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Summary of session 1: Structure and fracture mechanisms of aggregative materials

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1 INTRODUCTION

This paper is a report on the session with the same title, held as part of the International Workshop on Fracture Toughness and Fracture Energy -- Test Methods for Concrete and Rock, at Sendai, Japan, in October, 1988, on request of the organizing committee. The papers in this session can largely be divided into two groups: 1) on the effects of fracture on structural behavior: size effect, brittle/ductile transition, and unstable snap back behavior, and 2) on the micro/meso-structural and mechanical effects on macroscopic tensile properties of cementitious materials. The discussion below reflects this grouping.

2 EFFECT OF FRACTURE ON STRUCTURAL BEHAVIOR

The size effect of structural components is well known. Experiments of reinforced and unreinforced concrete beams under flexure, shear and torsion have shown reduction of beam strength with beam size [Taylor (1978); Bazant et al (1989); Hillerborg (1989)]. Zaitsev and Kovler (this volume) established theoretically that the size effect of concrete structures has two sources: Material strength and notch sensitivity. They suggested that these properties are both related to the nature of material heterogeneity, although the exact nature was not explicitly described.

The transition of brittle behavior to ductile behavior in reinforced and unreinforced concrete structures was addressed in the paper by Carpinteri (this volume), who also numerically simulated the snap-back behavior in certain structural component tests. Carpinteri approached these issues based on the brittleness number s defined by

(1) $s = G_F/(f_t\ b)$

where G_F is the fracture energy, f_t is the tensile strength and b is the beam depth. For small value of s, brittle behavior may be expected, and results in the snap back phenomenon in the limit. The brittleness number can be roughly interpreted as a ratio between the size of the process zone near the crack tip and a characteristic dimension of the structural component containing the crack which led to eventual failure. Multiplying the numerator and denominator of s by f_t and recognizing that Young's Modulus E scales roughly with the square root of f_t, it c be shown that

$$(2) \quad s \propto (G_F E/f_t^2)\sqrt{f_t}/b$$

The term in the bracket has been related to the size of the process z by Li and Liang (1986). It is also the definition of a material characteristic length first proposed by Hillerborg (1983). Thus for material with a small characteristic length, as in the case of harden cement paste with relatively smaller amount of heterogeneity (compare to concrete), the process zone and the brittleness number is small (f a given beam size, i.e. fixed b), resulting in brittle behavior and notch sensitivity. In contrast, for a fiber reinforced concrete with relatively larger amount of heterogeneity and a large characteristic length, the process zone and the brittleness number will be correspondingly larger, resulting in more ductile structural behavior and less amount of notch sensitivity. [This discussion holds for ceme concrete and fiber reinforced concrete for which significant change i property occurs only in G_F.] This observation also explains why resul from uniaxial tension test of mortar are much more sensitive to mater flaws and loading and specimen alignments (usually leading to underestimation of tensile strength), whereas the same uniaxial tensi test applied to fiber reinforced concrete can produce results which a much more consistent and reliable.

In simulating structural behavior, account has to be given to the possibility of non-planar crack propagation, and requires the imposit of certain fracture criteria. Carpenteri (this volume) described a numerical technique for simulating mixed mode fracture propagation. Niiseki (this volume) considered a new general fracture criterion for heterogeneous materials based on thermodynamic principles.

The use of fracture mechanics to simulate concrete structural behav implies the need for determining certain fracture parameters which ca be considered as material properties. There is as yet no firm standa method for fracture testing, either in concrete or rock, and this is course a major topic of discussion in this Workshop. The paper in th session by Hashida (this volume) described a novel testing procedure the tension-softening curve of rock based on a technique developed by and co-workers at MIT (see, e.g. Li and Ward, this volume, for curren status of this method). There are several other papers on fracture testing method in the two sessions on "Methods to Determine and to Evaluate the Fracture Toughness and the Fracture Energy of Aggregativ Materials" applied to concrete and to rock.

