Evaluation of aggregate size-dependent of asphalt mixtures in cracking behavior

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Synopsis

This paper focuses on the evaluation of aggregate size effect in the cracking behaviour of asphalt mixtures. The research was undertaken using both experimental and numerical approaches; actually experimental results were fundamental to an optimize improvement of numerical analysis in order to evaluate in details the aggregate size dependent of mixtures in the cracking behaviour. The experimental section based on Indirect Tensile Tests (IDT) and Semi-Circular bending tests (SCB) performed on different fine-graded mixtures bounded with the same mastic. The numerical investigation based on the use of a displacement discontinuity boundary element method (DDM) modelling the specimens by means of a 2-D version of the program DIGS (*Discontinuity Interaction and Growth Simulation)* which patterns the micromechanical structure of the mixture using Voronoi tessellations.

Experimental stress-strain curves were obtained monitoring strain measurements using strain gauges of different lengths placed on the more stressed zone of specimen surfaces. The comparison between mixtures behaviour showed a very little change in the tensile strength which belongs in the error range of test procedures. The numerical analysis was performed on mixtures composed by 4-mm to 12-mm nominal maximum aggregate size. The results were consistent with the expectations: the predicted stress-strain curves showed a similar general behaviour, the ultimate strength and the softening slope measured almost the same. This implies that the characteristic performances of mixtures are strictly dependent on other parameters, as the mastic composition and the air void percent. Besides, test simulations showed a visible size aggregate dependent in crack propagations: the presence of smaller sized aggregates creates strong discontinuities and developments of many micro-cracks; this can be observed even in the softening behaviour which evolves in a constant way.

The research program showed the potential of the DDM to characterize asphalt mixtures properties and to study crack growth and propagation in dependence of different parameters. The big benefit of the numerical analysis consists in a simple and rapid investigation without incoming in faults during experimental procedures.

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The investigation of asphalt mixture cracking resistance is one of the major topical issue in asphalt pavement research. A comprehensive understanding of the mechanism of crack propagation is essential to improve pavement performances in both thickness design and mixtures optimization.
Unfortunately, the complexity of modelling asphalt mixture crack propagation has always precluded the research development in the fracture mechanics field as discussed in Birgisson et al. 2002 [1]. Actually, a good insight of how and where fracture initiates and propagates is essential to improve mixtures performances in terms of cracking resistance.
Many factors, related to asphalt mixtures contents, contribute to influence pavement performances as aggregate size effect, binders specifications and air voids percentage. It's important to understand when, how and in which measure these factors might increase or decrease mix qualities in terms of macro-cracks growth.
In this paper the attention paid to the significance of aggregate size effects on asphalt mixtures fracture response.
The research was carried out by means of both experimental and numerical investigations using specific laboratory tests and an indirect boundary element method.
Experimentally, two tests set-ups were investigated: the Semi-Circular Bending test (SCB) and the Indirect Tension Test (IDT), which respectively represent the deflections induced by the vehicle traffic and the traction induced by the deflections. The specimens were prepared according to the Superpave™ specification using two different mixtures produced with the same binder but different aggregate gradations.
The numerical investigation was undertaken using the Displacement Discontinuity Method (DDM), a boundary element method developed by Crouch to assessing cracking in granular material such as asphalt concrete, traditionally used in the fields of rock mechanics and geotechnical engineering. Afterwards, Napier and Pierce [2] introduced the "multipole method" technique for solving multiple interacting crack problem that involved several thousand boundary elements by means of two tessellation schemes (Delanuay and Voronoi).
Birgisson et al. [3] [4] applied the DDM to asphalt mixture microstructure modeling, to simulate specifically the cracking behavior of both Superpave Indirect Test (IDT) and Semi Circular Bending Test, using new tessellation patterns "Voronoi with internal fracture path" introduced by Steen, Vervoot e Napier [5]. The method proved to be an efficient tool for the characterization of asphalt mixture fracture properties regardless of the particular testing setup used in the simulation, since predictions showed good agreement with the experimental results in the stress-strain curves (for both the ultimate load and the post peak response).
The numerical investigation provided for three different specimen models (IDT with and without a centered hole to create a fracture notch, and SCB) consisting of different aggregate size gradations from 3 mm to 12 mm average aggregate size. The DDM proved to be a very powerful medium for asphalt mixtures content influence investigation since it results more quickly and efficient compared to the laboratory tests, as well as more reliable. The simulations allowed to investigate the fracture behavior changes according to the specific aggregate gradation so that the significance of the aggregate size effect was estimated.

EXPERIMENTAL INVESTIGATION

For the laboratory section, two fine mixtures (C56 and C57) described in table 1, were realized to perform IDT and SCB tests. The mixtures were produced with a natural asphalt binder of 50/70 PEN bitumen; the C56 mix is a 10 mm nominal maximum size with 6.5 percent (± 0.5 percent) air void and 5.4% design asphalt content, while the C57 mix is a 16 mm nominal maximum size with 6.5 percent (± 0.5 percent) air void and 5.6% design asphalt content. Specimens were compacted using a Superpave Gyratory compactor to produce 6500 g, 150 mm diameter cylindrical specimens. Specimens of 150 mm diameter by 25 mm thick were sliced to perform resilient modulus, creep compliance and strength test at 10°C using the Indirect Tensile test with the system developed by Roque and Buttlar [6] [7], some of these were re-sliced to obtain 75 mm height Semi Circular shaped specimens.

