



Extended summary

## Experimental Evaluation of the Adhesion at the Interface Between Pavement Layers and Orthotropic Steel Decks

*Curriculum: Analisi e Progetto dell'architettura e del Territorio –  
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**Abstract.** Steel orthotropic deck is the most suitable solution for long-span bridges in virtue of its low weight and good mechanical properties. However, it can be subject to corrosion caused by rain and deicing salts which can infiltrate the pavement layers.

Waterproofing coats typically show a lack of adhesion with smooth steel surface and/or with bituminous paving materials. Coats that create good adhesion with steel (epoxy or methacrylic resins), tend to have poor affinity with bitumen. For this reason, monolithic aggregate particles are typically spread on the “not-hardened” waterproofing coat in order to make the interface rough. In some extreme situations (small-radius curves or steep slopes) even mechanical reinforcements, consisting of steel nets or bars welded to the deck surface, are necessary to avoid pavement slippage.

The PhD research was carried out with the aim to evaluate the shear properties of steel-concrete interfaces in orthotropic deck bridges. Different bond-improving methods were accurately studied, classified and tested in order to identify the advantages/disadvantages presented by each technique.

The results showed that epoxy asphalt guarantees the highest performance regardless of the test temperature; bituminous and methacrylic membranes have a similar shear resistance, respectively related to good cohesion and friction; the presence of steel nets or bars on the deck surface significantly improves the slippage resistance at the interface, even if shear properties are not as high as that of epoxy asphalt system.



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Besides interface characterization, physical, mechanical and rheological properties of two pavement mixtures for orthotropic decks, i.e. hot mix asphalt with polymer-modified bitumen and epoxy asphalt concrete, were evaluated.

Experimental analysis demonstrated that epoxy asphalt concrete has higher properties than hot mix asphalt in terms of strength and stiffness, although its workability is lower. Viscoelastic characterization proved that epoxy asphalt is not a thermorheologically simple material, as time-temperature superposition principle is not valid either for Young's modulus and Poisson's ratio.

**Keywords.** adhesion, bond coat, bridge pavement, interface, orthotropic deck.

## 1 Problem statement and objectives

Steel orthotropic deck is an effective solution for the building of long-span bridges, which need to be as light as possible without penalizing the bearing capacity of the deck [1]. However, one of the criticalities of the orthotropic deck is the scarce compatibility, in terms of adhesion, between the steel and the asphalt concrete which is generally used for the surface layers of road pavements. Consequently, the paving courses may be subject to early cracking, increasing the risk of deck corrosion and reducing the comfort and safety for drivers [2].

As in the case of cement concrete bridges [3], the simplest solution consists in the application of a special bituminous tack coat on the deck surface in order to provide both waterproofing and adhesion to the asphalt pavement [4, 5]. Typical examples of these bonding coats are polymer-modified bitumens, bituminous membranes and methacrylic primers. Other techniques for orthotropic deck surfacing consist in the laying of specific wearing courses, such as epoxy asphalt concretes, which allow the performance requirements to be met as regards waterproofing, bonding at the interface with the steel plate, durability, reliability and skid-resistance [6, 7]. Alternatively, mechanical reinforcements, such as steel nets or bars, can be welded to the steel surface in order to prevent the slippage of the upper asphalt pavement [6].

The present PhD research aimed at the mechanical characterization of steel-pavement interface of orthotropic deck bridges, in order to identify the most suitable solution in terms of shear performance at the interface.

## 2 Research planning and activities

Different bond-improving systems were accurately studied, classified and tested in order to evaluate the advantages/disadvantages presented by each technique. The analysis involved the following types of interfaces:

- interface coated with polymer-modified bitumen (PmB);
- interface coated with bituminous membrane (BM);
- methacrylic membrane system (MMS);
- epoxy asphalt system (EAS);
- reinforced steel surfaces (RSS), in particular:
  - net-reinforced steel surface;
  - bar-reinforced steel surface.

The adhesive properties of these systems were investigated through direct shear tests performed by mean of ASTRA device, a suitable equipment for interface characterization [8, 9]. To simulate the orthotropic steel deck pavement system, double-layered specimens were manufactured: the lower layer was a steel plate while the upper layer consisted of an asphalt mix for leveling course. An exception was represented by EAS, whose upper layer was made of epoxy asphalt concrete. Shear tests were performed at different temperatures and normal stresses.

In addition to shear tests, physical, mechanical and rheological properties of epoxy asphalt concrete (EAC) were characterized, as the material was supposed to perform differently from traditional hot mix asphalt (HMA).

