Characterization of Debonding at the Interface between Layers of Heterogeneous Materials coming from Roads

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Résumé:

Afin de proposer des solutions innovantes pour la maintenance d'un réseau routier vieillissant, il est nécessaire d'étudier les décollements dans les structures, mécanismes encore assez mal connus. L'essai de fendage par coin est choisi ici pour étudier en mode I l'initiation et la propagation de fissure à l'interface de tels matériaux hétérogènes. Le test est adapté à des éprouvettes bicouches extraites de sections expérimentales. La résistance à la traction et l'énergie de rupture sont estimées à partir des courbes d'essais force de fendage – déplacement d'ouverture de fissure. Les techniques de corrélation d'image numérique sont utilisées pour préciser ces mesures.

Abstract:

Studying debonding mechanisms is a necessity in order to propose innovative solutions to maintain an old efficient transport road network. Nowadays, this type of cracking in pavement structures is still not well understood. The Wedge Splitting Test is chosen here to study experimentally in mode I the interface crack initiation and propagation of such heterogeneous materials. The test is adapted for bi layer specimens extracted from full-scale pavement sections. The tensile strength and the fracture energy are firstly estimated from the splitting force - Crack Mouth Opening Displacement curve. The Digital Image Correlation technics are used to precise the measurements.

Keywords: **Interface, Fracture energy, WST, Heterogeneous material, Road structure**

Nomenclature:

F_M	Vertical machine load	S_F	The surface area of the final fracture surface of the sample
F_H	Horizontal load	Δ	Crack Mouth Opening Displacement
F_V	Vertical load	E	Elastic modulus
α	Angle of wedge	δ_{DIC}	DIC Crack Mouth Opening Displacement
F_S	Split load	F_{Smax}	The maximum split load
G_F	Fracture energy	$G_{Faverage}$	The average fracture energy
S_A	Surface fracture energy		

1 Introduction

Road structures are made by a superposition of different layers of heterogeneous materials (bituminous materials, cement concrete, composite grids, etc). The durability of such composite structures depends on severe climate conditions that occur during their lifetimes and multiple heavy loads that move on them [1]. Various damages are identified such as delamination mechanisms at the interface between surface pavement layers. Studying debonding phenomenon is a necessity in order to propose innovative solutions to maintain an old efficient transport road network. This also helps to develop new concepts for turning road infrastructure with new added functionalities such as those that integrates into the road surfaces a dynamic charging box for electric vehicles. Nowadays, this type of cracking in pavement structures is still not well understood [2]. As for edge delamination in composite field, edge effect of existing joints, or vertical cracks in a pavement layer, creates such a high concentration of both normal and shear interface stresses that the crack could propagate along the interface between the two different layers before penetrating through one of materials or even debonding elsewhere far from them [3] [4]. Appropriate fracture opening pure mode and mixed mode tests under several load conditions and environmental conditions (mainly temperature and moisture) need to be adapted or developed for the specific bending study of such multilayered structures.
In this paper the static Wedge Splitting Test (WST) [5] is chosen. The objective is to present and to compare experimental results of interface debonding obtained on composite specimens coming from road construction and the lab. The bi-layer specimens are made of a concrete overlay casted directly onto a bituminous material layer such as it exists in Ultra-Thin White Topping pavement structure (UTW). These structures show an interesting rehabilitation option for urban pavements that exhibit structural deterioration [6]. The tensile strength and the fracture energy are estimated from the splitting force (F_S) - Crack Mouth Opening Displacement (CMOD) curve. To precise the first measurements of the displacement field between the two crack lips, Digital Image Correlation (DIC) technics are used.

2 The Wedge Splitting Test (WST) principles

In order to obtain the fracture mechanical parameters of interfaces, many test methods have been developed. Among all of them [7], initially used for cement concrete material, the Wedge Splitting Test (WST), proposed by Tschegg (1986) [5] and developed by Brühwiler and Wittmann (1990) [8], is an adaptation of the standard compact tension test (ASTM 1983). The WST provides stable crack propagation in quasi “pur” mode I. It is a convenient test that does not require any sophisticated equipment and allows the use of cubical geometry for samples of important size coming from roads.

