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About the analysis of microcracking in concrete

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Abstract

This paper deals with the techniques of characterisation of cracks and microcracks in concrete and mortars. It gives an overall view of the methods of observation in relation with image analysis. Image analysis is a useful tool to extract crack patterns from samples of concrete, since many fields are necessary to be studied at high magnifications. An analysis of the procedures and of the provided 2-D data is proposed. The parameters of damage characterisation are listed and discussed. Improvements and ways of research are suggested, mainly to extend 2-D results to 3-D space by means of crack-pattern modelling. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

A lot of works dealing with cracks or microcracks in cement-based materials have been published these last years. The aim of the authors was either to relate the microcracked state of concrete (or mortar) to its physical properties, or to evaluate the microcracking produced by a loading (thermal action, shrinkage, creep or mechanical loading).

The aim of this paper is to point out the difficulties that appear in studying microcracks and cracks in cement-based material.

2. Strategy for microcracking study

2.1. Choice of the tool for observations

Two tools are necessary to characterise microcracking: one for observation and one for quantitative analysis.

Different methods have been used for observing microcracking and cracking since the 1960s. Here they are summarised in a schema (Fig. 1) where tools are related to the accuracy of the observation.

If we discard indirect methods (like acoustic ones) for focusing for attention to techniques which give images, two ways seem to come up: scanning electronic microscopy (SEM) coupled with the replica technique and optical microscopy. These methods are complementary towards their resolution, both give bi-dimensional images avoiding bias, can be applied to mortar or concrete, do not required special shapes or dimensions of specimens and finally, are not to difficult to use.

The replica technique as a tool for investigating microcracks in concrete has been introduced by Ollivier [1] and used by several authors [2,3], for instance. Its main advantage is to allow taking crackprints on surfaces of concrete without disturbing the core or the building. Among other works, microcracks created by compressive loading [3,4] or produced by creep and shrinkage [5] have been studied.

In parallel, some authors have developed and enhanced methods based on optical microscopy for microcrack study in concrete [6,7]. These techniques necessitate a dye impregnation preliminary to the observation but no drying is required, thus avoiding any bias. Often, the dye in excess is eliminated by a light polishing. Of course, dye not only fills cracks but also macropores and porous interfacial zones.

2.2. Problem of the scale

As illustrated by Fig. 2, the first difficulty in using images for investigation of cracks pattern comes

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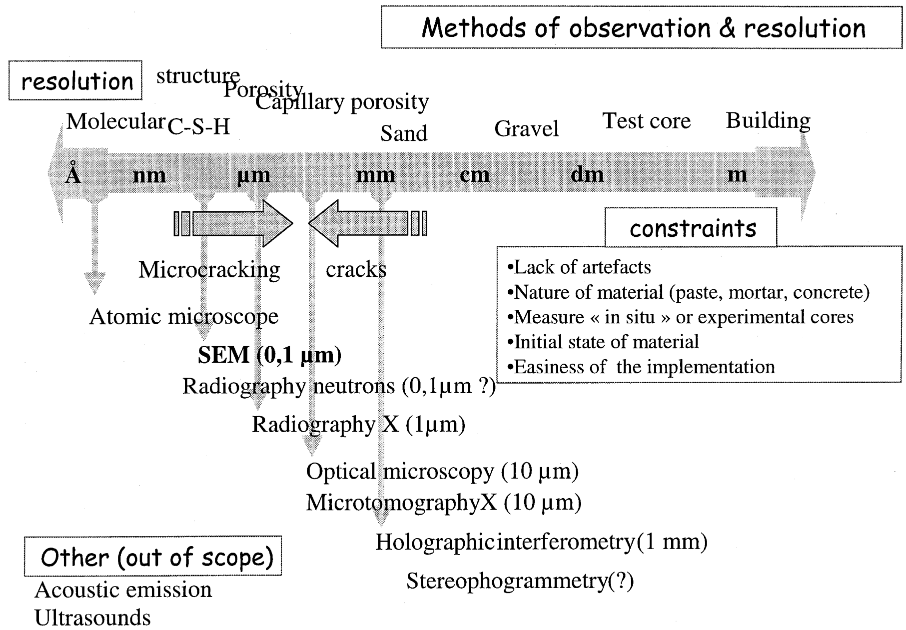

Fig. 1. Scales covered by different methods of observation.