At this aim, volumetric analysis of EAC was carried out by examining the compaction procedure through shear gyratory compactor.

Mechanical characterization was achieved through indirect tensile tests carried out at different temperatures. The water sensitivity of EAC was evaluated by comparing the indirect tensile strength of dry specimens (not water-conditioned) with that of samples kept in water bath at 40 °C for 72 hours before testing.

Rheology of epoxy asphalt concrete was studied through cyclic compression tests. EAC cylindrical specimens were stressed by sinusoidal load waves with different frequencies. Test was repeated at different temperatures. Axial compression and transverse dilation were measured using two couples of strain gauges glued on opposite sides of each specimen at mid-height. The same tests were performed on HMA specimens as reference.

### 3 Analysis and discussion of main results

#### 3.1 Shear tests on different steel-pavement interfaces

In the present section a comparison between the different techniques is presented in order to identify the most suitable solution in terms of shear performance at the interface. In particular the analysis is carried out regarding not only peak tangential stress but also separating cohesive and friction contributions. In addition, the effect of two test temperatures, 20 °C and 40 °C is considered.

Figures 1 and 2 show the shear resistance, respectively at 20°C and 40°C, of each kind of interface tested in presence of normal stresses equal to 0.2 and 0.4 MPa.

From the histograms it can be immediately noticed that epoxy asphalt system (EAS) shear resistance is definitely higher than every other interface. This indicates that epoxy resin has a particularly strong adhesive power with steel, determining an excellent shear strength on smooth surfaces. Besides, it can be asserted that such result is mainly related to the sensitively high cohesive contribution, while friction is less significant. In fact, as  $\tau_{\text{peak}}$  values for  $\sigma_v = 0.2$  MPa and  $\sigma_v = 0.4$  MPa are comparable at both test temperatures.

It is important to underline that also methacrylic materials are able to create a very strong adhesion with steel, despite results obtained for methacrylic membrane system (MMS) interface are not so high. As EAS provides epoxy asphalt concrete for the overlay, the binder in the mix can blend with not-fully-hardened bond coat and create a uniform phase system. On the other hand, MMS provides ordinary HMA for the pavement. As the membrane has already cured when asphalt concrete is laid and as bitumen does not create any adhesion with methacrylic materials, the system, on the whole, presents a critical weak interface between membrane and pavement, determining a lower shear resistance than EAS.

The performance of bituminous (BM) and methacrylic membrane systems (MMS) is similar to PmB at the temperature of 20 °C. However, when temperature increases up to 40 °C, the benefit related to application of BM or MMS is visible. This result is very important as the risk of asphalt layer slippage and debonding is higher when increasing temperature and it has been showed that pavements of steel orthotropic deck can even reach the temperature of 70 °C in tropical climates [10].