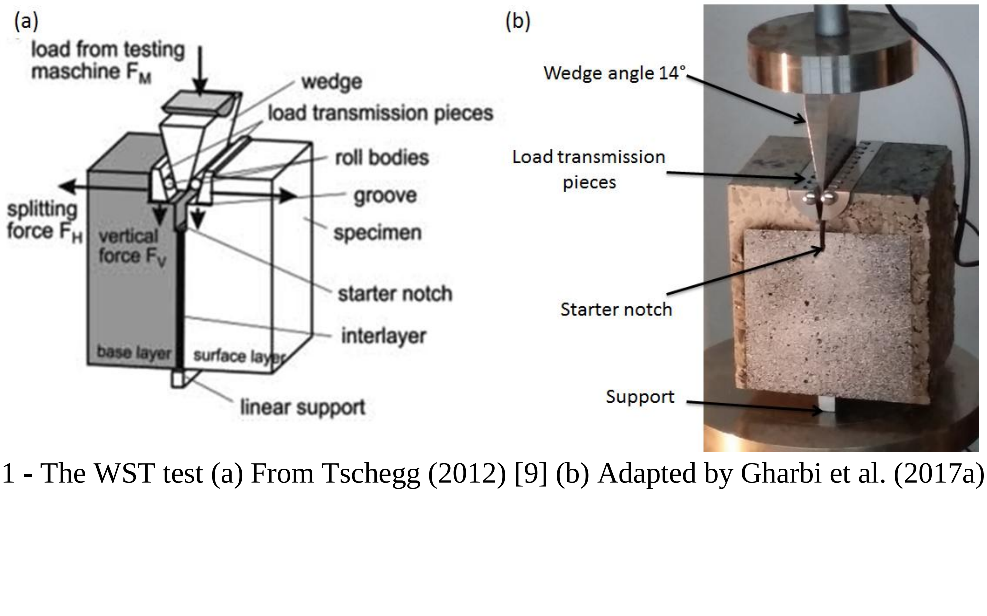

FIG. 1 - The WST test (a) From Tschegg (2012) [9] (b) Adapted by Gharbi et al. (2017a) [10]

The vertical force F_M generated by the testing machine is transmitted from the wedge to the specimen by means of load transmission pieces and transformed into a much higher horizontal force F_H and a low vertical force F_V (figure 1). The horizontal force $F_H = F_M/2tg(\alpha)$, "where "α" is the half of wedge angle, leads to tensile fracture and results in a splitting for the specimen. From the total Load $(F_s = 2F_H)$ - Crack Mouth Opening Displacement (δ) curve of the test, the quasi "pure" Mode I of the fracture energy G_F of concerned heterogeneous materials is classically calculated by means of the equation (1). The energy S_A is obtained from the area under the $F_s - \delta$ curve and S_F from the final fracture area of the specimen.

$$G_F = \frac{S_A}{S_F} \quad (1)$$

Tschegg et al. (2007) [11] used the WST to investigate the bond behavior and crack resistance of asphalt-concrete interfaces. The WST has been used since 1986 until now generally with a rectangular groove or with load transmission pieces placed on the upper surface of the specimen (figure 1a). The WST test has been adapted [10] for specimens extracted from full-scale pavement sections (figure 1b). Cubical shape specimens of important size (compared to the granular maximum size of the materials) are prepared with a cylindrical groove instead of a traditional rectangular groove.

3 The experimental program

In the aim to deep the characterization on the interface bond in UTW composite pavements, bi-layer specimens coming from the field and from the lab are prepared, tested and compared.

The WST specimens are prepared with a semi-circular groove (diameter equal to 56 mm) made by coring [10]. Then, a starter notch of 30 mm in height and 5 mm in width is introduced by sawing. Load transmission pieces, made of steel materials, contain ball bearings in order to minimize the friction forces. The wedge angle is chosen equal to 14° (figure 2a). The interface specimens (of 150mm width) are tested on a testing machine with a load capacity of 2.5 KN, and with a constant cross head speed of 0.7 mm/min. One of the surfaces of the bi-layer specimen is prepared with whiting chalk powder to visualize the crack propagation during the test. Two LVDT sensors (with a measured range of 10 mm and about 0.09 mm of estimating uncertainty) are placed at the end of the starter notch to measure horizontal displacements (figure 3b). LVDT 1 is used to measure the crack opening displacement "δ". The opposite surface of the bi-layer specimen is prepared with a speckled pattern for further DIC analysis (figure 3c).

