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Influence of aggregate size and free water on the dynamic behaviour of concrete subjected to impact loading

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Abstract. Concrete is a material widely used in civil engineering. Thus the knowledge of its mechanical behaviour is a major safety issue to evaluate the ability of a structure to resist to an intense dynamic loading. In this study, two experimental techniques have been applied to a micro-concrete and a common concrete to assess the influence of the aggregate size on the dynamic response. First, spalling tests on dry and wet specimens have been performed to characterize the tensile strength of concrete at strain rates in the range 30 – 150/s. Then, edge-on impact tests in sarcophagus configuration have been conducted. The cracking pattern of the micro-concrete and the concrete plates in wet and dry conditions have been compared to appraise the influence of aggregate size and free water on the damaging process.

1 Introduction

Although concrete is widely used for construction all around the world, its mechanical behaviour is not well understood in dynamic conditions. The tensile properties of concretes constitute generally the main weakness of these materials. Toutlemonde [1] performed direct tensile tests on different concretes at relatively low strain rates (up to 1/s). The influence of aggregate size and the free water were particularly investigated. The results showed that, in this range of loading rate, the aggregate size presents a limited influence on the tensile strength while the free water appeared as a prominent parameter. An enhancement of tensile strength of 3 MPa was observed between quasi-static value (obtained at 1 e-5/s) and the dynamic one (at about 1/s) for wet specimens while dry concrete samples present a limited improvement of about 1 MPa in the same range of loading rate. At higher rates of strain, spalling tests are suitable to identify the dynamic strength of concrete [2-4]. Klepaczko and Brara [2] adapted the Hopkinson bars apparatus to test concrete in dynamic conditions by removing the output bar. Using this technique, several experimental data have been gathered on wet and dry specimens. Unfortunately, no measurement was performed directly on the specimen. Based on the same principle, Schuler et al. [3] used an acceleration sensor placed on the rear face of the specimen to get the free surface velocity, and computed the tensile strength from this signal. Weerheijm and Van Doormaal [4] realised experiments on concrete using a similar configuration. They used strain gauges on the tested concrete specimen to obtain local data

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concerning the loading field that allowed deducing the tensile strength. In this study, two concretes are compared: the MB50 micro-concrete with a maximum aggregate size of 2 mm and the R30A7 concrete, a common concrete with a maximum grain size of 8 mm. In the first part, these materials are presented and their main mechanical properties are given. A second part is dedicated to the experimental campaign of spalling tests performed to investigate the sensitivity of the tensile strength to the strain rate. In the third part, another technique is applied to investigate the response of a concrete target to a ballistic impact: the so-called edge-on impact tests have been conducted on both concretes. Consequently, by crosschecking all experimental data, the influence of aggregate size and free water on the dynamic response of concrete has been appraised.

2 Tested concretes

2.1 The MB50 micro-concrete

Due to their macroscopic heterogeneities, concretes are generally difficult to test in dynamic conditions. The MB50 micro-concrete has been designed to be representative of a standard concrete with a small maximum aggregate size (2 mm): the distribution of aggregates and the water to cement ratio are similar to a common concrete. This particularity allows reducing the tested volume which is convenient for laboratory testing. Its main properties are gathered in Table 1. Several experimental data are available for this material in direct tension [1], in bending [5] or in splitting [6]. Moreover, its compressive behaviour has been studied in simple compression [7] and under high confining pressure [8-10].

2.2 The R30A7 concrete

The R30A7 concrete has been designed to be representative of a standard concrete. Oppositely to the MB50 micro-concrete, bigger inclusions are included: its maximum aggregate size is 8 mm. Its behavior has already been studied in confined compression [11] and quasi-oedometric tests [12]. Its composition and its main mechanical properties are reported in Table 1.

2.3 Tested specimens

The specimens used for spalling tests are cylinders 46 mm in diameter and 120 or 140 mm in length. To perform edge-on impact tests plates of 200 x 120 x 15 mm^3 were used. They were all obtained from large blocks (30 x 30 x 20 cm^3) by drilling, cutting and grounding. After the machining processes, they have been stored in water saturated by lime to avoid the dissolution of portlandite. On the one hand, saturated specimens were picked up from water less than one hour before testing and regularly re-hydrated during their preparation. On the other hand, a second set of specimen was desiccated at 60°C during several weeks. The loss of water was regularly checked until the mass of the specimen stabilized.

