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FRACTURE MECHANICS AND DURABILITY OF HIGH PERFORMANCE CONCRETE

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ABSTRACT

The crack path through composite materials such as concrete depends on the mechanical interaction of inclusions with the cement-based matrix. Fracture energy depends on the deviations of a real crack from an idealized crack plane. Fracture energy and strain softening of normal, high strength, and self-compacting concrete have been determined by means of the wedge splitting test. In applying the numerical model called „numerical concrete" crack formation in normal and high strength concrete is simulated. Characteristic differences of the fracture process can be outlined. Finally results obtained are applied to predict shrinkage cracking under different boundary conditions. Crack formation of high strength concrete has to be seriously controlled in order to achieve the necessary durability of concrete structures.

KEYWORDS

composite material, high strength concrete, fracture process, shrinkage cracking

1. INTRODUCTION

Crack formation in concrete is often at the origin of serious damage due to corrosion. The fictitious crack model (FCM) as developed originally by Hillerborg and his co-workers [1] is a powerful tool to predict crack formation in composite materials such as concrete. For a realistic prediction we need fracture energy and strain softening of the material. At present there exists a wealth of data for normal concretes [2,3]. Considerable less data are available for high performance concrete.

Sometimes the term high performance concrete is used for high strength concrete. In fact high performance concrete has a much wider meaning [4]. Strength is an important performance among others such as ductility, self-compacting ability, low shrinkage, high modulus or wear resistance. In this contribution we will consider crack formation of high strength and normal concrete. Fracture energy and strain softening depend on the composite structure of the material. It is essentially governed by the mechanical interaction of the aggregates with the cement-based matrix. In Fig. 1 the influence of maximum aggregate size on the specific fracture energy is given.

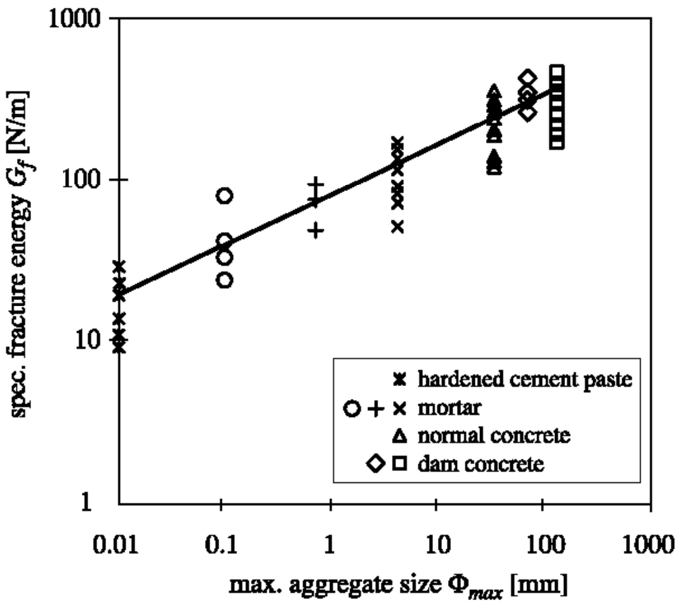

Figure 1: Specific fracture energy of cement-based materials as function of maximum aggregate size.

The lowest fracture energy is measured on pure hardened cement paste. In this case the maximum aggregate size is estimated to be 0,01 mm which corresponds to the dimension of the remaining unhydrated clinker particles. The highest value is observed in dam concrete with a maximum aggregate size of 120 mm [5]. In between the influence of maximum aggregate size on fracture energy can be described by a power function.

$$G_f = a \cdot \Phi_{\max}^n \tag{1}$$

From the data shown in Fig. 1 one obtains the following values for the parameters a and n in equ. (1): a = 80,6 and n = 0,32 [5].

In pure hardened cement paste and in fine mortar a crack can develop along a plane. The small and strong particles impose minor deviations from an ideal fracture surface only. In Fig. 2(a) a typical flat fracture surface of a mortar with a maximum aggregate size of 2 mm is shown. In Fig. 2(b) a fracture surface of normal concrete with a maximum aggregate size of 32 mm is shown. As most aggregates (river gravel) are stronger than the cement-based matrix a crack is forced to run around the inclusions. From Fig. 2(b) it can be clearly seen that a crack once it meets an aggregate either has to run out of the plane and leaves a blank aggregate surface behind or it runs in the opposite direction. In the latter case the aggregate is torn out of the matrix. The negative imprints can be seen in Fig. 2(b).

