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# Multi-parametric characterization of mode I fracture toughness of asphalt concrete: Influence of void and RA contents, binder and aggregate types

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## Abstract

This study aims to evaluate the fracture toughness ( $K_{Ic}$ ) in mode I cracking using semi-circular bending test (SCB). Experiment has been performed to investigate the influence of bitumen grade (using P15/25 and P50/70 bitumens), reclaimed asphalt (RA) content (using 0%, 20% and 40% RA contents) and temperature (using  $-20\text{ }^{\circ}\text{C}$ ,  $-5\text{ }^{\circ}\text{C}$ ,  $10\text{ }^{\circ}\text{C}$  test temperatures), through ANOVA. Additional investigations have been performed: (i) to evaluate the effect of the use of polymer modified bitumen (PMB), (ii) to evaluate the effect compactness using 5% and 8% air void contents, (iii) to evaluate the effect of aggregate type using siliceous-limestone and porphyry aggregates. The results show an important decrease in  $K_{Ic}$  when temperature increases from  $-5\text{ }^{\circ}\text{C}$  to  $10\text{ }^{\circ}\text{C}$  and a slight decrease between  $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$ . The results also show that increasing RA content increases slightly the  $K_{Ic}$ . It was found from the ANOVA that the influent parameters can be ranked as follows: temperature, RA content and binder grade. The investigations show that PMB increases the  $K_{Ic}$  value than pure bitumens. Porphyry aggregates increase the  $K_{Ic}$  by about 16% than silica-limestone aggregates at low temperatures between  $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$ . However, this ranking is slightly inverted at  $10\text{ }^{\circ}\text{C}$ . In addition,  $K_{Ic}$  decreases by about 12% at  $10\text{ }^{\circ}\text{C}$  with an increase in air voids (by 5% to 8%). Void content effect is more significant at  $-5\text{ }^{\circ}\text{C}$  and  $10\text{ }^{\circ}\text{C}$ , and negligible at  $-20\text{ }^{\circ}\text{C}$ .

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**Keywords:** Fracture toughness; SCB; Bituminous mixture; Reclaimed asphalt

## 1. Introduction

Cracking is one of the factors inducing early deterioration of the asphalt pavement structures in cold regions. It is caused by the combination of mechanical loads and climatic factors such as temperature cycles, freeze-thaw cycles and water infiltration. Cracking is a phenomenon which

occurs in two steps: the initiation of microcracks and their propagation. Microcracks initiation has several causes: thermal shrinkage, joints cracking, fatigue, debonding, poor laying of mixtures, differential swelling of sub-base soils due to freeze. Traditionally, thermal cracking can be reduced using soft asphalt. This approach which gained successful results reaches its limits due to the use of hard bitumen to support the heavy weight traffic increasing and the use of reclaimed asphalt (RA) [1]. Moreover, because of the climate changes and the potential increase of temperature, the use of soft bitumen becomes

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### Nomenclature

a	crack length, mm	$P$	class of penetration, 0.1 mm
B	specimen thickness, mm	RA	reclaimed asphalt
D	specimen diameter, mm	SBS	Styrene-Butadiene-Styrene
e	notch width, mm	T	temperature, °C
$F$	load, N	$T_{RB}$	softening temperature, °C
$F_{max}$	maximum load, N	u	displacement, mm
$f\left(\frac{a}{w}\right)$	dimensionless geometrical factor	w	specimen width, mm
$f^*\left(\frac{a}{w}\right)$	geometrical factor, $m^{1/2}$	<i>Greek symbols</i>	
$K_{IC}$	critical stress intensity factor, $N \cdot mm^{-3/2}$	$\alpha, \beta$	proportion of fresh and recover binder
LA	Los Angeles abrasion test, %	$\sigma$	stress, MPa
MDE	Microdeval abrasion test, %	$\sigma_{max}$	maximum stress, MPa
p	percentage of RA, %		
PMB	polymer modified bitumen		

inappropriate because of the risk of rutting [2]. Furthermore, the deteriorations that occurred on the national roadways in France during the cold winters in 2009–2010 and 2010–2011, proved the fragility of road networks and the limits of the historical test methods (water sensitivity, permanent deformation, stiffness modulus, fatigue) [3,4]. Among the factors identified as potential root causes, there are: cracking due to freeze–thaw cycles, debonding, water sensitivity and the frequency of temperature cycles around 0 °C [3][5]. One way to improve pavement structures durability consists of a better selection of the constituents to prevent early cracking in winter periods.

Three test methods are commonly used to characterize fracture toughness of bituminous mixes: the semi-circular bend (SCB) historically used for rocks materials [6–9], the single-edge notched beam (SENB) [10,11] and the disk-shaped compact tension (DCT) tests. The two first methods are versatile, they have been used to evaluate the mode I and mixed modes I/II and I/III fracture toughness by several authors [12–15].