3 Dynamic tensile testing: spalling experiments

To test the concrete at high strain rates, one can conduct spalling tests. During this experiment, the impact of a projectile generates a compressive pulse propagating through an instrumented bar (cf. Fig. 1). A part of the wave is transmitted to the concrete cylinder while the other part is reflected back in the bar. The compressive loading propagates through the specimen on which several strain gauges are placed. When it reaches the free surface, the incident compressive pulse is reflected into a tensile wave propagating in the opposite direction. A tensile field appears along the specimen leading to its dynamic failure.

Table 1. Composition and main mechanical properties of the MB50 and the R30A7 concrete.

Composition	**MB50 [1]**	**R30A7 [11]**
Aggregates (kg/m^3)	0	1008
Sand (kg/m^3)	1783	838
Cement (kg/m^3)	400	263
Water (kg/m^3)	200	169
Admixture (kg/m^3)	12	0
Water / Cement	0.5	0.64
Maximum aggregate size (mm)	2	8
Main mechanical properties	**MB50 [6]**	**R30A7 [11,12]**
Compressive Strength (MPa)	70	29
Tensile Strength (MPa)	3	3.6

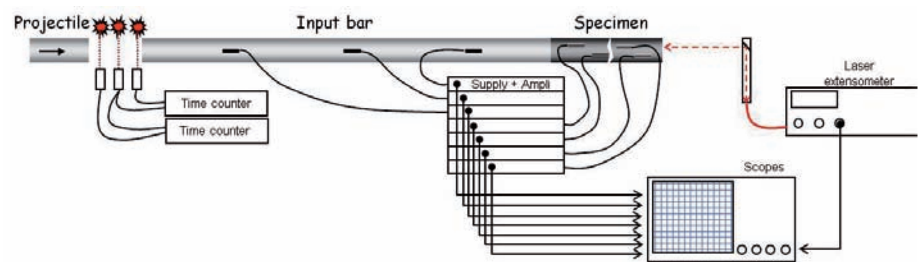


Fig. 1. Experimental configuration of the spalling test.

These tests are unu sual because t he mechanical eq uilibrium of t he speci men is n ever reached during th e e xperiment. In thi s stu dy, t he b asic setup co nsists of a proj ectile and a Ho pkinson bar diameter 46 mm a nd le ngth r espectively 75 an d 1200 mm m ade of aluminium alloy to redu ce the impedance mismatch with concrete. Several strain gauges are placed on the input bar to characterize the incident loading. Other gauges are glued directly on the specimen. Linked to the high frequency scope (Ban dwidth: 500 MHz, recordin g frequency: 10 MS/s), th ey allo w recording t he s tress field evolution during the spalling test. Moreover, a la ser extensometer (Bandwidth: 1.5 MHz) points out the rear face of the tested specimen to g et the free velocity signal. From this last experimental data the d ynamic te nsile stre ngth σ_{dyn} is ide ntified using t he li near acou stic ap proximation of No vikov [13]:

$$\sigma_{dyn} = \frac{1}{2} \rho \, C_0 \, \Delta V_{pb} \tag{1}$$

where ρ is the density, C_0 is the one-dimensional wave velocity and ΔV_{pb} is the pullback velocity, i.e. the diff erence bet ween t he maximum v elocity reac hed at th e rear f ace and th e reb ound v alue of velocity (cf. Fig. 2).

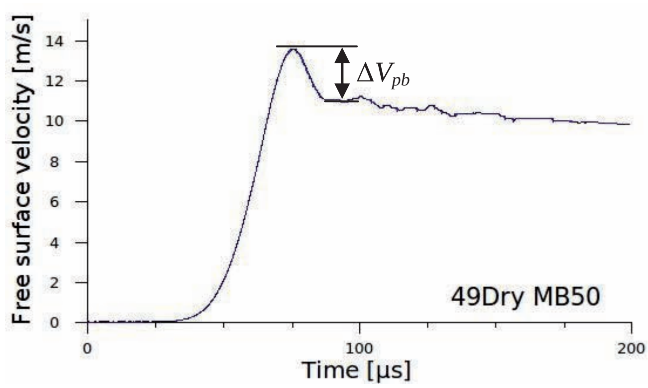
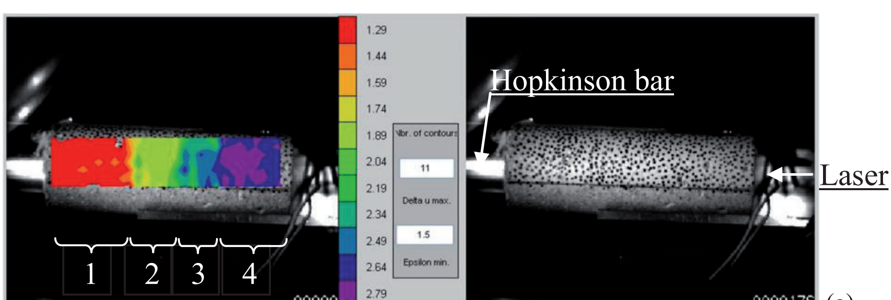