Table 1: Aggregate Gradations

Sieve size	C56 % Passing	C57 % Passing
25 mm	100	100
19 mm	100	96
12.5 mm	93	87
10 mm	84	73
5 mm	54	38
2 mm	38	23
1 mm	27	17
500 µm	19	12
200 µm	13	8
106 µm	9	5
75 µm	6	3

Semi-Circular Bending Test (SCB)

The SCB is a three point bending fracture test performed using 150 mm diameter and 75 mm height semi-circular shape specimens statically loaded by a central loading ring. The load transmission occurs with a displacement control system; while the top loading ring drops with a 0.08 mm/sec speed. One strain gauge with a length of 20 mm is placed on the surface of the specimen in the centre bottom area to measure horizontal deformations during fracture tests. Figure 1 shows the SCB experimental set-up.

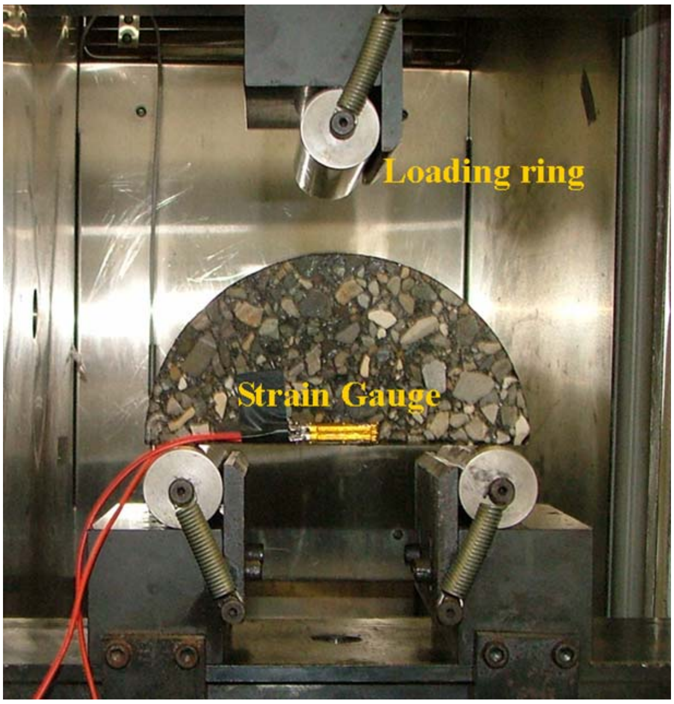

Figure 1 : SCB test set-up

Bending tests are traditionally considered the most suitable for investigating pavement failure due to fatigue traffic distresses. The SCB provides a difficult interpretation of the tensional state due to shear stresses developing in the zone surrounding fracture propagation.
The major SCB disadvantages consist in the particular specimen and specialized equipment needed, even if it is considered the best interpreter of bottom-up fracture propagation mode.
The horizontal stress was measured using an equation based on the three point bending moment formula for linear elastic material, adapted to asphalt mixtures by means of a finite element study conducted by Molenaar [8]:

$$\sigma_h = \frac{4.8P}{Dt} \quad (1)$$

where P is the applied load, D is the diameter and t is the thickness of the SCB specimen; it must be pointed out that the equation is valid only if the distance between the supports is equal to 0.8 D.
In the past many studies related to the stress development of a bending semi-circular specimen were undertaken, since the SCB stress field interpretation is certainly not a simple one. Molennar [8] in his finite element study, showed that high tractions develops at the bottom edge of the specimen as well as a compressive arch along the semicircular boundary.
These uncertainties obstacle the obtainment of fundamental material parameters as tensile strength or fracture energy, besides the experimental tests showed that strains developing along the vertical axis are not constant, probably due to the specimen shape anti-symmetry.

Indirect Tensile Test (IDT)

The IDT is an indirect test in which a static load is applied on the top and the bottom plates (25.4 mm wide and 50.8 mm long); horizontal strains during loading are measured by a 5 mm strain gauge placed at the centre of the specimen as shown in figure 2. The load transmission occurs with a displacement control system by bottom plate 0.05 mm/sec speed dropping.

