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USE OF THE CONFOCAL MICROSCOPE TO STUDY PRE-EXISTING MICROCRACKS AND CRACK GROWTH IN CONCRETE

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Abstract

The possibility of using the confocal microscope to study some aspects of concrete fracture mechanic have been explored. Observations of crack initiation and propagation have been made on cementitious materials at various locations at micro level on specimens having a representative volume. The size and distribution of surface cracks prior to loading have been determined. The morphology of propagating cracks under stable and unstable conditions obtained through the use of a specially-developed loading device has been characterised. Finally, the aspect of the fracture surfaces has been observed and their fractal dimensions determined.

1 Introduction

Further development of existing fracture mechanics models requires the understanding of various microscopic phenomena involved in crack behaviour and the search for improvement of the techniques. Among the existing techniques to study crack growth and the fracture surface in concrete, confocal microscopy appears to be well-suited. It allows in-situ observation of crack growth on representative concrete samples without the size limitation encountered in SEM techniques. With confocal microscopy, it is possible to observe on specimens of usual macroscopic testing sizes - for instance cross sections of 20 x 30 cm - microcracks of 0.7 μm width. The specimens can be placed in a controlled or ambient atmosphere, thus avoiding vacuum drying or metallisation and the resulting risk of artefacts in the form of new microcracks. On saw-cut specimens individual aggregates are left visible allowing study of the crack path. The sample may need initial polishing but not drying, although polishing of macroscopic concrete samples does not provide the same optical quality as on small samples. The confocal principle resolves the problem of depth of focus met in classical optical microscope and allows study of sample surfaces with a poor polishing quality. The confocal microscope is also very well-adapted to measure the effective area of fracture surfaces of cementitious composites. In fact, among experimental techniques usually used for the acquisition of tridimensional surfaces, confocal microscopy allows study of features in the range of 1 to 1000 μm compared to the nanometer scale of atomic force microscopy (Lange et al. (1993)). This range is especially important since the cement paste can be clearly separated from the thinnest aggregates. On the other hand, confocal microscopy allows the user to obtain quantitative information on the three-dimensional structure of a microscopic object in this range and to measure roughness parameters and surface area.

This paper presents the results of a first set of observations on concrete microcracking obtained with a confocal system which needed some special developments for this kind of application. The aim of this work is to explore the possibilities of the confocal microscope to characterise microscopical aspects of unstable crack propagation, to observe morphological aspects under stable crack growth (and the interaction with pre-existing microcracks) and fracture surfaces. Theoretical aspects have been treated in Huet (1994a), (1994b) and (1995).

2 Confocal microscope

In the confocal microscope a point source is imaged in the object plane. The light reflected by the object, or, in some cases, the fluorescent light, is directed to a photo-multiplier via a small aperture named the pinhole (Fig.1). The aperture acts as a spatial filter and physically excludes light coming from above or below the focal plane of the microscope objective. Laser light reflected from a dichroic mirror into a scanning device moves in a raster scan in an x-y plane. A computer displays each point as a pixel on a screen. The image is generated simultaneously on a monitor. The arrangement of the detector pinhole, conjugated with the illumination pinhole, ensures that only information from the focal plane reaches the detector. This produces very thin optical sections of high contrast. By coupling a step motor to the focusing unit, it is possible to carry outoptical sectioning. This high-precision focusing stage which is

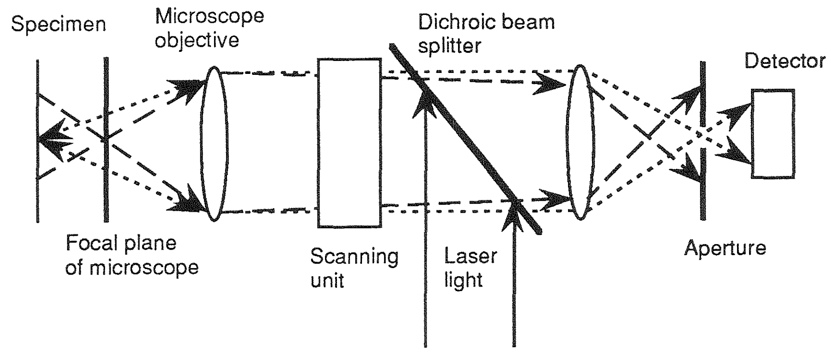


Fig. 1. Basic concept of a confocal laser scanning microscope

computer-assisted allows the user to produce whole series of sectional images by changing the focal plane and storing them on optical disks. This information can be used to produce an image of great depth of focus (extended depth of focus image) by overlaying the images of a section series or to rebuild a three dimensional image of an object.

