



Mechanistic Fatigue Evaluation of High-RAP Asphalt Concretes for Airport Pavements

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Abstract. Cores of Surface, Binder and Base high-RAP asphalt concretes (i.e. from 15% to 40% by aggregate weight) were extracted from a field trial constructed in a high-capacity airport. The viscoelastic properties and fatigue performance are investigated according to the mechanistic-based Simplified-Visco Elastic Continuum Damage model. It provides low-time consuming laboratory testing and data processing using FHWA tools to obtain intrinsic properties of the materials. Mixture-level results showed that RAP do not significantly reduce fatigue resistance. From the structural-level simulations using FlexPAVE™ v2.2, accounting for dynamic load, climatic effects and aging in a three-dimensional finite element model, emerged that a 20-year service life can be achieved under Boeing 737-800 loading. These findings highlight the suitability of high-RAP mixtures for airport pavements and the possibility to adopt the S-VECD model. Future studies will assess damage contributions from the entire aircraft traffic spectrum to quantify cumulative distress.

Keywords: Airport · RAP · fatigue · S-VECD · FlexPAVE™

1 Introduction

High-Reclaimed Asphalt Pavement (RAP) asphalt concretes (ACs) ensure environmental benefits, such as reduced consumption of natural resources and lower carbon footprint. Nevertheless, performance and durability should not be compromised.

The impact of RAP requires a reliable evaluation. The traditional pavement design approaches are empirical or in elastic domain, not efficiently capturing the mechanical behavior and deficiencies of such mixtures. The mechanistic-based Simplified-ViscoElastic Continuum Damage (S-VECD) model allows the fatigue performance characterization based on the intrinsic properties of the asphalt mixtures [1]. Laboratory testing and data analysis can be completed within few days with excel spreadsheet provided by FHWA. Moreover, the three-dimensional finite element analysis with the FlexPAVE™ v2.2 software predicts the pavement performance under moving loads and using realistic climatic conditions with aging effects [2]. However, FlexPAVE™ has been developed for roadway loading conditions, and its application to airport pavements—where loads are significantly higher and geometrically different—is not documented.

In this context, this study evaluates the performance of three high-RAP asphalt mixtures using the S-VECD model, for potential use on a taxiway of a high-capacity airport.

2 Field Trial and Main Properties of the Asphalt Concretes

A field trial was constructed in July 2025 in an Italian high-capacity airport. The pavement structure shown in Fig. 1a consists of three AC layers and two cold recycled materials (CRMs) layers with different bitumen emulsion and cement dosages. The RAP content is 96% and 100% in CRM_1 and CRM_2, respectively. The stiffness moduli of the CRMs layers at 20 °C reported in Fig. 1a were back-calculated from the deflection basins of an HWD campaign carried out one week after the construction. The pavement lays on a subgrade that ensures a minimum bearing capacity of 50 MPa.

The dense-graded aggregate gradation, the RAP content (deriving from old milled polymer-modified pavements) and the Nominal Maximum Aggregate Size (NMAS) of ACs are reported in Fig. 1b. The polymer-modified bitumen classified as PG 82–10 was added with different dosages (*total bitumen*) in Surface, Binder and Base ACs: 4.8% (5.4%), 3.2% (4.6%) and 2.5% (4.8%) by aggregate weight. The high temperatures of the PG (HPG) of the virgin and RAP bitumen are 82 °C and 100 °C, respectively.

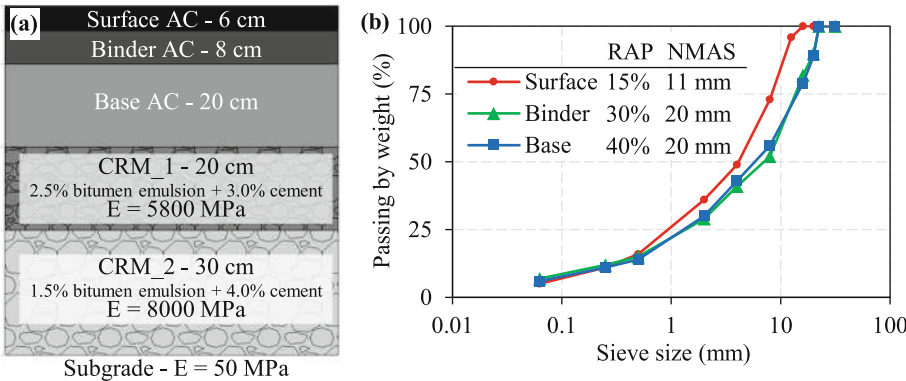


Fig. 1. (a) Pavement structure of the field trial and (b) aggregate gradation of the ACs

