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INTERFACE FRACTURE IN CEMENT-BASED MATERIALS

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Abstract

Macroscopic observed crack growth in heterogeneous materials like concrete is initiated by microcracking in the interfacial zone (IZ) between matrix and aggregate. Interface fracture has proven to be a dominant mechanism in concrete fracture. In a micromechanical lattice type model that has been developed in the Stevin Laboratory, cracking of the IZ is simulated by removing a beam from the finite element mesh. The main issue of the lattice model (and most of the numerical models available for heterogeneous materials) is a sound explanation of the fracture parameters needed in the model. Therefore, an experimental program has started to study the fracture behaviour of the IZ between matrix and aggregate, and to validate the lattice model in this respect. It will be shown that the density of the IZ has a major effect on the stress-crack opening behaviour measured in the experiments. A two dimensional splitting type experiment is designed, which is easy accessible to numerical simulations with the lattice model. Next to a conventional experimental measuring technique an optical microscope is applied to monitor crack growth at the surface of the specimen. Recently the microscope has been adapted for automatically scanning surface cracks, propagating through the specimen.

1 Introduction

The three level approach proposed by Wittman (1983) seems to be a good starting point for understanding the behaviour of the interfacial zone (IZ). In this context numerous studies have been carried out which incorporate the microlevel of the IZ. The main goal for most researchers of micromechanical modelling is using the outcome as input for models at an higher level (meso- or marcro-level), see for instance Bentz et al. (1992) and Van Mier & Vervuurt (1994). However, most studies performed at the microlevel only give a visual qualification of the IZ and some factors which may affect the behaviour. An obvious relation shown, is the correlation between bond strength and concrete strength which is for example mentioned in an overview on cement-aggregate bond by Struble & Skalny (1980). The bond strength is affected strongly by the aggregate type and varying the water-cement ratio of the matrix (Mindess, 1989). From the micromechanical point of view, interfaces are treated as products of hydrated cement. At the meso level, the IZ can be seen as a link in a three phase material. These three phases are the matrix, the aggregates and the IZ between matrix and aggregate. When the IZ is considered to be completely brittle, Linear Elastic Fracture Mechanics (LEFM) can be applied, as demonstrated by Zaitsev (1983), Wang (1994) and Lee et al. (1992). The mathematical solution for this LEFM approach is descibed by Rice (1988). In finite element modelling at the meso-level an appropriate way for simulating the IZ seems to be an array of small elements connecting the two dissimilar materials, see Van Mier et al. (1993) and Schorn (1993). Interfacial fracture is simulated by removing a beam in the IZ as soon as a fracture criterion is exceeded. Wang (1994) gives a representation of the IZ as an element without any thickness (singular elements). This seems to be more realistic since the interfacial thickness is less than 50 micron (Bentz et al., 1992), which is much less than the beam length. It is mentioned that the interfacial thickness depends strongly on the type and nature of the aggregates used, as will be shown in this paper too.

In spite of the fact that the interface is qualified as a layer of importance, still no quantifications are given to this zone. The main goal of this investigation is to retrieve more knowledge of this uncertain factor in many numerical programs. In the following section the test set-up and experimental equipement developed for studying the IZ between matrix and aggregate will be presented. In addition some prelimenary results will be discussed of specimens containing a mortar matrix and a single aggregate of two types of rock. Simulations with the numerical lattice model are presented in these proceedings by Vervuurt et al. (1995). The lattice model is discussed in detail in Schlangen (1995), available in these proceedings as well.

2 Testing equipement

For the two dimensional splitting type experiments either one, two or three cylindrical aggregates are embedded in a matrix (Fig. 1a). At the moment however a test series is carried out in which only one (eccentrically positioned) aggregate is used. The aggregates used are single sized with a diameter of 20 mm. For reference also specimens are tested without any aggregates. For the aggregates two different rock types are used so far, i.e. a porous rock (Bentheimer sandstone from Germany) and a dense rock (Polar White granite from Brasil). It is expected that the porous sandstone gives a more dense IZ compared to the granite. Because of the high porosity (and thus high water absorption) of the sandstone, two different curing conditions are used. For half of the experiments with sandstone, the aggregate is saturated before casting the matrix. For the remaining specimens with sandstone aggregates, the rock is put to drying for 24 hours at 105 °C before casting the matrix. In this paper they will be refered to as wet and dry sandstone aggregates. For the matrix, two different mixtures are used each with three different water-cement ratios, i.e. a cement paste with water-cement ratio

