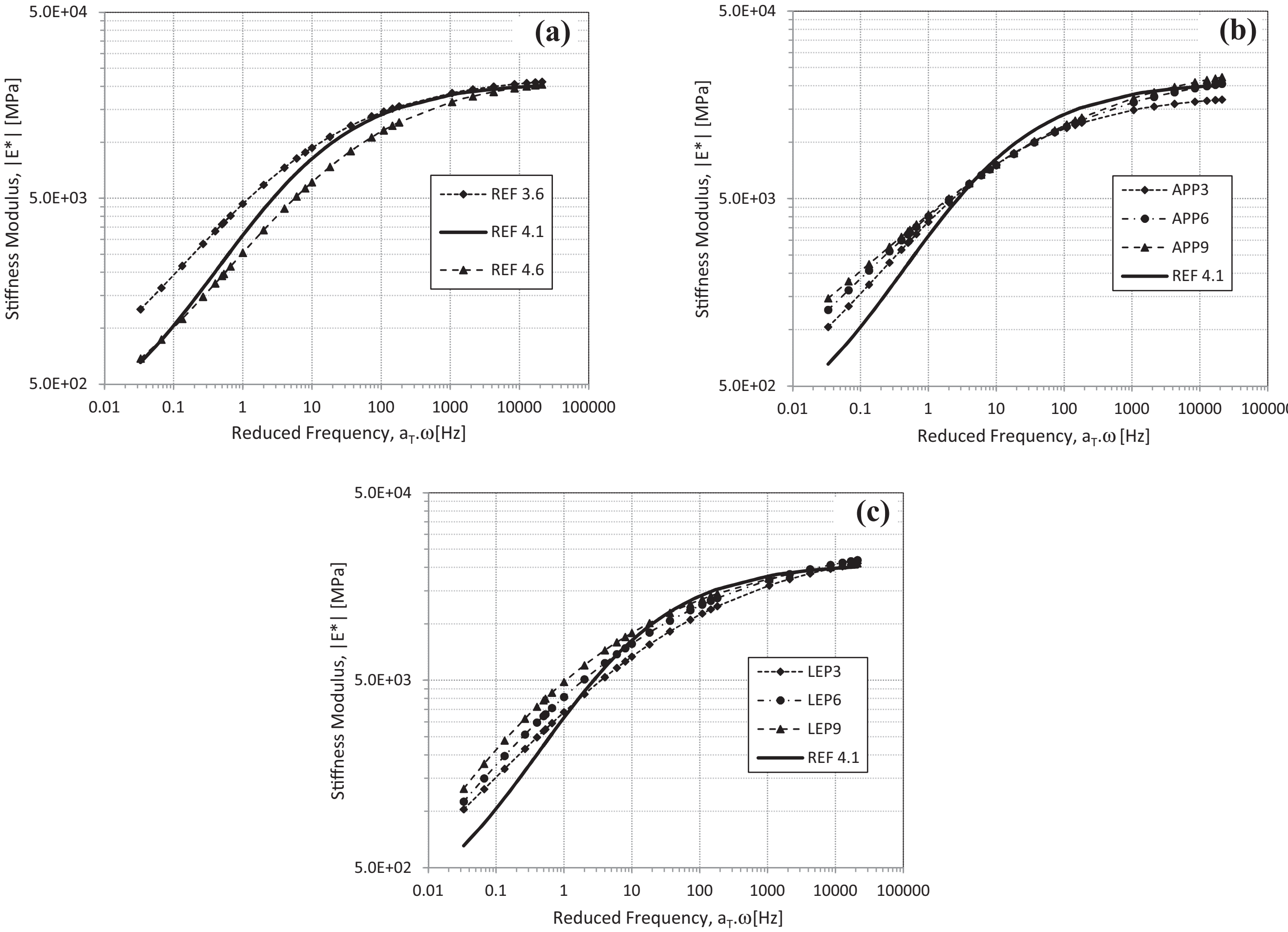

Fig. 6. Master curves of dynamic stiffness modulus: (a) REF, (b) APP, (c) LEP.

