OPTICAL MICROSCOPY AND NUMERICAL SIMULATIONS OF INTERFACE FRACTURE IN CEMENT-BASED MATERIALS

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A splitting test for studying the interface between aggregate and matrix is presented. A perfectly horizontal splitting load is applied at relatively thin specimens (thickness 15 mm). Since the geometry enhances only two dimensions, the experiments are easy accessible for simulations with a numerical lattice model. Emphasis is put on the influence of the type of aggregate. Porous (sandstone) and dense (granite) aggregates are compared to each other. The results indicate that the strength of the aggregate increases with the density. However, the performance of the ITZ decreases. The overall strength of the specimen decreases when the results of the single aggregate tests are compared to identical tests on plain matrix alone (no aggregate embedded). These observations are confirmed by numerical simulations.

INTRODUCTION

Fracture in concrete is characterized by the three phases in the material, i.e. the aggregate particles, the matrix or cement paste, and the interfacial transition zone (ITZ) between matrix and aggregate. However, in this context, it is important which level of observation is considered, since in the limit case, when the material behaviour of large structures is studied, concrete may be considered as a single-phase or continuum material. Nevertheless, to describe the material (or structural) behaviour at such a level, knowledge of lower levels of observations is required (1) next to a good definition of the boundary conditions, given by the structure. Overall effects (observed at the macro-level), may overrule the effects of microstructural phenomenon in the material, but, since fracture of concrete remains a local effect, the behaviour of the material at the microlevel and the meso-level have to be considered in order to obtain qualitatively correct predictions at the macroscopic level. When these lower levels are considered, failure of concrete is always initiated in that part of the material where the combination of low strength and high stress is normative. In general this is the ITZ between the aggregates and the cement paste (2). Notches and other boundary conditions of a specimen, cause stress concentrations, and therefore contribute to the mechanism of crack initiation and crack growth (3). In this paper, structural effects are not studied explicitely, but the emphasis is on studying the ITZ.

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A number of methods have been proposed for investigating the mechanical bond properties of the ITZ (4). In this paper splitting tests are discussed, in which a single sized (cylindrical) aggregate particle is embedded at a prescribed position in the matrix. Additional to conventional displacement measurements, visual observations at the meso-level were performed. For this purpose a long distance optical microscope was adopted.

EXPERIMENTS

Because the optical microscope monitors only the surface of the specimen, relatively thin (15 mm) specimens were used with planar dimensions 125×170 mm (Figure 1a). To fix the position of crack initiation, a 30 mm deep notch was sawn at half width of the specimen. An open frame has been developed in which the specimen is positioned during testing (Figure 1b). The base of the notch is chosen just beneath the upper bar of the loading frame. At the top of the specimen two loading platens are glued, between which a perfectly horizontal splitting load can be applied. A new device (Figure 1b) was developed for this purpose. It was decided to apply a horizontal load rather than the more common wedge-splitting-load (5), in order to avoid vertical stresses in the specimen. For the displacement measurements, two LVDTs (measuring length 15 mm) are glued across the top of the notch, at each side of the specimen. The crack-mouth-opening-displacement (CMOD) is calculated as the average of these two LVDTs and has been monitored either until complete fracture of the specimen occured or until a maximum CMOD of approximately equal to 160 μm was measured. The system is explained in more detail in (6) and (avphd).

To retrieve more detailed information regarding the (micro)cracks that develop at the surface of the specimen, real time measurements are performed with a high resolution long-distance-optical-microscope (i.e. QUESTAR RMS). The system was already available at the laboratory for quite some years but was suitable for manual scanning only. Recently, the system has been upgraded for automatically rescanning the crack path and storing the digitized images (6).

Different types of matrix were casted around a carefully prepared aggregate particle. For the matrix, four different mortars and three cement paste mixtures were tested. The mix proportions, as well as the standard test results are reported in (6). For the aggregates, several types of rock were used. Cored cylinders were embedded at a prescribed position in the matrix, as indicated in Figure 1a. The results of a splitting test of plain matrix material are compared to the results of a specimen containing either a dense aggregate particle (granite) or a porous aggregate particle (sandstone).