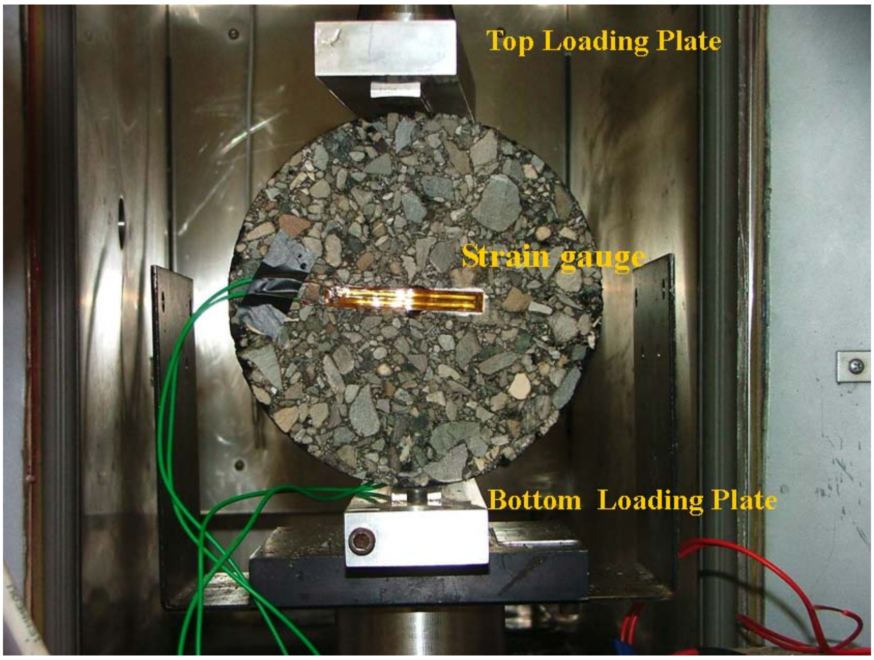

Figure 2 : IDT test set-up

In contrast with SCB test, the IDT utilizes circular shaped samples obtained easily from gyratory cylindrical specimens, besides it must be pointed out that the specific test set-up is simpler in the overall execution.
The horizontal stresses were computed basing on Roque and Buttlar [6] [7] description:

$$\sigma_h = \frac{2P}{\pi Dt} \quad (2)$$

Where σ_v is the average horizontal stress developing in the centre specimen area, P is the total applied load, D is the diameter and t the thickness of the IDT specimen.

The IDT test was performed even using a notched specimen, since fracture tests are usually performed on notched specimens. The notch serves to concentrate the stress in order to make cracks initiation propagating along determined paths. Numerous investigation on the notch size and shape selection were made by Birgisson and Roque [9], they drew the conclusion that, to be efficient, the notch must be large enough to assure the crack will initiate and propagate along the desired path; besides, it must be pointed out that the effect of the notch must be accurately monitored because it causes changes in material behaviour.
The final decision was to drill a 8 mm diameter circular hole at the centre of the specimen.

Experimental results

Following the test procedures described above, several specimens were tested to investigate the aggregate size effect on asphalt mixtures fracture behaviour. For each mixture and each test set-up, three replicates were performed at 10°C , obtaining the average stress-strain curves. Figure 3 shows the comparison between C56 and C57 mixes slopes obtained in both SCB and IDT tests. It must be pointed out that no strains were monitored during notched IDT test, since glued strain gauges are certainly not adequate to acquire strains on a drilled area.