3 Experimental Program

Cores were extracted from the field trial, and 38-mm diameter by 110-mm tall specimens were horizontally cored from the AC layers. The S-VECD characterization was carried out on these specimens with the Asphalt Mixture Performance Tester (AMPT). Thus, **dynamic modulus tests** were conducted at 4 °C, 20 °C and 40 °C, and at the frequencies 20 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz and 0.1 Hz. A sinusoidal axial compression load was applied, setting a strain level between 50 $\mu\epsilon$ and 75 $\mu\epsilon$ (AASHTO TP 132, 2019). After a **fingerprint dynamic modulus test** in axial tension-compression mode of loading at the same temperature of 21 °C (based on the bitumen PG) and frequency of 10 Hz of the fatigue test, the specimens were subjected to actuator displacement-controlled **cyclic loading** in direct tension. The input strain level varied to obtain valid data with duration between 2000 and 80000 cycles. The number of cycles to failure N_f corresponds to the cycle in which the product of peak-to-peak applied stress and cycle number reaches a maximum value (AASHTO T 411, 2023).

4 Viscoelastic Properties and S-VECD Fatigue Results

The viscoelastic characterization was carried out with dynamic modulus tests. The average experimental data of the dynamic modulus $|E^*|$ of three replicate specimens for each AC were fitted adopting the 2S2P1D model and simultaneously calibrating time-temperature shift factors (AASHTO TP 132, 2023).

Figure 2a shows the dynamic modulus mastercurve (experimental data and model), and the average air void content ($\%AV_{ssd}$) measured using the saturated surface dry (SSD) method. The AV of the Surface (9.4%) is mainly due to microporosity intrinsic to its composition. As expected, the Base AC is stiffer than the Binder AC, that is stiffer than the Surface AC. The higher stiffness of Binder and Base ACs with respect to Surface AC is mainly due to the coarser aggregate and the lower bitumen content. Moreover, the higher stiffness of Base AC with respect to the Binder AC can be attributable to the higher amount of RAP, combined with lower bitumen content and lower $\%AV_{ssd}$. The phase angle δ mastercurves in Fig. 2b indicate a similar viscoelastic behavior of the ACs. A slightly down-shifted trend is registered from Surface to Base ACs especially at low reduced frequencies, denoting a predominancy of the elastic component of the dynamic modulus with respect to the viscous one.

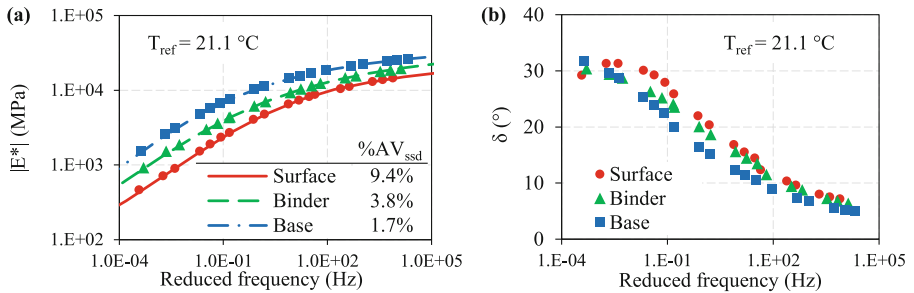


Fig. 2. (a) Dynamic modulus mastercurve and (b) phase angle mastercurve at 21.1 °C.

Table 1 summarizes the main parameters of the three fatigue tests for each AC, used for the S-VECD analysis. Even though some parameters (i.e., DMR and N_f) are out of the suggested range, those tests were considered valid since the precision criteria for damage characteristic curves and D^R are satisfied (AASHTO T 411, 2023). The fingerprint test is needed to evaluate the specimen-to-specimen variability through the dynamic modulus ratio (DMR), that is the ratio between the fingerprint dynamic modulus ($|E^*|_{fp}$) and the average representative dynamic modulus from the mastercurve, both evaluated at the temperature of 21 °C and the frequency of 10 Hz.

Table 1. Main parameters of the S-VECD fatigue tests.