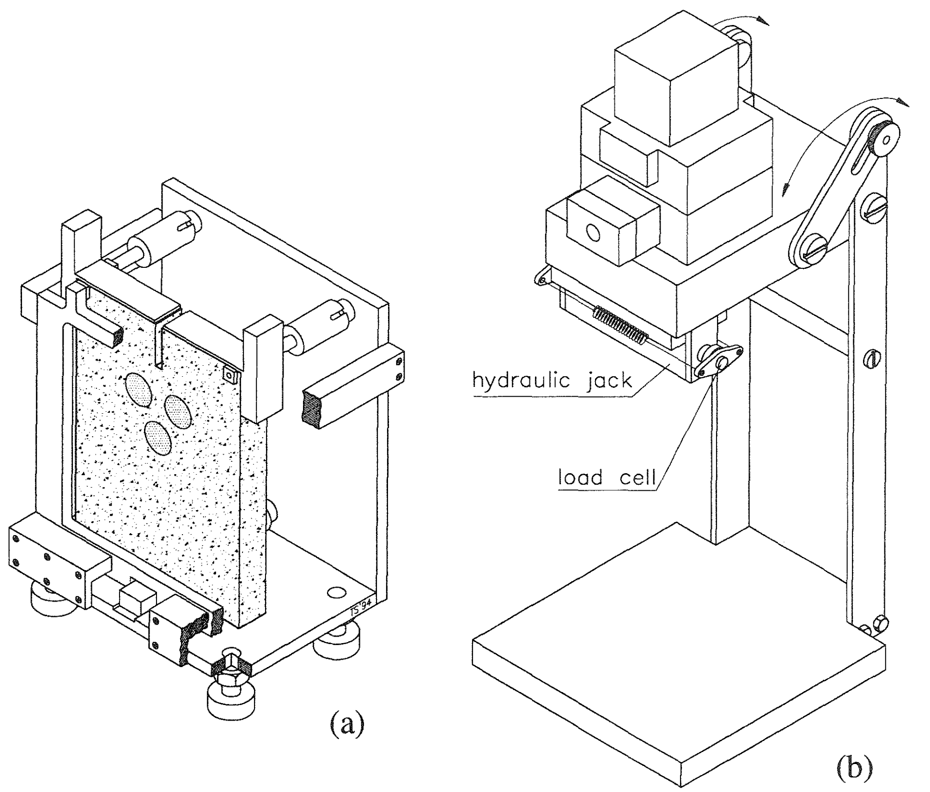


Fig. 1. Specimen with three embedded aggregates. During the test the loading frame (a) is placed in the loading device (b).

of 0.35, 0.4 and 0.45 and a mortar with 50 % (v/v) quartz sand (maximum aggregate size 0.125 mm). For the mortar water-cement ratios of 0.4, 0.45 and 0.5 are tested. A white cement is used for maximum contrast with the cracks using the optical microscope discussed below. After the matrix has been casted around the aggregates, the mould is covered with plastic to avoid shrinkage cracking. After 24 hours of hardening the block is demoulded and placed under water with laboratory temperature. Subsequently, the block is kept under water for two weeks before sawing eight specimens with a thickness of 10, 15 or 20 mm. A notch of 5x30 mm is sawn at half width of the specimen. The specimens are sawn on two levels from the central part of the block, and placed back under water. One hour ahead of the experiment (15 to 18 days after casting), the specimen is removed from the water and prepared for testing. The experiments are carried out at constant temperature (20 °C) and constant relative humidity (50 %).

The loading device consist of a loading frame containing the specimen and a loading device (see Fig. 1a and 1b respectively). For testing, the frame is centered under the loading device. The loading device provides for a perfectly horizontal splitting load which is applied by the hydraulic jack at the top of the specimen. Two loading platens are glued to the specimen for transferring the load. The load is measured with two load-cells; one on each side of the hydraulic jack. Three springs are attached between the loading frame and specimen to ensure that the specimen remains vertical during testing. The vertical position of the specimen is essential because of surface-crack measurements with an optical microscope (Questar Remote Measurement System, see Fig. 2). The optical system consists of a high resolution microscope (QM100) connected to a CCD camera. Both the microscope and camera are fixed on a cradle which can be translated

