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Mixed-mode debonding approach to evaluate water sensibility in bi-layer composite pavement

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Abstract In order to evaluate water sensibility on the interfacial properties between layers of composite pavements, a four-point bending (4PB) test on bilayer structure in a water bath is proposed. Using the virtual crack closure technique, the individual strain energy release rates are calculated with a specific model. The debonding driven by Mode I failure is recognized as the main mode. For bilayer specimens made of a cement concrete overlay on bituminous material, the specific test has shown a competition between the different failure mechanisms. A very good bond resistance between layers compared to the fracture tension resistance of the cement concrete layer is observed. In this work, first results of the water effect on the behavior of such a material interface are presented. The final fracture length of the specimens, curves of force-displacements and first digital image correlation results show the influence of water immersion on the debonding failure mode.

Keywords four-point bending test, water, debonding, composite pavements.

1 Introduction

Composite pavement systems, made of concrete/asphalt and asphalt/concrete structure, show good potential for becoming an interesting rehabilitation option for urban pavements that exhibit structural deterioration (De Larrard et al., 2005). However, due to shrinkage phenomenon of cement materials, the existing vertical crack combined to environmental and traffic loading lead to failures that may develop as delamination between layers (Chabot et al., 2008). Typically, such debonding initiates and propagates under the combined influence of normal and shear stresses (Chabot et al., 2005). The presence of water, whatever its phase is, adds to this complex phenomenon an irreversible damage that cannot be ignored

(Vandenbossche et al., 2011) (Raab et al., 2012). The damage can be driven with two mechanisms: (a) loss in strength and durability of materials due to the presence of water in the pore of asphalt concrete (b) loss of mechanical behavior of bond between layers. Evaluating the effect of water on the interface behavior is complex. In order to capture this effect on the interface between layers of composite pavements, a four-point bending (4PB) test is applied on bilayer structure in a water bath. Without water, the specific test has shown significant interface debonding in mixed mode (mode I and II) condition (Hun et al., 2012) (Chabot et al., 2013). In this work, results of the effect of the water immersion on the behavior of a cement concrete / asphalt material interface are presented. Final fracture length, curves of force-displacement and digital image correlation (DIC) are used to investigate if the presence of water in the bi-layer specimen influences debonding failure mode during the 4PB test.

2 Theoretical characterization of the bond during the 4PB test

Following results stemming from concrete beams strengthened by externally bonded plates, a 4PB test has been adapted for the pair of bituminous and cement concrete materials (Hun et al., 2012). This test has the advantage to investigate the interfacial behavior under mixed mode conditions without using any supports or applying any loads directly on the bituminous material (Figure 1).

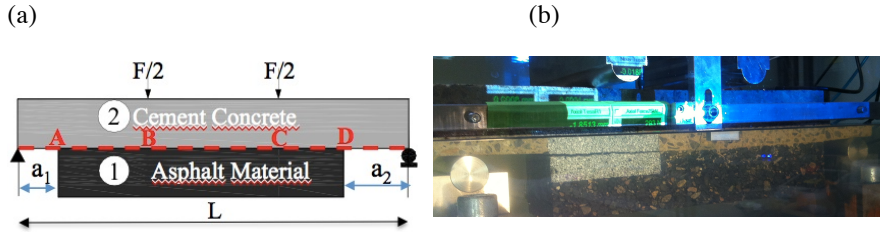


Fig. 1 (a) The four-point bending test configuration; (b) The debonding phenomenon into water

The multi-particle model of multilayer materials (M4) with five kinematic fields per layer is chosen to design and to investigate the debonding results of the 4PB test on bi-layer specimens. The approximations of the so-called M4-5n (n: total number of layers i) offer the advantage of defining the out-of-interface plane normal $\nu^{i,i+1}$ and shear stresses $\tau^{i,i+1}$ at interface between layers i and i+1. As opposed to other classical models, the main interest of this modeling is to yield finite stresses at a free edge or crack tip at the interface point location of two different layers and accelerate the computation process (Chabot, 1997). For crack initiation problems, two delamination criteria in the angle-ply laminates have been proposed (Chabot, 1997) (Caron et al., 2006). The first one is based on the maximum value

of interface stresses. Using the virtual crack closure technique (VCCT) (Bui, 1978) (Moutou Pitti et al., 2008), the second criterion is based on an analytical calculation of the individual strain energy release rates (G_I , G_{II} , G_{III}). Applied to the 4PB test under 2D plane strain assumptions, the M4-5n solutions are given in a previous work with parametric calculations (Chabot et al., 2013). It indicates that a competition exists between tensile stress at the bottom of the cement concrete in layer 2 (between points B and C) and interface normal and shear stresses (at points A and D) (Figure 1a). In order to obtain the debonding phenomenon between the two layers onto only one side, a non-symmetrical geometry of the specimens is proposed. A higher geometrical value of a_2 length compared to the a_1 length one favors delamination on the side a_2 first (Figure 1a). For the 4PB test with a debonding crack length 'a' (Figure 1b), the analytical expression of strain energy release rates is given in (Eq. 1) where b is the width of the beam. e^i , E^i and ν^i denote the thickness, Young's modulus and Poisson's ratio of each layer i respectively. Only G_I is a pure quadratic function of the normal interface stress. G_{II} takes into account the combined terms containing the shear interface stress, shear force Q_1^i of each layer i .