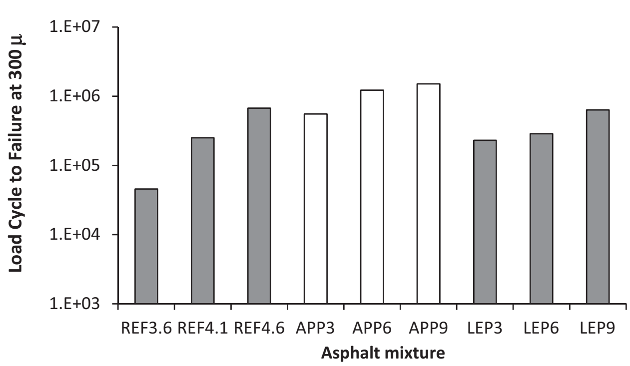

Fig. 7. Fatigue life of all mixtures at 300 µ.

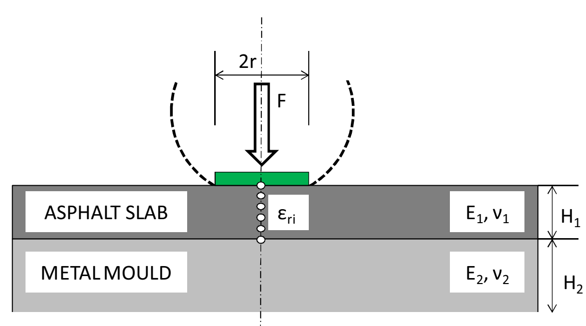

Fig. 8. System of two layers used to compute the resilient strain in an asphalt slab.

where ε_r and ε_p are, respectively, the resilient (elastic) and permanent strains, a_i are the nonlinear regression coefficients, β_i are the calibration factors depending on location, N is the number of load repetitions and T is the temperature [°F]. The parameter B_σ is a function of the lateral confinement, which depends on the depth from the surface and thickness of the asphalt layer, as reported by following equations from [20]:

$$B_\sigma = (C_1 + C_2 \cdot z) \times 0.3282^z \quad (2)$$

$$C_1 = -0.1039H_{\mathrm{HMA}}^2 + 2.4868H_{\mathrm{HMA}} - 17.342 \quad (3)$$

$$C_2 = 0.0172H_{\mathrm{HMA}}^2 + 1.7331H_{\mathrm{HMA}} + 27.428 \quad (4)$$

where H_{HMA} is the thickness of the hot mixture asphalt (HMA) layer and z is depth within the HMA layer.

Eq. (1) is the result of a huge calibration campaign [28] that provides the equation with a high robustness. The final calibrated a_i values: a_1 = −3.4488, a_2 = 1.5606 and a_3 = 0.4791, were determined via a global calibration using data from field sections [28,29] and β_i = 1 [26]. The same values are used in the NCHRP 1-37A modeling approach and are assumed to be mixture independent.

The results of the rutting tests were applied to the NCHRP model to verify the possibility of predicting the pavement rut depth based on the results of the laboratory wheel tracking tests.

Table 4
Computed values of the dynamic modulus from master curves and resilient strains (ε_R) from the software BISAR 3.0®.

Temp.	Mixture ID	REF3.6	REF4.1	REF4.6	APP3	APP6	APP9	LEP3	LEP6	LEP9
60 °C	E (MPa)	220	120	100	260	290	320	150	220	330
	ε_r (μ)	1448	2654	3185	1225	1027	995	2123	1448	965
30 °C	E (MPa)	1200	930	660	990	1220	1420	980	1100	1350
	ε_r (μ)	265	342	483	322	261	224	325	290	236