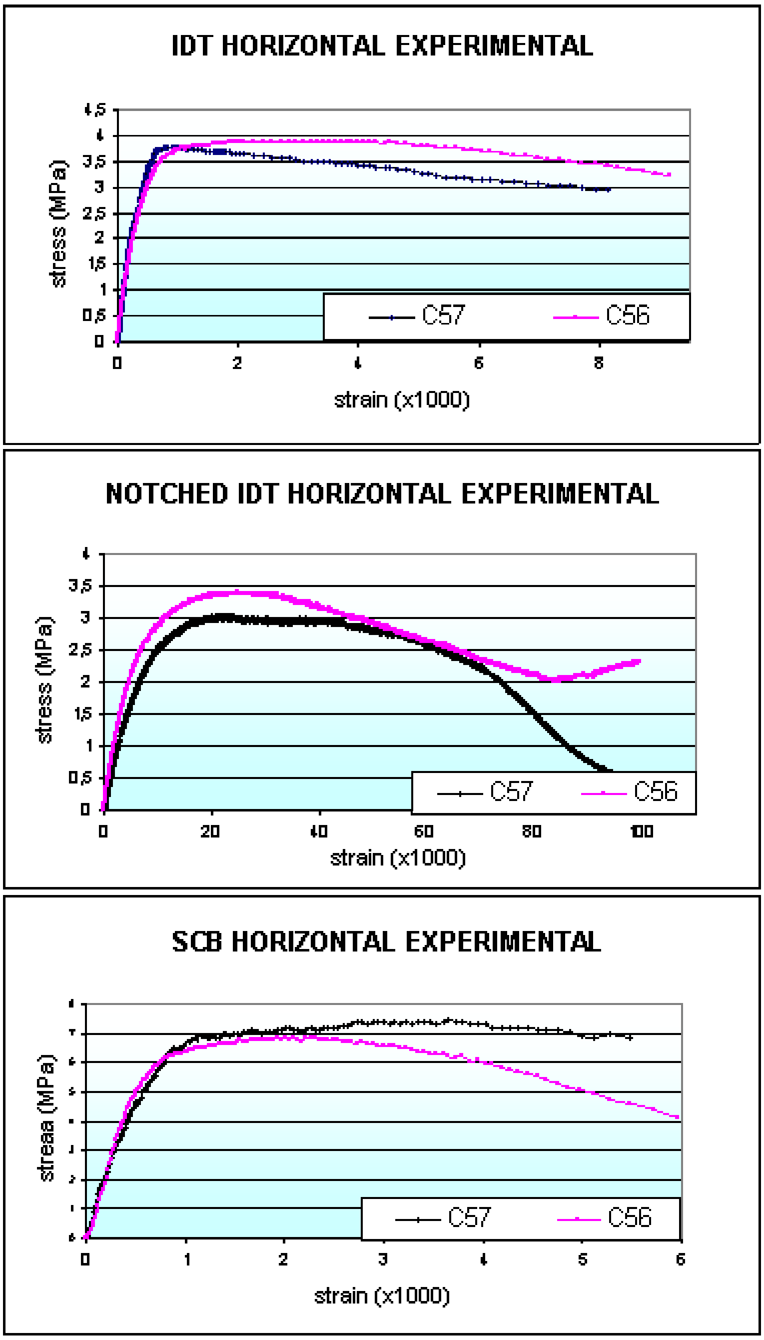

Figure 3: Comparison between the two mixes experimental behaviours.

Looking at the experimental results, the immediate remark is the low influence of aggregate size on the stress-strain curves. Actually, if tensile strengths are compared (table 2), it must be noted that these values differ by a very little factor which belongs to common tests error ranges.

Table 2: Tensile strength values

	IDT unnotched	IDT notched	SCB
Tensile strength (MPa) C57	3.77	3.03	7.45
Tensile strength (MPa) C56	3.89	3.42	6.85

It must be noted that SCB and IDT tensile strength values are noticeably different; this is due to the way of tensile strength determinations. Actually, the Superpave IDT test protocol specifies that the tensile strength must be taken at the onset of fracture, which occurs before the peak strength. In contrast, the SCB procedure takes the peak on the stress-strain curve as the tensile strength; this approach bring to a computation of a large amount of fracturing and damage before the peak is reached, as the results showed.
Besides, observing the notched and unnotched IDT strength values, it can be concluded that the presence of the hole causes a material discontinuity, decreasing its fracture resistance. However the difference between notched and notched strength is almost unimportant so that the hole approach, localizing crack initiation, can be considered a good method to analyse cracking behaviour.

NUMERICAL INVESTIGATION

The numerical aggregate size effect investigation was carried out using the Displacement Discontinuity Boundary Element Method (DDM). The code with a liner variation displacement discontinuity elements (DIGS) was applied in combination with a Voronoi Tessellation with internal fracture paths approach to account for the presence of aggregate and material defects.
The numerical model consists of two types of elements: exterior boundary elements and potential crack elements, representing respectively the boundary surface of the specimen and internal sites where potential crack elements, which are randomly placed within the specimen forming a pattern of predefined paths, are selected for mobilization (slip or open). At each load step stresses are computed at collocation points inside the potential crack elements; these stresses are then checked against a non linear material failure criterion (Mohr - Coulomb) to determine whether or not a crack has been activated. All the numerical method details are explained by Birgisson and Napier [1] [2] [3] [4] [5].

Numerical Models

Firstly the three different specimen geometries were modelled. The perimeters were defined by means of specific numbers of boundary elements: 152 for the unnotched IDT, 202 for the notched IDT, 128 for the SCB. The area within specimens was meshed by a Voronoi polygon tessellation and connecting the geometric centres with polygons vertexes. For each specimen shape 6 different aggregate size were obtained changing the geometric centres number; in table 3 are listed the specifications corresponding to 3 mm, 6 mm, 12 mm, average aggregate size.

Table 3: Area within specimens description

Specimen Shape	Geometric centres	Internal Fracture Elements
IDT notched – 3 mm	1396	10049
IDT notched – 6 mm	400	3323
IDT notched – 12 mm	239	2201
IDT unnotched – 3 mm	939	6349
IDT unnotched – 6 mm	312	2605
IDT unnotched – 12 mm	189	1798
SCB unnotched – 3 mm	630	4841
SCB unnotched – 6 mm	181	1775
SCB unnotched – 12 mm	110	1295

The boundary elements selected to be loaded were 8 (corresponding to the load plate/ring), other 8 elements were imposed to be constrained in the bottom edges corresponding to the plate/rings supports, while the remaining elements along the circumference were specified with zero traction to simulate traction free surface.

The material properties, listed in table 4, were obtained by an iterative process which led to an accurate match between predicted and measured stress - strain curves (as shown in figure 4). In details, the local tensile strength cut-off (T_0) of the mastic between aggregates was selected, based on curve fitting, to be similar to the global measured tensile strength of the C56 mixture as well as the cohesion at the zero intercept while the friction angle before failure was taken to be 38 degrees, based on calibration, since direct measurements were not available. The Young Modulus was obtained by averaging the vertical and horizontal stress - strain curves secant modulus at fifty percent of the ultimate stress level, while the Poisson Ratio was obtained by IDT resilient modulus test. All the other parameters were selected by calibration.