To clarify the most significant effects of the type of aggregate, two characterisic examples are given in Figure 2 and 3. Each figure shows the observed final crack patterns and corresponding load-CMOD curve for a single aggregate particle embedded in a mortar matrix. The dotted line in the graph shows the softening curve of a similar specimen without the large aggregate. Failure in a specimen with a granite particle starts at the notch, and is related to the first peak in the load-CMOD curve (Figure 2a). Because of the presence of the aggregate, the crack is arrested and a second increase of the load is found. Another (steep) drop of the load is observed in the load-CMOD response, when the crack starts to grow along the interface. Cracking proceeds to the left edge of the specimen (Figure 2b), which is reflected by the final softening branch in the load-CMOD curve. The fact that the crack initiates at the notch instead of along the ITZ like in (normal) concrete, can be explained by the fairly large dimensions and isolated location of the single aggregate. In Figure 2c and 2d two stages of cracking are reported. Each stage is indicated by a black dot in Figure 2a. The image in Figure 2c is monitored just before the second peak is reached. At this stage a few microcracks have developed in the ITZ. In the stage after the second peak (Figure 2d) the crack is fully developed and during the remainder of the test only further crack opening is observed in this area. When a sandstone aggregate is used (Figure 3) the crack is more likely to grow through the aggregate, instead of along the interface. Moreover, the second peak in the load-CMOD curve is much higher than in the case of the granite. For the specimens containing sandstone aggregates it should be mentioned that not all cracks grew through the aggregate, but (depending on the porosity, and thus the strength, of the ITZ) also cracking along the ITZ could occur.

SIMULATIONS

Simulations are performed with the lattice model developed in the Stevin Laboratory (3). In the model the specimen is discretized using a network of brittle breaking beam elements. Cracking is obtained by removing one element in each (linear elastic) load-step from the mesh. For the model a so-called random lattice was used with an average beam length of 1 mm and a randomness of the node configuration of A=0.75 (7). Three beam types are distinguished when the material structure is considered, i.e. beams falling inside the aggregate, beams belonging to the matrix, and beams in the ITZ between aggregate and matrix. Comparing the results of the simulations with the experimental observations, it is attempted to obtain a better understanding of the input parameters of the beams in the ITZ. Only a few (single valued) parameters, are required in the lattice model, i.e. the beam strength and stiffness for each phase. For calculating the stresses in the beams a fracture law is introduced with two additional parameters. In this paper only the influence of the strength and stiffness of the beams in the ITZ is studied.

In Figure 4 three simulations (derived from a series of simulations) are shown. They resemble the results of a specimen containing a granite and sandstone aggregate (Figure 4b and 4c respectively), and a specimen containing no aggregate at all

(Figure 4a). In the remainder of this paper, the simulations will be referred to as simulation 4a, 4b and 4c for Figure 4a, 4b and 4c respectively. For a complete overview of the simulations performed the reader is referred to (7).

The crack patterns of the selected simulations are obtained at the end of each simulation. For the specimen containing no aggregates (simulation 4a), cracking proceeds in a curved path from the notch to the specimen edge. This is consistent to the experimental observations (6). Crack initiation in a specimen containing a granite aggregate (simulation 4b), is observed at the notch, whereafter cracking in the ITZ starts. When the strength of the beams in the ITZ decreases, the position of crack initiation switches from the notch to the interface. This effect can be quantified by the number of broken bonds during the first stage in the fracture process (in the pre-peak region), which was 63% of the total amount of broken beams. Increasing the stiffness of the interface beams (for constant beam strength), also causes an increase of this ratio, since stresses tend to become larger with increasing beam stiffness. However, the impact of these changes is less pronounced compared to changing the beam strength. It is noted that, when only small changes are made to the input parameters (compared to simulation 4b), crack growth was arbitrary above (like in Figure 4b) and beneath the aggregate, while in the experiments, always crack growth around the upper side of the aggregate occured. Nevertheless, in both the experiments and the simulations, interface cracks were observed, almost along the complete circumference of the aggregate. In the experiments, however, the aggregate is obstructed from pull-out, because of frictional effects between the aggregate and matrix. In the simulations, this effect can not be modelled since two parts of a separated lattice are allowed to overlap.

For a specimen containing a sandstone aggregate (simulation 4c) the strength of the interfacial beam elements seems to be the controlling parameters as well. Both in the experiments and simulations crack growth was observed through the particle as well as along the interface. In the experiments this can be explained by the porosity of the ITZ (due to less good compaction). In the simulations no clear correlation was found between intra-particle fracture and the strength or stiffness of the interfacial beams. In simulation 4c the percentage of bond elements failed at the peak-load was about 8%, which is caused by a more continous crack growth from the notch compared to simulation 4b.

CONCLUSIONS

In the paper results are presented of experiments and simulations of interface fracture. In order to study failure of the ITZ, a single aggregate was embedded in a matrix of cement paste or mortar. Granite and sandstone aggregates were compared to a specimen containing no aggregates at all. From the experiments it was concluded that for increasing aggregate density, a transition in the failure mechanism is found from interface cracking to intra-particle cracking. A lattice model is adopted for simulating the interface tests. It is shown that the strength of the beam elements has a more pronounsed effect on the fracture behaviour than varying the stiffness of the beams in the ITZ. The amount of interface beams broken at the peak-load increases when the strength of the ITZ beams decreases or, alternative when the stiffness increases.