The above discussion suggests the connection between material structure (in the form of heterogeneity, the process zone size and th material characteristic length) and structural behavior (in the form brittle/ductile behavior transition, snap back behavior, and size effects). It is therefore important to understand quantitatively how the material structure affects the tensile material properties such a strength and fracture energy (or tension-softening curve). This topi was addressed in the paper by Bazant and Kim (this volume), who, following the work of Horii (1987), developed a simple highly idealiz model of the internal mechanism of fracture. Progressive failure of material is simulated by the extension of cracks arranged in a period configuration, and presumably resembling the existence of microcracks the actual concrete. A more realistic analytic model which accounts the volume fraction and size distribution of aggregates, the weak interface between aggregate and cement, and matrix crack interception by aggregates was considered by Li and Huang (1989a,b). This model was able to predict pre-peak non-linear tensile behavior as well as post-peak tension-softening behavior. A numerical model of similar nature has been considered by Zaitsev (1985). More detailed observations of the effect of material structure on composite behavior are discussed in the following section.

3 EFFECT OF MATERIAL STRUCTURE ON COMPOSITE PROPERTIES

The rest of the papers in this session deal with the effect of material structure on the composite properties. There are three types of factors which contribute to the material structure: material mix, environmental and pre-loading. Table 1 lists the various factors and the corresponding observed macroscopic tensile behavior discussed in the papers. In certain cases, the mechanism and/or micro/meso-mechanical model linking the specific factor and the macroscopic behavior are also presented.

Under the topic of material mix, Wittmann (this volume) showed the decrease of tensile strength of hardened cement paste with water/cement (w/c) ratio. He related this phenomenon to the micromechanism of extension of the critical elongated pore in the paste, governed by the Griffith curve. Consistent with previous test results of Higgins & Bailey (1976), an increase of w/c ratio reduced the fracture toughness of paste material, and resulted in a lower tensile strength of the HCP. Also consistent with the previous test results of Higgins & Bailey (1976), Mihashi et al (this volume) showed that the fracture energy (and tensile strength) of cement (actually a mortar) increased with age. Presumably, this phenomenon is related to the increase in cement matrix density associated with the amount of hydration products.

Observation of HCP fracture toughness reduction with w/c ratio is consistent with the data of Mihashi et al showing the decrease of concrete tensile strength f_t with w/c ratio, and data of Wittmann et al (1987) showing the decrease of concrete fracture energy G_F. The meso-mechanical model of Li and Huang (1989a,b) offers a link between cement toughness, concrete f_t and G_F. In this model, tensile strength of the concrete is associated with the branching of the aggregate/cement matrix interface crack into the cement matrix at the largest aggregate. The model additionally indicates that tension-softening behavior is controlled by the propagation of this dominant matrix crack. It may be expected that a larger w/c will also adversely reduce the interface bond strength.

The influence of maximum aggregate size d_{max} on tensile properties was studied by Mihashi et al (this volume) and Wittmann (ibid.). Their results both indicated an increase of critical crack width w_2 and of fracture energy G_F with increase of d_{max} of concrete. A similar trend could be found by regression of data on G_F collected by Hillerborg (1984). These trends were also predicted by the Li and Huang model.

The work of Tognon and Cangiano (this volume) revealed increased notch sensitivity and transgranular (as opposed to intergranular) fracture in autoclaved very high strength concrete. It is likely that autoclaving promotes the transformation of the cement matrix from a gel structure to one with higher crystallinity, and that the interfacial bond strength is increased by the removal of excess water that could be trapped at these sites in normal conditions. The effect of aggregate type on composite properties was studied by Wu et al. (ibid.). The replacement of gravel by sintered fly ash as aggregates in structural lightweight aggregate

Table 1: Factors influencing the macroscopic properties of cementitious composites

I. Mix Factors:

Factors	Macroscopic	Micro/Meso-mechanisms*	References
w/c in hardened cement paste (HCP)	f_t decreases	Extension of critical elongated pore according to Griffith curve: a) Maximum pore size increase b) K_{1c} of cement decrease	Wittmann
Age	f_t and G_F increase	Cement matrix density increases with hydration products, leading to increase in K_{1c} of cement	Mihashi et al
w/c in concrete	f_t and G_F decrease	Bond strength and matrix toughness decrease	Mihashi et al
dmax of aggregates	G_F and w_2 increase	Matrix crack deflection at aggregates & pull-out of aggregates at large crack width	Mihashi et al
Dam concrete vs. normal concrete	Same	Same	Wittmann
Aggregate type: sintered fly ash vs gravel	G_F decrease	Weak aggregates do not arrest or deflect an impinging dominant crack	Wu & Zhang
Autoclaving in very high strength concrete (VHSC)	Notch sensitivity incr. Intergranular --> transgranular fracture	Cement matrix: gel --> crystalline structures Increased bond strength	Tognon & Cangiano
Fiber	G_F increased	Mechanisms different for various fiber types: Crack bridging (fiber pull-out, rupture, abrasion, etc.); crack deflection; multiple cracking	Ohgishi et al

*Some of these mechanisms are alluded to in the referenced papers, others are the opinion of the session reporter.