$$G_T(a) = G_I(a) + G_{II}(a)$$

$$\text{with } \begin{cases} G_I(a) = \frac{1}{2b} \cdot \frac{13(e^1 E^2 + e^2 E^1)}{35E^1 E^2} (\nu^{1,2}(a))^2 \\ G_{II}(a) = \frac{1}{2b} \cdot \frac{4(e^1(1+\nu^1)E^2 + e^2(1+\nu^2)E^1)}{15E^1 E^2} (\tau^{1,2}(a))^2 \\ \quad - \frac{1}{2b} \cdot \left(\frac{(1+\nu^1)}{5E^1} Q_1^1(a) + \frac{(1+\nu^2)}{5E^2} Q_1^2(a) \right) \cdot \tau^{1,2}(a) \end{cases} \quad (1)$$

3 Results and discussion

4PB tests on bi-layer specimens are performed under controlled static conditions (0.7mm/min, 20°C constant temperature). To improve the understanding of the fracture scenario of bi-layer materials of such a 4PB test, Digital Image Correlation (DIC) technics are used (Sutton, 1983) (Figure 2). The largest resolution of the camera is 1388x1038 pixels at 63 frames per second. In order to control and measure the imposed displacement (U_z), a linear variable differential transducer (LVDT) sensor is placed at the mid-span ($L/2$) on the top of the specimen ($z=e^1+e^2$) (figure 1). The force (F) is recorded directly on the hydraulic testing machines. During the test, to find the correspondence between each image and the loading conditions, the resulting force and the displacement values are inserted in the images (Figure 2).

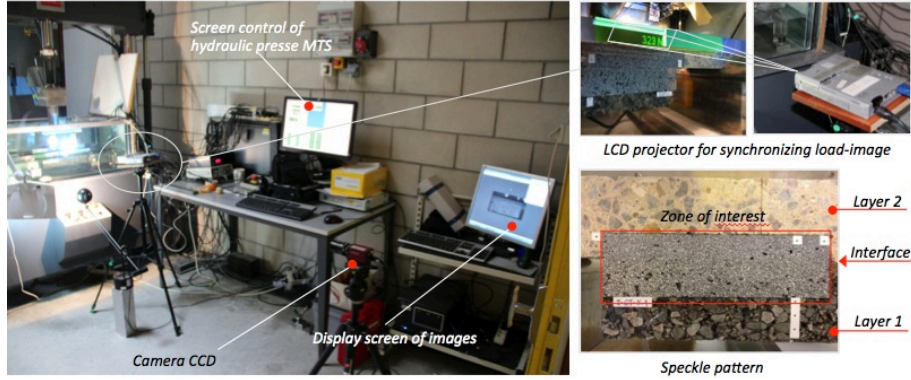


Fig. 2 General description of the immersed 4PB equipment with DIC system

A reference specimen made with an aluminum (Alu) homogeneous layer 2 sticks with epoxy glue, on PVC homogeneous layer 1 ($L=420\text{mm}$; $b=125\text{mm}$; $a_1=40$; $a_2=71$; $e^1=30.6$; $e^2=40.6$ mm; Young modulus ratio: $E^2/E^1 \approx 22.4$; $\nu^1=0.30$; $\nu^2=0.34$) is first tested to validate the M4-5n strain energy release rate results compared to classical ones from the literature. Table 1 shows that the energy release rates of the M4-5n calculus are validated successfully compared to Dundurs's approach (Dundurs, 1969). Mode I is recognized as the main failure mode.