Numerous investigations have been performed on the experimental level to evaluate the effect of mixes' formulation on the fracture toughness. Aliha et al. [16] carried out investigations in mixed mode I/II to evaluate the effect of SBS modifier. They found that SBS modifier improves fracture toughness of the mixes. They also investigated the influence of mixes compactness on the fracture toughness. They found that increasing the air void content by 3% to 7%, decreases the mixed mode I/II fracture toughness. The influence of the binder content has been studied by Biligiri et al. [17] considering 4.4% and 5.4% binder content. Their investigations have been performed on very dense mixes containing 1% and 2% air void content. They found that increasing the binder content decreases the fracture toughness. A comparative study between granite and limestone aggregates has been reported by Li et al. [18]. They showed that granite aggregates increase the fracture

peak than limestone aggregates. Their conclusions regarding the influence of void content and modifier are consistent with the results obtained by Aliha et al. [16]. The effect of the bitumen grade on the fracture toughness has been also investigated by Li et al. [18]. According to their conclusion, soft bitumen (PG 58) leads to lower fracture peak than hard bitumen (PG 64). Recently, Saha et al. [19] investigated the effect of binder content, void content, temperature and specimens' thicknesses and provided a relationship between the fracture toughness  $K_{IC}$  and these parameters.

Unlike the previous works whose results are globally consistent, the investigations performed to quantify RA content influence lead to contradictory results. Shu et al. [20] shows that increasing RA content increases the tensile strength and decreases the post-failure tenacity, so the J-integral decreases and therefore the cracking resistance of the mixes. Their results have been confirmed by Aurangzeb et al. [21], while Huang et al. [22] and Tang [23] reported contrary results. According to Tang [23] the fracture toughness performed on asphalt mixes containing 30, 40 and 50% RA content reveals the ranking list changes with varying temperatures. None of the asphalt mixtures evaluated in his research preserves its own advantage for the entire temperature range from –30 to –10 °C.

The influence of the SCB specimen size has been investigated by Molenaar [24] and Saha et al. [25]. Their studies allow to define the dimensions of the SCB specimen permitting to fulfill the plane strain conditions and to consider the measured fracture toughness as a material property. They provided a set of size effect conditions to be fulfilled and the dimensions (width, crack length) for the classical specimen diameters (100 mm, 150 mm, 225 mm).

The influence of temperature and loading rate on the fracture energy have been investigated by several authors [24]. Their results are consistent and tend to confirm that increasing the loading rate or reducing the test temperature

increases the fracture toughness. Moreover, Molenaar [24] and NGuyen [11] respectively showed that the time-temperature superposition principle (TTSP) used to characterize the linear viscoelastic behavior of mixes is still valid for the mode I crack propagation.

This study aims to evaluate the influence of porphyry and silica-limestone aggregates on the fracture toughness of bituminous mixes. It also aims to provide additional experimental data to the literature regarding the influence of: (i) PMB modified bitumen, (ii) bitumen grade, temperature, reclaimed asphalt (RA) and void content. This study falls within the framework of post-normative research conducted to evaluate the relevance of the new European standards, therefore, the experiment is carried out in accordance with the standard EN 12697-44 published in 2010 [8].

This paper is organized as follows:

- the first part shortly describes the theoretical basis of the determination of the fracture toughness for semi-circular bending (SCB) test,
- the second part focuses on the description of the constituent materials, their characterization and the preparation of the specimens for the test,
- the last part is devoted to the experiment and the results discussion.

## 2. Fracture toughness of SCB samples

Since a decade, SCB test has drawn more and more attention in the asphalt pavement community [26]. It consists of two supporting rollers at the straight (bottom) edge and a loading roller at the mid-point of the semi-circular arch as shown on Fig. 1. These rollers are schematized by simple supports. They allow to limit frictions. The spacing between the two supports is variable even if the common value is  $0.8 \times D$  (where  $D$  is the specimen diameter).

Monotonic load is applied through the loading strip during a SCB test. This loading induces a traction stress at the straight bottom edge of the specimen which maximum is located in the middle as presented in Fig. 1. In contrast to the SENB geometry, no exact relation of this maximum stress can be obtained for the SCB geometry. However, some approximate relations are given in Refs. [8,22,25,33].

Van de Ven et al. [28] showed that the bending tensile strength (BTS) of un-notched SCB specimen is given by  $BTS = k \times \frac{P_{max}}{BD}$ , where  $k$  is a constant factor  $k = 4.263$  for a support span of  $0.8D$ . This constant  $k$  can be obtained through 3D FEM analysis of the SCB test by considering a support span of  $0.8D$  and specimen thickness  $B = 1$  m. This constant is the product of the maximum stress at the middle of the bottom surface times the bottom surface ( $B \times D$ ) and divided by the applied force,  $k = \frac{\sigma_{max}}{F_{max}} \times BD$ . Then, it comes out:

$$\sigma_{max} = 4.263 \frac{F_{max}}{B \times D} \quad (1)$$

where  $F_{max}$  is the maximum applied force,  $D$  is the specimen diameter and  $B$  the specimen thickness.