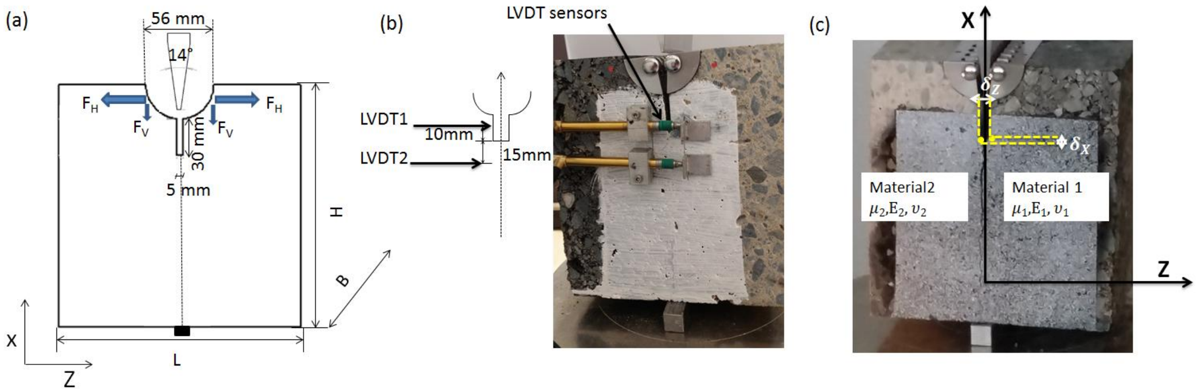

FIG. 2 - The adapted WST test (a) Dimensions of the specimen shape (b) LVDTs (c) DIC

One of the objectives of this work is to study the influence of bonding methodology on the fracture energy. For that purpose, two types of interface treatment of bi-layer composite specimens, both made of a concrete overlay casted directly onto a bituminous material layer, are tested.
Four specimens (noted BE), of the same dimensions of $(L \times H \times B)\ 200 \times 200 \times 150\ mm^3$, are taken from an existing accelerated test section with shot blasted interface treatment [3] [12]. The cement concrete layer (E =32600MPa; υ=0.25) is casted onto a new bituminous material (E =13000MPa at 15°C 10Hz; υ=0.35) layer. Details are given in Table 1.

Tableau 1 Materials characteristic of test specimens

Specimens	Bituminous aggregates size (mm)	Concrete aggregates size (mm)	Concrete air content (%)	Bituminous air content (%)	Water / Cement
BE from [12]	0/14	0/14	4.80	7.0	0.61
1GT from [13]	0/10	0/11	2.33	9.6	0.68

Six other specimens (noted 1GT), four of which have the same dimensions as $202 \times 204 \times 121\ mm^3$ and two others with $120 \times 200 \times 150\ mm^3$, are taken from a laboratory study and do not have specific interface treatment [13]. The cement concrete with elastic modulus of 36000 MPa (υ = 0.25) is casted directly onto the bituminous material (E=13690 MPa at 15°C and 10 Hz; υ = 0.35) previously prefabricated.

4 Results and Discussion

This section gives the main findings obtained from the WST for the different sample types.
As obtained in [13] and illustrated in figure 3, failure observations indicate that a total delamination occurs exactly between layers location. It is observed for all specimens tested even though the cement material has been flowing on top of the bituminous material and whatever its interface treatment is.