3 Materials, specimens and loading fixture

Experiments have been carried out on concrete having the following composition: cement content = 265 Kg/m^3, water/cement ratio = 0.57, maximum aggregate size = 65 mm and age = 2 years. The specimens were maintained in a moist room up to ten days prior to testing.

Compact tension specimens were made from concrete plates with the dimensions of 120 x 120 x 5 mm. The initial depth of notch was 60 mm. The ligament has a semi-chevron shape along 10 mm (Fig. 2).

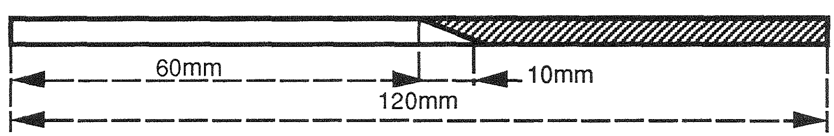


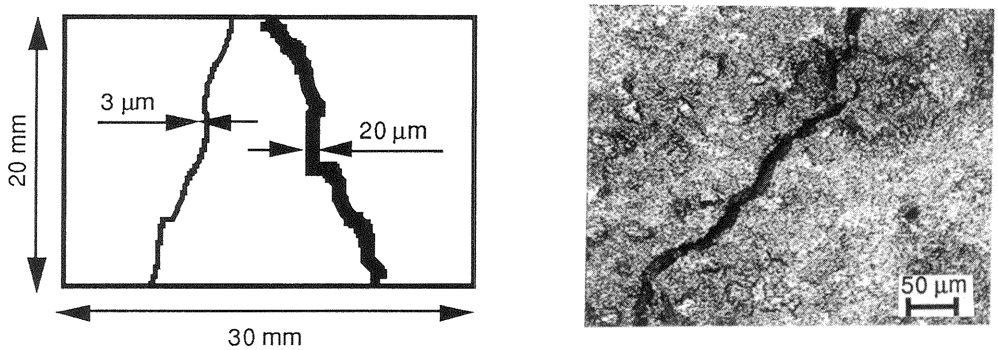
Fig. 2. Semi-chevron notch in CT specimen

Observations were made on the plate face containing the wedge of the semi-chevron. Regarding the aggregate size (0 - 65 mm), this small thickness allows to stay close to the bidimensional case for which the propagation on the surface is quite similar to propagation in the depth. In particular this should make possible comparisons with two-dimensional numerical simulations such as that proposed by Wang et al. (1992), (1994).

A loading fixture for stable crack propagation has been specially developed for use under the field of the confocal microscope. It combines compact dimensions with the possibility to test representative specimens (120 x 120 x 5 mm³). Loading under displacement control is achieved by hand using a screw system. The relative displacement of the loading points for one turn is 250 μm.

4 Drying-shrinkage microcracks in cement paste

Shrinkage microcracks have been observed on the top of a 16 by 32 cm cement paste cylinder demolded after three days and exposed to a laboratory atmosphere. Observations are made by the extended-depth-of-focus mode of the confocal microscope in order to avoid polishing. This provides an in-focus image over the whole observation field. The observations reveal tortuous crack paths with a low density of microcracks in the cement paste at the scale of observation. For instance, in a field of 20 x 30 mm and with a magnification of 320, only two microcracks (20 μm and 3 μm mean width) have been observed (Fig. 3). Their widths are small (microscopic scale) but their lengths are macroscopic compared to the width.

