Fracture Mechanics of Concrete Structures
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FRACTURE MECHANICS OF MASS CONCRETE - WET-SCREENING PROCEDURE (FMWS)

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Abstract
The wet-screening method characterised by sieving-out a set of (large) aggregates of the fresh concrete is used for the testing of fracture mechanics material parameters of mass concrete. The reduction of the maximum aggregate size enables the testing of small samples under usual laboratory conditions. The real fracture mechanics behaviour of the original mass concrete is obtained by an extrapolation procedure.
Key words: fracture mechanics, material testing, mass concrete, wet-screening

1 Introduction

Mass concrete as mainly used in hydro-engineering constructions possesses some typical features which require different design strategies and treatment compare to concrete used in building engineering. The large cast-in-place concrete sections generate high temperatures during the process of hydration. These temperatures quite often may cause thermal-stress-related cracking as a consequence of internal or external restraint. Further cause of cracking may be seen in an inadequate design of the construction (notches, corners, jagged dam-foundation interface, etc.) and in stresses due to unusual load and reaction conditions (earthquake, excessive change of climate, discontinuous supporting, etc.).

Fracture mechanics methods via appropriate fracture criteria may offer possibilities for the investigation of such (cracked) structures. The term "appropriate" primarily is to understand in connection with the availability of a "valid" fracture mechanics (FM) material parameter for the problem to be investigated. This requirement however particularly is difficult to meet in the case of mass concrete where the size of the aggregates can often spread up to 120mm and across, since the characteristic dimensions of the test samples for LEFM-conditions should be (by rule of thumb) at least within the range of ten to twenty times the size of the maximum aggregate. Postulating these requirements for an appropriate material parameter for mass concrete, samples must have dimensions which are obviously too large for practical testing.

Therefore special procedures are required to overcome this problem. The methods generally are based on "size effect" models which have been developed from different points of view. All of those models imply homogeneous (granular) composition, which is not given in the case of mass concrete when standard testing machines with limited samples size are used.

Within this contribution some new aspects based on a special "wet-screening" technique are shown up. The investigation program includes the testing of samples with 1000 mm characteristic dimension and an aggregate size up to 80 mm and smaller samples with gradually screened out grains.

An extensive and detailed discussion concerning this mater has been carried out by Šajna (1998).

2 Characteristics of mass concrete

According to the ACI (1997) definition „Mass concrete is any large volume of cast-in-place concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change to minimise cracking".

The most effective way to diminish the temperature rise of mass concrete is to reduce the heat generation. This can be achieved by using cement of low heat generation and/or by reducing the cement content which on the other hand requires large aggregates to minimise the overall grain surface to be covered with cement gel. This besides other aspects results in maximum aggregate sizes of 80 to 120 mm and more.

To gain reasonable results in testing of concrete materials a certain ratio of the sample size to the maximum aggregate size should be provided. This requirement in case of mass concrete is difficult to meat because of the lack of laboratory and testing equipment to handle large specimens. Therefore special proceedings had to be considered from which the „wet-screening“ method is the most commonly used one.

In the case of fracture mechanics material testing of mass concrete rather few investigations have been carried out up to now.

A fracture toughness assessment of dam concrete based on results of size-effect investigations for normal concrete was carried out by Brühwiler (1988). Saouma et al. (1991) presented an in situ field test method for the determination of fracture properties of dam concrete. On the basis of a testing program of large WST specimens (1372 mm) of concrete with maximum aggregate sizes up to 76 mm different fracture models were proposed by Brühwiler et al. (1991). Linsbauer(1991) tested mass (dam) concrete taken out of an existing dam. Based on the WST method the fracture energy was determined on drilling cores of two different sizes.

The idea presented and experimentally evaluated in this presentation is to use the wet-screening procedure for the determination of the fracture mechanics material characteristics of concrete.