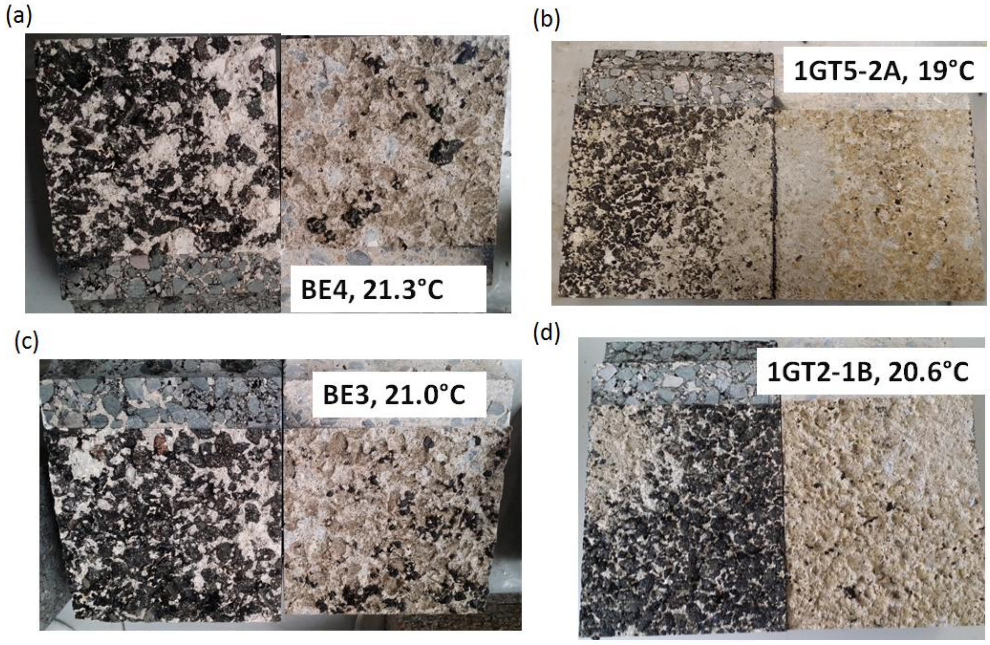

FIG. 3 - Fracture surfaces of tested specimens corresponding to: (a, c) BE materials (b, d) 1GT materials.

Using the LVDT1 sensor (figure 2b), the all $F_S - \delta_{LVDT1}$ curves are given on the same figure 4a. Results are quite dispersed for each type of specimen but a clear difference on the maximum load values is noticed for the two interface treatment types. The maximum loads obtained for BE specimens, with shot blasted interface treatment, are about two times bigger than the ones for 1GT specimens. Figure 3(b, d) shows the lack of residual bituminous material on the cement concrete surface of the delaminated 1GT specimens compared to corresponding BE surfaces may explain its initial poor bond.

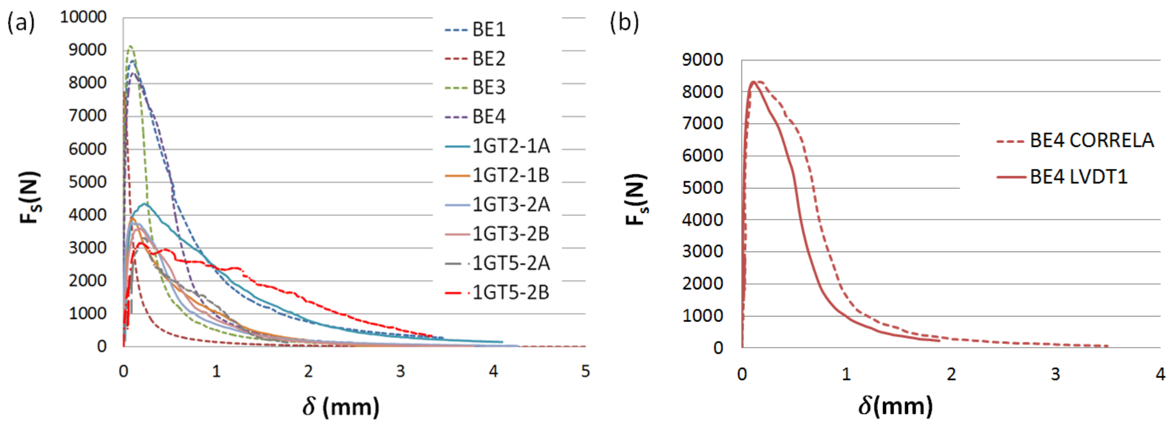

FIG. 4 (a) Load displacement curves (0.7 mm/min, T ≈ 20°C) (b) Example of load – displacement curve obtained by DIC technics compared with LVDT1 measurement on the BE4 specimen