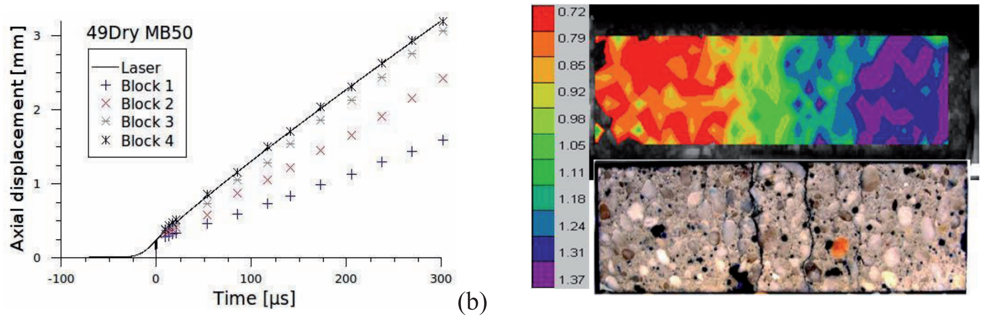
Fig. 2. Free surface velocity recording with the laser extensometer – 49Dry test performed on MB50 micro-concrete.

The experimental campaign was conducted on dry and wet specimens of concrete and micro-concrete. During the experiments, an ultra-high speed camera with a maximum frame rate of 1 Mfps has been used to study the fragmentation kinetics in both concretes. After the test, frames have been post-processed with the Correli Q4 data image correlation (DIC) software (LMT-Cachan) to perform quantitative measurements of the displacement field. An example of spalling test performed on MB50 micro-concrete specimen is presented in Figure 3a. The corresponding field of displacement (in pixels) obtained by using Correli Q4 is shown. No cracks are visible on the specimen at this point. Nevertheless the correlation results reveal several discontinuities of displacement. In Figure 3b the displacement deduced from the velocity signal of laser extensometers is compared to the average value of fragments, time t = 0 corresponding to the beginning of tensile stresses in the concrete specimen according to strain gauges. A good agreement between these two techniques is observed. This technique has been applied to spalling test performed on R30A7. Figure 3c presents the displacement field and shows that the detected discontinuities correspond to fracture planes of the specimen. Thus the DIC method allows detecting early the damage in the specimen and carrying out an accurate evaluation of the strain field.

The spalling strength sensitivity to the strain rate of the micro-concrete and the concrete has been studied between 30 and 150/s by varying the impact velocity of the projectile. Dynamic tensile strengths obtained are plotted in Figure 4. The trends of the MB50 micro-concrete are similar to data of R30A7 concrete. This observation supports the hypothesis that aggregate size has a limited influence even at high strain rates.



(a)



(b) (c)

Fig. 3. (a) Displacement field measured by Digital Image Correlation (scale in pixels) in a spalling test (MB50 specimen – 49Dry test), (b) Comparison of axial displacements deduced from DIC and from the laser extensometer signal (MB50 49Dry test), (c) Comparison of the displacement field (in pixels) and the post mortem cracking pattern of a R30A7 specimen (23Wet test).