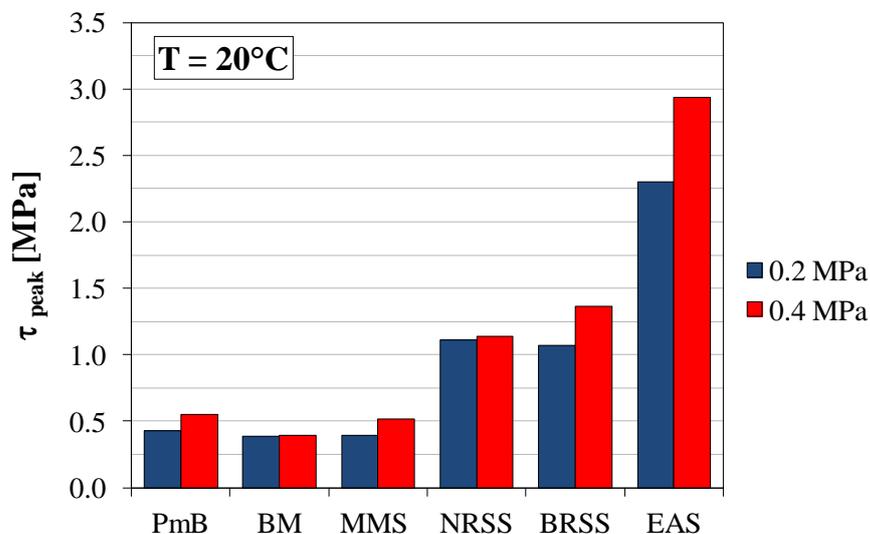


Figure 1. Comparison between different interfaces at T = 20 °C

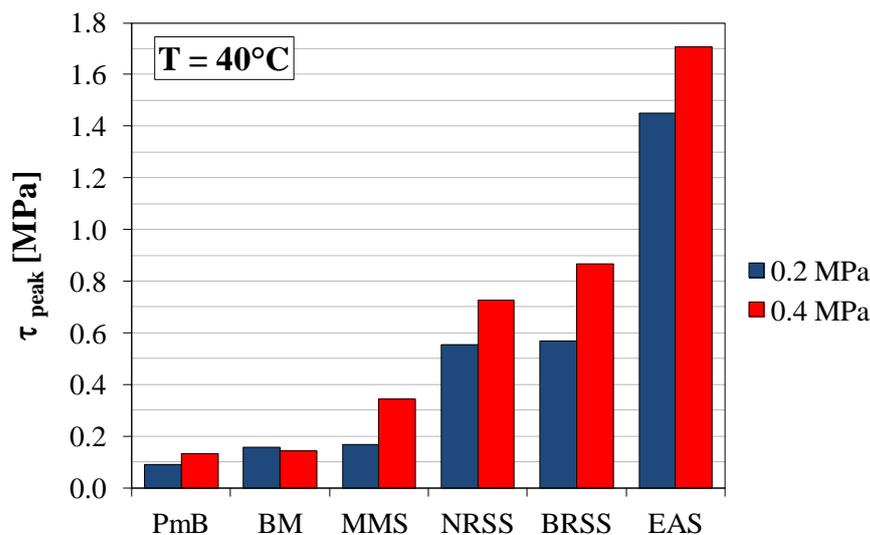


Figure 2. Comparison between different interfaces at T = 40 °C

Table 1 shows the values of cohesion and the friction angle calculated for each interface at 20 and 40 °C. EAS is not present in the table as the tests at  $\sigma_v = 0$  MPa could not be performed because, without the confinement effect due to the normal load applied at the interface, the specimens showed an instable behavior during ASTRA shear tests.

By analyzing these results, it can be noticed that, in general, cohesive contribution is markedly temperature-sensitive, as c-values highly reduced from 20 to 40 °C.

In addition, it can be observed that the behavior of BM and MMS is importantly different. For BM the slipping resistance is mainly due to the cohesive contribution, that proved to be very good especially at high temperatures thank to the important amount of polymer contained in the membrane and in the primer. Differently, the incidence of the friction on

the shear strength is not relevant, determining similar  $\tau_{\text{peak}}$  values independently from the magnitude of the normal load. On the other hand, the shear resistance of MMS interface is due almost entirely to the friction between the membrane and the HMA, while cohesion is rather poor. So, an excellent performance is expected in presence of traffic-related tangential stresses, but the risk of pavement shoving and detaching is high for bridges located in areas characterized by high thermal gradients (both seasonal and daily). In fact, the cohesive contribution is the main responsible in bearing thermal dilation/contraction-induced stresses.

Table 1 permits to make considerations about reinforced interfaces in comparison with smooth ones. From the results it can be affirmed that the presence of nets or bars on the steel surface allows to reach significantly high shear resistance values, as an effect of the failure interface shifting from the bond coat level (interlayer slipping) to within the asphalt concrete layer (in-layer slipping) [11]. In fact, as shown in Figure 1, the peak tangential stress at 20 °C for net-reinforced steel surface (NRSS) and bar-reinforced steel surface (BRSS) is at least twice than that of PmB coated smooth interface. The benefit is even higher when increasing temperature to 40 °C (Fig. 2).

The effect of the reinforcement is visible on both cohesive and friction contributions. Indeed, for reinforced systems cohesion does not refer to the steel-asphalt concrete interface, but to HMA internal cohesion, related to the dilatant contribution due to aggregate interlocking and especially to the asphalt binder viscosity. As bitumen stiffness is temperature-dependent, reinforced interface cohesion decreases when increasing temperature. This explanation is also confirmed by similar the cohesion values determined for NRSS and BRSS.

On its hand, friction angle depends on the geometry of the reinforcement: under a vertical stress the sharp-edged bars allow an improved connection with the asphalt concrete than the rounded rods of the net. So, BRSS interface shows a higher friction angle than the NRSS interface at both test temperatures. However, it has to be taken into account that the shear properties of interfaces characterized by an in-layer failure (as reinforced systems) are strictly depend on the bulk density of the compacted HMA [12].

In addition, it is remarked that the performance of EAS is still better than reinforced systems, with peak tangential stresses at least twice as high as reinforced interfaces (Figs 1 and 2). This indicates that the chemical adhesion between the steel surface and the epoxy asphalt bonding coat is so strong that allows EAS shear resistance to be significantly higher than that of a HMA-HMA interface of a well-compacted monolayer sample.