Obviously the necessary fracture energy increases with the maximum aggregate size if the size distribution remains similar. In contrast to the energy consuming crack formation in normal concrete a crack in high strength concrete runs through the inclusions and forms approximately a plane as observed on fine mortars and pure hardened cement paste (Fig. 2(c)). In this case mechanisms of mechanical interaction between inclusions and matrix cannot be activated. This leads to the more brittle behaviour of high strength concrete. By means of the well-known model „numerical concrete“ [6] damage and crack formation in normal and high strength concrete will be simulated. Finally results obtained will be applied to predict shrinkage cracking under different boundary conditions.

(a) (b) (c)

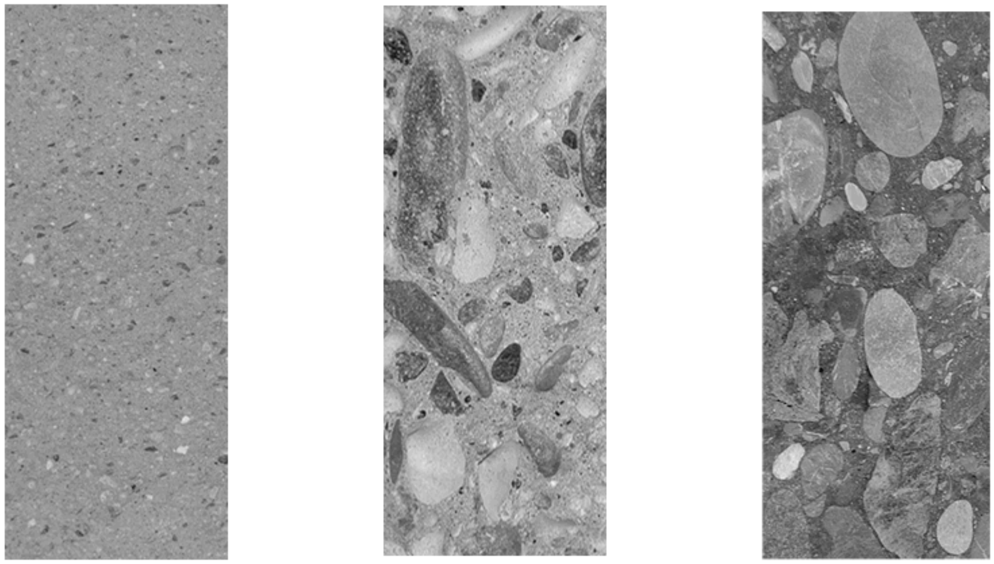

Figure 2: Fracture surface of (a) mortar, (b) normal concrete and (c) high strength concrete.

2. MATERIALS AND EXPERIMENTAL RESULTS

2.1.Concrete Composition

Three types of concrete have been produced. The mix composition is given in Table 1. The maximum aggregate size has been chosen to be 32 mm for all these mixes and the size distribution follows a Fuller curve. In this way the range from a normal concrete to a high strength concrete is covered. Cubes with a side length of 150 mm and cylinders with a diameter of 150 mm have been casted.

TABLE 1: MIX COMPOSITION OF THE THREE DIFFERENT TYPES OF CONCRETE

	Mix A	**Mix B**	**Mix C**
Cement Type	CEM I 425	CEM I 42,5	CEM I 52,5
Cement content kg/m^3	400	400	400
Water/cement ratio	0,55	0,38	0,28
Plasticizer	-	0,5 % Glenium 51	1,5 % Glenium 27
Microsilica	-	-	10%

2.2.Experimental results

In order to be able to simulate shrinkage crack formation a series of material parameters has to be determined. First the compressive strength and the elastic modulus have been measured as function of age. The values obtained at an age of 14 days are compiled in Table 2. Strength has been measured on cubes and the modulus of elasticity on cylinders.

