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# Interlaminar Mode-I Fracture Characterization Underwater of Reinforced Bituminous Specimens

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**Abstract.** In order to investigate the interlaminar mode I fracture behavior of pavements, Wedge Splitting Tests (WST) have been developed for specimens extracted directly from field sections. As part of the French *SolDuGri* project focusing on bituminous pavement reinforced by glass fiber grids, WST are applied under static loads and different climatic conditions. This paper highlights the impact of water on such an interlaminar bond characterization. Results derived from samples of five to ten specimens (unreinforced or reinforced with two types of grids) tested under each type of conditions are reported here. The Digital Image Correlation (DIC) technique has been used herein. Depending on the glass fiber grid used, the observation of fractured interfaces and splitting force-crack mouth opening displacement (CMOD) curves does reveal differences. The presence of water in the bituminous emulsion influences on the dispersion of results depending on some type of interfaces. These interlaminar mode-I fracture characterizations should yield greater insight into results recently obtained from accelerated pavement tests conducted on the IFSTTAR fatigue carousel.

**Keywords:** Fiber grids, Interface, Moisture, Wedge Splitting Test, Digital Image Correlation.

## 1 Introduction

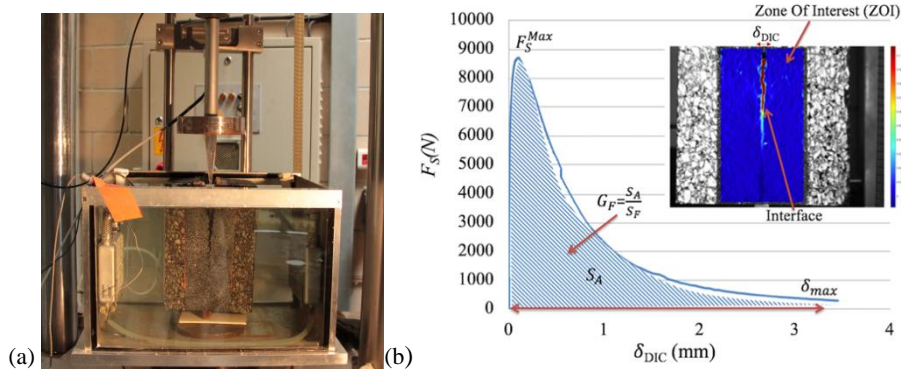
In an effort to delay the reflective cracking propagation phenomenon or to reinforce top bituminous layers, one of the main ideas proposed for roads by the fiber manufacturing industry is to insert grids into bituminous pavement structures [1-3]. The durability of such composite structures depends in part on ensuring a strong bond between grids and bituminous materials. This condition is essential, especially when using grids inside top pavement layers. Along with rolling loads and temperature variations, the presence of water near the interface must be considered in studying debonding mechanisms [4]. To better understand the interlaminar mode I fracture

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behavior of pavements, Wedge Splitting Tests (WST) have been developed, whether underwater or not, for specimens extracted directly from road sections [5-6]. These tests have displayed rather interesting results, in comparison with results obtained on actual pavement test sections. As part of the French *SolDuGri* project (ANR-14-CE22-0019), which examines bituminous pavement reinforced by glass fiber grids [7], WST are applied under static loads and different climatic conditions. Subsequent to works aimed at characterizing the interfacial bond of multilayer composite specimens [8], a water immersion WST was introduced. This paper briefly presents the WST equipment and testing campaigns before giving the main results obtained and then drawing a conclusion.

## 2 Underwater WST and Specimen Characterization

Extracted from *in situ* bituminous sections and in accordance with a RILEM recommendation [4], a large number of specimens differentiated by both type and testing conditions were prepared and assessed [5]. Specimen dimensions were chosen so that the interface dimensions contained a minimum of 3x3 grid meshes [6]. This project's two selected glass fiber grids, denoted G3 and G4 for P6 and P7 specimen types respectively, have a mesh size of  $40 \times 40 \text{ mm}^2$ . Their tensile strength equals  $100 \text{ kN/m}$ , with the two grids differing from each other in the type of coating resins employed (stiffer for G3) [7]. They were glued with a  $500 \text{ g/m}^2$  bitumen emulsion applied on the bituminous material layers ( $E = 11,300 \text{ MPa}$  at  $15^\circ\text{C}$  and  $10 \text{ Hz}$ ;  $\nu = 0.35$ ). Due to the field compaction conditions, the bituminous material displayed average void contents of 4% and 6% below and above of the grid respectively; it was composed, in accordance with French bituminous mix standard NF EN 13108-1, using an aggregate size of 0/10 and 5.6% bitumen of 35/50 penetration grade.



**Fig. 1.** WST: a) Specimen tested under water, b) the 3 indicators of the  $F_S - \delta_{DIC}$  curve

Similarly to Chabot *et al.* [8], an aquarium designed for testing specimens under water was built (Fig. 1a). The specimens were first vacuum-saturated with water at a depressurization of up to  $86 \text{ kPa}$  (15 min in an air box, then 2 h in water). Next, they were stored in a water bath at around  $20^\circ\text{C}$  before being tested under the static

condition of a controlled 2mm/min displacement. Considering " $\alpha$ " (equal to  $7^\circ$  here) as one-half the wedge angle, the splitting load can be written:  $F_S = 2F_H$ ;  $F_H = F_M/2tg(\alpha)$ . During testing, both the Crack Mouth Opening Displacement (CMOD) and crack propagation length were measured by means of the Digital Image Correlation (DIC) technique (Fig. 1b).