This relation is obtained under plain strain hypothesis. Eq. (1) will be used in this study to evaluate the maximum stress. Therefore, the fracture toughness  $K_I$  can be calculated through the following relationships proposed by Rooij et al. [29] and Jacobs et al. [30]:

$$K_I = \sigma_{max} \times f^* \left( \frac{a}{w} \right) \quad (2)$$

where  $f^* \left( \frac{a}{w} \right) \propto \sqrt{\pi a} \times f \left( \frac{a}{w} \right)$  and

$$f^* \left( \frac{a}{w} \right) = -4.9965 + 155.58 \left( \frac{a}{w} \right) - 799.94 \left( \frac{a}{w} \right)^2 + 2141.9 \left( \frac{a}{w} \right)^3 - 2709.1 \left( \frac{a}{w} \right)^4 + 1398.6 \left( \frac{a}{w} \right)^5 \quad (3)$$

where  $a$  is the notch depth,  $w$  is the specimen radius.  $f^* \left( \frac{a}{w} \right)$  is a geometrical factor determined by FEM analysis. Note

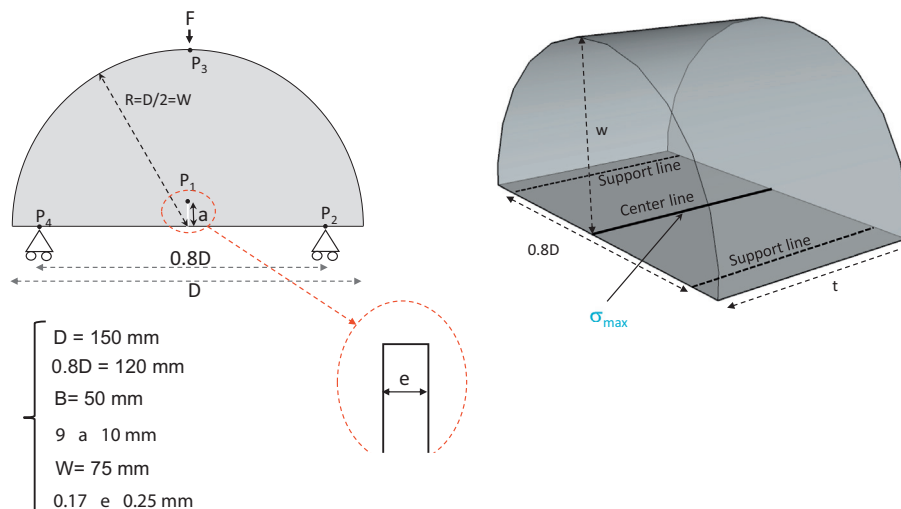


Fig. 1. Geometry of SCB specimen.

that  $f^*(\frac{a}{w})$  is expressed in  $mm^{1/2}$ . This geometrical factor is better adjusted for a very narrow range of crack depth  $a$  ( $9 \leq a \leq 11$  mm) and a support span of  $0.8D$ . Others relations have been published elsewhere for several support span distances or for plane stress conditions [26,27,31–34].

### 3. Materials and mix design

#### 3.1. Aggregates

The present study has been carried out using two different aggregates widely used in France for bituminous mixes production: porphyry and silica-limestone. To our knowledge their cracking ability has never been investigated in the literature even if they have been widely used for road construction in cold regions (in the middle and in the east of France). The porphyry aggregates came from the “pont de colonne” quarry in Bourgogne region in the middle of France. Their Los Angeles (LA) and Microdeval (MDE) properties are respectively 17% and 8%. The silica-limestone aggregates came from Alsace region in the East of France. The LA and MDE properties of silica-limestone aggregates are respectively 20% and 10%. These properties show that porphyry aggregates are more resistant to abrasion than silica-limestone aggregates. The aggregates consist of several fractions 0/2, 2/6.3 and 6.3/10. The mixture composition is given in Table 1.

#### 3.2. Bitumens

Three types of bitumen have been selected for this study: hard bitumens (complying with NF EN 13924-1), paving grade bitumens (specified in EN 12591) and SBS-PMB (specified in EN 14023). SBS (Styrene-Butadiene-Styrene) polymer has been used to modify bitumen. These bitumens have been selected to investigate the cracking ability of hard bitumens, common paving grade bitumens. Also, this study allows to evaluate the potential effect of SBS commonly used to modify bitumen in order to improve its viscoelastic properties. Table 2 gives the conventional properties' penetration and softening point of the binders. The paving grade bitumens consist of P50/70 bitumen. Soft bitumens P70/100 and P160/220 have been used as a fresh binder to produce reclaimed asphalt mixes. 5.4% binder content has been used to produce the asphalt mixes.

#### 3.3. Reclaimed asphalt

The RA used in this study was obtained from a motorway pavement in Alsace region (highway realignment in

Table 1  
Composition of the mixture.

Material	Bitumen	Aggregate			
		Filler	0/2	2/6.3	6.3/10
Percentage	5.4%	2.8%	26.1%	23.7%	42%

Sélestat), by milling the thickness of the pavement corresponding to a single layer (surface course) in order to obtain a homogeneous material. After two decades in service, the pavement has been milled and thus the RA binder is supposed to be very hard after being exposed to long term aging. The RA bitumen (also called recover binder) has a penetration of 13 (in 0.1 mm) and  $T_{RB}$  of 66.80 °C. 0%, 20% and 40% RA contents have been investigated. The mixture rule has been used to estimate the penetration and the softening temperature of the final binder [35]:

$$\alpha \log(P_1) + \beta \log(P_2) = (\alpha + \beta) \log(P_{binder}) \quad (4)$$

$$(T_{RB})_{binder} = \alpha(T_{RB})_1 + \beta(T_{RB})_2 \quad (5)$$

where  $\alpha + \beta = 1$ ,  $\alpha$  and  $\beta$  are the fresh binder (1) and the recover binder (2) percentages in the final binder.  $P_1$  and  $P_2$  are respectively the penetrations of fresh and recover binders and  $T_{RB_1}$  and  $T_{RB_2}$  their softening points respectively.

