Fracture Mechanisms in Concrete Systems under Uniaxial Loading

R. N. Swamy, University of Sheffield, England.

INTRODUCTION

Pastes, mortars and concretes are essentially anisotropic and heterogeneous systems. They consist of flaws, voids and cracks generated during volume changes during setting and hardening. The deformational behavior and fracture process in these materials is therefore complex and cannot be explained by simple laws of mechanics.

FRACTURE PROCESS IN HARDENED PASTE.

On a macroscopic scale, the hardened paste is probably the nearest to a homogeneous, elastic material. It displays largely elastic behavior, with some slow microcracking near the crack tip and consequent curvilinearity near failure (Refs. 1, 2). However, there is little slow crack propagation (in the accepted sense) in such a material, and once cracking occurs it tends to be self-propagating almost continuously throughout the material. Cracking thus effectively heralds the onset of instability; a major proportion of the energy is dissipated as surface energy, and an unstable fracture occurs. One result of this unstable crack propagation is that the volume change in the paste under uniaxial compression decreases continuously representing progressive consolidation. In energy terms, the hardened paste is probably the nearest to a notch-sensitive material, and a modified classical fracture mechanics approach should explain its fracture.

FRACTURE PROCESSES IN MORTAR AND CONCRETE.

Mortars and concretes are, on the other hand, truly multi-phase systems. Aggregate inclusions impart greater stiffness to the matrix, and reduce its cracking and dimensional instability. However, their differential stiffness adds heterogeneity to the system, and creates weak interfacial contact zones between aggregate and matrix. The

The strength, stiffness and stability of the interface are thus very much factors in determining the fracture process in mortar and concrete.

The discontinuities in the contact zone prevent the immediate fast propagation of a continuous crack. They enable a multiplicity of crack growth, and extensive microcracking at crack tips with consequent inelastic deformation and redistribution of stresses. When a microcrack stops and fails to penetrate further, whether owing to the presence of an inclusion of greater stiffness, to the greater bond resistance of the matrix phase, or to the stress conditions inhibiting crack growth, stress stabilization takes place by the initiation of a new crack or the growth of an existing crack in the neighbouring interfacial bonds as a consequence of the additional stress concentration produced by the previous crack arrest. This process of numerous discrete microcracking may be repeated many times, and a condition of quasi-equilibrium between surface and mechanical energy may exist over a considerable range of loading. The volume increase observed in mortars and concretes near failure condition is directly related to this stability of crack growth due to the presence of aggregates.

ROLE OF AGGREGATE INCLUSIONS.

The role of aggregate inclusions in a cement matrix is complex, comprehensive and crucial. As the size and gradation of the aggregate inclusions increases, the system becomes more heterogeneous, displays inelastic behavior earlier, shows greater stability of crack growth, displays greater ductility towards failure, reduces the failure strain of the matrix, and increases post yield deformation. The volume content of the aggregate particles also influences the mode of failure. Mortars and concretes with low aggregate content behave like a quasi-homogeneous system and tend to show a predominantly brittle type of

failure. At high aggregate concentrations, there is an increasing amount of interfacial cracking, and although the critical stress at volumetric changes also decreases, a slow and stable fracture occurs (Refs. 3, 4).

Thus both geometry and volume content of aggregate particles directly influence the energy requirements for crack propagation, and fracture toughness. Results show that concretes with typical coarse aggregate contents have about twenty percent greater resistance to crack growth than mortars with similar water-cement and sand-cement ratios (Ref. 1.). On the other hand, for the same water-cement and sand-cement ratios and notch geometry, the fracture toughness of mortar is about 2 to 3.5 times that of paste, and that of concrete from about 1.4 to 2.5 times that of mortar (Ref. 5).

EFFECTS OF MOISTURE MOVEMENT.

Probably one of the most important factors that determines the internal stress distribution prior to loading is due to drying shrinkage and moisture movement. The spacing and distribution of aggregates, their size, and most important, the relative stiffness of the matrix and aggregate, all contribute to the complex stress conditions in the matrix which may exist in different states of stiffness within the system. The aggregate restraint can also create sufficiently high tensile stresses that cause local bond failures, and it is these bond cracks and interfacial discontinuities which create through their geometry, the nuclei for potential crack propagation and fracture. The stress conditions in the matrix, aggregate and interface, thus very much determine the origin and nature of microcracking in concrete systems (Ref. 6, 7).

INTERFACIAL BOND.

The mechanism of interface breakdown is probably the most significant factor in the fracture process of the concrete system. Since the aggregate-matrix interface constitutes a substantial proportion of the total fracture surface, the interfacial bond influences significantly the stability of the concrete system. Cracking - and fracture - is thus essentially a heterogeneous process and consists of a series of stable local tensile-shear failures at the bond interface that give concrete its stability and a degree of ductility.

POST-YIELD DEFORMATION.

The presence of aggregate inclusions, and of discontinuities and bond cracks enables mortars and concretes to sustain deformation beyond the maximum stress. The existence of the descending part of the stress-strain curve is a confirmation that initial microcracking in concrete occurs primarily at the bond interfaces. In post-yield deformation, the changes in surface energy due to progressive debonding, the energy dissipation due to friction at the interfaces, and the inelastic deformation at the interface discontinuities all contribute to sustaining the load further.

FAILURE MODEL.

The process of numerous discrete stable cracking is the inherent property of the heterogeneity of concrete. It makes concrete highly redundant, and permits energy release without disruption. Progressive debonding, and the varying relative aggregate-matrix elemental stiffnesses influence significantly the fracture process. In defining a failure model, the following energetics must be considered : the surface energy of the cracks, time-dependent irrecoverable deformation, the kinetic energy associated with velocity of crack propagation, friction damping at interface discontinuities, the energy of the applied stress field, and energy at stress concentrations where cracks are initiated due to differential stiffness (Ref. 8).

REFERENCES.

1. Lotl, J. and Kesler, C.E., Highway Res. Board, 204 (1964).
2. Spooner, D.C., Mag. Conc. Res., 24, 85 (1972).
3. Swamy, R.N., RILEM Mat. & Struct., 4, 13 (1971).
4. Swamy, R.N., Int. Conf. Civ. Eng. Mat., 1, 301 (1971).
5. Shah, S.P. and McGarry, F.J., Proc. ASCE, 97, 1663 (1971).
6. Swamy, R.N., Proc. Inst. of Civ. Eng., 47, 288 (1970).
7. Swamy, R.N., Int. Conf. Mech. Beh. of Mat., 4, 132 (1971).
8. Swamy, R.N., Proc. Int. Conf. Struct. Conc., 212 (1968).