3 The wet-screening procedure (WSP)

The wet-screening procedure - sieving to remove from fresh concrete all aggregate particles larger than a certain size - in dam engineering is a commonly used and by the ACI (1997) recommended procedure for the testing of the compressive strength.

By the wet-screening procedure a set of aggregates larger than a certain size is „screened-out“ of the fresh concrete which is to be tested. The maximum aggregate size is reduced but the strength of the aggregate, the strength of the cement matrix and the strength of the bond between both remain unchanged. This may lead to the conclusion that in case of the wet-screening procedure where the amount of the cement content per volume is increased and the water to cement ratio is kept constant, the strength of the concrete is unchanged.

An experimental investigation presented in the following sections should prove these considerations and explore the influence of the wet-screening procedure on the fracture mechanics characteristics of concrete.

4 Basic investigation - normal concrete

The scope of this preliminary study was to apply the wet-screening procedure for the testing of standard fracture mechanics material characteristics of “normal” concrete.

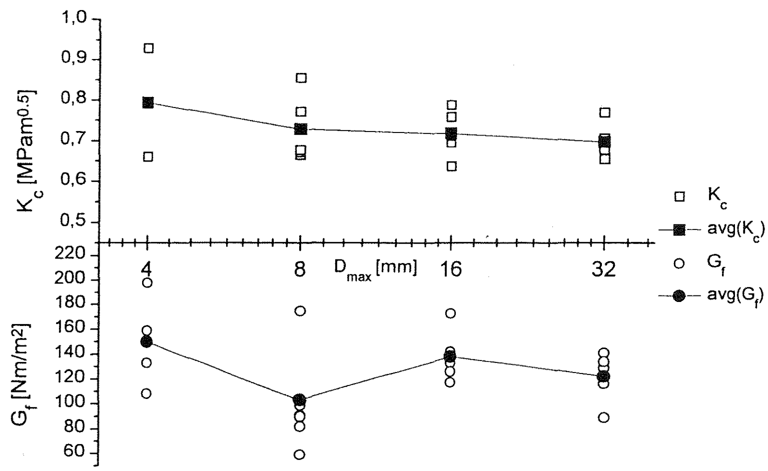

Fig. 4.1: Fracture toughness and fracture energy

The fracture mechanics tests for each of the wet-screened charges with 32, 16, 8 and 4 mm maximum aggregate sizes were performed with the wedge splitting method on 150 mm cubes. The results presented in Fig. 4.1 compare surprisingly well even under consideration of the scattering.

5 Main Investigation - mass concrete

The main investigation is directed to the development of a procedure for the prediction of fracture mechanics material parameters of mass concrete based on the testing results of small samples consisting of wet-screened concrete. Large specimens made of mass concrete (large aggregates) were cast to simulate the situation in a structure. The size of the specimens was decreased according to the wet-screening aggregate reduction steps, whereby the ratio of the specimen to the maximum aggregate size has been kept constant.

5.1 Testing procedure

The layout of the testing procedure includes the sample geometry, the mixture proportion and the treatment of the concrete samples, the testing equipment and the loading conditions. For the testing of large samples a new testing method - Horizontal Wedge Splitting Test method (HWST) has been developed by Linsbauer et al. (1998).

5.1.1 Specimen geometry

The wedge splitting test as a test method and "cubes" with a pre-cast notch up to one third of the height as test specimens were used in this investigation. Three different specimen sizes were chosen to investigate the size-effect:

a 950 mm sample simulating the conditions of the real building, a 190 mm cube representing a specimen of laboratory size and a 350 mm "cube" (Table 5.1).

5.1.2 Mixture proportions and treatment of the concrete samples

The admixture proportion of the start-up mass concrete with a maximum aggregate size of 80mm was as follows: 2000 kg aggregate, 200 kg cement, 40 kg fly ash and a w/c-factor of 0.625.