#### 3.4. Specimen preparation

The bituminous mixes have been manufactured in accordance with the standard EN 12697-35 which defines the mixing temperature based on the bitumen grade. For mixes produced with RA, the fresh aggregates have been overheated in accordance with Eq. (6) so that the mixing temperature fulfills the requirements defined in the standard EN 12697-35, RA temperature ( $T_{RA}$ ) being imposed to 110 °C to limit recover bitumen aging

$$T_{Aggregates} = \frac{100 \times T_{mixture} - p \times T_{RA}}{100 - p} \quad (6)$$

“p” is the RA percentage in the final mixture (considered to be 0%, 20% or 40% in this study).

Nine asphalt mixes have been manufactured to evaluate the influence of RA content (0%, 20% and 40%), bitumen grade (P15/25, P50/70), aggregate type (porphyry, silica-limestone), SBS-PMB and void content (5%, 8%) (see Table 3). Each mixture manufactured is compacted into three cylindrical specimens with gyratory compactor to get cylindrical specimens with 150 mm diameter, each specimen is sawed into four semi-circular samples. Each semi-circular specimen has been grooved with an ultra thin blade which has 0.16 mm thickness. This thinner groove is expected to improve the repeatability by limiting the crack bifurcation and ensuring mode I crack propagation. Each notch has approximately 10 mm depth. The real depths, thicknesses and the tilting angles of the grooves have been measured by WERTH optical apparatus which has a optical magnification  $\times 20$  (see Fig. 2). Specimens are rejected if one of the four following geometrical criteria is not satisfied: (i) the mean tilting angle measured according to the flat surface is greater than 3°, (ii) the mean depth “a” is out of the interval [9, 11] mm, (iii) the mean width “w” is out of the interval [74.5, 75.5], (iv) the mean thickness “B” is out of the interval [49.5, 50.5] mm. For all the



Table 2  
Binder properties.

Binder	Class	Penetration (in 0.1 mm)	Softening point $T_{RB}$ (in °C)
Hard bitumen	P15/25	20	67.60
Paving grade bitumen	P50/70	58.1	49.65
Polymer modified bitumen	PMB25/55-60	40	62

Table 3  
Experimental design.

main experiments					
Mix	Binder	Aggregate	RA content (%)	Binder content (%)	Void content (%)
AC1	P15/25 Bit.		0	5.4	8
AC2	P15/25 Bit.	porphyry	20	5.4	8
AC3	P15/25 Bit.		40	5.4	8
AC4	P50/70 Bit.		0	5.4	8
AC5	P50/70 Bit.	porphyry	20	5.4	8
AC6	P50/70 Bit.		40	5.4	8
Additional experiments					
AC7	P50/70 Bit.	porphyry	0	5.4	5
AC8	P50/70 PmB	porphyry	0	5.4	8
AC9	P50/70 Bit.	silica-limestone	0	5.4	8



Fig. 2. Manufactured specimens.

specimens prepared, the notches' widths  $e$  are between 0.17 mm and 0.25 mm. These notches are very narrow than the 0.35 mm required by the european standard EN 12697-44. Other authors used thick saws which have 0.4 mm to 3 mm thickness, greater than the thickness specified in the standard EN 12697-44 (0.4 mm in [14,16]) (0.6 mm in Ref. [36]) (2 mm in Ref. [18]), (3.175 mm in Ref. [37]). 2 mm thick metallic plates have been glued on the bottom surface of the specimens at the areas of the two lower supports in order to avoid punching effect. The semi-circular specimens and the optical system for the measurement of the tilting angle and the crack depth and width, are shown in Fig. 2.

#### 4. Experimental principle

Before testing, two specimens are chosen, drilled and equipped with thermal sensors. The equipped specimens and the others (to be tested) are introduced into the climatic chamber at the same time, this allows to record the

core temperature evolution in the samples. The core temperature kinetics are presented in Fig. 3. When the core temperature in the two equipped specimens reaches the desired temperature plateau, specimen to be tested is taken out of the climatic chamber for starting the experiment. Then, as indicated in the standard EN 12697-44, the SCB test is carried out rapidly. At the end of each test series, the equipped specimens are removed from the climatic chamber. The next specimens' series are introduced into the climatic chamber when the equipped specimen reaches ambient temperature. The duration from the specimen removal (from the climatic chamber) to its testing until failure is shorter than one minute. A constant displacement rate of 5 mm/min is applied during the mechanical test. The test has been carried out at two temperatures (10 °C and -20 °C). The resulting force  $F$  and displacement  $u$  are recorded during the test. Fig. 3(c) shows the evolution of the recorded force versus the displacement for specimens tested at -20 °C and 10 °C. For each mixture, at least three

