DAMAGE MECHANISMS IN FIBRE REINFORCED CONCRETE COMPOSITES

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Concrete's are composites containing an aggregate and a binder as major components. The latter can be either cementitous or not. The aggregate in the material body constitutes a dense random packing of a wide range of particle sizes, thereby providing the load-bearing skeleton. Bond between these phases is - particularly for river aggregate - relatively weak, so that damage evolution is intimately connected with the geometrical statistical features of the aggregate packing. When bond cracks coalesce, they are confronted eventually with fibres, which strongly influence the further opening up of such cracks. The main characteristics of the damage evolution process under direct compressive or tensile loadings is described for plain and fibre reinforced cementitious composites.

INTRODUCTION

'Concrete' belongs to a class of *macroscopically heterogeneous composites*: structural dimensions are governed by those of the coarse aggregate. The size of the largest particles depends on the type of application (generally, 30 to 60 mm). A reduction of particle size will yield mortar. Concrete and mortar are representatives of the same category of *cementitious composites*. A wide variety of concrete composites is on the market. They are composed of a binder and a filler. The filler can consist of relatively hard and strong particles, but also natural or artificial lightweight aggregates are in use. In normal concrete the particles form a load-bearing skeleton in compression. Short wires are added to positively influence the structural degradation process. Size of fibres and largest particles are of the same order of magnitude (Fig. 1).

Cementitous binders have been blended with hydraulic ashes, or combined with polymers, epoxies, etc. Also cement-free or ceramic binders have been developed. High strength can be achieved with cementitious binders. Microsilica

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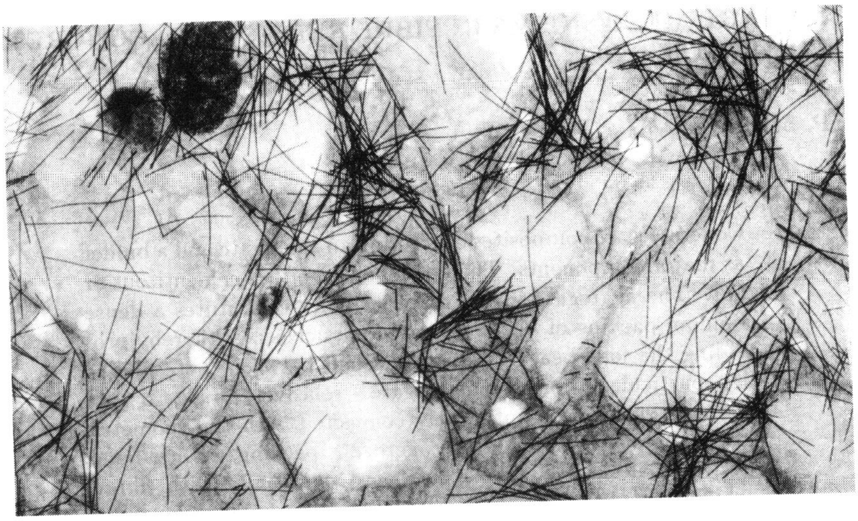

Fig. 1. Particulate and fibrous structure of steel fibre concrete.

or condensed silica fume are added to the Portland cement for that purpose. Particularly bond along the particle-matrix interfaces - being the weakest chain link in the mechanical system - is significantly improved by the reduced spacing at the interface. Hereby, van der Waals binding forces will be disproportionally increased. As a result of the wide variety of composites denoted as CONCRETE, it is only possible to deal with mechanisms of damage evolution in general sense. Further, normal weight concrete containing river aggregate is taken as a reference.

DAMAGE EVOLUTION AT STRUCTURAL LEVEL

The hard and strong particles play an essential role in the damage evolution process. The aggregate take up a dualistic position. The aggregate forms the load-bearing skeleton. Moreover, the particles can arrest propagating cracks. But the particles are also loosely bonded to the matrix, leading to premature debonding. A process of crack coalescence will gradually break down the load bearing capacity. The process of structural loosening can be distinguished in four ranges, as suggested earlier by Glucklich (1):

- Bond cracks and high stress concentrations are the result of the transfer from the fresh into the hardened state. Under low global stresses part of these stress peaks will be released through interface debonding. Crack development over the first part of the stress-strain branch has a consequence an isolated character and is strongly governed by stochastic infuences. The effect on the global strain development is insignificant, so that the behaviour is generally defined as quasi-elastic.