Table 1. Cohesion and friction angle values.

Temperature T [°C]	Interface	Cohesion c [MPa]	Friction angle $\phi$ [°]
20	PmB	0.35	24.6
	BM	0.29	15.1
	MMS	0.16	41.7
	NRSS	0.80	41.1
	BRSS	0.75	55.5
40	PmB	0.07	7.8
	BM	0.18	5.1
	MMS	0.03	33.6
	NRSS	0.23	48.2
	BRSS	0.23	54.9

## 3.2 Epoxy asphalt concrete characterization

### 3.2.1 Compactability tests

Volumetric properties of epoxy asphalt concrete were evaluated according to European Standards EN 12697-8 and EN 12697-10. Figure 3 shows the air voids content  $V_m$  as a function of the number of gyrations  $N$  in a semi-logarithmic graph for two epoxy asphalt concrete (EAC) samples and for a traditional HMA [13].

From the figure it can be observed that the compactability curve for epoxy asphalt was not a line (in semi-logarithmic scale), as for HMA, but presented two parts with different slopes. In effect, the slope of the first part was very similar to that of HMA, but it resulted very short as the flex point was located around gyration number 25. After the flex, the slope for EAC importantly reduced, determining a noticeable drop in mixture workability. This may probably be related to the curing of epoxy asphalt which significantly affects both volumetric and mechanical properties of the mixture.

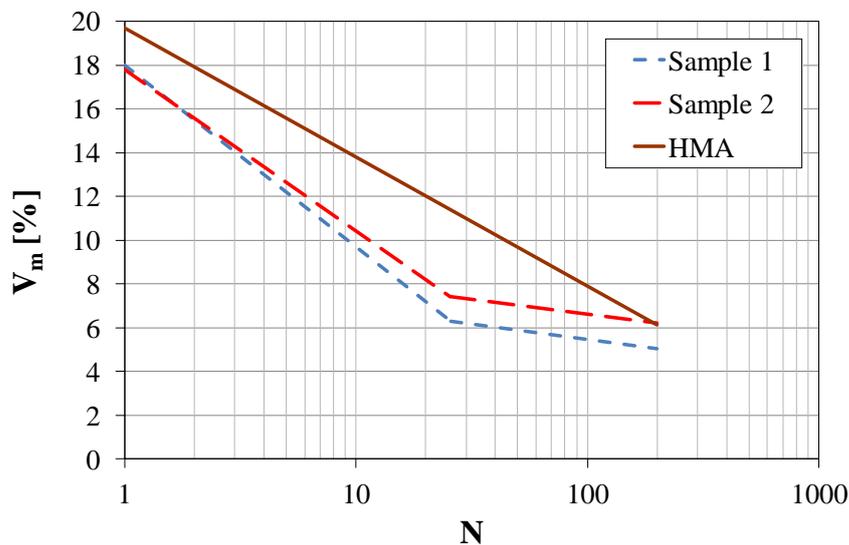


Figure 3.  $V_m$  as a function of  $N$  for EAC and HMA.

### 3.2.2 Indirect tensile tests

Experimental results (Fig. 4) showed that at all test temperatures, epoxy asphalt concrete demonstrated to have an indirect tensile strength sensitively higher than bituminous mixtures. In particular, taking into account that Italian specifications for highway infrastructures establish a minimum indirect tensile strength of 0.95 MPa for asphalt concrete with polymer-modified bitumen at 25 °C, it resulted that ITS values for epoxy asphalt were bigger of almost two orders of magnitude. This result was probably related to the high resistance of epoxy asphalt binder, which created a very strong and hard mastic when mixed with filler (indeed the amount of fines in the mixture was about 10 %). Besides, the adhesion between epoxy asphalt and aggregate proved to be very strong, too.

Moreover, the histogram in Figure 4 shows that epoxy asphalt concrete, differently from HMA, did not decrease its tensile strength when increasing temperature but presented the

minimum ITS values at  $T = 20\text{ }^{\circ}\text{C}$ . This indicates that for temperatures lower than  $20\text{ }^{\circ}\text{C}$  epoxy asphalt inherits the thermoplastic behavior from the bitumen contained in the binder, while somewhere between  $20\text{ }^{\circ}\text{C}$  and  $60\text{ }^{\circ}\text{C}$  there is a reversal in the mechanical behavior, and the mixture acts as a thermosetting polymer. The present finding is very important as it denotes that epoxy asphalt concrete has an excellent resistance to high-temperature distress such as rutting or shoving.