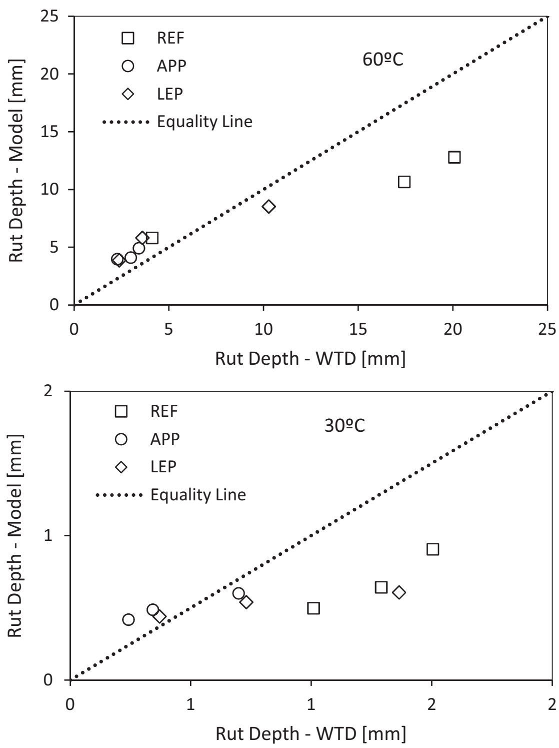

Fig. 9. Rut depths from the model compared to the rut depths from the wheel tracking device (WTD) at 60 and 30 °C.

To apply the rutting test results to the NCHRP model, a simplified system was developed to calculate the resilient strain (Fig. 8). The system is composed by two elastic homogeneous layers, representing the slab and the metallic mold of the wheel tracking test. The resilient strain (ε_r) was calculated below the static vertical force (F) distributed uniformly on a circular area of radius (r).

The computation of the resilient strain was implemented in BISAR 3.0® software. Because the strain response of a material is a function of its stiffness, the master curve of the dynamic stiffness modulus was used to obtain the stiffness for each mixture, each test temperature and a frequency of 0.44 Hz corresponding to the loading frequency of the wheel tracking device. This simplified approach provided resilient strain values for each mixture (Table 4).

This approach was used to compute the resilient strain and thereby give an indication of the predicted permanent deformation to compare to the measured results from the tests. Using Eq. (1), the permanent deformation was computed at 10,000 load cycles per each mixture and plotted against the values obtained in the wheel tracking tests (Fig. 9).

By analyzing Fig. 9, it can be observed that the dispersion of the points around the equality line increases with the rut depth. This tendency was most likely due to the influence of volumetric characteristics on the rut behavior and in particular the variability of air voids contents of the mixtures. Therefore, taking into account the number of points used to fit the curves, the R^2 value of 0.77 can be considered quite respectable, especially given the diversity of