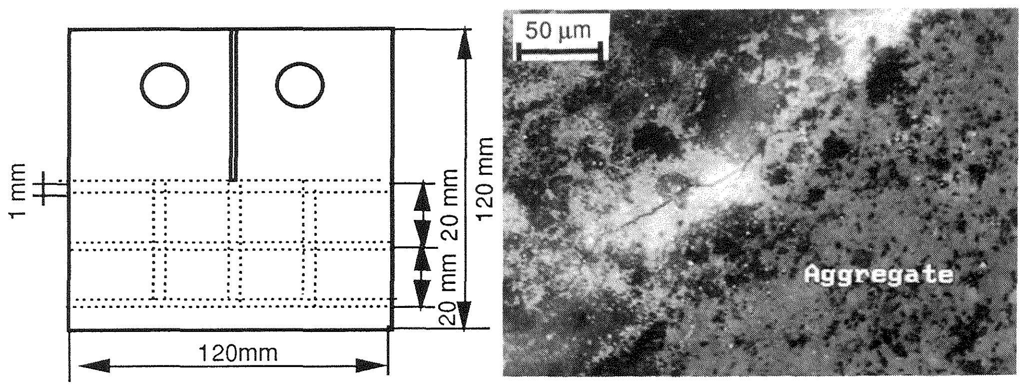


(a) (b)

Fig. 3. a) Location of shrinkage microcracks in the observed field, and b) an example of observed microcracks on unpolished specimen

5 Initial microcracking in concrete

In order to study the effects of endogenous and/or drying-shrinkage stress, the possible evolution of microcracks under loading and the interaction of the pre-existing microcracks with a propagating main crack, it is important to identify the initial state of microcracking prior to the testing. The sample being very large compared to the scale of observation (320x magnification), we studied the distribution of initial cracks first randomly by defining an observation grid on the specimen surface according to Fig. 4a. The grid is composed of barely overlapping observation fields of 640 by 480 μm. Each horizontal band in the figure represents two adjacent bands comprising 480 observations. The surface is scanned along the grid and the position of microcracks and their morphology is recorded in order to follow their evolution at different loading steps. It appears that pre-existing microcracks are narrow in width (about 0.7 μm to 1.2 μm) and that their density is low at this level of magnification. In fact only 9.7% of the observed fields contained microcracks. Microcracks varied in lengths from 50μm to 420μm and were sometimes longer than the observation field. Generally each observation field contained at most one microcrack (Fig. 4b). However around some pores (about 80 to 100 μm in diameter), several microcracks could be seen. The observation of the pre-existing microcracks during crack growth showed that the initial microcracks located at more than 20 mm from the crack path remained unchanged during the crack growth and after the passage of the crack and complete fracture. On the contrary, those who were in the immediate vicinity of the path extended to reach the main crack.



(a) (b)

Fig. 4. a) Observation grid of pre-existing microcracks and b) an example of pre-existing microcrack

6 Controlled crack growth under loading

Under progressive increase of the imposed displacement at the loading points, cracking initiates by the growth of one main microcrack situated at the notch tip. If an aggregate-cement interface is situated at the notch tip, cracking always initiates at the interface. This single growing microcrack is characterised by a tortuous path and sometimes by some short branching. It may cross aggregates depending on their nature or their initial state of microcracking. The identification of the precise location of the main crack tip is very difficult. In general, micrographs clearly show the tendency of the crack to propagate along the interfaces or, depending on the aggregate nature, close to it (up to about 80μm). This behaviour can be explained by the existence of pre-existing microcracks at the interface, as described in section 5, and the higher porosity due to microscopic wall effects along the grains. Figure 5 provides a "map" of the cracks illustrating this phenomenon. It appears