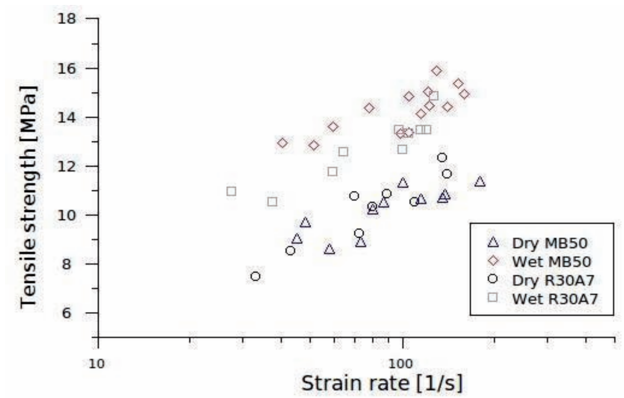


Fig. 4. Dynamic tensile strength of the MB50 and the R30A7 concretes obtained from spalling tests.

4 Damage under impact: edge-on impact test

4.1 Principle of the EOI experiment

A localized dynamic loading on a concrete structure like a ballistic impact or a detonation leads to characteristic outcomes. In order to improve the understanding of the fragmentation of concrete, the edge-on impact test was developed at the Ernst Mach Institute – Germany [14] and at the Centre Technique d'Arcueil – France [15]. This experimental technique has been designed to reproduce in a two-dimensional configuration the loading of a ballistic impact. The growth of damage is visualized using a high speed camera at the surface of the target. The principle of the experiment consists in projecting a striker on the edge of a plate composed of the material to be tested. The loading wave generates a high compressive zone near the impacted zone and then spreads into the target. The radial displacement of matter induced by the passage of the incident pulse generates dynamic tensile stresses in the hoop direction that result in intense fragmentation composed of radial cracks. Ceramics [14], glasses [15], ultra-high strength concrete [16] have been tested with edge-on impact tests. In this study, several tests were performed on dry and wet specimens of the MB50 micro-concrete and of the R30A7 concrete in the so-called sarcophagus configuration: concrete plates are encapsulated in an aluminium box that keeps fragments close to their original position (cf. Fig. 5). After the test, a coloured hyperfluid resin is injected to highlight the damage pattern. Additionally, a dynamic confinement system [5] was used to locally increase the pressure in the projectile-specimen contact zone at the beginning of the loading, reducing this way the compressive damage and improving the spread of the incident wave in the tile (see Fig . 5).

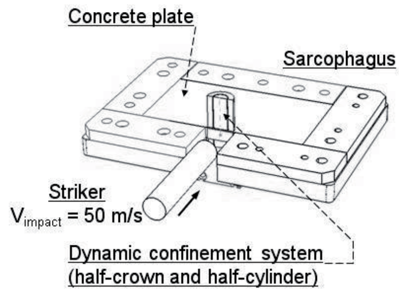


Fig. 5. Experimental configuration of the EOI test.

4.2 Experiments conducted on the MB50 micro-concrete

Several numerical simulations were conducted to determine a test configuration (impact velocity and length of projectile) that creates a dynamic tensile loading in the concrete target comparable to that observed in spalling tests. It was established that a projectile 22.5 mm in diameter and 100 mm in length with an initial velocity of 50 m/s may generate a tensile strain rate of about 150/s at 50 mm from the impact spot [17].

First EOI tests were carried out on MB50 micro-concrete plates of 200 x 120 x 15 mm^3. The specimens were infiltrated post mortem and polished to reveal the cracks. The results obtained on dry and wet specimens are reported in Figure 6. It can be remarked that a higher cracking density has developed during the test performed on a dry specimen. Moreover, the existing cracks in the wet target seem thinner and more closed. Consequently, free water in the micro-concrete shows a significant influence on the damage pattern. Performing these tests on concrete R30 A7 allows determining the influence of aggregate size on damages due to an impact loading.

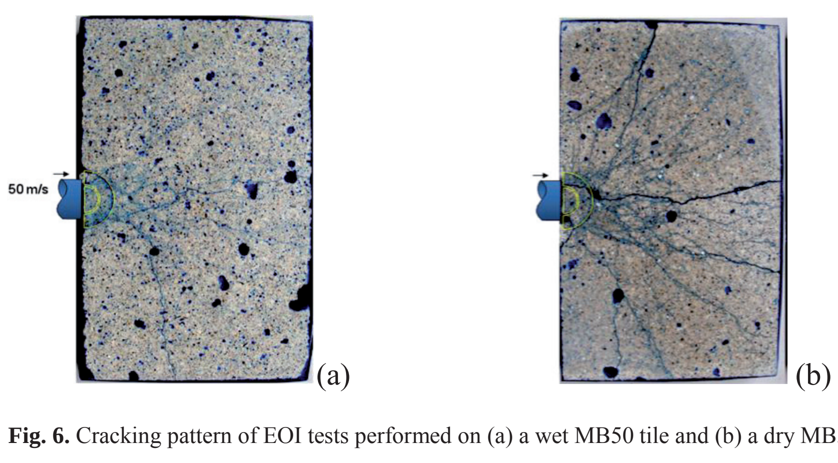


Fig. 6. Cracking pattern of EOI tests performed on (a) a wet MB50 tile and (b) a dry MB50 tile.