Table 4: Material properties used in displacement discontinuity model

Parameters	Values	
Young Modulus (MPa)	12200	
Poisson Ratio	0.36	
	Potential crack elements	
	Mastic	Internal facture paths
Cohesion C_0 (MPa)	3.80	8.40
Tensile Strenght T_0 (MPa)	3.80	8.40
Friction Angle φ_0 (Degree)	38	40
Residual Cohesion C_R (MPa)	0.18	0.28
Opening Crack Limit D_{NCR} (MPa)	0.12	0.28
Residual Friction Angle φ_R (Degree)	32	34
Cohesion Softening C_{soft}	1.00	1.00
Tension Softening T_{soft}	10.0	10.0

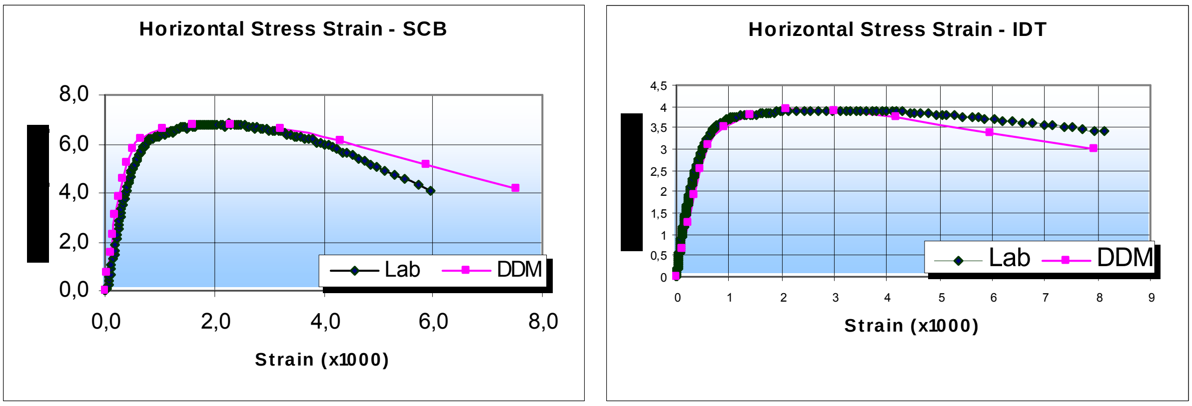

Figure 4: Predicted and measured IDT and SCB stress- strain curves

For each load step, stresses were computed using eqs (1)-(2), while strain values were computed using the following eq:

$$\varepsilon_h = \frac{\Delta H}{L_{gauge}} \tag{4}$$

where ΔH is a horizontal deformation measured at the horizontal strain gauge location and L_{gauge} is the gauge length.

Numerical Results

A qualitative analysis of tests simulation is quoted in figures 5, 6, 7; the three images correspond respectively to: 1) model without loading; 2) load step in which the tensile strength is reached; 3) ultimate load step. Simulations show crack propagation patterns consistent with observed cracking behavior; actually, IDT specimen failures appear as a vertical crack trough the center, while SCB specimens show cracks initiating within the center-bottom area (the highest bending moment area) and developing into a central macro-crack along the vertical plane.