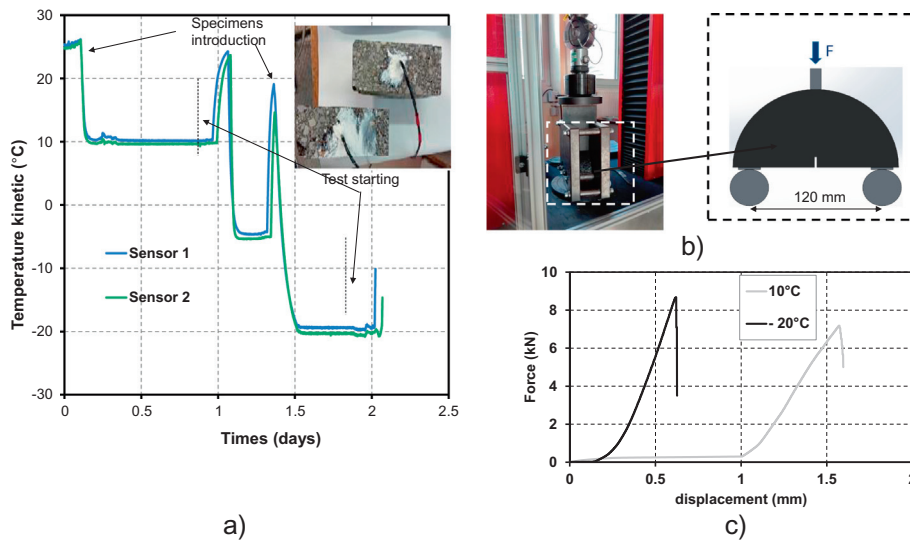


Fig. 3. Experimental setup and example of data recorded.

semi-circular samples have been used to evaluate the average fracture toughness.

**5. Results and discussion**

Test results are presented in two steps. In the first step, only the influence of bitumen grade, temperature and RA content is discussed based on full factorial design. The second step deals with the investigation of the influence of the additional parameters (aggregate types, void content and PMB).

*5.1. Full factorial plan results analysis*

Specimens have been prepared with hard bitumen (P15/25) and paving grade bitumen (P50/70). 0%, 20% and 40% RA contents have been considered and the tests have been performed at low and intermediate temperatures

–20 °C, –5° and 10 °C. The response surface has been represented to provide a better comprehension of  $K_{IC}$  evolution by consolidating the simultaneous response of the parameters. Fig. 4(a), (b) and (c) illustrate the consolidated effect of RA content in conjunction with binder grade and temperature respectively on the fracture toughness. The real penetration values of P15/25 and P50/70 given in Table 2 have been used to represent the surface response.

Fig. 4(a) shows that increasing RA content increases the fracture toughness. Indeed, increasing RA content could lead to poor cohesion between the fresh and the old binder. However, in the case of good miscibility between the binders, the stiffness of final binder could increase due to the addition reclaimed asphalt hard binder. As shown by Huang et al. [22], the increase in stiffness modulus induces an increase in fracture peak which is directly linked to the fracture toughness. The increase in RA content from 0% to 40% increases the fracture toughness by approximately

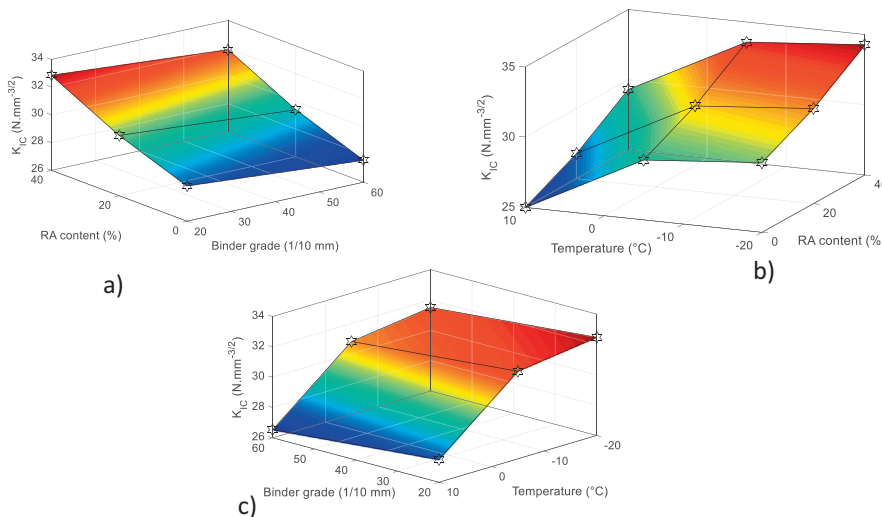


Fig. 4.  $K_{IC}$  Surface response according to the studied parameters.

15% whatever the test temperature. Also, it can be seen that the fracture toughness of hard binder P15/25 is slightly higher than the soft binder P50/70 fracture toughness. This observation is consistent with the results expected since hard bitumen are stiffer than soft bitumen, therefore the fracture toughness should increase according the increase in the stiffness. The decrease in the fracture toughness is about 3% between P15/25 and P50/70 bitumens whatever the test temperature. From the results presented in 4(a) it can be seen that the influence of binder grade is less pronounced than the RA content effect.