4.3 Experiments conducted on the R30A7 concrete

Standard concretes include generally aggregates at the centimetre scale. Consequently, it is necessary to evaluate the influence of aggregate size on the dynamic response of concrete. EOI tests were performed on dry and wet specimens of R30A7 concrete keeping the previous parameters: the projectile has a diameter of 22.5 mm and a length of 100 mm and is projected onto the target at a speed of 50 m/s. Like for the MB50 micro-concrete, the specimens were infiltrated post-mortem and polished to bring out the cracks. The damage patterns are presented Figure 7. Again, the influence of free water is obvious: the damage is much more pronounced in the dry tile. In the same way as the MB50 micro-concrete, an intense cracking developed near the impacted area. Farther, many long radial cracks are observed. Oppositely, in the wet tile the cracking network is less developed and cracks are hardly visible. Besides, one can see that few aggregates are broken: cracks have circumvented the inclusions during their propagation.

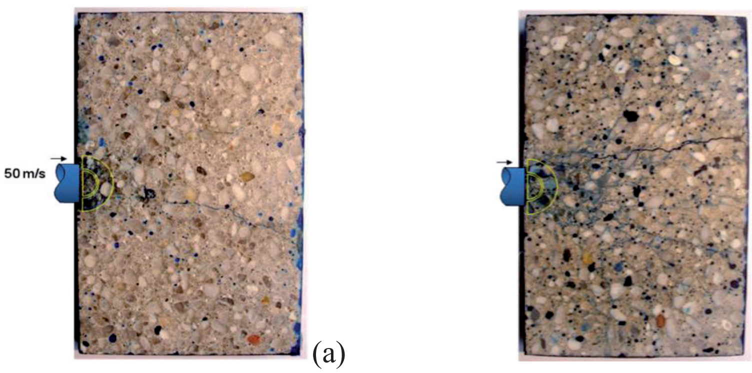


Fig. 7. Cracking pattern of EOI tests performed on (a) a wet R30A7 tile and (b) a dry R30A7 tile.

4.4 Maximum aggregate size influence on damage under impact

Despite significant differences in terms of microstructure between MB50 micro-concrete and R30A7 concrete, damage patterns produced by impact are very similar: in wet conditions small cracks and limited crack opening are noted, whereas in dry conditions a pronounced damage is observed. It is interesting to note that few aggregates are broken, cracking being predominantly inter-granular: thus the matrix behaviour seems to drive the dynamic fragmentation. Consequently, the maximum size of aggregates appears to play a limited role on the cracking pattern of samples subjected to impact. Otherwise, the free water appears as a more important factor. The differences between dry and wet samples are more pronounced than between micro-concrete and concrete.

5 Conclusions

To assess the importance of aggregate size on the tensile behaviour of concrete subjected to high speed dynamic loading, two experimental methods have been used. On the one hand, a campaign of spalling tests has been conducted on a standard concrete with a maximum aggregate size of 8 mm and a micro-concrete (maximum grain size: 2 mm). For both materials these experiments have been carried out on dry and wet specimens. The dynamic tensile tests performed between 30 and 150/s showed very similar results for both concretes despite their difference of the microstructure size. The moisture has shown a great influence on the dynamic strength of both concretes. Moreover an ultra-high speed camera has been used. The acquired frames have been post-processed with a Digital Image Correlation software. It allowed identifying the fracture planes at the early stage of damage and evaluating finely the strain field evolution during the spalling test. On the other hand, EOI tests have been conducted to assess the influence of aggregate size on the damage pattern of concrete when subjected to an impact loading. Similar trends than in spalling tests have been observed in both concretes: the cracking is predominantly inter-granular. Again, the free water changes more significantly the damage pattern. These observations show that the results obtained from dynamic tensile experiments on a micro-concrete, easier to test, can be transposed to a standard concrete.

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