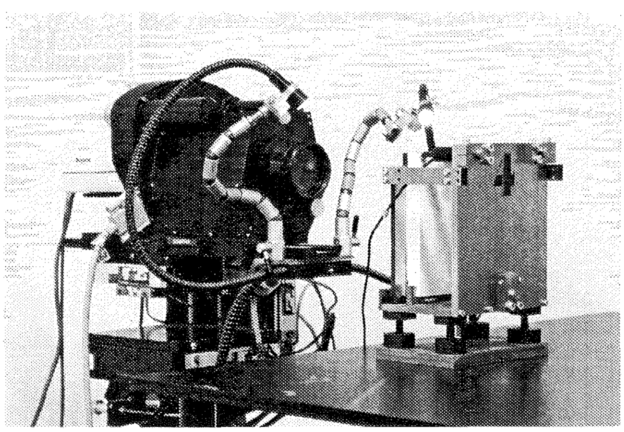


Fig. 2. Photograph of the Questar Remote Measurement System (QM100-RMS) and the loading frame.

in three orthogonal directions using three stepper motors. Because of the limited range of the stepper motors only the region between the notch and the cylindrical aggregates is studied in detail. Recently the stepper motors have been computerized for scanning the specimen surface during loading. Software for controlling the stepper motors and digitizing the images of the CCD camera has been developed and is integrated in an image processing program. The system is discussed in detail in Vervuurt & Van Mier (1994 & 1995). Next to this new measuring technique, a conventional deformation controlled test is carried out. The crack mouth opening displacement (CMOD) is measured at the top of notch (measuring length 13 mm) and is used as feed back signal in the servo controlled system.

3 Results and discussion

At the moment a test series is performed in which effects from the aggregative material and the matrix are investigated. Three water-cement ratios are studied for each of the two mixtures. A single aggregate of Bentheimer sandstone (wet or dry) or granite is embedded in a matrix of mortar or cement paste. The results presented in this section are limited to specimens with a mortar matrix (50 % quartz sand and 50 % cement) with a water-cement ratio of 0.5. The thickness of the specimens was 15 mm. The characteristics for these tests are shown in the overview at the end of this section (Table 1).

3.1 Reference tests

For a few reference tests (no aggregates) the stress-crack opening diagrams and final crack patterns are shown in Fig. 3. At present only a single experiment has been carried out for the mortar mixture shown in Fig. 3a, but comparison with similar experiments containing a mortar matrix with water-cement ratio of 0.4 shows the same behaviour (Fig. 3b). The main difference is that the tests of Fig. 3b show a somewhat more curved crack pattern. Nevertheless the load-deformation curves of the experiments are comparable, except for the more steep descending branch when the crack is more curved. In spite of the lower water-cement ratio, a lower peak load is observed for the mixture with w/c ratio 0.4. This may be explained from the fact that compaction of the specimens shown in Fig. 3b was not optimal. Regardless of the mixture used, the failed specimen shows a crack starting from the notch, propagating in a curved line to the edge of the specimen. The curved shape can be explained from rotations of the principal stresses in the specimen during cracking. Vertical crack growth is prevented by the compressive (bending) zone in the lower half of the specimen. Comparing various reference tests, crack patterns in both directions of the specimen were observed which confirms symmetry of the set-up.

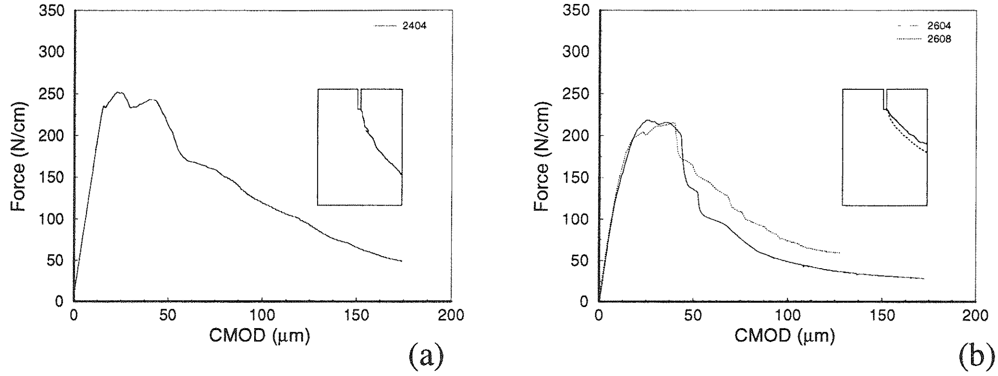


Fig. 3. Load-deformation curves and final crack patterns in splitting tests whithout any aggregates. The mixture of (a) contained a mortar matrix (water-cement ratio 0.5). For the two specimens in (b) the same mixture with water-cement ratio 0.4 was used.