AC	Specimen (%AV _{ssd})	IE*Ifp (MPa)	DMR (0.85–1.25)	Input strain (μϵ)	N _f (2000–80000)	D ^R	S _{app}
Surface	1 (11.1%)	5746	0.82	800	563	0.721	40.0
	2 (8.0%)	6458	0.93	450	15777	0.723	35.5
	3(8.9%)	6984	0.98	550	19553	0.707	35.5
Binder	1 (4.9%)	8579	0.89	320	56577	0.725	23.1
	2 (2.7%)	9835	1.03	330	4201	0.744	24.4
	3 (2.0%)	12038	1.25	280	10065	0.651	19.6
Base	1 (0.9%)	15325	1.04	210	62465	0.617	21.9
	2 (1.4%)	15173	1.04	240	16593	0.553	19.8
	3 (1.2%)	15227	1.03	250	12897	0.535	18.0

Figure 3a shows the experimental damage characteristic curves, representing the decrease of the pseudostiffness C as the amount of damage S increases until failure, whose calculation is based on the pseudostrain. This latter makes the curve independent of testing conditions and configuration. Thus, the different C - S curves of a certain mixture should overlap, as obtained in this study (Fig. 3a). Figure 3b shows the fit of such curves with the Eq. (1), and the %AV_{ssd} of the tested specimens (close to the ones tested by dynamic modulus, as required by AASHTO T 411 (2023) to be significant).

$$C = 1 - C_{11} \cdot S^{C_{12}} \text{ with } C_{11}, C_{12} \text{ fitting coefficients} \tag{1}$$

The C - S curves of Binder and Surface ACs have a similar initial decrease of the pseudostiffness different from the one of Base AC, indicating a higher capacity to withstand the damage at low stiffness. The trend of the C values at failure (higher for Base, followed by Surface and Binder ACs) is inverted for the damage S values at failure (around 400000), expressing the rate of fatigue resistance loss during cyclic loading. Thus, it is not possible to assess which AC show a better fatigue damage evolution.

The S-VECD model provides the pseudo energy-based failure criterion D^R (Eq. (2)), that quantifies the average loss of integrity of the material during the fatigue loading.

$$D^R = Cum(1 - C)/N_f \tag{2}$$

D^R values of the ACs investigated are reported in Fig. 3c. Surface and Binder ACs shows comparable toughness, whereas a lower toughness emerged for the Base AC ascribable to the 40% of RAP with respect to the 30% of RAP in Binder AC.

The fatigue cracking index parameter S_{app} , that accounts for the effects of a material’s modulus and toughness on its fatigue resistance, is reported in Fig. 3d. Higher S_{app} indicates better fatigue resistance of the mixture. As obtained, S_{app} is sensitive to several factor, including aggregate gradation, binder content and RAP content [3]. S_{app} is calculated for a given climatic PG; the climatic PG 58-10 representative of the airport

location was used. The overall performance is higher for the Surface AC, likely due to the mixture composition and high polymer-modified bitumen. Conversely, the S_{app} parameter of the Binder and Base AC is significantly lower. The effect of the higher RAP content in Base AC emerges in the slightly lower S_{app} value with respect to Binder AC.

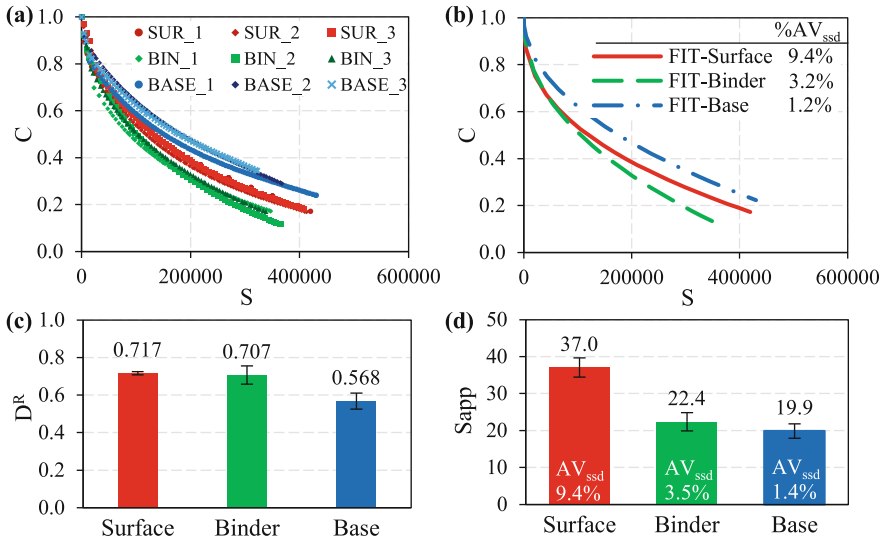


Fig. 3. (a) Experimental and (b) fit of the damage characteristic curves; (c) failure criterion D^R and (d) synthetic index S_{app} values (error bars represents the standard deviation).