• Deterministic influences will gain momentum over the next loading range. A selective set of interface cracks will grow during this stage, leading to partial orientation in the crack population (Stroeven (2)). Main direction is parallel to that of global compression or perpendicular to that of global tension. Deformations will be non-linear. Hence, the axial stress-axial strain curve will reveal a discontinuity at the starting point of this loading stage (Moczko, *et al* (3)). Effect on Poisson's ratio is nevertheless small, but a slight increase in compression and a similarly small decline in tension is found.

• The next stage of damage evolution is characterized by an acceleration in the formation of so called 'bridge cracks', resulting from coalescing bond cracks. In compression, the larger bond cracks propagate from the 'equatorial' area along the surface of conically-shaped, triaxially compressed zones at the particle's poles. These areas are pre-weakened by bond cracks of smaller particles, which form an *en échelon* crack array (Fig. 2). The en échelon cracks coalesce due to high local shear stresses. The number of cracks thereby starts declining, whereas average size increases. Due to the oblique orientation of these "shear bands", the global orientation distribution looses its predominant axial orientation (Stroeven (2)). The interaction between neighbouring cracks is of rising importance. This leads to a discontinuity in the strain development perpendicular to the major crack direction, and hence in Poisson's ratio. This 'point' is associated with the fatigue strength.

• Under compression the material continuously redistributes the internal stresses to compensate for the detrimental effect of cracking, i.e. a reduction in local load-bearing capacity. Gradually, the process of coalescence concentrates in one or more process zones. An acceleration in this process is marked by a reversed tendency in volumetric strain, which shortly thereafter attains its lowest value (associated with the long term strength).

• BOP is an insignificant point in structural sense. It only demarcates in a global sense the onset of yielding. The cracking process has beyond discontinuity a dynamic character: a premature structural collapse can occur, unless the driving force of the system can be reduced fast enough. This is particularly so after BOP. The material body's possibilities for compensating the reduction in bearing capacity by re-distribution of its internal stress field during crack coalescence are more restricted in case of tensile loading. The process of crack coalescence will therefore in the latter case be less advanced at BOP.