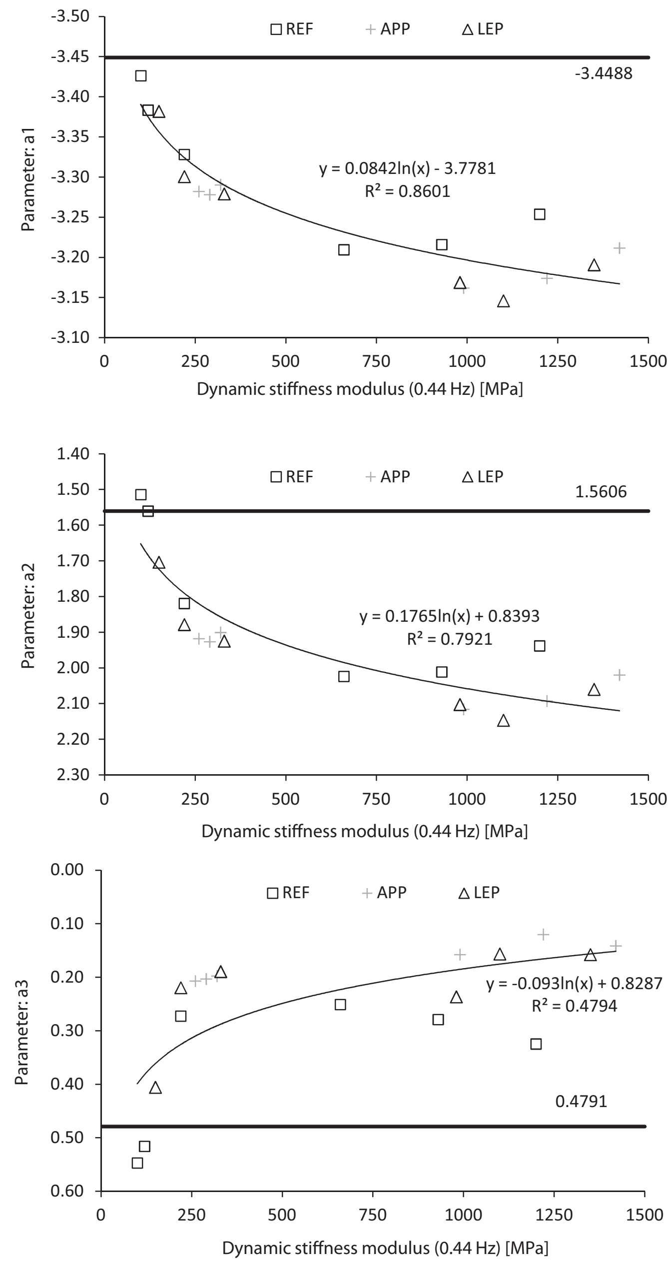

Fig. 10. Coefficients a_1, a_2 and a_3 versus the stiffness modulus at 0.44 Hz for all mixtures.

asphalt mixtures included in the data set. Thus, the model and the results from the test can be correlated. The comparison at 30 °C did not show as a good reliability. However, the comparison showed that the in situ rutting performance of the asphalt mixtures can be predicted using the NCHRP model and the results from the wheel tracking tests.

The previous analysis was made calculating the resilient strain for a set of asphalt mixtures which exhibit different stiffness moduli ranging from 224 MPa up to 3185 MPa. For these values, the coefficients a_i (Eq. (1)) were iteratively adjusted until the summed squared errors between measured and predicted rut depth were minimized. The optimized coefficients are mainly a function of the mixture but they are also dependent on the temperature used during the test that affects the stiffness modulus of the asphalt mixtures. Thus, the calculated coefficients a_i were plotted versus the stiffness modulus at 0.44 Hz (Fig. 10).

A unique regression curve was found by plotting the optimized coefficients (a_1, a_2, a_3) from all mixtures versus the stiffness modulus. As shown in Fig. 10, the values from modified and unmodified mixtures belong to the same curves with a R^2 of 0.48 to 0.86 depending on the coefficient considered.

5. Conclusions

The objective of this research was to evaluate the rut resistance of different types of modified mixtures containing (i) amorphous polyolefin polymer and (ii) a particular polymer obtained by combining LDPE (low density polyethylene) and EVA (ethyl-vinyl-acetate). The rutting test results indicate that the addition of both amorphous polyolefin polymer and LDPE + EVA polymers caused a significant reduction in rut depth; the rut depth and the slope of rut-cycle curve decreased when the additive content increased. In terms of the other performance indicators, the stiffness modulus was strongly affected and the same for the fatigue resistance for high asphalt content.

The joint analysis of permanent deformation and fatigue resistance shows that the ranking of the studied mixtures is identical for both tests. The APP mixtures had better performance in permanent deformation and fatigue. The LEP mixtures behavior was the worst behavior.

However, it is important to mention that the bitumen used in the asphalt mixtures has an important effect in the mechanical behavior of the asphalt mixtures and in the presence of the additives, such as the ones used in the work, can produce asphalt mixtures with different behavior.

The wheel tracking test results were implemented in the NCHRP Project No. 1-37A rut model. The comparison between the estimated (test) and predicted (model) rut depths showed a good correlation in terms of R^2 at 60 °C, meaning that the NCHRP Project No. 1-37A rut model fits the wheel tracking test results. The relationship between the stiffness modulus and calibrated coefficients is a useful tool for reproducing results from wheel tracking tests independent of the mixture and dosage or type of additive.

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