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The role of aggregate in the fracture of concrete

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The fracture of concrete is reviewed. Tests on notched and unnotched beams made from concretes containing aggregates of different sizes and types are described. A simple model is proposed to elucidate and formalize the role of the aggregate particles in a brittle matrix. It is concluded that aggregate particles cause cracks to form in a concrete matrix at a lower stress than that at which the matrix would crack if it contained no aggregate. It is also concluded that aggregate particles impede the extension of matrix cracks.

1. Introduction

Concrete is a brittle, low-strength composite. Essentially it contains three constituent elements: a matrix of cement paste and fine aggregate, coarse aggregate, and the matrix/coarse aggregate interfaces. Despite its universal use as a cheap construction material, our understanding of the behaviour of concrete under load is far from complete. In this paper the testing of a series of notched and unnotched concrete beams is described and the results are interpreted in the light of a proposed simple model of a single aggregate particle in a brittle matrix.

2. Fracture of concrete

What is known about the failure of concrete? Consider the loading of a concrete specimen in tension. Before loading is even begun, portions of the aggregate–matrix interfaces will have failed [1] due to shrinkage strains which occur during curing. These interface failures, or bond cracks, extend and multiply as the specimen is loaded until, on attainment of the discontinuity, or cracking strength, cracks begin to form in the matrix [1–4]. The initiation of these matrix cracks is distinguished by:

(1) a sudden change in the slope of the stress/strain curve;

(2) an increase in the acoustic emission rate, and

(3) dilatation of the concrete.

As the stress is further increased, these matrix cracks, in turn, extend and multiply, and ultimately precipitate fracture of the material.

Early fracture-oriented concrete studies [5–7] concentrated on determining the fracture toughness of various cement-paste, mortar and concrete mixes. Specimens of standard geometry containing pre-formed notches were tested and the ultimate load used to determine the fracture toughness, K_c. Two distinguishing aspects of concrete fracture are now well documented.

(1) A crack in cement-paste, mortar or concrete does not propagate with the classical suddenness of a crack in a perfectly brittle material. Rather, a period of slow, stable crack growth precedes unstable failure.

(2) The fracture toughness is not constant: it varies with the dimensions of the specimens tested and, to a certain extent, with the length of the preformed notch.

Thus the concrete cannot, for fracture studies, be regarded as an ideal brittle, elastic, homogeneous material: a region of inelastic response must exist in the vicinity of the crack tip, an effect which, for the crack lengths usually considered, invalidates linear stress analyses. Evidence does exist, however, that K_c is constant [8] (i.e. a material property) when it is determined from specimens containing sufficiently large cracks.

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3. The role of aggregate

Although aggregate is often regarded merely as a low-cost filler material in concrete, many attempts have been made to establish its role in concrete behaviour. The complexity of the problem, that of a graded, imperfectly bonded aggregate in a brittle, relatively inhomogeneous matrix, is formidable: thus, it is understandable that the effect of the aggregate is usually established empirically and that little is known of the mechanisms involved.

Published accounts of the role of aggregate in concrete fall into two categories.

(1) Those relating to macroscopic testing, in which concretes containing different types and sizes of aggregate are tested, and the aggregate's effectiveness is linked empirically to its size, shape, grading, surface texture, and other properties.

(2) Those describing experimental and analytical studies of models, in which the interaction of the matrix with a single aggregate particle, or with an ordered array of aggregate particles, is studied.

Much of the macroscopic testing has been performed with the aim of establishing the effect of the maximum aggregate size, and the strength and nature of the interfacial bonding. For example, Walker and Bloem [9] determined that the compressive strength of concrete varied inversely with the maximum aggregate size – the larger the aggregate, the weaker the concrete. And Jones and Kaplan [3] found that concretes containing smooth aggregates cracked at a lower stress than did comparable concretes containing coarser textured aggregate, although the ultimate compressive strengths were similar. Thus the lower bond stresses intuitively associated with the smooth aggregate apparently led to the formation of matrix cracks at a lower stress, but did not decrease the stress at which these cracks became unstable. Darwin and Slate [10] also found little interdependence between the bond strength and ultimate strength.