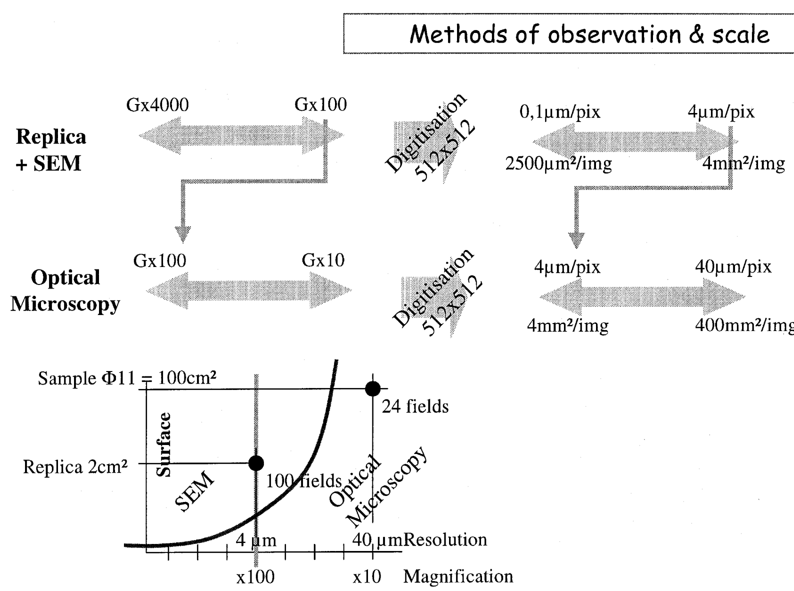

Fig. 2. The area covered by each field increases as the square of the resolution.

from the fact that images give a local information of the material. Most often, there is a disproportion between the size of the core-test (or furthermore, the building) and the dimensions of the images (or fields).

For example, testing a single section of $\phi 11 \times 32$ cm test-core, typically requires 24 images in optical microscopy at $G \times 10$ magnification. Each field has a side of 2 cm which is also the dimension of one replica. If such a replica if observed within a SEM at $G \times 100$, it will be cut in 100 fields. Hence, even with low magnification, analysis of cracking necessitates a lot of data. Contrariwise, the mechanical damage resulting of the apparition of the cracks can be globally characterised by the sample behaviour. Finally, image-based techniques deliver data which are abundant but partial at a time so that one has to be careful when analysing these data.

2.3. Difficulty of the segmentation

The segmentation of cracks consists in recognising them from the images. In the past, this operation was done by hand from photographs. But some researchers made attempts at using image analysis for this purpose [8–10] in order to make up an automatic process.

The usual stages of such a treatment are

- combination of the RGB components into one image in the case of colour acquisition,
- filtering: for avoiding over-segmentation,
- binarisation, most of the employed methods being only based on the radiometric histogram (for instance, the maximisation of entropy algorithm),
- shape analysis and elimination of non-crack objects: this stage necessitates the individual analysis of each convex component in the image and is time consuming,
- skeletonisation.

Once this treatment has been done, authors perform their analysis. Some remarks can be pointed out about segmentation.

- Most noise filters introduce blur outlines and therefore affect boundaries of cracks.
- Some algorithms of binarisation, more sophisticated than the one presented above, could be applied for extracting cracks with more accuracy; among them, classification algorithms, growing form algorithms, watershed, for instance. Often, the employed techniques always give a result, whatever cracks are present or not on the images: the algorithm must be completed by a decision stage.
- Objects other than cracks would be also extracted like granulates, hydrates, fibres and so on, for enabling the observer to reconstitute the context of cracking.
- Systematic skeletonisation forbids crack-width analysis. In fact, most of the techniques of preparation of samples do not give accurate image of the crack opening.