Furthermore, from Figure 4 it can be noticed that epoxy asphalt concrete showed a low water sensitivity, denoting similar ITS for both dry and wet conditioned samples.

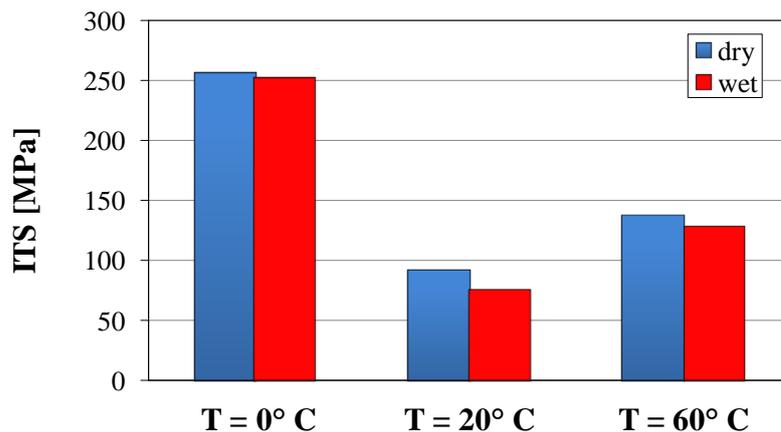


Figure 4. Mean ITS values at different test temperature and conditioning

### 3.2.3 Cyclic compression tests

Figure 5 shows the comparison between master curves at  $10\text{ }^{\circ}\text{C}$  of different samples in a bi-logarithmic scale  $|E^*|$ - $f_R$  graph. It can be noticed that epoxy asphalt concrete is importantly stiffer than hot mix asphalt at all reduced frequencies. This indicates that at all working temperatures EAC has a higher resistance to permanent deformation distresses as rutting and shoving. However, as the order of magnitude is comparable with HMA and at the light of the results from ITT, it can be affirmed that the risk of brittle behavior and consequent early cracking is definitely avoided.

In order to evaluate the viscous properties of the mixture, results were plotted in the Black space ( $|E^*|$  versus  $\phi_E$ ) as shown in Figure 6. In the graph the parabolic-shape trend can be identified for HMA. However, for EAC the curve did not result continuous but a gap was present in proximity of the phase angle peak. This indicates that the Time Temperature Superposition Principle (TTSP) is not valid for epoxy asphalt concrete. In addition, it can be observed that the shift in the phase angle was localized between the experimental data at  $20\text{ }^{\circ}\text{C}$  and  $30\text{ }^{\circ}\text{C}$ . Hence, there is a change in the material rheological behavior in that range of temperature.

It is important to highlight that a change of EAC behavior was observed also in ITT for a larger but fitting range of temperature ( $20\text{ }^{\circ}\text{C} - 60\text{ }^{\circ}\text{C}$ ). So, the same explanation can be assumed, i.e. that, increasing temperature beyond a value about  $25\text{ }^{\circ}\text{C}$ , epoxy asphalt (binder and, thus, concrete) shifts from a thermoplastic behavior, inherited from the bituminous component, to a thermosetting behavior, related to the epoxy resin contained.