Modulus of rupture testing gives an indication both as to the effect of aggregate on the initiation of matrix cracks, and its effect on their propagation: the cracking strength, if it is accurately recorded, is a yardstick of matrix crack initiation, while the ultimate strength, coupled with the extent of the inelastic deformation exhibited by the beam, indirectly expresses the aggregate's influence on the extension of matrix cracks.

Fracture testing of notched beams directly reflects the role of the aggregate in influencing the extension of matrix cracks. The effect of the aggregate on the initiation of a matrix crack is by-passed as the notch initiates a matrix crack at relatively low stresses. A typical example of notched beam testing is reported by Naus and Lott [6], who found that the fracture toughness of cement-paste and of mortar increases markedly with the addition of coarse aggregate. Similar results have been obtained by others.

4. Experimental beam testing

Notched and unnotched beams were tested in three-point flexure. As is indicated in the first columns of Table I, the beams were made from four different mixes and each mix was used for at least four different sizes of beams.

4.1. Mix information

Details of the concrete mixes are given in Table II and an aggregate grading curve is given in Fig. 1. The mix components were obtained locally. Ordinary Portland cement (ASTM Type I) was used, and it was purchased as a single lot to ensure uniformity.

The basalt and greywacke concretes had the same grading curve and they varied only in the type of large aggregate (4.75 to 2.36 mm) they contained: the basalt was a strong, crushed aggregate with a textured surface and a high absorptivity, while the crushed greywacke was a

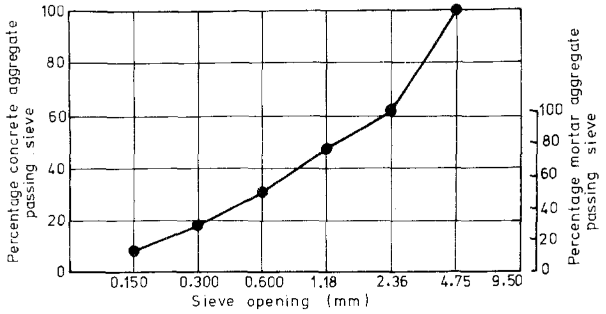

Figure 1 Grading curve for the concretes and mortar.

TABLE I Summary of beam-testing results

Specimen group			Mix	Flexure		Fracture toughness			
Span (mm)	Depth (mm)	Thickness (mm)		No. of specimens tested	Modulus of rupture (MPa)	No. of specimens tested	Effective modulus of rupture (MPa)	Ultimate fracture toughness (MN m$^{-3/2}$)	Discontinuity fracture toughness (MN m$^{-3/2}$)
800	200	100	Basalt	2	7.3	6	5.1	1.03	0.97
			Greywacke	3	7.4	5	5.4	1.06	1.05
500	125	75	Basalt	3	8.2	6	6.0	0.95	0.91
			Greywacke	3	7.3*	6	4.4*	0.70*	0.63*
300	75	50	Basalt	3	8.5	6	6.3	0.80	0.74
			Greywacke	3	8.3	6	7.7	0.94	0.90
			Mortar	3	9.0	6	6.4	0.78	0.71
			Cement-paste	3	13.7	6	6.3	0.76	0.76
150	38	25	Basalt	3	10.2	6	6.7	0.69	0.65
			Greywacke	3	9.6	6	9.2	0.81	0.80
			Mortar	3	10.6	5	8.3	0.71	0.70
			Cement-paste	3	15.5	6	8.4	0.60	0.60
100	25	25	Mortar	3	10.8	6	10.1	0.72	0.72
			Cement-paste	3	15.5	6	8.4	0.60	0.60
48	12	12	Mortar	3	13.0	5	11.4	0.58	0.55
			Cement-paste	2	17.3	6	10.1	0.55	0.55

*Inadequately compacted beams.