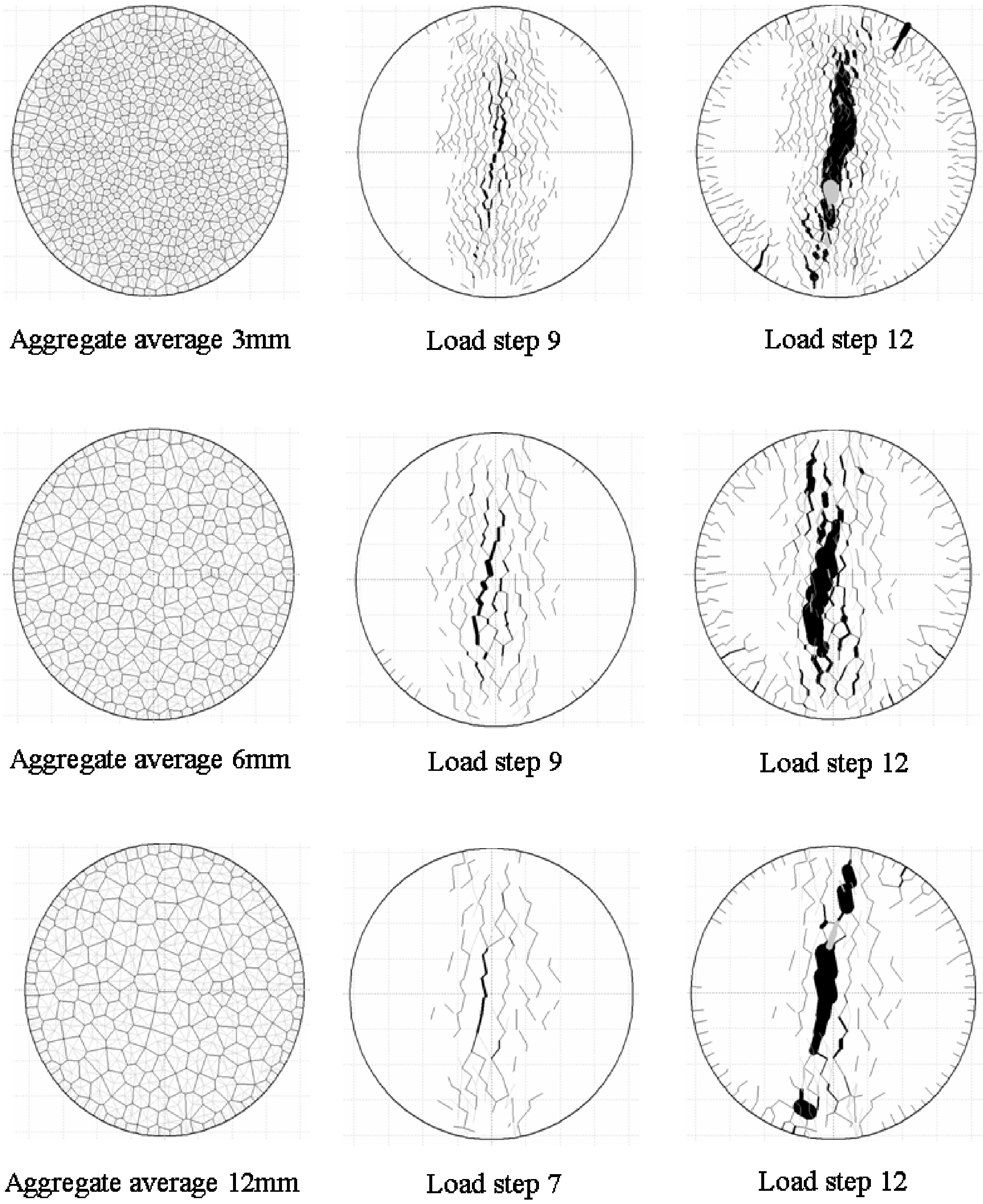

Figure 5: Unnotched IDT simulations

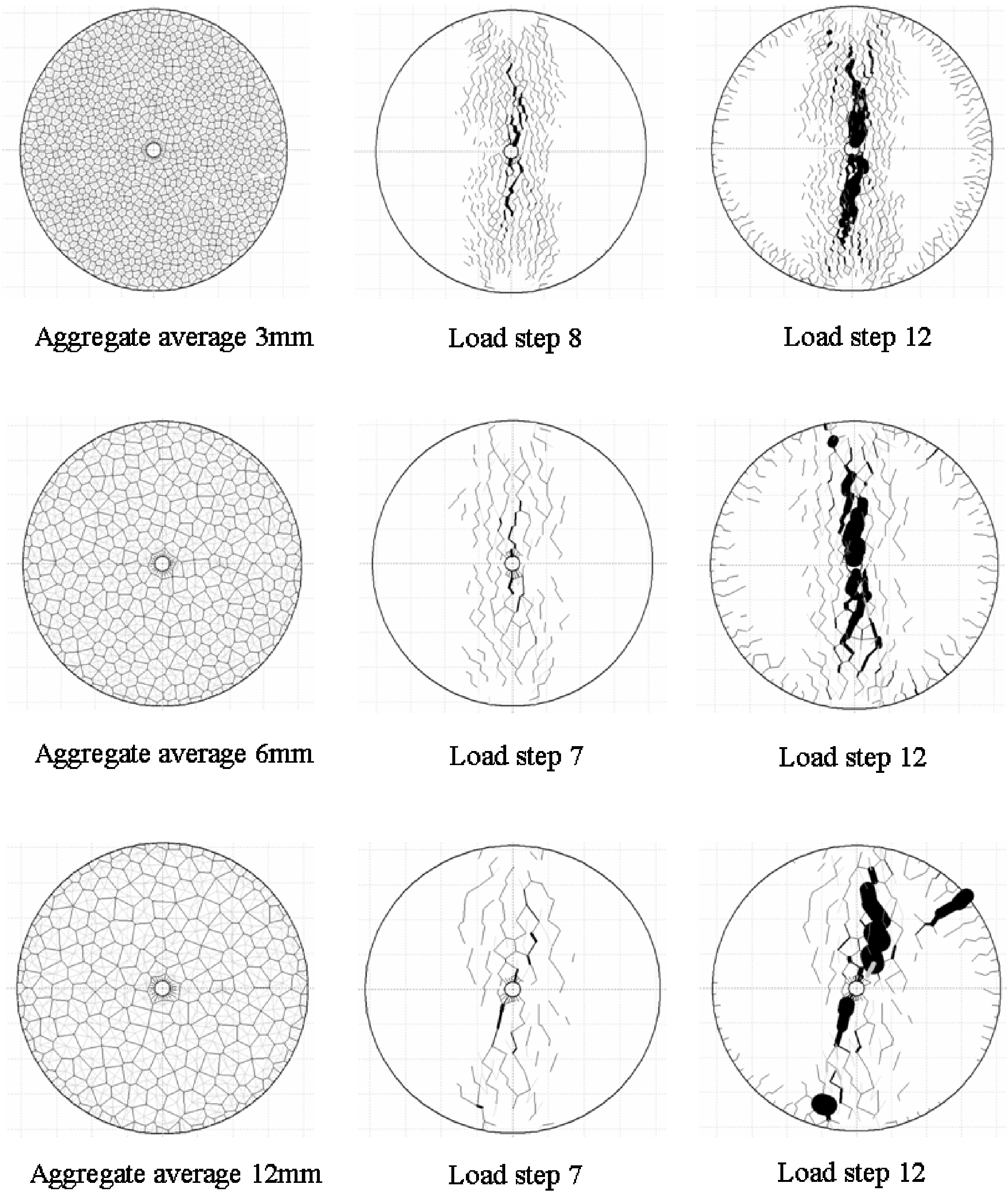

Figure 6 : Notched IDT simulations

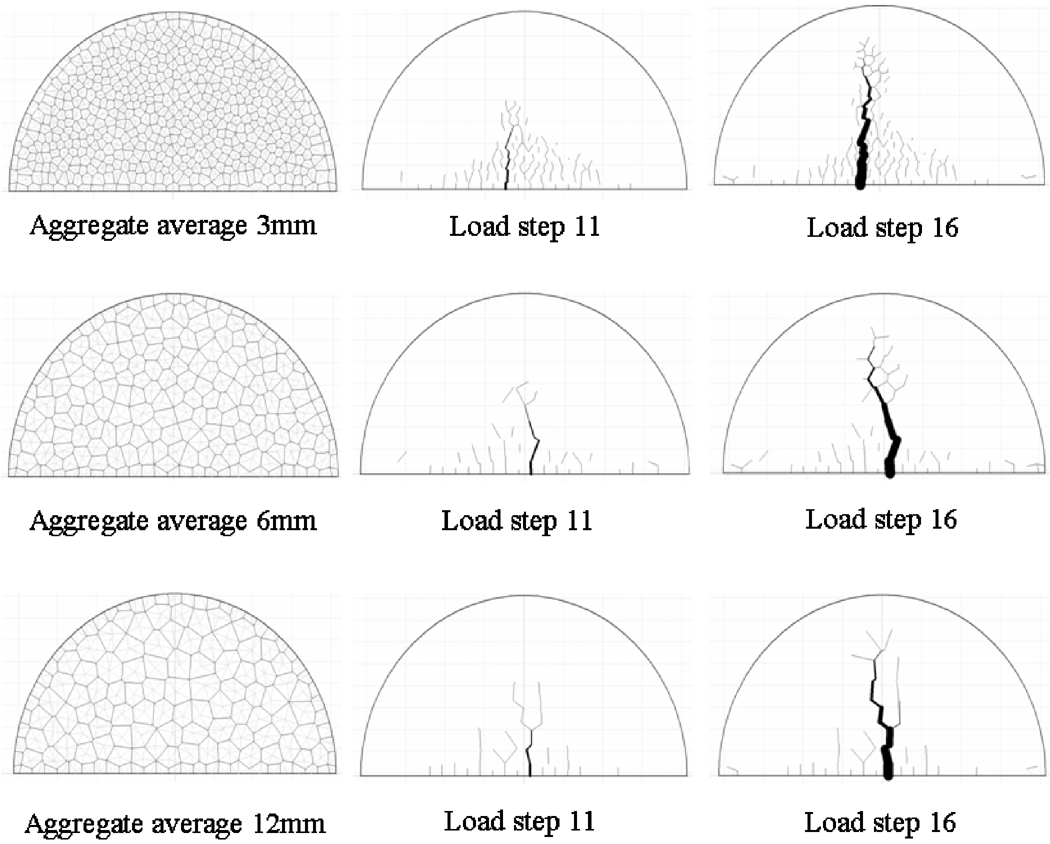

Figure 7: SCB simulations

Numerical stress-strain behaviours of the 6 different aggregate gradation mixtures were investigated for each test set-up; the results are shown in figure 8.

In each test, for small strains values, horizontal stresses overlap regardless of aggregate sizes, and the curves develop in a linear way up to fracture points which occur at similar tensile stress values. It must be noted that, once these point are reached, softening slopes are very similar too, enhancing the remarks done for the experimental section. The only curve which slightly differ from the others corresponds to the maximum average aggregate size analyzed. As discussed by Birgisson and Soranakom [10], a small size effect is noticeable where a larger aggregate size results in a stiffer response. Actually, the larger the aggregate size, the fewer resulting cracks in the specimen. Smaller average aggregate sizes tend to yield more numerous crack planes in the specimen, so that the initiation of a crack band can happen easier and sooner than in larger aggregate mixture where fewer crack planes are observed.