The start-up concrete was wet-screened from a maximum aggregate size of 80mm stepwise to a maximum grain size of 60, 30 and 16 mm. The admixture proportions of the wet-screened concrete in the main investigation were not defined due to the lack of a high power testing equipment necessary for the tests of large samples of concrete with 80mm aggregates.

The complete testing program is listed in Table 5.1.

Table 5.1: Test program

max. aggregate size [mm]	specimen length×height×thickness [mm]		
	950×950×400	350×350×160	200×190×200
80	x		
60		x	
30		x	x
16			x

5.2 Test results

The test results of the main investigation concerning the experimental evaluation of the new method for the determination of the fracture mechanics parameters of mass concrete in the form of horizontal load vs. CMOD diagrams are presented in Fig. 5.2. Due to the different specimen dimensions at a first view no direct correlation between large and small samples can be made.

The fracture toughness as a function of the specimen size and the influence of the max. aggregate size on the fracture energy are shown in Fig. 5.3.

Both the fracture toughness and the fracture energy values show a clear size-effect. But the influence of the maximum aggregate size is small in comparison to the size-effect if the stepwise reduction of the maximum aggregate size follows the wet-screening procedure (WSP).

To enable a direct comparison between values gained of samples with different size the diagrams are normalised (FMWS). The applied horizontal splitting load is normalised by the specimen height and thickness, the measured CMOD is divided just by the specimen height. The quantity presented on the y-axis is the applied stress. The quantity on the x-axis represents a non-dimensional deformation or strain. The normalised diagrams are presented in Fig. 5.4.

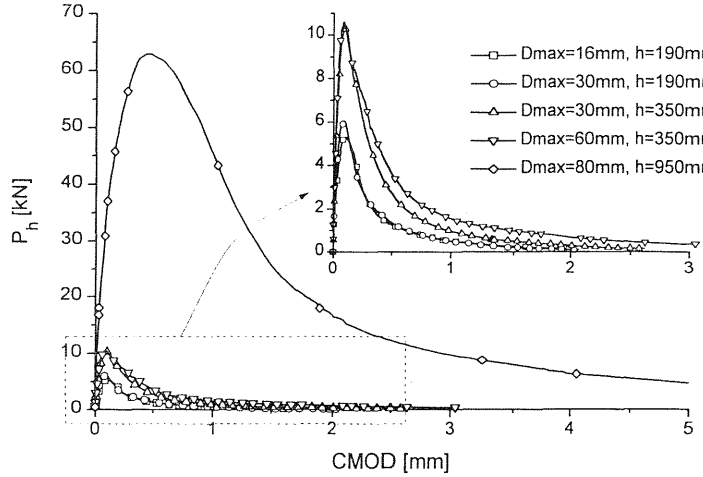

Fig. 5.2: Horizontal load vs. CMOD (WSP)

The normalised diagrams are concentrated in a small bandwidth which may be seen as a confirmation for using the wet-screening procedure in fracture mechanics material testing of mass concrete.