From the WST load-displacement curve (splitting load ( $F_S$ ) - CMOD ( $\delta_{DIC}$ )), Fig. 1b), the debonding propagation resistance of the interface is classically obtained by determining the specific fracture energy  $G_F$  given in Eq. 1, i.e.:

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

In Eq. 1,  $S_F$  is the fracture area of the specimen and  $S_A$  the splitting energy calculated from the area under the  $F_S - \delta_{DIC}$  curve (Fig. 2b). From this curve, results depending on the three values of  $F_S$ ,  $G_F$  and  $\delta_{DIC}$  can be compared as follows.

From more than 100 prepared specimens, dedicated to studying the effects of water on the various types of interfaces, fracture debonding mode I tests were conducted first at ambient temperature in air and then under water at around  $20^\circ\text{C}$ . Moreover, in order to obtain information on the temperature effect, the reinforced P7 specimens (i.e. with the G4 grid inserted) were tested under a colder water of around  $7^\circ\text{C}$ . All the testing conditions have been repeated at least ten times. However, some of the first tests performed (not reported here) have been interrupted due to a bad geometry of the samples resulting from the sawing process. Table 1 summarizes the average moisture characteristics of each specimen type and underwater testing condition.

**Table 1.** Moisture characteristics of specimens tested under water.

Specimen name	Test T ( $^\circ\text{C}$ )	Dry mass (g)	Wet mass (g)	Absorbed water volume ( $\text{cm}^3$ )	$S_r$	Immersion time (h)
P8	$\sim 20^\circ\text{C}$	$\sim 15320$	$\sim 15540$	$\sim 157$ (103 to 238)	$\sim 48$ (31 to 71)	$\sim 45$ (26 to 74)
P6 (G3)	$\sim 20^\circ\text{C}$	$\sim 15130$	$\sim 16132$	$\sim 180$ (118 to 250)	$\sim 52$ (37 to 66)	$\sim 26$ (21 to 28)
P7 (G4)	$\sim 20^\circ\text{C}$	$\sim 14550$	$\sim 14680$	$\sim 130$ (103 to 189)	$\sim 43$ (34 to 61)	$\sim 41$ (7 to 96)
P7 (G4)	$\sim 7^\circ\text{C}$	$\sim 14551$	$\sim 14900$	$\sim 133$ (83 to 265)	$\sim 42$ (28 to 83)	$\sim 36$ (18 to 98)

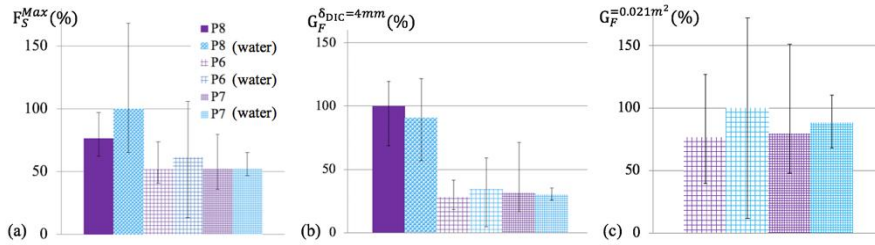
Each specimen was weighed both before and after being saturated with water. Its absorbed water volume could then be evaluated as a function of void content. According to European Standard NF EN 12697-12, the degree of saturation ( $S_r$ ) for each specimen was calculated and reported in Table 1.

### 3 Results and Discussion

Figure 2 summarizes the WST results obtained both in air and under water at around  $20^\circ\text{C}$ . Under these two testing conditions, it is shown that regardless of the grid used to reinforce the bituminous material, i.e. G3 or G4 grid for a P6 or P7 specimen, respectively:

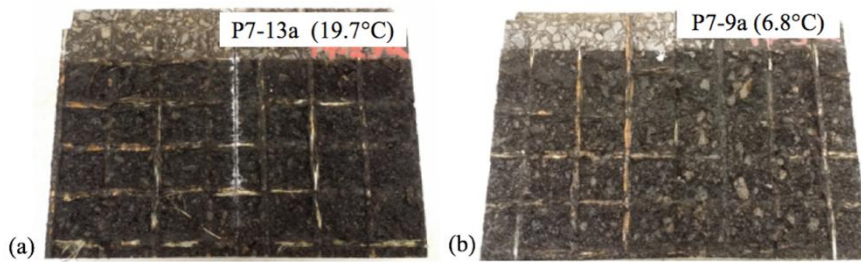
- The maximum bonding value of  $F_S^{Max}$  is smaller for P6 and P7 specimens than for unreinforced P8 specimens, whose value reaches 100% in underwater tests (Fig. 2a);
- The fracture energy  $G_F$  obtained, for the same value of  $\delta_{DIC} = 4mm$ , is reduced for P6 and P7 specimens compared to unreinforced P8 specimens, whose  $G_F$  value reaches 100% in air (Fig. 2b).