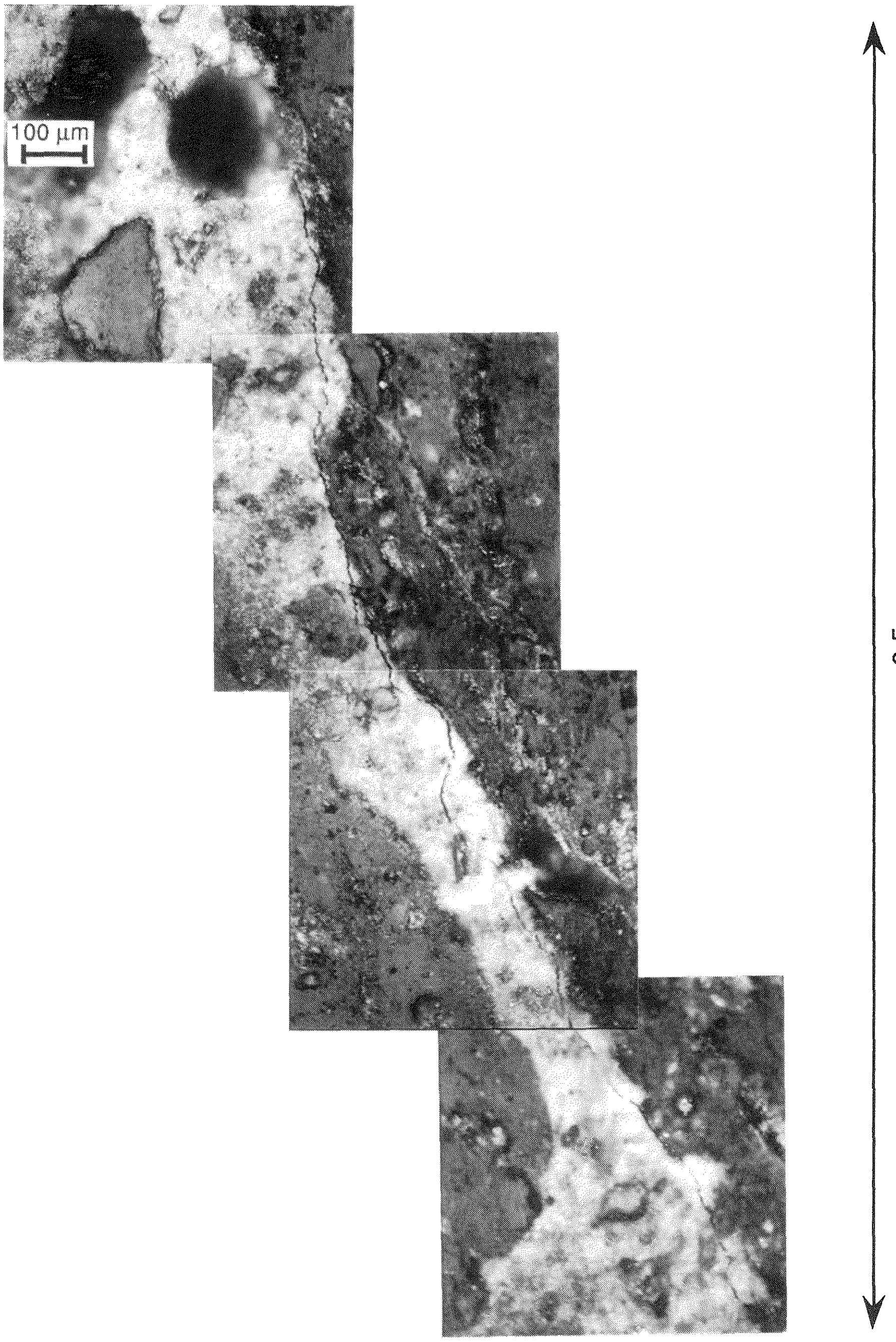


Fig. 5 Composite collage of micrographs illustrating the crack path under stable growth

also that cracks are attracted by large pores. For a given imposed deformation increment, cracks usually end at the aggregate/cement-paste interface or in a pore having a large diameter compared to crack width. This depends on whether the crack propagation takes place in the interfacial region around the aggregates or in the paste separating one aggregate from another. The growth occurs by sudden small jumps.

The main crack is usually continuous but some discontinuity between regions of the main crack has been observed. Tearing away of small material cannot be seen in the branching zone at advanced stages of the growth process and for larger crack widths. It is impossible to predict the path that a crack would take on a subsequent displacement increment. Some microcracks have occasionally been observed in the region of this so-called crack tip but, at the present stage of the investigation, it is difficult to say whether they were pre-existing microcracks, or newly created ones or just resurfacing of the (partly hidden) main crack. This will require further development of the methodology.