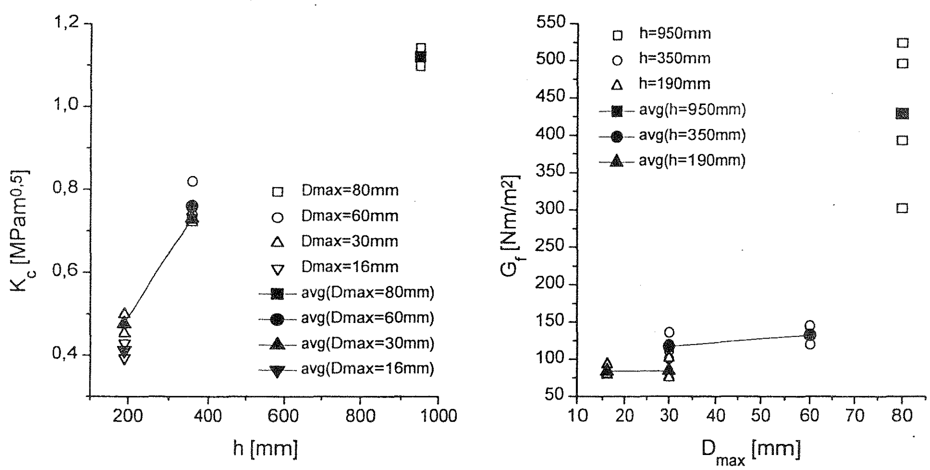

Fig. 5.3: Fracture toughness as a function of the specimen size and fracture energy as a function of the maximum aggregate size (WSP)

This will be shown via the following considerations, which naturally are based on an extrapolation procedure.

5.3 The efficiency of the FMWS

The efficiency of the FMWS is shown up by an extrapolation procedure both for the fracture toughness and the fracture energy.

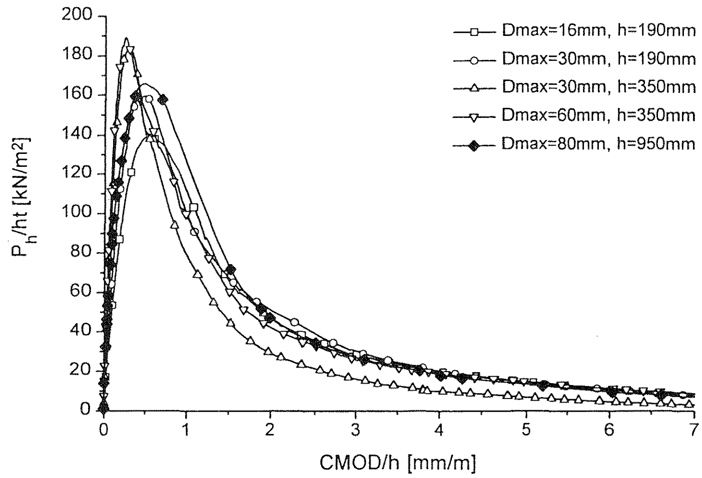

Fig. 5.4: Normalised horizontal splitting load vs. normalised CMOD diagrams

5.3.1 Extrapolation of the fracture toughness

The extrapolation method proposed here is based on the normalised load-CMOD diagrams presented in Fig. 5.4. Based on these diagrams it is assumed that the normalised ultimate load is independent of the specimen size and independent of the maximum aggregate size in case of the application of the fracture mechanics wet-screening method (FMWS). Under this assumption the ultimate load depends only on the specimen size. The fracture toughness of the mass concrete in the mass structure can be predicted if the fracture toughness of the wet-screened concrete determined on the specimen of laboratory size is known, as

$$K_{c,2} = K_{c,1} \cdot \sqrt{\frac{h_2}{h_1}} \quad \text{for} \quad \frac{h_1}{D_{max,1}} = \frac{h_2}{D_{max,2}} \quad \text{(size compatibility)} \qquad [5.1]$$

where $K_{c,1}$ and $K_{c,2}$ is the fracture toughness of the wet-screened concrete determined on the laboratory-size specimen and the fracture toughness of the "original" concrete in the structure respectively, h_1 and h_2 are the representative sizes of the specimen and the structure, $D_{max,1}$ is the maximum aggregate size of the wet-screened concrete and $D_{max,2}$ is the maximum aggregate size of the "original" concrete.

The fracture toughnesses of the original and the wet-screened concrete experimentally determined by the specimens of different sizes and the mathematically extrapolated fracture toughnesses are listed in Table 5.2.

Table 5.2: Measured and extrapolated values of the fracture toughness (***x.xx*** - measured values; test results)

K_c [$MPam^{0,5}$]			extrapolated to				
		h [mm]	190	190	350	350	950
	h [mm]	D_{max}	16	30	30	60	80
extrapolated from	190	16	***0.41***		0.55		0.92
	190	30		***0.47***		0.63	
	350	30			***0.73***		1.21
	350	60				***0.75***	
	950	80					***1.09***

The extrapolated values of the fracture toughness in a certain range correspond well with the measured values.