• During yielding, crack development is more and more concentrating in the

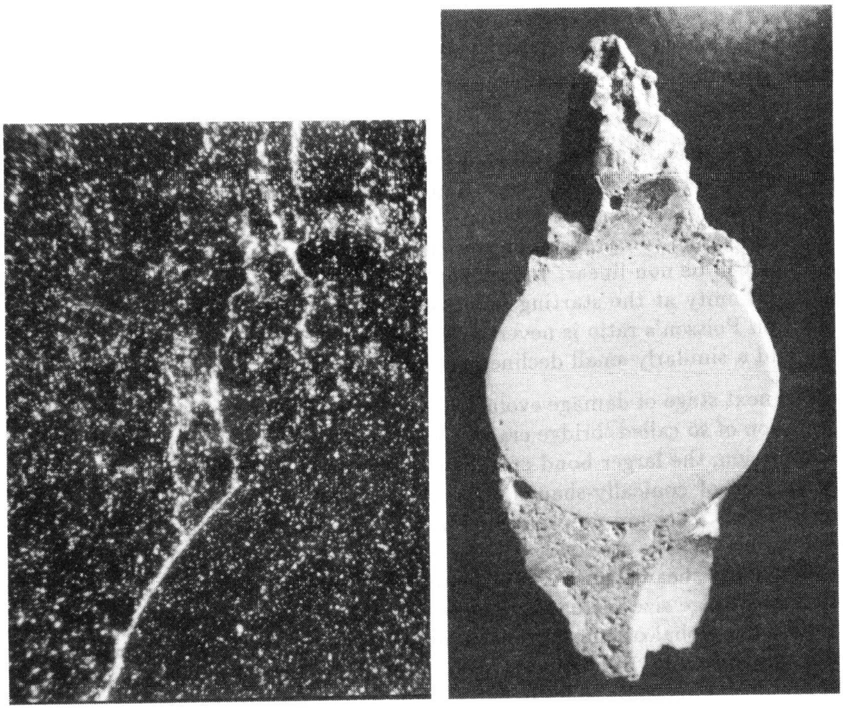

Fig. 2. “En échelon” crack array, at the left, and particle with conical mortar deposites found among the debris at the end of the direct compression test, at the right.

fracture process zone(s). Even in an advanced state, when the path of the macrocrack is becoming more obvious, it is impossible to set boundaries to these zones (Buresch (4))). Nevertheless, major crack development takes place in a zone extending over about three times maximum grain size (Stroeven (5)). For full destruction of the material under controlled deformations the major portion of crack coalescence has to take place beyond ultimate, both in tension as well as in compression.

- Fibres do not change mechanisms along the ascending branch of the stress-strain curve. Bond cracking is not influenced at all. Fibres control the opening up of cracks, a contribution becoming more significant upon continuing crack coalescence They enhance the capacity for stress re-distribution and give the material in the post-ultimate domain a considerable amount of toughness due to fibre pull-out and fibre sliding over the crack edges.

ANALYTICAL AND EXPERIMENTAL EVIDENCE

Vile (6) was probably the first to propose a model for meso-cracking underlying global damage evolution in direct compression. The topic also received attention by Stroeven (2), Lusche (7), Mihul (8) and Perry and Gillott (9). They also provided experimental evidence in support of the model, which recognizes the interface between particles and matrix as the weakest link. Elastic solutions for single inclusions in an infinite matrix predict in direct compression a relatively unfavourable stress situations at the 'equator'. The matrix material at pole positions is in biaxial (or for 3-D solutions: triaxial) compression. Such solutions are readily available and date back some sixty year. The 3-D solution by Goodier (1933), and the 2-D one's given by Muskhelishvili (1953) and Sezawa and Nishimura (1931) have been elaborated by Stroeven (2) for concrete; solutions for various stress components were presented in graphical form. The 3-D case is shown to yield the more unfavourable results. Of course, in direct tension relatively high triaxial tensile stresses will arise at the poles. The conditions of the elastic continuum are fulfilled for photoelastic models. Thibodeau and Wood (10) used rubber as matrix material and as a consequence even detected in a compression test tensile stresses in the equatorial regions. This is in conformity with the elastic solutions for larger values of Poisson's ratio. Creep deformations can cause Poisson's ratio in concrete also to rise above the conventionally applied value of 1/6, however. In addition to stresses being relatively high at the interface, bond strength is shown to be low by micro-hardness investigations, the oldest ones of which are due to Lyubimova and Pinus (11). More recent studies also evidence "valley"-shaped hardness changes over the interphase layer (Yuji, (12)).

The effects of high stress and low strength lead to debonding which can be visulalized by reflective photoelasticity (e.g. Frocht (13); Stroeven (2)). The formation of structuring elements consisting of either a single (larger) particle, or of small clusters of nearby particles, provided with the conically-shaped "hats", can be seen. Strings of such elements constitute the skeleton of the material body. After rupture in direct compression the elements can still be found among the debris, as shown by various authors (Fig. 2). A very sensitive, contact-free approach is by holographic interferometry. The method only allows the observation of the specimen's surfaces. When the outer layer of the concrete composite is removed, it nevertheless renders possible to study damage evolution around particles (Stroeven (2)) or around linear steel elements.

CONCLUSIONS

The paper describes the mechanisms of structural loosening on mesolevel of a wide variety of (fibre) concretes, although prime reference in this paper is given to normal weight concrete containing river aggregate. Insight into such mechanisms allows to more systematically develop new concrete composites. This paper is a brief introduction in the subject. More specific details could have been added, but the scope of this paper did not allow to do so.

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