7 Observation of crack propagation in unstable conditions

Unstable dynamic crack propagation has been obtained by the impact of a steel ball on a concrete plate simply supported at its centre (Fig. 6a). The drop height has been chosen so that the crack does not reach the sample

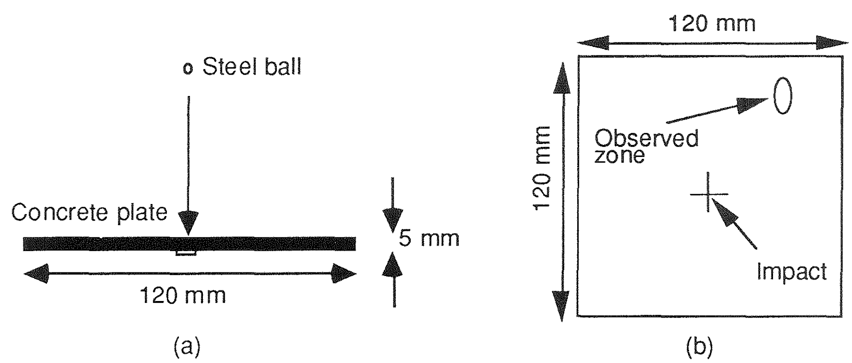


Fig. 6. a) Dynamic load application ; b) observed zone on concrete plate

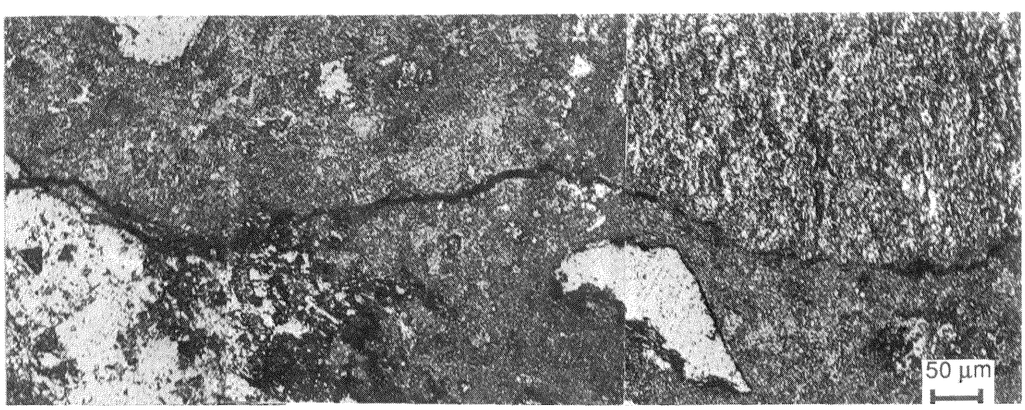


Fig. 7 Crack propagation in unstable conditions

borders. The observed zone being far from the impact point demonstrates the capacity of the crack to propagate by creating its own stress field (Fig. 6b.), Huet (1994). The crack path is tortuous and rarely branched. Observation shows a low crack density near the crack tip. Fig. 7 presents an example of crack propagation under unstable conditions.

8 Observation and measuring of the fracture surface

The fracture surface and its roughness on specimens of cement paste or mortar can give us information on their characteristics. The tortuosity of the cracks and the roughness of the fracture surfaces depend on the processes of microcracking and crack propagation and affect the amount of dissipated and diffused energy, see Huet (1994a), (1994b), (1995).

The most common roughness parameter is R_l defined as the ratio of the actual profile length to the projected profile length. R_l is used to give surface roughness by measuring the profile length of contours created by vertical sections through a surface. Although R_l is determined easily, it is only an approximation of the desired roughness parameter R_S given by the ratio of the actual surface area to the projected surface area. The computation of R_S requires that the surface area be measured directly. We have calculated the roughness R_l from the zx profiles of the topographical images obtained by a confocal microscope of the fracture surface of a hardened cement paste specimen (Fig. 8).