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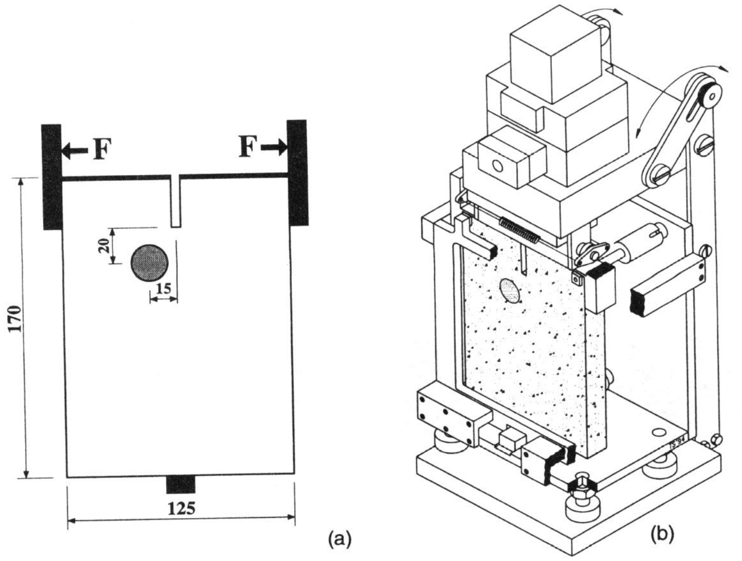

Figure 1: Specimen geometry (a) and experimental set up (b). Measurements are given in mm and the thickness of the specimens tested was 15 mm.

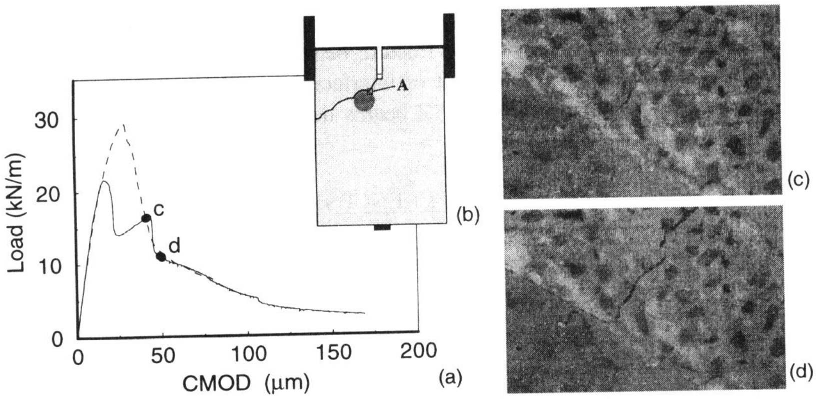

Figure 2: Load-CMOD curve (a), corresponding final crack pattern (b), and two stages of crack growth in area *A* (c,d).

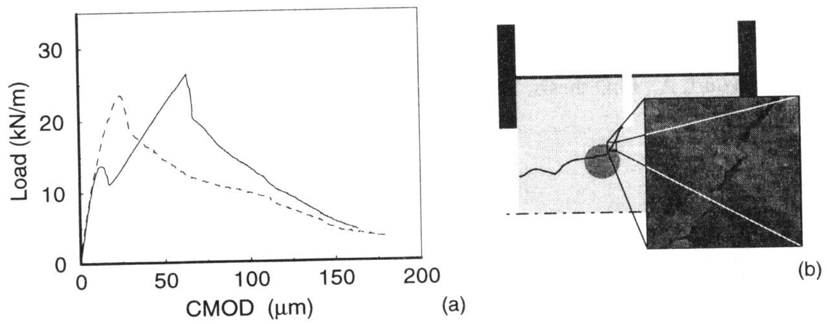

Figure 3: Load-CMOD curve (a) and corresponding final crack pattern with a detail of the ITZ for a specimen containing a sandstone aggregate (b).

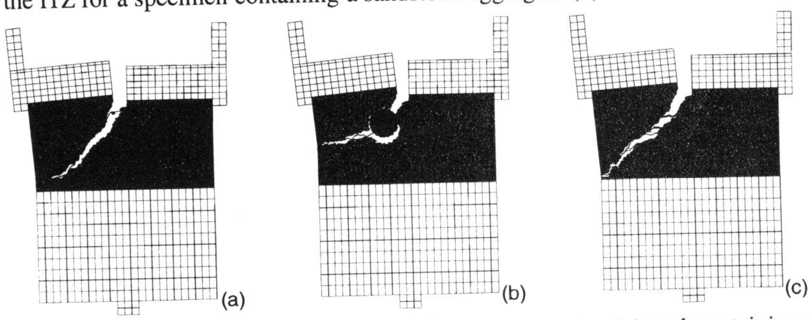

Figure 4: Simulation of a specimen containing no aggregates (a) and containing a granite (b) or sandstone (c) aggregate.