2.4. 2-D parameters

A crack pattern is schematised in Fig. 3, with the main characterising parameters.

Among the parameters analysed by the different authors, the parameters derived from the length of cracks play a privileged role. The specific length L_A, the intercepts $N_L(\theta)$ – or the diametrical variation – and the degree of orientation ϖ are often used for the characterisation of microcracking.

It seems that an effort must be made to characterise crack width and other parameters when the crack pattern must be transport properties of the material. For example, Gerard and Marchand [11] have proposed a predictive model of the diffusion properties of concrete based on two parameters: the crack density and the mean effective crack width L_4. But it appears that their model needs also a tortuosity parameter (τ) and that it relies on to the hypothesis of the continuity of the crack pattern. This interesting work shows clearly the way for

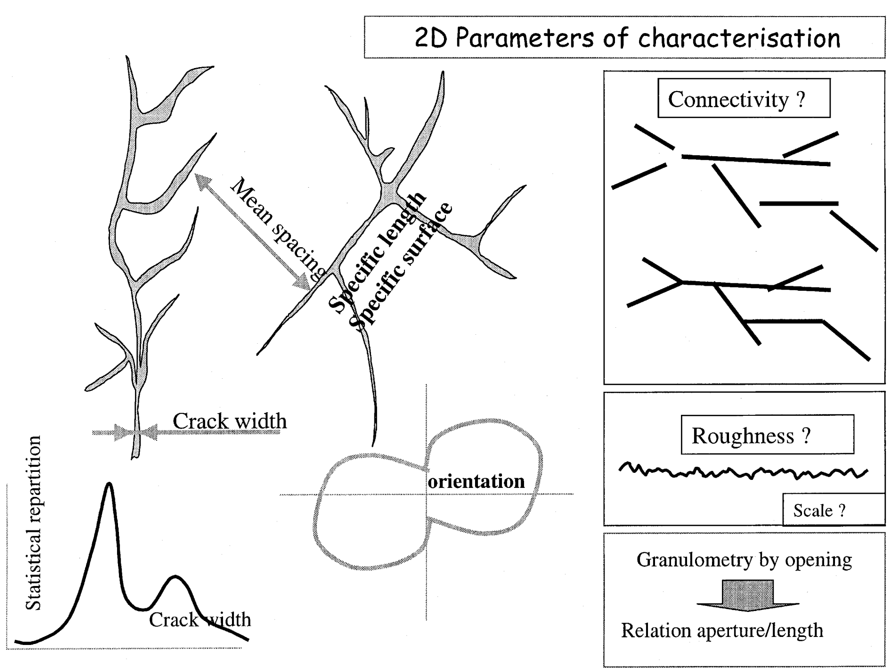

Fig. 3. Some parameters in the plane of observation.

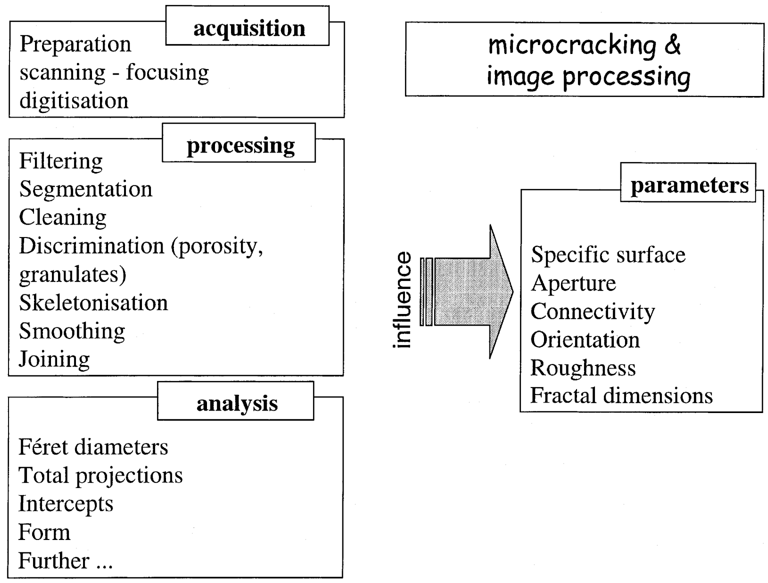

Fig. 4. Variability of the measured parameters.