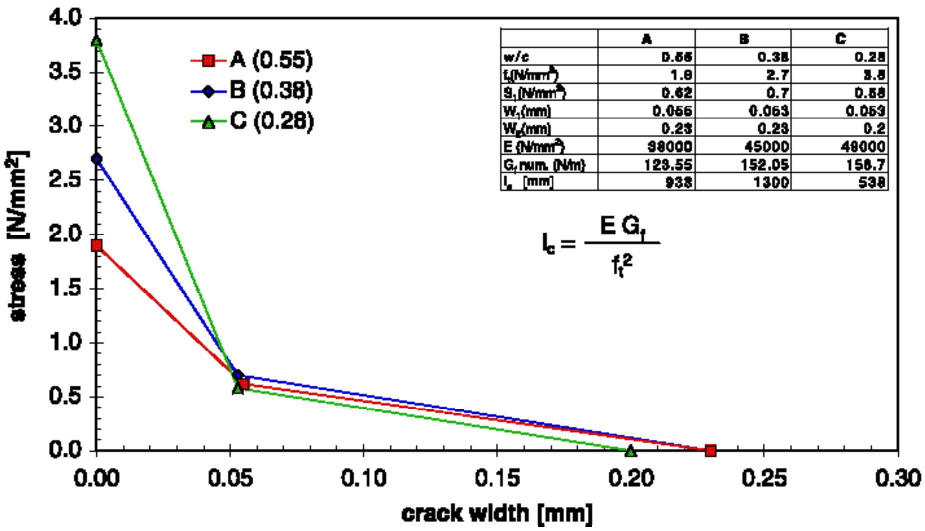

Figure 3: Bilinear relation for strain softening.

TABLE 2: COMPRESSIVE STRENGTH AND ELASTIC MODULUS AT AN AGE OF 14 DAYS

	Mix A	**Mix B**	**Mix C**
Compressive strength N/mm^2	35,3	57,4	112,2
Modulus of elasticity N/ mm^2	38.000	45.000	49.000

Fracture mechanics parameters have been determined by means of the wedge splitting test [7]. These tests have been carried out on cubes with a sawn notch having half the heigth of the cube. Results obtained after inverse analysis are shown in Fig. 3. The insert in Fig. 3 summarizes the obtained parameters of the bilinear model. In the last line the characteristic length l_c is given as calculated by the following equation:

$$l_c = \frac{EG_f}{f_t^2} \tag{2}$$

This length can be considered as an indication of the brittleness of a material. In addition to the mechanical properties we also need the hygral diffusion coefficient and the shrinkage as function of relative humidity. The hygral diffusion coefficient can be calculated from measured drying data [8]. On this basis it is possible to calculate time-dependent moisture distributions in concrete elements prepared with different types of concrete and under different boundary conditions in order to predict crack formation.

3. NUMERICAL SIMULATION OF CRACK FORMATION

In the preceeding section we have outlined all the material parameters which have to be known or determined before the risk of crack formation can be realistically estimated. As a next step we will simulate numerically crack formation in a composite structure such as concrete. We consider concrete to be built up by coarse aggregates embedded in the mortar matrix.

As we want to compare crack propagation in ordinary and high strength concrete we need parameters of two matrixes, i.e. a cement-based mortar with a w/c-ratio of about 0,5 and 0,35 respectively. Based on earlier experiments the data compiled in Table 3 have been used for the numerical simulation. To simulate crack propagation a specimen used for wedge splitting experiments has been chosen. The composite structure of concrete has been simulated by generating randomly dispersed hexagonal aggregates. The size distribution of the aggregates follows a Fuller curve. The material parameters attributed to the aggregates and the two different matrixes under investigation are all given in Table 3. The composite structure to be analysed is shown in Fig. 4 (a) and (b).

TABLE 3: MATERIAL PARAMETERS USED IN THE NUMERICAL SIMULATION

Materials	Aggregates	Matrix in NC	Matrix in HSC
E (GPa)	60.0	20.0	30.0
υ(-)	0.2	0.2	0.2
f_t (MPa)	10.0	3.0	8.0
w_1 (mm)	0.002	0.02	0.01
σ_1 (Mpa)	1.0	0.5	1.0
w_2 (mm)	0.008	0.03	0.02
G_F (N/m)	14.0	37.5	50.0

(a) (b)