These two results lead to concluding that compared to unreinforced P8 specimens, the interfacial bond characteristics of reinforced P6 specimens (with a G3 grid) and reinforced P7 specimens (G4 grid) are reduced by roughly 1/3 relative to the crack initiation process and by 2/3 relative to propagation resistance.



**Fig. 2.** Comparison of results (normalized values): a)  $F_S^{Max}$ , b)  $G_F^{\delta_{DIC}=4mm}$ , c)  $G_F^{0.021m^2}$

The fracture energy  $G_F$  values reported in Figures 2b and 2c, for the same fracture area (i.e.  $S_F = 0.021m^2$ , corresponding to an average crack length of around 0.140 m, as measured by DIC), illustrate that the dispersion in results under water is greater for both P8 specimens and reinforced P6 specimens in comparison with reinforced P7 specimens. Delamination at the interface may have occurred in the tack coat for P8 and P6 specimens, while it clearly occurred in the P7 grid. Figure 3 shows that the G4 grid has broken in all parts of P7 specimen interfaces [5]. This outcome is also observed at 7°C (Fig. 3b).



**Fig. 3.** Fracture surface view of a reinforced P7 specimen tested under water: a) ~20°C, b) ~7°C

From the literature, it has been shown that water and immersion times may exert a negative influence on the interlayer bond. This influence has been demonstrated by means of shear fracture testing at hot temperatures (i.e. 40°C to 60°C) [9] as well as

mixed-mode testing between cement and bituminous materials around 20°C [8]. No clear effect of water has been found here, except on the dispersion of results. However, the dispersion of WST results, for the interfaces between such bituminous materials tested under fracture mode I at 20°C and 7°C, is not due to differences in the limited specimen storage time in water (Table 1). In fact, during the test, the water itself was responsible for altering tack coat strength among all specimens tested under water, except for P7. The G4 grid bonded to the tack coat seems to have altered bitumen resistance by further destroying the adhesion between the granular layer and the bitumen. Moreover, fracture surface observations at low temperature around 7°C (Fig. 3b) highlight this phenomenon to a greater extent than observations at 20°C (Fig. 3a). Indeed, the mode I fracture energy spent for debonding reinforced P7 specimen interfaces at 7°C exceeds that spent at 20°C (Fig. 4).

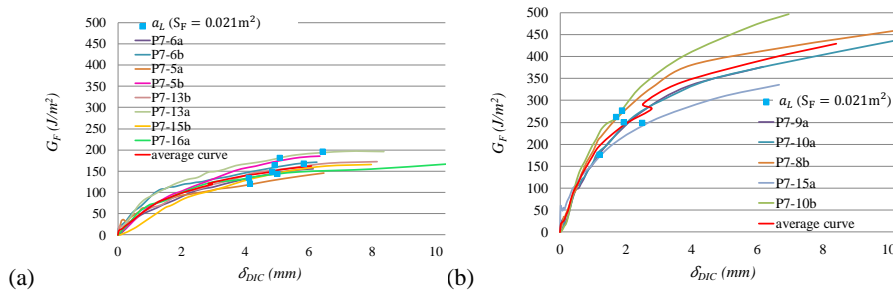


Fig. 4.  $G_F$  results for reinforced P7 specimens tested under water: (a)  $\sim 20^\circ\text{C}$ , (b)  $\sim 7^\circ\text{C}$

## 4 Conclusion

In conjunction with four-point bending fatigue tests and accelerated loading tests (APT) conducted on several pavement structures throughout the course of the French *SolDuGri* project (ANR-14-CE22-0019) [10], the WST has been developed specifically for specimens extracted from road sections [5-6]. This approach has led to experimentally characterizing the Interlaminar Mode-I Fracture of the interlayer bond of pavement reinforced with fiberglass grids. To investigate the effect of moisture on the interlayer bond, a water immersion WST has also been proposed. In this paper, the WST campaigns were carried out in air and under water. The final fracture surface observations and the splitting force-CMOD curve results for 3 types of specimens have been presented. Two types of grids, denoted G3 and G4, were used; they only differ from each other in the coating resins applied. The resin used for the G3 grid is stiffer than the one used for the G4 grid [7]. Compared to the WST results of unreinforced specimens, the bond between bituminous layers when adding these two grids is reduced for both by roughly 1/3 relative to crack initiation and by 2/3 relative to propagation resistance. At 20°C, the presence of water in the materials exerts an influence on the dispersion of all results, except for specimens reinforced with the G4 grid. For the G4 grid, WST results under water at two temperatures (7°C and 20°C)

illustrate the thermal effect on bonding behavior; also, it was shown that the G4 grid does indeed adhere to the bituminous material. The fracture mechanisms are localized inside the G4 grid itself and on the bond between aggregates and tack coat bitumen emulsion. This laboratory study yields greater understanding of some of the poor interface bond results obtained recently in the field during the APT campaign.

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