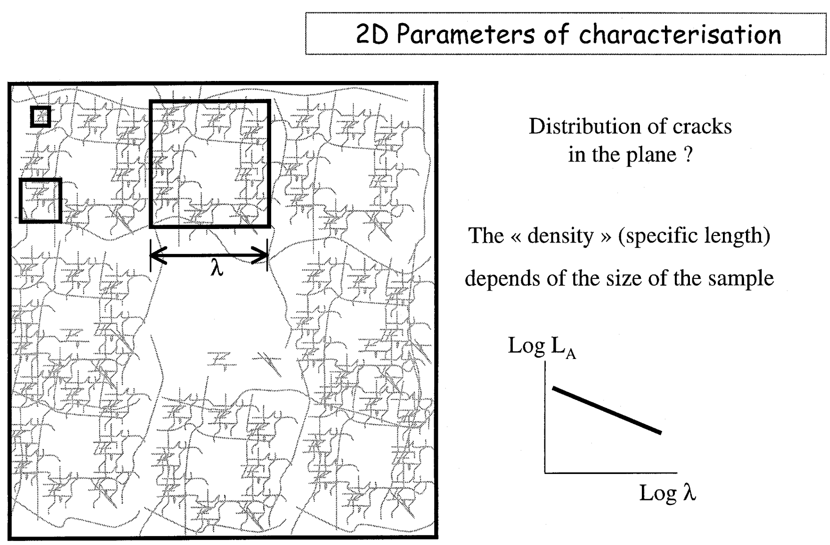

Fig. 5. Cracks can have non-uniform density.

future researches on crack pattern: roughness, crack width, spacing and connectivity must be accurately quantified.

The variability of the parameters with all the stage of preparation of the sample, of the images and of the image processing must be studied (Fig. 4).

It has to be pointed out that stereological parameters must be in accordance with the Hadwiger laws [12]. For example, the parameter L_A, most often named "crack density" by the authors, depends on the magnification at which the observations have been made. As $W(\lambda L_2) \neq \lambda^2 W(L_2)$, the quantity L_2 (from which L_A is derived) is not scale homogeneous. This phenomenon is reported by Ammouche et al. [10] but the authors minimise it (the magnifications they use vary only between $G \times 25$ and $G \times 80$).

In fact, this variability of the crack density with the magnification can be related to different aspects.

A first aspect comes from that small details of cracks disappear when magnification decreases. Indeed, the thinnest cracks are visible only when the resolution is sufficient. The full exploitation of this simple statement could lead to information on the crack widths. Magnifications of the system used for observation play the role of sieves and could thus enable to establish a kind of "granulometry" of cracks.

A second aspect is that cracks can cover the observed surface in a non-uniform manner, so that "holes" appear at all scales. The Fig. 5 shows schematically such a pattern like a Sierpinski carpet. A fractal dimension can be computed from measurements made at different scales as described by Mandelbrot [13].

A third aspect is related to the roughness of the crack pattern. Several techniques based on image analysis have been proposed for determining the fractal dimension due to the roughness. Among them, the method of compass due to Richardson, the method of dilation due to Minkowski, the method of the boxes and the method of density-correlation are reported in [12–15] and summarised in [16].

2.5. 3-D parameters

Further to 2-D parameter values deduced from image analysis of plane observation, the next step is to extend the results to the three-dimensional space occupied by the test-core (or the building). The alternatives are listed in Fig. 6.

Today, in most situations, results are extended to 3-D space by applying stereological laws. Many times, only the crack density is exploited. For example, the specific surface of cracks S_V is derived from its density L_A by the formula $S_V = (4/\pi) L_A$ which supposes the isotropy of the crack pattern in all the 3-D directions. This last hypothesis does not often apply. It is rarely checked because no study is performed on different oriented planes. In fact, this stereological relation is not adequate in most situations and it could be replaced by $S_V = L_A$ when a privileged direction due to geometry of the sample and the direction of the loading produce a pattern which is probably cylindrical.