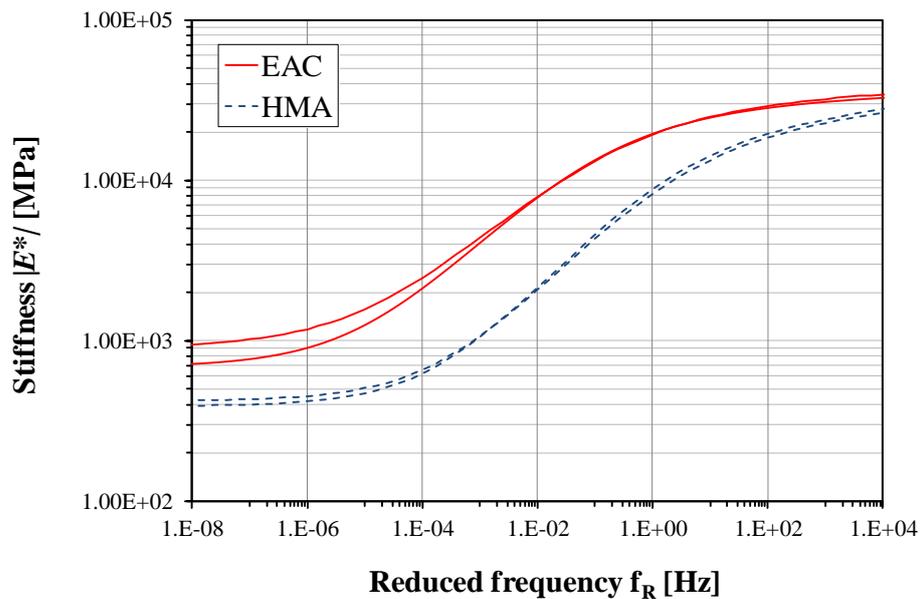


Figure 5. Specimen master curves in bi-logarithmic scale

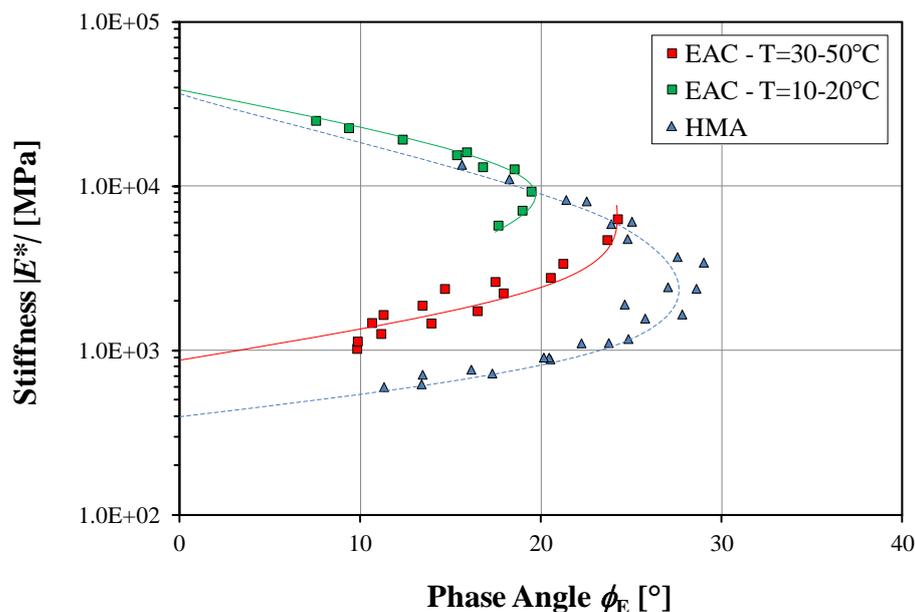


Figure 6.  $|E^*|$  versus  $\phi_E$  (Black Space) for HMA and EAC

Three dimensional characterization of HMA and EAC was carried out in terms of Poisson's ratio. Figure 7 reports Poisson's ratio absolute value and phase angle master curves for HMA. Results confirmed a clear dependency on temperature and frequency, with  $|v^*|$  values ranging from 0.27 to 0.35.

Respect to the corresponding Young's modulus,  $v^*$  plots show a greater dispersion of results, which is a consequence of the very low values of horizontal strain that were registered during the tests. Indeed, it has to be considered that a variation in Poisson's ratio of 0.1 corresponds to a transverse deformation of about  $0.2 \mu\text{m}$ . So, such data dispersion is

acceptable and, however, not avoidable with the instruments used. Nonetheless, even in the presence of this experimental noise, unique curves can be identified, suggesting that TTSP can be considered valid for  $v^*$ .