Assuming that the maximum value of the load gives only the initial-point of the interface debonding, the specific fracture energy value G_F is chosen as an indicator of the crack growth resistance of the considered material. The mean values of the G_F and F_{Smax} values obtained using the WST tests are detailed in Table 2. The fracture area S_F is almost the same for all the specimens tested in this study. From figure3 (a, c) it can be seen for BE4 and BE3, which present a high value of the specific energy of 246 J/m^2 and 159 J/m^2 respectively, a more or less homogeneous distribution of bituminous materials in the two surfaces of the interface. However, for the 1GT specimen, figure 3 (b, d) shows the lack of the bituminous material in its different surfaces. That may also explain the good bonding of the shot blasted interface presented in BE specimens and the difference in the fracture energy value.

Table 2 WST's results for tested specimens.

Specimens	T (°C)	S_F (m²)	F_{Smax} (N)	S_A (N.m) LVDT1 → DIC	G_F (J/m^2) LVDT1 → DIC	$G_{Faverage}$ LVDT1(J/m^2)
BE1	20.3		8687	7.23→11	343→543	
BE2	20.3	0.021	7753	1.24	58	201
BE3	21.0		9131	3.39	159	
BE4	21.3		8321	5.25→6.24	246→293	
1GT-3-2A	20.6		3779	2.65	125	
1GT-3-2B	20.7		3601	2.69→3.02	126→168	
1GT-2-1A	20.6	0.018	4346	5.59	263	
1GT-2-1B	20.6		3901	2.74	128	181
1GT5-2A	19.0		3314	2.46	115	
1GT5-2B	20.0	0.017	3151	5.64	327	

In the aim to precise the fracture energy measurement, digital image correlation (DIC) technics are used [14]. The optical measurement is a CCD AVT PIKE F-145C camera (resolution 1388 × 1038 pixels[2]). The region of interest for the calculation of the displacement fields is (769×819 pixles[2]). The subset size 64×64 pixels[2] is chosen with vertical and horizontal gaps of 1 pixel. The horizontal factor scale is about 0.20 mm/pixel. The opening displacement and the sliding displacement of two initially coincident points on the crack surfaces behind the crack tip (figure 4a) are measured and calculated by means of the Correla 2012 software [15]. Figure 4b shows an example of $F_S - \delta_{DIC}$ obtained by DIC technique compared to $F_S - \delta_{LVDT1}$ curve measured for the BE4 specimen. As given in Table 2, the fracture energy value calculated by DIC technics is generally higher than the one obtained by means of LVDT sensor measurements. But the results indicate a high dispersion of the specific fracture energy values. The number of specimens tested is not enough to better understand the all process of delamination of such an interface between layers made of cement concrete casted onto bituminous material.

5. Conclusions

In this paper, the Wedge Splitting Test (WST) is used for the static comparison of debonding at the interface of heterogeneous material layers coming from road and the lab. Several bi-layer specimens made with cement concrete material casted directly onto the bituminous material with two types of interface treatment have been tested at ambient temperature. The experimental study confirms results obtained in [3] [12] that indicate that shot blasted treatments of the interface seem to play a role much more important on the initiation delamination state than during the all propagation process of debonding. Although DIC technics offer interesting possibilities to study the crack initiation and propagation during the WST, the quite high dispersion of the results confirms the necessary for testing in the future at least more than 10 specimens per WST configuration. Displacement fields determined by the DIC technique will be introduced in the elastic model proposed by Dundurs (1969) [16] to calculate the strain energy release rate. In the aim to better understand the bond between bituminous layers in reinforced pavement with grids, as studied in [17-18], other experimental campaigns will be realized by mean of this test to investigate debonding at different testing conditions such as different temperatures, immersion or not in a water bath as described in [19].

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