TABLE II Mix details

	Basalt concrete	Greywacke concrete	Mortar	Cement-paste
$\frac{\text{Weight water}}{\text{Weight cement}}$	3.0	3.0	1.9	–
$\frac{\text{Weight aggregate}}{\text{Weight cement}}$	0.42	0.42	0.42	0.30
Sufficient air-entraining agent to make air content (vol %)	5.5	5.5	5.5	5.5
Compression strength (70 mm cubes) (MPa)	73.3	72.0	71.1	*

*Cement paste cubes did not fail in compression.

more angular, smoother surfaced aggregate of low absorptivity.

The mortar was composed of that part of the basalt or greywacke concrete passing a 2.36 mm sieve. Thus the mortar was basically the matrix in which the large aggregate particles of the concrete mixes were embedded. The cement paste was a mixture of cement and water. To facilitate its placing, the cement paste had a lower water–cement ratio than the other mixes.

4.2. Beam sizes

At least four groups of beams were cast from each mix. Each group contained six notched and three unnotched beams. A span-to-depth-to-thickness ratio of 12:3:2 was sought, although squarer sections were adopted for the smaller beams to avoid impractically thin beams. The largest beams were made from basalt or greywacke concrete and the smallest beams were made from cement paste.

4.3. Notch forming

The creation of a truly sharp notch in a cement-paste, mortar or concrete specimen is difficult. Some investigators have used diamond saws to cut notches, and others have cast them. While neither

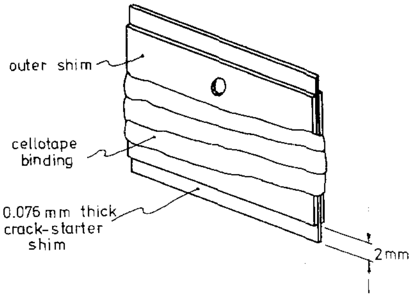

Figure 2 Notch-forming shim.

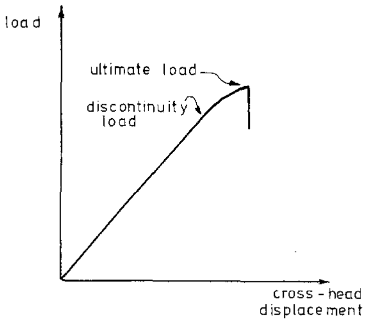

Figure 3 Load versus cross-head displacement for a beam test.

method, in itself, produces a sharp notch, the slow crack growth which occurs prior to the onset of instability and the shrinkage stresses imposed during curing result in the formation of an effectively sharp crack at the notch tip. No difference has been observed in the response of beams notched by these methods. The casting method was used in this project. As is shown in Fig. 2, two thicker shims imparted stiffness to a thin (0.076 mm) brass notch-forming shim, which was withdrawn immediately prior to testing. These notch formers were fixed in plywood moulds fabricated for this project.

4.4. Beam making and testing

The two largest sizes of beams were compacted with a Kango vibrating hammer, and a vibrating table was used for the smaller specimens. The 625 mm x 125 mm x 75 mm greywacke beams were inadequately compacted, and this is reflected in their strengths. All beams were covered with plastic sheeting after placing and stripped the following day. They were cured in a fogroom and tested wet at 28 days: in particular, the cement-paste beams were cured in water, and each one remained underwater until moments before it was tested.

A 100 kN capacity screw-jack Instron TT-D test-machine was used, the beams being loaded so that their screeded faces were in tension. The end-supports and loading rig were similar to those used in modulus of rupture testing and a uniform strain rate was maintained by adjusting the cross-head displacement rate so that each beam failed in approximately 1 min. The Instron automatically recorded a plot of the applied load against the cross-head displacement.

4.5. Results

The curve shown in Fig. 3 is typical of the applied load versus cross-head displacement plots recorded for the beams. Two loads were recorded from these plots: the discontinuity load which corresponds to the first discernible sudden change of slope, and the ultimate load. For some of the specimens, no such change of slope was apparent, and the two loads are thus equal. A summary of results appears in Table I. Values of the fracture toughness corresponding to the discontinuity and ultimate loads are calculated from the relevant ASTM formula [11].

The modulus of rupture values are based on the beam's ultimate strength only – the instrumentation and/or method of test used precluded accurate resolution of the discontinuity strength. The effective modulus of rupture for the notched beams was determined by considering the notched beams to be equivalent to prismatic beams of cross-section equal to that of the notched beams at the plane of the notch.