Fig. 4(b) shows that between  $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$ ,  $K_{IC}$  decreases slightly while, between  $-5\text{ }^{\circ}\text{C}$  and  $10\text{ }^{\circ}\text{C}$  this decrease is more important whatever the RA content. It shows a quasi-plateau of the  $K_{IC}$  between  $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$  and an abrupt decrease for temperatures higher than  $-5\text{ }^{\circ}\text{C}$ . Therefore,  $K_{IC}$  does not depend linearly on the temperature. It has been observed that at lowest temperatures ( $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$ ) crack propagates through the mastic and aggregates, then  $K_{IC}$  is probably dependent to aggregate and mastic properties. At lowest test temperatures the properties of the mastic should tend to be constant because of the elastic behavior of the mastic and the aggregates. At  $10\text{ }^{\circ}\text{C}$  crack propagates through the mastic which is more dependent to the test temperature because of the viscoelastic behavior of the mastic. Therefore, the decrease in the fracture toughness could be explained by the decrease in the specimen stiffness and specially the decrease in the mastic stiffness when temperature increases. This dependency of  $K_{IC}$  to the temperature reveals a viscoelastic behavior which needs to be taken into account in future studies. Furthermore, from Fig. 5, it can be seen that at  $-20\text{ }^{\circ}\text{C}$ , crack propagates in straight path irrespective of the presence of aggregates, whereas, at  $10\text{ }^{\circ}\text{C}$ , cracks skirt the aggregate and propagate through the softer mastic.

Fig. 4(c) confirms the previous observations. The weak influent of binder grade is represented by a quasi-plateau

between  $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$  while the rapid decrease in  $K_{IC}$  is observed between  $-5\text{ }^{\circ}\text{C}$  and  $10\text{ }^{\circ}\text{C}$  due to the viscous effects.

Figs. 4(a), (b) and (c) show that temperature and RA content are the most influent parameters.

### 5.1.1. Statistical interpretation

The influence of the parameters used in the factorial plan (temperature, RA content and bitumen grade) has been evaluated. These parameter effects are presented in Fig. 6(a) and the level of significance in Fig. 6(b). The horizontal line in Fig. 6(a) corresponds to the mean fracture toughness  $K_{IC} = 30.10\text{ N}\cdot\text{mm}^{-3/2}$ . Fig. 6(a) shows that temperature, RA content and the interaction of binder grade and temperature have great effects on the fracture toughness. To evaluate if the variabilities of the studied parameters are significant or not, the significance level is presented in Fig. 6(b) in conjunction with the results of each parameter. Each parameter effect is considered significant if its significance level is at least equal to the threshold value given by the Fisher Snedecor value presented in Fig. 6(b). The value of Fisher Snedecor statistic has been computed with R software for a probability of 95%. Conclusion regarding the influence of a parameter is considered to be valid if the significance level reaches the threshold value, for a given probability. It can be concluded that temperature, RA content and the interaction of binder grade and temperature are the most influent parameters. The influence of binder grade effect is negligible compared to the others. Therefore, the following model can be used to estimate the experimental results:

$$K_{IC}^{mod} = \alpha_0 + \alpha_1[RA] + \alpha_2[T] + \alpha_3[RA.T] \quad (7)$$

$$\text{where } \alpha_0 = 30.10, \quad \alpha_1 = [-2.04; -0.23; 2.27],$$

$$\alpha_2 = [-1.89; 1.19; -3.08], \quad \alpha_3 = \begin{bmatrix} 0.20 & -0.59 & 0.39 \\ 0.26 & -0.5 & 0.25 \\ -0.46 & 1.09 & -0.63 \end{bmatrix}.$$

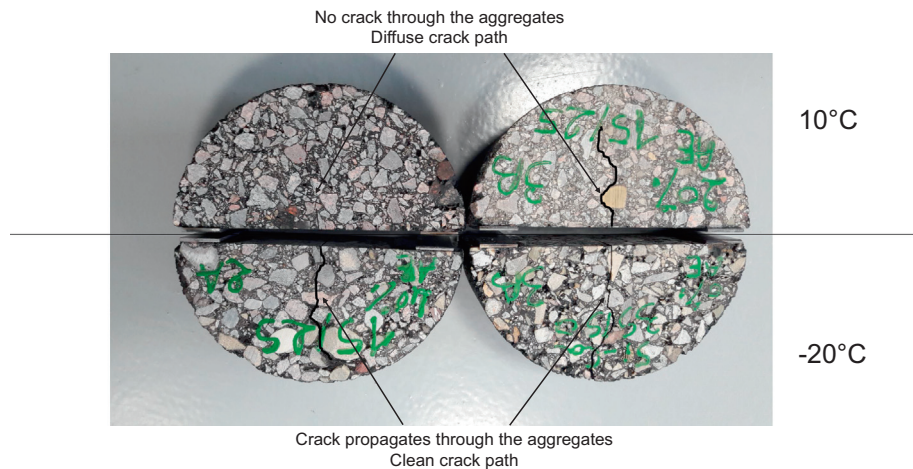


Fig. 5. View of the crack propagation through the specimens.