5.3.2 Extrapolation of the fracture energy

The extrapolation method proposed here is also based on the normalised load-CMOD diagrams presented in Fig. 5.4. Based on these diagrams it is assumed that the normalised work of fracture is independent of the specimen size and of the maximum aggregate size in case of the FMWS. Under these assumptions the work of the fracture depends only on the specimen size and can be calculated from the splitting load versus the CMOD diagrams.

The fracture energies of the original and the wet-screened concrete determined by the specimens of different sizes and the fracture energies calculated from the extrapolated diagrams are listed in Table 5.3.

Table 5.3: Measured and extrapolated values of the fracture energy (***xx*** - measured values; test results)

G_f [Nm/m^2]			extrapolated to				
		h [mm]	190	190	350	350	950
	h [mm]	D_{max}	16	30	30	60	80
extrapolated from	190	16	***87***		158		434
	190	30		***89***		162	
	350	30			***118***		326
	350	60				***161***	
	950	80					***463***

The measured and extrapolated diagrams are presented in Fig. 5.5.

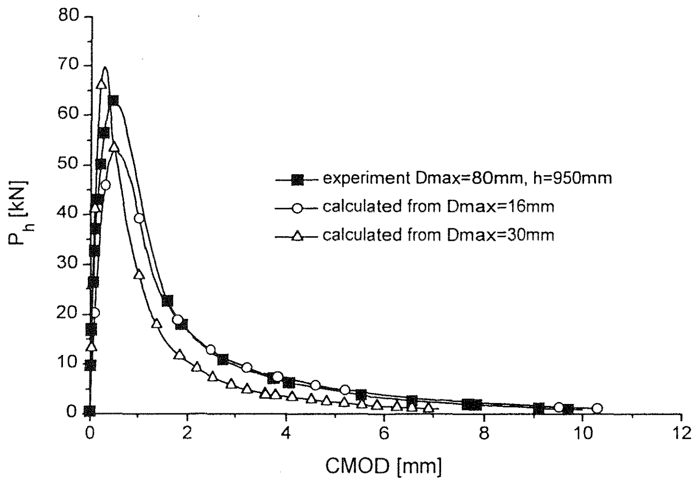

Fig. 5.5: The experimentally determined and the extrapolated diagrams of the D_{max}=80 mm h=950 mm specimen

The extrapolated values for the fracture energy in a certain range also correspond well with the measured values of the fracture energy.

6 Conclusions

The study concerning the validation of the use of the wet-screening procedure for the determination of the fracture mechanics material parameters of mass concrete results in the following statements:

- The „homogeneity problem“ of the laboratory size specimens can be resolved if the wet-screening procedure is used to reduce the maximum aggregate size of the "original" (mass) concrete.
- Within the tested range the influence of the maximum aggregate size on the fracture mechanics characteristics (the fracture toughness and the fracture energy) of the concrete is negligible in comparison to the size-effect.
- Within the tested range the normalised load versus normalised CMOD diagrams of concrete materials with different maximum aggregate sizes determined on specimens of different size are comparable.
- From the present test results it can be concluded that the fracture toughness of mass concrete can be extrapolated from the fracture toughness of the wet-screened concrete determined on the laboratory size specimens.
- The fracture energy of a mass concrete can be calculated from the normalised load versus normalised CMOD diagrams.

- As the influence of the maximum aggregate size on the fracture mechanics material parameters in the FMWS-method is negligible in comparison to the size-effect, the wet-screening procedure is a useful method for the determination of the fracture mechanics parameters of mass concrete.
- The presented wet-screening procedure proves to be a useful procedure for the determination of fracture mechanics characteristics of mass concrete.

The results presented within this investigation should be confirmed by additional experiments.

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