The small second peak, which is observed directly after the first peak in the load-displacement curve of Fig. 3a, is probably caused by some kind of crack-arrest after fracture has started. When the crack path changes direction during cracking, more energy is needed in comparison to a smooth crack path. An extreme case for this is when an aggregate is embedded in the matrix, along the path of cracking. This case will be discussed in section 3.2.

3.2 Interface fracture

The experiments discussed in this section contain a matrix similar to the reference test presented in section 3.1 (water-cement ratio 0.5). In Fig. 4a and 4b results are presented for granite and (dry) Bentheimer sandstone are given respectively. The slope of the ascending branches and the peak-loads for the experiments are given in Table 1. Both slopes are calculated as the steepest part of the ascending branch ahead of the following peak, calculated with the least square method applied to 15 (following) measuring points.

Directly after the first (micro)cracks have initiated at the notch, a peak is observed in the load-deformation response. Because of the presence of the aggregate the crack is arrested and a second (less steep) ascending branch is observed. The fact that the (first) peak for granite is somewhat lower compared to using sandstone as an aggregate, may indicate that microcracks develop in the IZ. However no evidence for this is found yet, since no microcracks have been observed in the IZ at the surface of the specimen, using the largest but one magnification factor (0.72 micron per pixel) available at the microscope. Beyond the first ascending branch the behaviour is different when sandstone or granite is used. For granite a second peak is observed when the IZ between aggregate and matrix starts cracking and softening

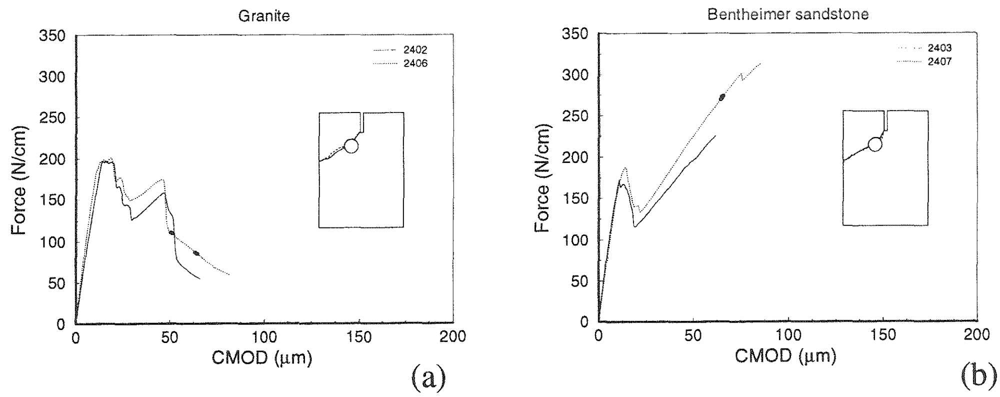


Fig. 4. Load-deformation curves and final crack pattern when granite (a) and sandstone (b) aggregates are used. The black spots in the curves refer to the stage of cracking shown in Fig. 5.

occurs during the remainder of the test. Because of the high density of the IZ for sandstone no crack growth is possible along the IZ which results in a tendency of cracking through the aggregate. It is shown in Fig. 5c (together with 4b) that no cracks along the IZ of the sandstone appear, not even just before brittle failure of the specimen. The slope of the second ascending branch as well as the second peak are higher for sandstone (E_{s_2} and F_{max_2} respectively in Table 1). After a large increase of the load, the specimen fails brittle and the final crack patterns are quite similar to the final crack patterns of the specimens with granite aggregates. It should be mentioned however that no stable tests (including the second peak) have been performed yet

Table. 1: Test characteristics for the mortar matrix specimens (w/c ratio 0.5). E_{s_1} indicates the slope of the ascending branch before the first peak (uncracked specimen) and E_{s_2} gives the slope of the second ascending branch. F_{max_1} and F_{max_2} are the loads for the first and the second peak respectively.