II. Environmental Factors:

Factors	Macroscopic	Micro/Meso-mechanisms *	References
Freezing (room temperature --> -18°C)	f_t and w_2 increase	Pore/void water turns into ice Stiff ice acts as bridges in fracture process	Mihashi et al

III. Pre-loading Factors:

Compressive pre-loading	Young's Modulus E decreases	Damage induced, possibly axial splitting 'microcracks'	Hordijk & Reinhardt
	Irreversible deformation	Same	
	Flat peak in σ–δ curve	Same	
	G_F increased	Crack deflection, blunting & branching due to interference with pre-load induced damage	

*Some of these mechanisms are alluded to in the referenced papers, others are the opinion of the session reporter.

concrete was found to mainly reduce the fracture energy. The moderate change in tensile strength suggests that this property is still much controlled by the interface cracks as in normal concrete. However the expanding dominant crack propagates through (instead of around) aggregates in its path, resulting in a low fracture energy.

The addition of fibers of various types clearly alters the material structure, and results in significantly improved fracture energy, as i shown by Ohgishi et al (ibid.). In our own laboratory, we have seen very different micro/meso-structures and deformation mechanisms resulting from different types of synthetic fibers. For example, certain aramid fibers appeared to cause the matrix cracks to wind arou the rigid cement paste-infiltrated fiber bundles, leaving behind smal pyramids on the fracture surface. On the other hand, high-tenacity polyethylene fibers appear to be well distributed. Significant amount of cement matrix spalling was observed on the fracture surface in this type of FRC. These micro/meso-mechanisms have strong influence on the FRC mechanical properties, as is observed in tension-softening measurements.

On environmental factors, the only one studied was the effect of freezing on mortar (Mihashi et al, this volume). The test data showe definite increase in f_t and w_2 of the frozen specimens. It was suggested that the transformation of pore/void water into ice which th acted as bridges in the developing microcracks was responsible for the observed phenomena.

Finally, the effect of pre-loading was studied by Hordijk and Reinhardt (ibid.). Compressive pre-loading appeared to cause a drop i elastic modulus and an increase in G_F. Also irreversible deformation and a flat peak in the tension-softening curve of concrete were observed. The micromechanism of damage, possibly in the form of axial splitting 'microcracks', induced by the compressive pre-loading, was suggested. The increase in G_F may also be related to the deflection, blunting or branching of the developing tensile crack under direct tensile loading, when the compressive pre-loading induced microcracks interfere with the developing tensile crack.

This session presents many interesting observations of tensile property variations as affected by mix, environmental, and pre-loadin factors which may be related to alterations of the material structure. The connections between macroscopic properties and these factors are a present very qualitative and often conjectural. In the interest of material engineering, it would be desirable to have a stronger link by means of micro/meso-mechanically based quantitative models. Such mode provide a means of modifying or controlling the micro/meso-structure i order to achieve desired macroscopic composite properties.

4 CONCLUSIONS

The papers in this session deal with cementitious composites (here to mean cement, mortar, concrete and FRC) at several size scales. On the microscale level consideration was given to: the pore size and distributions resulting from w/c ratio changes, ice formation as a result of freezing, hydration products as a result of age, etc. On the meso-scale, aggregate size and type, cement matrix toughness, and inclusion of fibers were dealt with. On the macro-scale, the tension softening curve including tensile strength, critical crack width, and fracture energy were measured. Details at each hiarachy (introduced t concrete by Wittmann, 1983) determine the properties at a higher level

Finally the macroscopic material properties have direct influence on the behavior of specimens or structural components. Discussions with regard to size effect, brittle/ductile transition, and unstable snap back behavior were presented.

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