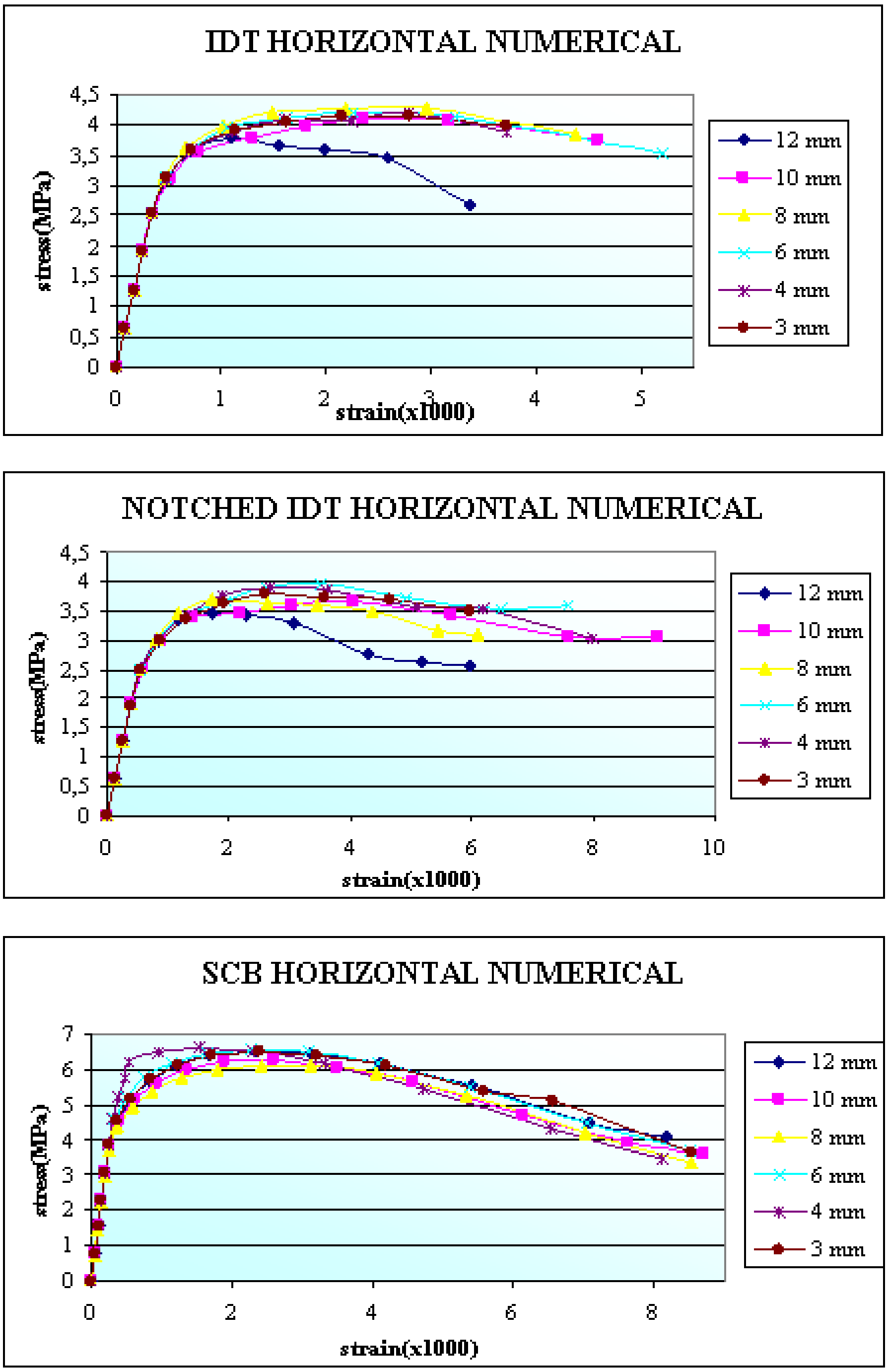

Figure 8 : Comparison between the different aggregate sizes numerical behaviors

CONCLUSION

The work described in this paper focused on the investigation of aggregate size effect on asphalt mixtures cracking behaviour. The research was developed in both experimental and numerical investigations: experimentally by means of specific test performing to characterize the investigated materials consisting of the same binder and two different aggregate gradations; numerically by means of the Displacement Discontinuity Method to study in detail the material cracking behaviour for 6 different average aggregate sizes.

The laboratory study showed that for each test the resulting cracking behaviour was similar for both mixes; in specific tensile strengths values obtained for the two mixes differed slightly pertaining in common error ranges of laboratory tests.

According to previous remarks, the numerical study led to an additional verification. Actually, maintaining the same mixture properties due to the specific mastic and fracture paths, and changing only the average aggregate size from 3 mm to 12 mm, stress-strain curves overlap at least up to fracture points. Softening behaviours differ slightly for all gradations except for the 12 mm average aggregate size which results in a

stiffer behaviour probably due to fewer crack planes observed in the simulation. It must be pointed out that the numerical study appears a very powerful tool in these type of investigation since it allows a very detailed analysis, faster and more reliable than laboratory tests (eliminating common test execution errors).
From all the results obtained it can be concluded that aggregate size effect is unimportant if the change in average aggregate size is not sizeable. Since this research was based on the only grading size variance maintaining all the other components unchanged (as mastic or air void percent), the conclusion drawn is that varying grading sizes is too reductive for asphalt mixtures cracking behaviour analysis.

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