5 FlexPAVE™ Pavement Performance Simulation

The investigated structure (Fig. 1a) has a design life of 20 years. The viscoelastic and S-VECD fatigue properties of the ACs were input. The virgin and RAP bitumens HPG were input to calibrate the oxidation kinetics Pavement Aging Model parameters needed for the Asphalt Mixture Aging-Cracking Model embedded in FlexPAVE™ [4]. CRM_1 and CRM_2 were modeled as linear elastic, with HWD-based stiffness moduli reduced to 1500 MPa and 2000 MPa, respectively, to account for shrinkage cracking. [5]. The subgrade with 50 MPa stiffness modulus was modeled as linear elastic.

The traffic spectrum with its growth rate was converted into an equivalent number of the Boeing 737-800 aircraft take-offs [6], characterized by a dual tandem axle load of 754 kN. This results in 200000 annual take-offs over 20-year, which is representative of a high-capacity airport in Italy. The velocity of 30 km/h was considered for the taxiway. FlexPAVE™ was developed for roadway loading conditions, indeed the tire spacing is fixed and the tire pressure is set at 1.8 MPa (the actual value is 1.4 MPa).

Hourly and daily temperature variations of the airport location were considered.

Figure 4a shows the %Damage evolution, computed as the ratio of the damaged area to the total effective area. Figure 4b plots the fatigue damage contour in the ACs layers transversal section in terms of the damage factor, i.e., the amount of damage at

the nodal point (1 is fully damaged and 0 is no damage). The top and bottom %Damage after 20 years of service is about 15% and 20%, respectively, whose more than a half is reached during the first 2 years (Fig. 4a). The on-set of bottom-up cracking involves 2 cm at the end of design life. The top damage affecting the surface layer at a distance of about 1 m from the load is ascribable to fatigue (as confirmed by in-field experiences), whereas in the upper areas of the other layers is ascribable to thermal stresses.

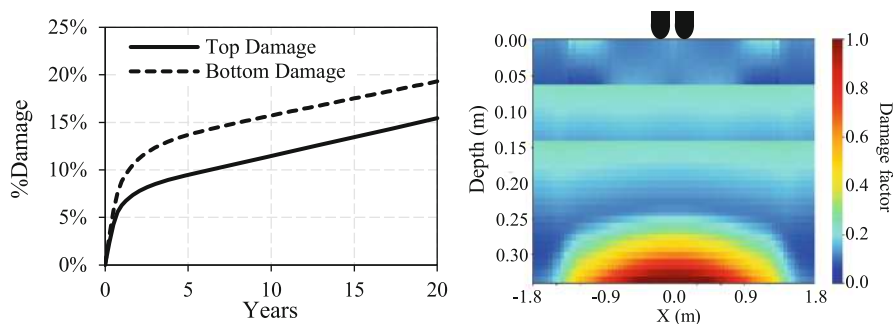


Fig. 4. (a) %Damage evolution and (b) damage contour after 20 years of service.

6 Conclusions

This study evaluated the fatigue performance at mixture and structural level according to the S-VECD model of Surface, Binder and Base ACs cores of a field trial with up to 40% of RAP. The viscoelastic results agree with the ACs composition, and the fatigue performance is not significantly penalized by the high RAP content. FlexPAVE™ results confirms that the pavement structure, where the ACs lay on 50-cm thick CRM layers, satisfies the 20-years design life under the aircraft Boeing 737-800 loading condition, showing the on-set of the bottom-crack and limited damage on the top.

Given the promising results, future work will focus on evaluating the damage with FlexPAVE™ for each aircraft of the traffic spectrum (different load and main gear configuration, since the considered Boeing 737-800 represents a relative light loading condition), to determine the cumulative damage factor within the transversal section, and on the characterization of CRMs with the S-VECD model.

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