	Specimen number	E_{s_1} GPa	F_{max_1} N/m	E_{s_2} GPa	F_{max_2} N/m
No aggregates	2404	1.6	2.5		
Granite	2402	1.6	2.0	0.2	1.6
	2406	1.9	2.0	0.2	1.8
Sandstone	2403	1.9	1.7	0.3	2.3*
	2407	1.7	1.9	0.3	3.1*

* Brittle failure

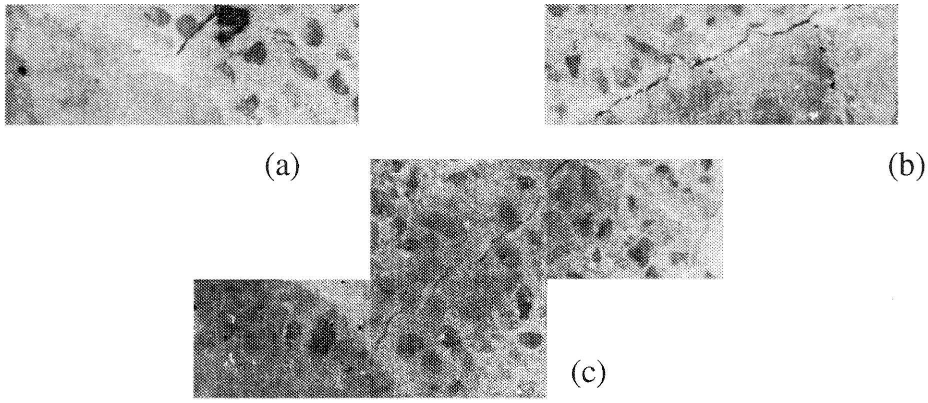


Fig. 5. Optical observations of cracks in the IZ. The moments of scanning are pointed out in the load-deformation curves in the previous figure.

for this mixture. When the second peak is reached in a stable way it may well be possible that the crack path is rather different, as seen in tests on sandstone embedded in a matrix of cement paste (w/c 0.35). Fig. 6 shows the final crack pattern and stress-crack opening diagram for this test. The Bentheimer sandstone was dryed before casting.

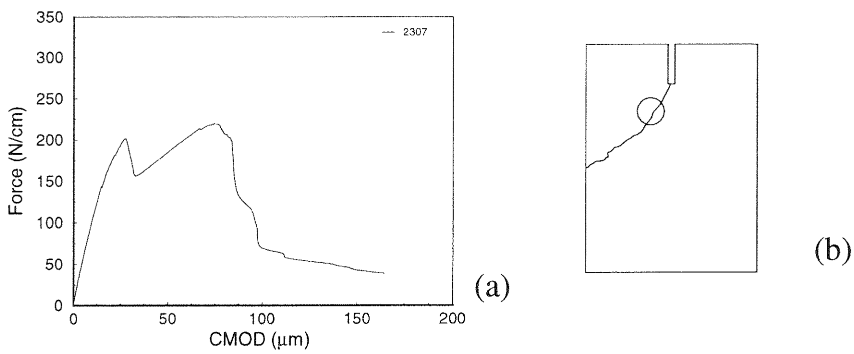
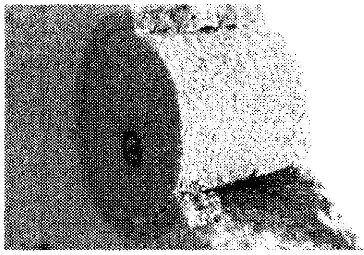


Fig. 6. (a) Stress-crack opening diagram and final crack pattern for cement paste specimen (w/c ratio 0.35) containing a (dryed) sandstone aggregate.

It has been shown during the experiments that the behaviour of the specimen strongly depends on the strength and structure of the IZ. A good example was given for a specimen with a sandstone aggregate which showed a (stable) behaviour quite similar to the granite described above. Studying the IZ after testing however showed large pores along the interface (Fig. 7). It may be obvious that all tests should be evaluated on an individual basis before drawing any generalized conclusions, as shown with the latter example.


(a)


(b)

Fig. 7. Detailed observations of fracture in the IZ. In Fig. (a) a detail is given from the fracture surface of the sandstone aggregate and (b) shows the surface of the matrix. In the experiment a mortar with w/c ratio of 0.4 was used. Note the large pores in figure (b).

4 Conclusions

An experimental technique is developed for studying the matrix-aggregate bond in cement-based materials. An optical microscope is applied for detailed measurements of crack growth in the IZ. Granite or sandstone aggregates are embedded in a matrix of cement paste or mortar. It was shown that both aggregative materials have a significant effect on the global behaviour of the specimen. The load for initiating crack growth is quite alike but, because of the much more dense IZ for porous materials a higher final peak-load is observed when sandstone is used. The stiffness of the cracked specimen is also higher for sandstone, as compared to granite. Only limited tests have been carried out to date, and no hard conclusions can be drawn. Moreover, numerical analyses with the micromechanical lattice model should accompany the experiments.

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