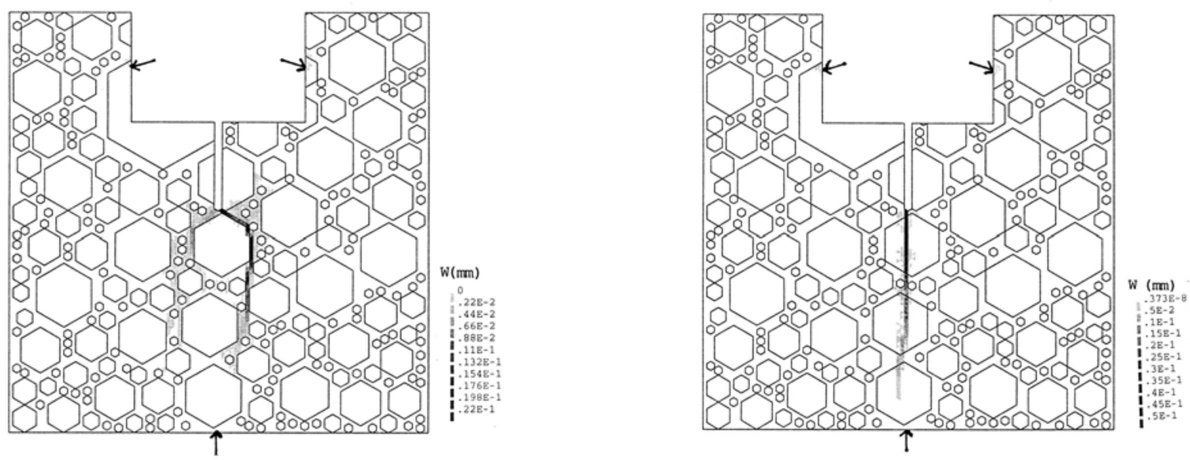

Figure 4: Damage (fictitious cracks) and crack formation in numerically simulated concrete: (a) normal concrete and (b) high strength concrete

If a moderate force F is applied the system reacts linearly elastic. But after a characteristic load is reached a fictitious crack (damaged zone) will be formed in the weaker matrix. The crack propagation in normal concrete is shown in Fig. 4. As the aggregates are stronger than the matrix cracks will run around the aggregates. Finally a damaged band with a width of about twice the maximum diameter of the aggregates is being formed. It is quite clear that due to the mechanical interaction between aggregates and matrix the fracture energy of the composite material becomes considerably bigger than the fracture energy of both the aggregates and the matrix.

If crack propagation in high strength concrete is simulated cracks can run through aggregates as the matrix and the aggregates are mechanically very similar. A typical example is shown in Fig. 4 (b). A comparatively narrow crack band is being formed in high strength concrete. The results shown in Fig. 4 agree well with the photos of crack surfaces as shown in Fig. 2.

4. SHRINKAGE CRACKING

Measured shrinkage is in fact the response of a concrete specimen to the strains and stresses generated by the drying process. If the water loss of a specimen with known geometry is measured the hygral diffusion coefficient can be determined by inverse analysis [8]. Then time-dependent moisture distributions can be numerically predicted.

The moisture profiles in normal concrete can be realistically predicted by the general diffusion equation [9]. In the case of high strength concrete a sink term has to be added to the diffusion equation because of the endogenous drying. If we compare the moisture profile after 7 days of drying for instance the drying process affects the surface near zone in normal concrete only. In high strength concrete endogenous drying, however, leads to an equilibrium hygral potential of 0,8 in the center of drying elements. This effect has a series of consequences with respect to crack formation. From shrinkage tests infinitesimal shrinkage i.e. shrinkage of an infinitesimal thin layer can be obtained by inverse analysis [10].

Crack formation in reinforced beams made of normal and high strength concrete has been simulated numerically. The entering material properties such as elastic modulus, tensile strength and strain softening, hygral diffusion coefficient, coefficient of hygral dilatation have all been determined experimenteally.

5. CONCLUSIONS

The following conclusions can be drawn from the results presented in this contribution:

- Crack formation and fracture energy depend on the mechanical interaction between inclusions (gravel or crushed stone) and the cement-based matrix.
- High strength means generally low ductility and increased risk for crack formation.
- A numerical model (numerical concrete) can be used to optimise composite materials such as concrete with respect to well-defined requirements: strength, ductility, durability etc.
- Endogenous shrinkage takes place in high strength concrete. This process creates stress states and internal damage which are not covered adequately by most codes so far.

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