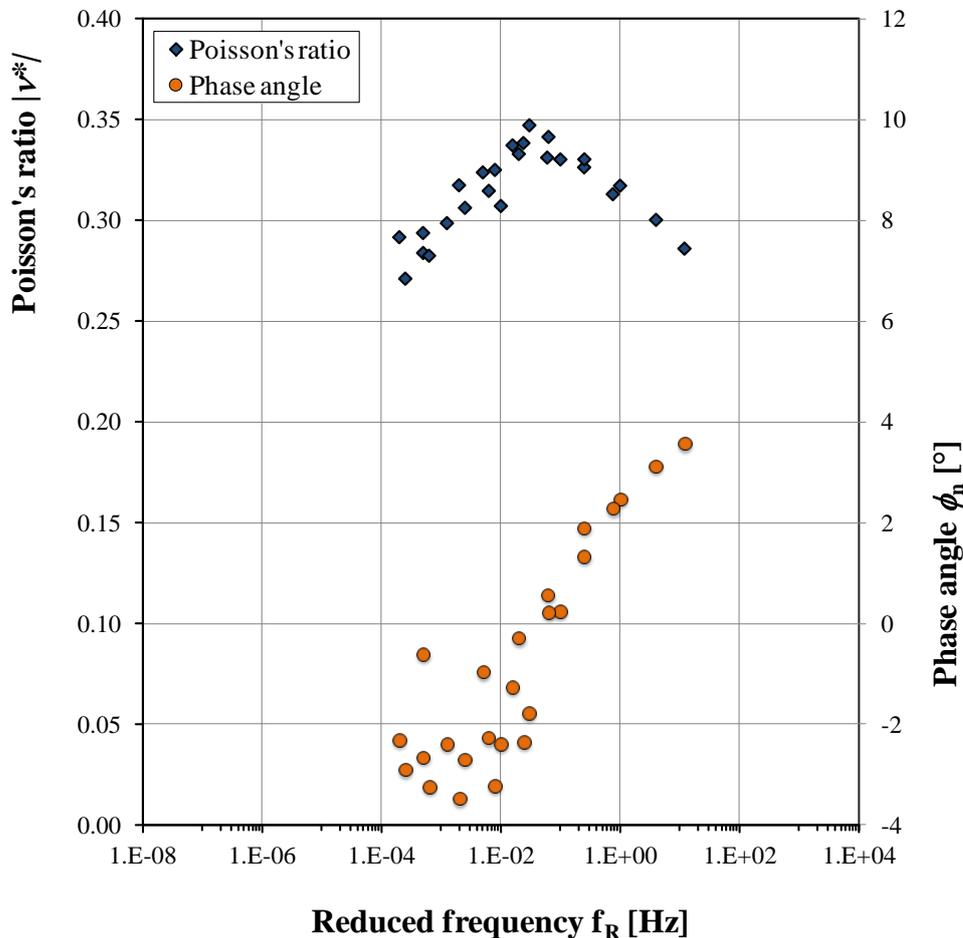


Figure 7. Master curves for  $|v^*|$  and  $\phi_v$  – HMA mixture

Figures 8 and 9 respectively report Poisson's ratio absolute value and phase angle master curves for EAC. Both components proved the dependency on temperature and frequency for epoxy asphalt concrete with  $|v^*|$  values ranging from 0.3 to 0.5. So Poisson's ratio for EAC resulted noticeably more sensitive to frequency and temperature variations as regards to HMA.

As for Young's modulus, by applying the shift factors for  $|v^*|$  to  $\phi_v$ , a discontinuous curve, with a gap between the temperatures of 20°C and 30°C, resulted for the phase angle. This indicates that the TTSP is not valid for Poisson's ratio of epoxy asphalt concrete.