The most accurate method for obtaining three-dimensional data would consist of rebuilding the spatial crack pattern from observations made in different planes. If the planes are parallel, this technique is similar

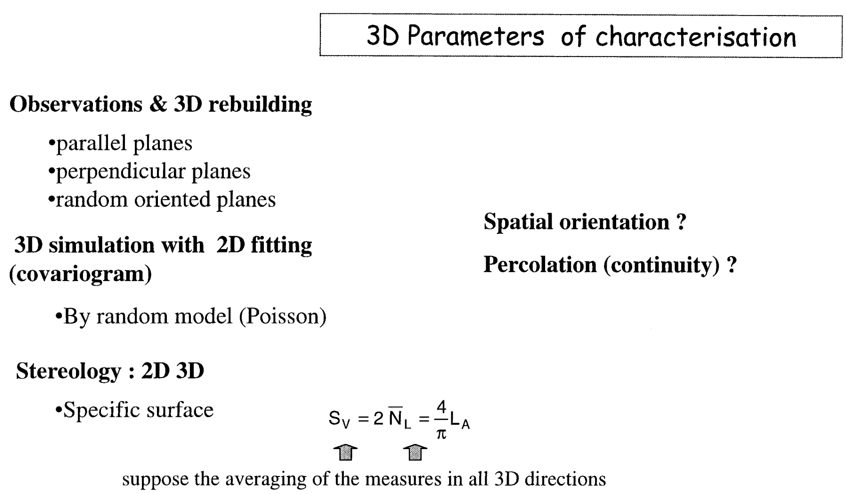

Fig. 6. How to obtain quantitative parameters in space.

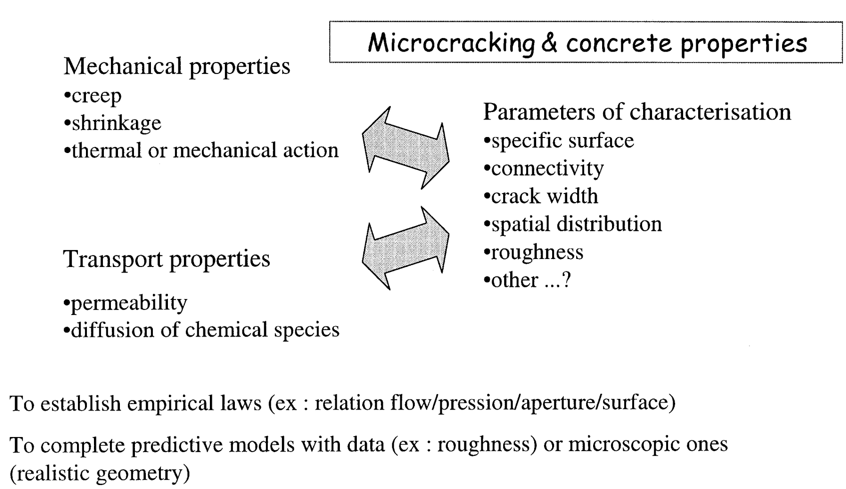

Fig. 7. What are the relations between concrete properties and crack parameters?

to tomography used in medicinal science. Unfortunately, this approach requires large amounts of data and it is not realistic in material science though some works have been published on this topic but always describing a very little volume [17].

In fact, only 3-D simulations seem to be able to give accurate results and a realistic geometry with reasonable amounts of data at a time. Such Boolean models, introduced by Jeulin [18], have been successfully used by Quenc'h et al. [19] or Ringot and Cros [20] to describe the structure of materials. Today, no attempt at using these powerful modellings on the 3-D structure of cracks has been published. However, applying statistic modellings for simulating crack patterns could be useful to derive important results, in particular about percolation properties related to the connectivity.

2.6. Microcracking and concrete properties

As suggested by Fig. 7, the ultimate stage of cracking analysis is to relate crack parameters with the properties of concrete.