Table 1 M4-5n energy release rate results compared to Dundurs ones for an Alu/PVC specimen

	Crack length (mm)	G_I (J/m ²)	G_{II} (J/m ²)	G_{Total} (J/m ²)
Dundurs	70 ± 1	93	35	128
M4-5n		106	21	127

As opposed to tests conducted on Alu/PVC specimens, the determination of strain energy release rate seems more complicated for bi-layer specimen made of cement concrete overlay on bituminous material. The competition between the poor tensile resistance of the cement concrete layer and the good bond of such an interface adds complexity to the analysis (Chabot et al., 2013). In order to evaluate the additional effect of water during the debonding process, an aquarium is built. Prior to being tested, the specimens are saturated during two hours in a vacuum box filled of water. The wall glass of the aquarium, with its refraction index identical to the water one, allows using the DIC system (Figure 2). M4-5n calculations indicate that, at a loading force of $F=4.2\text{kN}$, the tensile stress (R_t) at the bottom of the layer 2 made of the cement concrete tested air is supposed to reach its maximum tensile value (around $R_t=3.46\text{MPa}$) at point C before point B in this anti-symmetrical specimen geometry case ($L=420\text{mm}$; $b=100\text{mm}$; $a_1=40$; $a_2=71$; $e^1=e^2=60\text{mm}$; $E^2/E^1 \approx 17.5$; $\nu^1 = \nu^2=0.35$). Figure 3 resumes only the static 4PB results for specimens (I-PT-N°slab-N°specimen) instrumented with the DIC system.

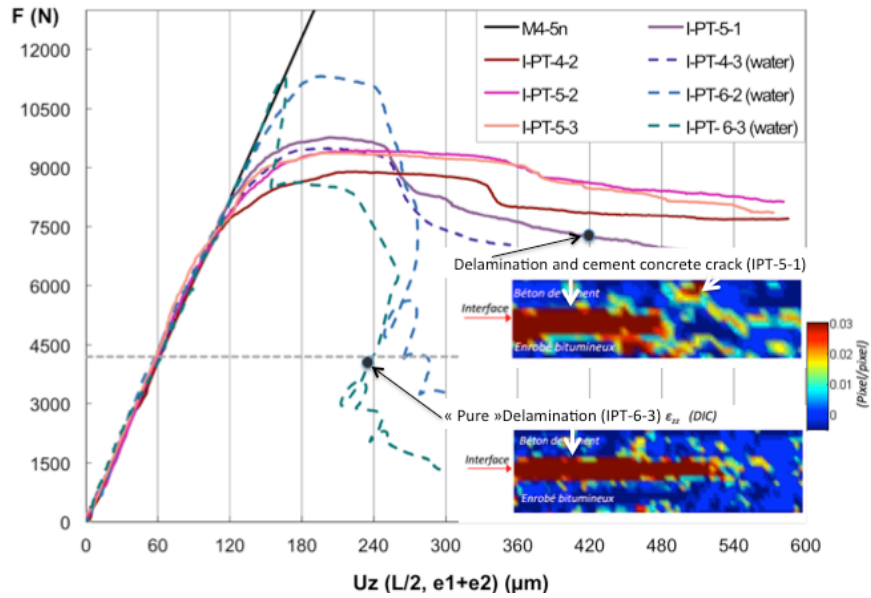


Fig. 3 Curves of force-displacement results of cement concrete/bituminous specimens tested on air and into water with the 4PB test (0.7mm/mn, T=20°C)

In this experimental work, among the specimens (4-2; 5-2; 5-3, 5-1) tested in air, only the 5-1 one has failed with an interface-debonding mode between layers. The bi-layer specimens tested into water (4-3; 6-2; 6-3) failed by debonding mode. The corresponding curves of force-displacement show that after the maximum value of the loading force, the force decreases suddenly (Figure 3). The final debonding length of bi-layer specimen (Figure 1b), obtained in this work and a previous one (Chabot et al., 2013), gives 59 mm for specimens tested in air (calculated from 4 specimens) compared to 97 mm for specimens tested into water (from 3 specimens). The image analysis confirms that, even if the IPT-5-1 specimen failed with interface debonding mode, a parasite crack is observed in the cement concrete material (Figure 3). On the contrary, for IPT-6-2 and IPT-6-3 specimens tested into water, no parasite cracks are observed.

For specimen tested into water, Table 2 indicates first G results. Due to the elastic assumption of the M4-5n and the material considered in that study, these results can be considered as maximum values.

Table 2 Average M4-5n energy release rate results for IPT-6-2 & IPT-6-3

	Crack length (mm)	G_I (J/m ²)	G_{II} (J/m ²)	G_{Total} (J/m ²)
IPT-6-2&3	16.5	155	18	173

All this preliminary results lead to confirm that water has an effect and favors interface debonding phenomenon in such an adapted 4PB test.

4 Conclusion

In order to investigate under water the mechanical behavior of interface between layers, a 4PB test has been adapted. Using the VCCT and debonding assumptions, individual strain energy release rates are calculated with a specific model. Debonding mode I should be recognized as the main failure mode. On specimens made with a cement concrete overlay on a bituminous material layer, all the results confirms that, in air, the delamination process is in competition with micro cracks at the bottom of the cement concrete layer during the test. On the contrary, water presence seems to favor debonding phenomenon in such a 4PB test. More investigations need to be done with more tests and in comparison to other debonding tests such as those done by (Tchegg et al., 2007) and the different Rilem TCs.

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