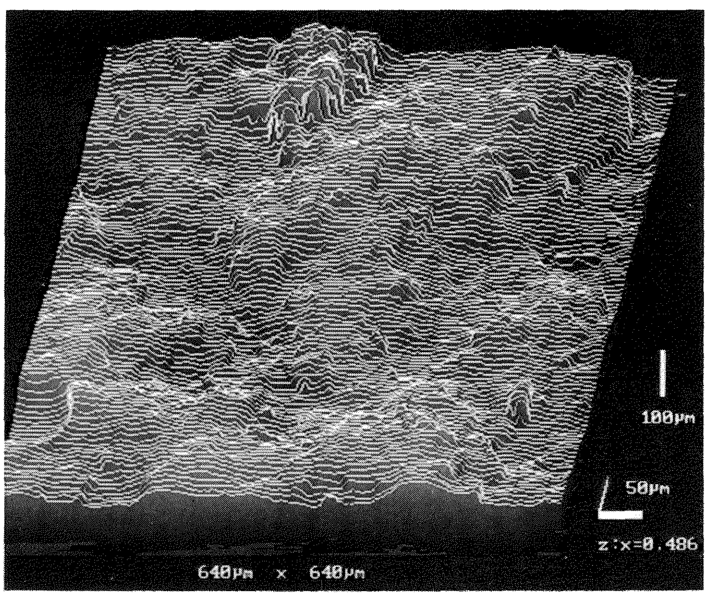


Fig. 8. Fracture surface of the cement paste reconstructed by a confocal microscope

The data has been extracted from four images of 80, 160, 320 and 640 magnifications. The roughness numbers are the ratios of the (mean) profile lengths to their projections (Table 1a).

Table 1. a) Roughness numbers and b) fractal dimensions of the fracture surface of cement paste for different magnifications.

a)

magni-fication	resolution µm/pixel	length(µm)		roughness number
		profile(1)	projected(2)	
80	5.0	3151.03	2560	1.231
160	2.5	1649.66	1280	1.289
320	1.25	849.97	640	1:328
640	0.625	445.11	320	1.391

b)

magnif. range	fractal dim. (D)
80-160	2.0668
160-320	2.0432
320-640	2.0664
80-640	2.0588

The table shows that the roughness number increases with the magnification, as bigger magnifications reveal more details. It means that roughness parameters are scale dependent. One way to obtain a scale-independent measure of the irregularities of the surface is to use fractal analysis and more specifically, fractal dimension. Based on the above data, Fig. 9 presents a log-log plot of roughness number against resolution r, the measuring yardstick corresponding to the size of one pixel in µm.

The figure shows a relatively constant slope, thus a fractal self similarity, in the range of magnifications applied. If m is the slope of the above Richardson plot, $D_l = 1 - m$ will be the fractal dimension of the profile and $D = 2 - m$ that of the surface.

The fractal dimensions of the fracture surface of cement paste for the different segments of the plot (between two magnifications) and the global fractal dimension (80-640) of the specimen studied are given in Table 1b.

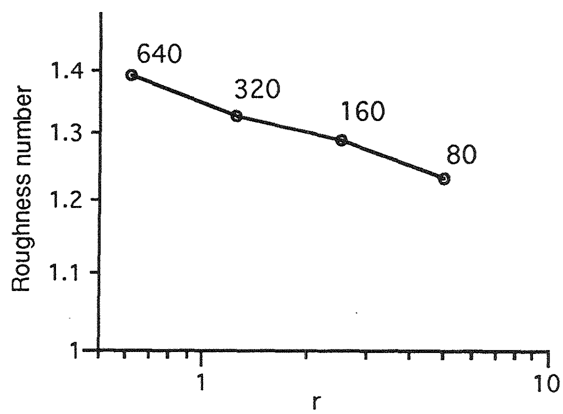


Fig. 9. Richardson plot of roughness numbers of the fracture surface of cement paste. Figures on the graphic represent magnifications

9 Conclusions

The use of the confocal microscope makes possible the observation of microcracks in concrete in various conditions. In particular, the development of an associated CT tensile set-up allows the observation of the initial state of microcracking and of slow crack growth in concrete. Observations of pre-existing cracks show that in our case their density is low and that they evolve only if they are situated in the immediate vicinity of the crack path. Cracking in concrete is marked by some short branching and a tortuous path avoiding the grains. The area in front of the tip of a growing crack exhibits some isolated microcracks which determine future crack path. At present, it is not possible to assert whether these must be attributed to the expansion of pre-existing microcracks or to the generation of new ones or still to resurfacing of the main crack partly diving below the surface. Cracks develop by running along the interfacial zones due to the mechanically weak character of this zone and the existence of pre-existing microcracks in this region. Confocal microscopy, providing topographical information, allows us to measure the roughness and the fractal dimensions of the fracture surface.

10 References

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