The pertinent parameters that must be used for this purpose appear through physical modellings such as diffusivity modelling, for instance [11]. The crack density often appears as a major parameter. But crack width, roughness, connectivity are also required and researchers do not dispose of sufficient or accurate data. Hence, today, they are compelled to make some assumptions or simplifications.

3. Conclusion

Even though microcracking of concrete has been studied for 40 years, its objective characterisation related to material properties still poses problems. Due to recent technological improvements in acquisition and processing such as image analysis, the amount of data that can be analysed has meaningfully increased. This makes possible more systematic and more accurate measurements. However, some stages stay unexplored and we recommend to develop methods for determining how cracks occupy the space and finally to establish statistical models of the crack pattern for determining the three-dimensional connectivity of the cracks.

References

[1] Ollivier JP. A non destructive procedure to observe microcracks of concrete by scanning electron microscope. Cem Concr Res 1985;15:1055–60.
[2] Ringot E, Ollivier JP, Maso JC. Characterisation of initial state of concrete with regard to microcracking. Cem Concr Res 1987;17:411–9.
[3] Turatsinze A, Bascoul A. Microstructural characterisation of mode 1 crack opening in mortar. Mater Structures 1994;27:71–8.
[4] Ringot E. Development of the map cracking in concrete under compressive loading. Cem Concr Res 1988;18:933–42.
[5] Sicard V, François R, Ringot E, Pons G. Influence of creep and shrinkage on cracking in high strength concrete. Cem Concr Res 1992;22:159–68.
[6] Knab LI, Walker HN, Clifton JR, Fuler ER. Fluorescent thin section to observe the fracture zone in mortar. Cem Concr Res 1984;14:339–44.
[7] Hornain H, Marchand J, Ammouche A, Moranville M. Microscopic observation of cracks in concrete – a new sample preparation technique using dye impregnation. Cem Concr Res 1996;26:869–81.
[8] Salomon M, Panetier M. Quantification du degré d'avancement de l'alkali-réaction dans les bétons et la microfissuration associée. In: Proceedings of the Third CANNET/ACI, International Conference on Durability of Concrete. Nice; 1994. p. 383–401.
[9] Al Hassani Y, Bascoul A, Ringot E. Microcrack study of cement-based materials by means of image analysis. Mater Res Soc 1994;370:43–8.
[10] Ammouche A, Breysse D, Hornain H, Didry O, Marchand J. A new image analysis technique for the quantitative assessment of microcracks in cement-based materials. Cem Concr Res 2000;30:25–35.
[11] Gérard B, Marchand J. Influence of cracking on the diffusion properties of cement-based materials. – Part I: Influence of continuous cracks on the steady-state regime. Cem Concr Res 2000;30:37–435.
[12] Coster M, Chermant JL. Précis d'analyse d'images. Presses du CNRS; 1989. p. 20–3.
[13] Mandelbrot B. Les objets Fractals. 2nd ed. Flammarion; 1983.
[14] Sandau K. A further method to measure fractal dimension and the maximum property. Acta Stereol 1996;15(1):83–90.
[15] Teixeria J. Experimental methods for studying fractal aggregates. On growth and form. NATO ASI, series E: applied sciences N.100, Cargése. France: Corsica; 1985.
[16] AI Hassani Y. Contribution á la reconnaissance de la fissuration dans le béton par analyse d'images. Ph.D. thesis, Toulouse; 1998.
[17] Tricart JP, Brevart O, Baranger R, Martinez L. Analyse quantitative d'images électroniques et chimiques. Bull Cent Rech Elf-Aquitaine 1991;15:279–305.
[18] Jeulin D. Ph.D. thesis, Ecole Supérieure des Mines de Paris; 1979.
[19] Quenec'h JL, Coster M, Chermant JL. Application of probabilistic models to the description of the growth of titanium carbides during liquid phase sintering. Acta Stereol 1993;13:287–92.
[20] Ringot E, Cros H. Boolean model of the fresh cement paste structure. Aussois, France: Réunion du réseau GEO; 1996.