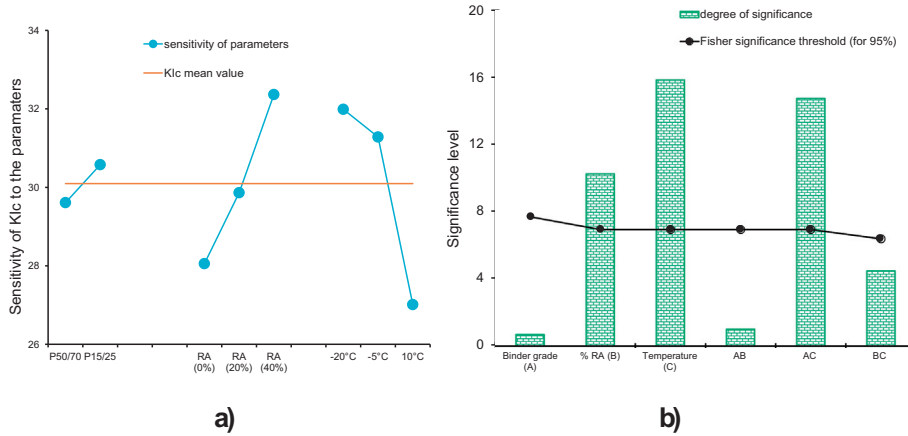


Fig. 6. Influence of parameters (a) and significance level (b).

[RA] is the reclaimed asphalt content vector  $\{0\%; 20\%; 40\%\}$  and [T] the temperature vector  $\{-20\text{ }^\circ\text{C}; -5\text{ }^\circ\text{C}; 10\text{ }^\circ\text{C}\}$ .

The comparison between the experimental results and the estimations is given in Fig. 7. These results show a good estimation of the fracture toughness.

## 5.2. Influence of additional parameters

### 5.2.1. Influence of SBS-modifier

Polymers are often used to improve rheological properties of bituminous binders and mixes. In this section, the influence of polymer addition into the bitumen is investigated using SBS polymer. SBS-PMB 25/55-60 binder has been prepared by mixing 5% SBS and bitumen. The fracture toughness of the mix produced with this binder has been evaluated and compared to the fracture toughness obtained with pure bitumens. This comparison is presented in Fig. 8. It shows that SBS polymer tends to increase by 10% the fracture toughness of the mix produced with P15/25 bitumen and by 15% the fracture toughness of P50/70 mixes. It is known that SBS polymer increases the stiffness of the binders. Thus, the increase in binder stiffness leads to an increase in fracture toughness. As shown by Aliha et al. [16] the classical modifiers (Sasobit, poly

phosphoric acid, crumb rubber) increase the binder stiffness and therefore the fracture toughness of these mixes.

### 5.2.2. Influence of aggregate type

Two types of aggregates are considered to evaluate the effect of aggregate types: porphyry and silica-limestone, all other factors being constant. P50/70 bitumen has been used to produce the mixes. The fracture toughness has been characterized and represented on Fig. 9(a). It can be observed that at low temperatures, mixes produced with porphyry aggregates have higher fracture toughness than those manufactured with siliceous-limestone aggregates. However, this observation changes at 10 °C. The difference observed at low temperature can be explained by the crack propagation through the aggregates. Indeed, the LA and MDE values given in Section 3.1 indicate that the porphyry aggregates are more resistant to abrasion than siliceous-limestone aggregates, therefore, crack can easily propagate through the silica-limestone aggregates than porphyry aggregates. These results are consistent with the fracture toughness of the constituent materials given by the suppliers. Indeed, the fracture toughness of the porphyry aggregate is  $54\text{ N}\cdot\text{mm}^{-3/2}$  while silica-limestone aggregate

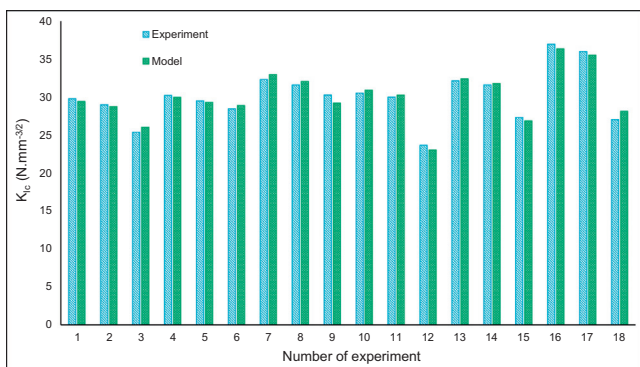


Fig. 7. Comparison between the experiment and the model.

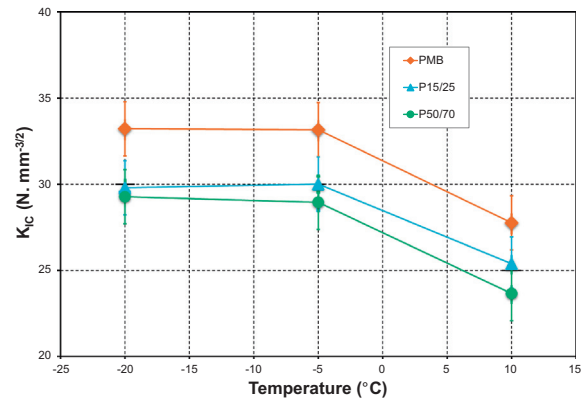


Fig. 8. Influence of temperature and bitumen grade or PMB on the evolution of  $K_{IC}$ .