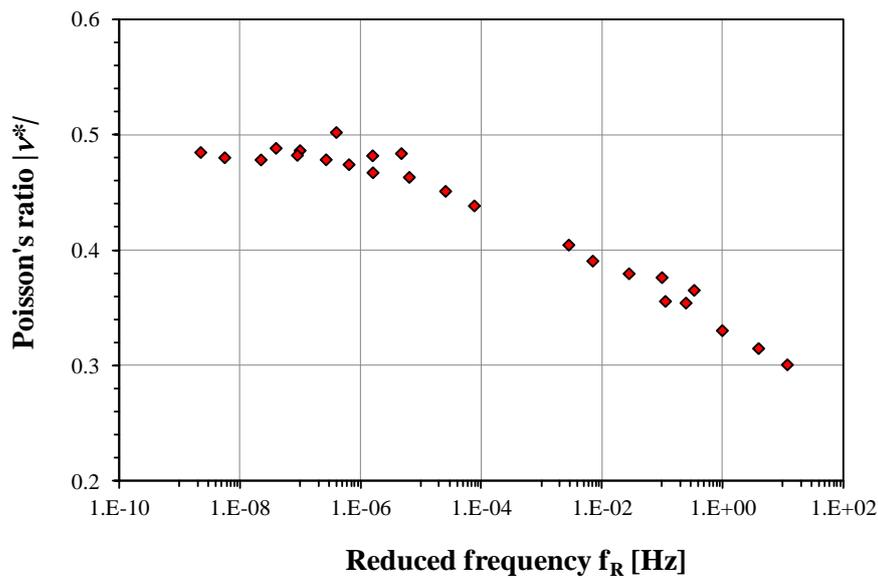


Figure 8. Master curve for  $|\nu^*|$  – EAC mixture

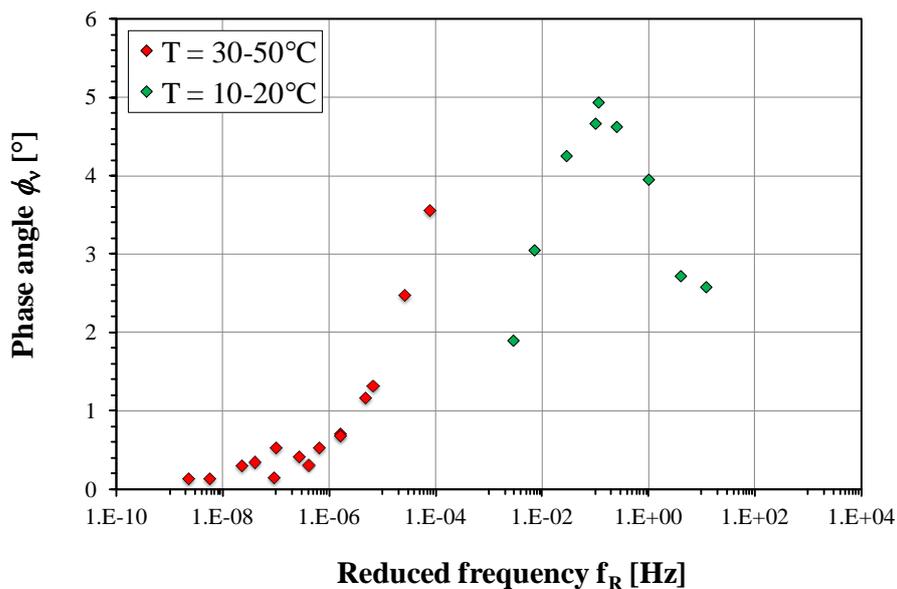


Figure 9. Master curve for  $\phi_v$  – EAC mixture

#### 4 Conclusions

Although steel orthotropic deck is currently the most widely adopted solution for long-span bridges, the poor adhesion to the upper asphalt layers still represents a serious problem with a not clear solution. In recent decades many techniques, which involve the use of special bituminous or polymeric bonding coats, have been applied with varying results to improve the level of adhesion of the asphalt pavement to the steel surface.

The present PhD research activities aimed at the mechanical characterization of steel-pavement systems in orthotropic deck bridges. Different bond-improving systems were accurately studied, classified and tested in order to evaluate the advantages/disadvantages

presented by each technique. The adhesive properties of these systems were investigated through direct shear tests performed by mean of ASTRA device, a suitable device for interface characterization. Tests were performed at different temperatures and normal stresses.

From the results it mainly emerged that:

- EAS shear resistance is definitely higher than every other interface;
- the performance of BM and MMS is similar to PmB at the temperature of 20°C. However, when temperature increases up to 40°C, the benefit related to application of BM or MMS is visible;
- behavior of BM and MMS is importantly different. For BM the incidence of the cohesion is noticeable, while friction contribution on the shear resistance is not as relevant. On the other hand, MMS cohesion is poor while friction angle is significant, especially at high temperatures;
- the presence of nets or bars on the steel surface allow to reach significantly high shear resistance values, as an effect of the failure interface shifting from the bond coat level (interlayer slipping) to within the asphalt concrete layer (in-layer slipping).

In addition to shear tests, physical, mechanical and rheological properties of epoxy asphalt concrete (EAC) were characterized, as the material was supposed to perform differently from traditional hot mix asphalt (HMA). From the findings, the following observations can be made:

- compactability curve for EAC is not a line (in semi-logarithmic scale) as for HMA. Indeed, it presents a first short part with a slope similar to that of HMA; then, after a flex point, the slope importantly reduces, determining a noticeable drop in mixture workability;
- ITS values for EAC are bigger than for HMA of almost two orders of magnitude. EAC showed the minimum ITS values at  $T = 20^{\circ}\text{C}$ , while higher values were obtained at both  $0^{\circ}\text{C}$  and  $60^{\circ}\text{C}$ ;
- EAC has a low water sensitivity, with indirect tensile strength ratio values higher than 80% at all test temperatures;
- EAC is stiffer than hot mix asphalt at all reduced frequencies;
- for both HMA and EAC complex Poisson's ratio confirms to be dependent from temperature and frequency;
- the Time Temperature Superposition Principle (TTSP) is not valid for both Young's modulus and Poisson's ratio of EAC.

To conclude, it can be affirmed that the present research has demonstrated to be valid in order to evaluate the behavior of different steel deck – road pavement interfaces subjected to tangential stress. Even if the ASTRA equipment, used in the experimental activities, does not directly reproduce the complex state of stress that interests real-scale bridges, it proved to be effective in order to characterize and compare the interface behavior of different wearing techniques.

Future recommended studies can involve the in-depth modeling of stress state of the whole deck-bond coat-pavement system, with reference to vehicle traffic, bridge vibrations and different thermal dilation/contraction of materials in contact.

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