5. Interaction of matrix crack and aggregate particle

In order to assist in interpreting the experimental results consider a simple model – that of a single aggregate particle in a matrix with particulars as indicated in Fig. 4.

5.1. Matrix-crack initiation

Weaknesses and failures exist at the interface before the model is loaded. Small flaws will also be present in the matrix. When the model is loaded matrix cracks can be initiated in a number of ways.

(1) A matrix crack may develop from flaws in the matrix with the aggregate particles exerting no influence.

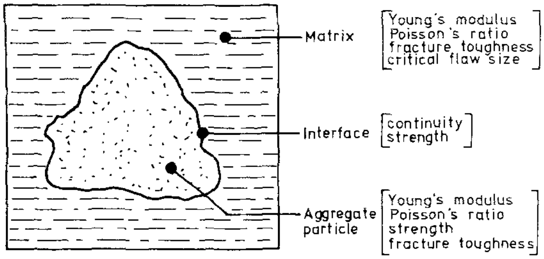

Figure 4 The single aggregate particle model.

(2) A matrix crack may form as a continuation of a bond crack at an interface.

(3) A stress-raising feature on an aggregate particle may initiate a matrix crack.

(4) The aggregate particle may break and thus cause a matrix crack to form.

(5) A matrix crack may develop from flaws in the matrix as in (1), but under a stress field influenced by the aggregate particle.

Mechanisms 2 to 4 are matrix-crack promoting rather than matrix-crack inhibiting. Mechanism 4 is unlikely to occur with the aggregates normally used on concrete. Mechanism 5 can inhibit or promote matrix-crack extension. For example, an interface bond failure could cause higher stresses in the neighbouring matrix or it could cause lower stresses.

No conclusive evidence exists to confirm the occurrence of any of the above mechanisms. Observation of the fracture surfaces yields little as it is impossible to distinguish the origin of the matrix cracking.

5.2. Interaction of matrix crack with aggregate

Once the matrix crack has formed, how does the aggregate particle affect its tendency to extend? The ways in which the crack can extend beyond the aggregate can be summarized as follows.

(1) The crack deviates from its plane and passes around the aggregate particle, through the matrix. In energy terms more crack surface is formed. Thus, the crack will be less likely to pass the aggregate particle at a given stress level. This can be seen in terms of stress, in that the inclination of the crack and the closeness of the aggregate will both tend to reduce the stress-intensity factor.

(2) The crack meets the aggregate, traverses the interface, and re-enters the matrix. Whether this inhibits or facilitates crack growth will depend on the fracture toughness of the interface and on the size and shape of the aggregate particle.

(3) Variations of (2) may occur, in which the newly formed crack is not continuous with the original crack. For example, the additional load thrown on the aggregate may cause it to initiate a further crack. Mechanisms of this type would promote side-cracking, (the formation of crack surface which is not part of the major fracture surface). Again the cracking strength may be increased or decreased.

6. Conclusions

(1) For a given size of notched beam there is an increase of fracture toughness with increasing aggregate size. This indicates that aggregate particles resist the propagation of matrix cracks.

(2) For the unnotched beams there is a decrease in the modulus of rupture with increasing aggregate size. This, coupled with the increase in fracture toughness associated with the notched beams, shows that the aggregate particles do initiate matrix cracks and the initiation of cracks is at a stress that decreases with increasing aggregate size.

(3) A comparison of notched beam results for greywacke concrete with results for similar aggregate-sized basalt concrete shows the greywacke aggregate particles inhibit matrix-crack extension more effectively than similar sized basalt aggregate particles. This may be due to the greater specific surface area of the greywacke.

(4) Although the notched beam results for greywacke concrete are higher than those for similar aggregate-sized basalt concrete, the moduli of rupture of the greywacke concrete are not correspondingly higher. Hence the greywacke particles initiate cracks at a lower stress than do the basalt particles. This is possibly a result of the greywacke particles having greater angularity or less effective bonding than the basalt particles.

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