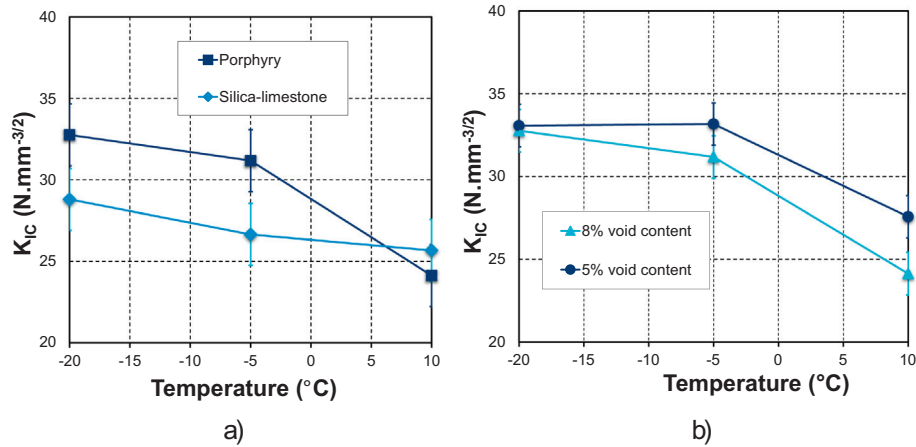


Fig. 9. Influence of aggregate type and void content.

fracture toughness is  $47 \text{ N} \cdot \text{mm}^{-3/2}$ . Since the same bitumen has been used to produce the mixes, one concludes that the fracture toughness of these latter ones follows the ranking of the fracture toughness of the aggregates.

At  $10^{\circ}\text{C}$  the fracture occurs mainly through the mastic and at the interfaces. However, during the experiment, a higher amount of porphyry aggregate specimens in which the crack propagates through the mastic and at the binder–aggregate interfaces was noted. This induces a slight decrease in the mean fracture toughness. Since, siliceous-limestone aggregates are known to have better adhesion to binder than porphyry aggregates, this could explain the higher fracture toughness obtained at  $10^{\circ}\text{C}$  with siliceous-limestone aggregates compared to porphyry aggregates.

### 5.2.3. Influence of void content

Two sets of specimens containing respectively 5% and 8% void content have been manufactured to evaluate the influence of void contents, all other parameters being constant. The fracture toughnesses have been evaluated and are presented in Fig. 9(b). These results show that the fracture toughness decreases when the void content increases. For porous specimens, the decrease in the fracture toughness is linked to the presence of voids which can favor the crack propagation or by the increase in stress concentration near the void tips which can facilitate cracking. The presence of air voids could significantly accelerate the crack propagation because of the interconnections between the air voids. The increase in the fracture toughness for dense specimens has been previously observed by Aliha et al. [16] for mixte mode I/II cracking and by Harvey et al. [38] for fatigue test. They pointed out that low void content creates a more homogeneous specimen (with better void distribution), reducing stress concentration, therefore more energy is required to break more compacted asphalt specimens.

## 6. Summary, conclusion and future extensions

The main objective of this study was to investigate the fracture toughness of bituminous mixes in the temperature range between  $-20^{\circ}\text{C}$  and  $10^{\circ}\text{C}$ . In this study, the fracture toughness  $K_{Ic}$  has been considered as the key parameter characterizing the cracking resistance of the mixes. The new investigation provided by this study is the evaluation of the effect of porphyry and silica-limestone aggregates on the fracture properties. These aggregates are widely used in cold regions (middle and east part in France) however their cracking resistance has never been evaluated. Even if the effect of RA on the fracture toughness has been already studied by several authors, the use of RA in hard bitumen never been studied to our knowledge. This study also evaluates the influences of bitumen grade, void content and PMB on the fracture properties of asphalt mixes. The results obtained lead to the following conclusions:

- At low temperatures, mixes with porphyry aggregates have higher fracture resistance than those containing silica-limestone aggregates. These results are consistent with the aggregates' mechanical properties. Since porphyry aggregates have lower LA and MDE values than silica-limestone aggregates, therefore it can be expected that crack will propagate more easily through silica-limestone aggregates than through porphyry aggregates. In addition, at low temperatures, crack propagates through the aggregates whereas at  $10^{\circ}\text{C}$ , it mainly propagates through the mastic.
- The comparison of mixes containing 5% and 8% of void content shows that dense specimens are more resistant to crack propagation than porous specimens.
- It is found that the fracture toughness obtained with Styrene-Butadiene-Styrene PMB binder is higher than the fracture toughness obtained with P15/25 and P50/70 bitumens.

- The results obtained also indicate that increasing RA content by 0% to 40% decreases slightly the fracture toughness. In addition, fracture toughness decreases very slightly between  $-20\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$  and decreases highly between  $-5\text{ }^{\circ}\text{C}$  and  $10\text{ }^{\circ}\text{C}$ .
- Future scope: Even though the study investigated mode-I fracture resistance using static SCB test, a similar experiment can also be conducted in mixed mode. Numerical study can be achieved to take into account the heterogeneities of the specimens.

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