DURABILITY OF CONCRETE
FRACTURE MECHANICAL ASPECTS

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SYNOPSIS

Concrete durability is viewed in the light of fracture mechanics. Principles are presented and applied to problems relating to concrete durability for the purpose of introducing fracture mechanics in durability research.

Key-words: durability, fracture mechanics, crack, tensile failure, shrinkage, pop-out, expansion, concrete, cement paste, structure.

1. INTRODUCTION

The behaviour of concrete materials under effects that seek to destroy the materials - alkali-silica reactions, frost attack, etc. - are mechanical phenomena that should be considered in the light of fracture mechanics.

Up to the present time, the theoretical treatment of such behaviour has been largely based only on continuum mechanics (theory of elasticity, theory of plasticity), which has proved entirely inadequate as a means of describing and explaining the behaviour of concrete.

For example, the existence of concrete as a coherent, strong material would be an impossibility if nature obeyed the theory of elasticity, and continuum mechanics does not provide the answers to several vital questions concerning crack initiation, stability, collapse, and crack configuration. Nor does continuum mechanics give any information about what determines the brittleness of materials - and does not say at all that brittleness is not a pure material parameter but that the brittleness increases with the size of the object.

The answers to these and other questions lie in fracture mechanics.

The purpose of this article is not to present finished solutions to current durability problems but to present fracture-mechanical theories and thoughts that may provide a better basis for durability research and general understanding.

2. FRACTURE MECHANICS

Fracture mechanics originated in about 1920, with the work of Griffith inter al. The principal aim was to understand and describe what happened during fracture in extremely brittle materials such as glass. Later, the discipline developed rapidly, but it is only in the last ten years that fracture mechanics has been used in the field of concrete, and then mainly in research. For these reasons the present paper endeavours to explain principles of fracture mechanics in a form suitable for application to concrete.

2.1 Tensile failure

Tensile failure occurs in the form of either parallel separation (ductile behaviour) or peeling-open of sharp cracks (brittle behaviour). see fig. 1.

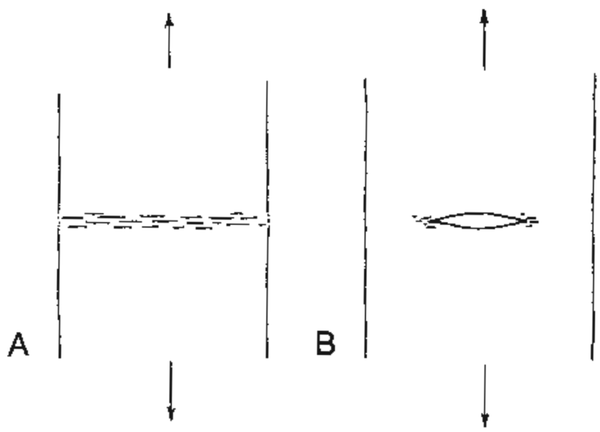


Fig. 1. Tensile fracture.
A shows fracture with yielding in a narrow zone. B shows peeling fracture where the internal forces are only active in small, heavily loaded zones at the tips of the crack.

2.2 Crack zone

During the formation of cracks in tension, a narrow zone undergoes heavy deformation accompanied by local structural changes. see fig. 2.

The width of the crack zone has hitherto only been paid sporadic attention (2).

The extent of the crack zone in the direction of propagation is frequently - although not always -proportional to and of the same order of magnitude as the characteristic length $l_{ch} = EG/\sigma_o^2$, see fig. 3.

2.3 Crack zone deformation

The crack zone deformation Δ_o determines the ductility of the material (see fig. 2). The greater the value of Δ_o, the lower will be the brittleness. The crack zone deformation is a material parameter.

2.4 Fracture energy G

The energy required to open a unit area of crack in tension is designated the fracture energy. G is the area under the stress-deformation curve (see fig. 2) and is a material parameter.

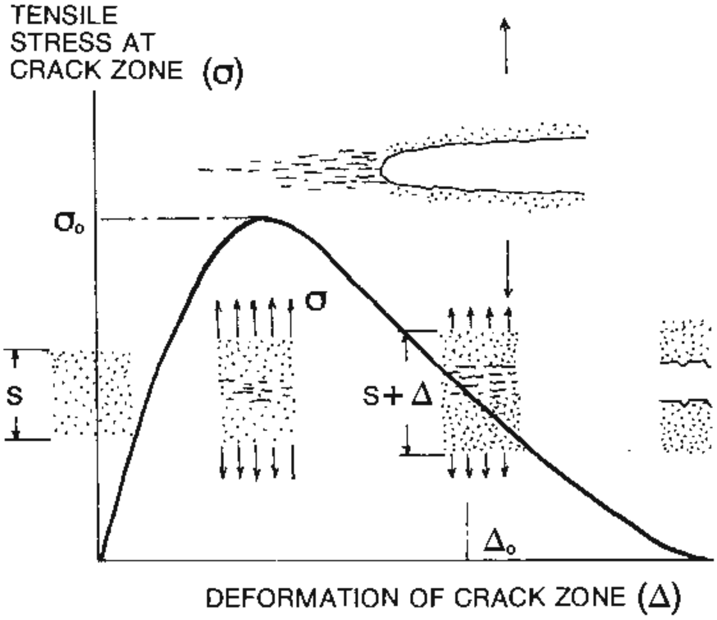


Fig. 2. Stress (tensile) as a function of the deformation of the crack zone in separation failure. The area under the curve represents the separation work per area newly formed crack, designated the fracture energy G.
The characteristic crack zone deformation Δ_o is defined by $G = \Delta_o \sigma_o$, where σ_o is the maximum tensile stress.
The crack zone deformations are of the order of magnitude 0.01-0.001 μm for glass, 2-10 μm for cement paste, 10-50 μm for concrete, and typically greater than 1 mm for steel-fibre-reinforced concrete.(1)

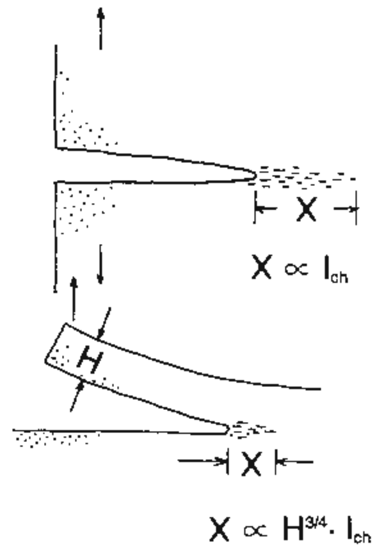


Fig. 3. Length of crack zone in peeling fracture.(1)

2.5 Tensile strength

σ_o is the maximum tensile stress during the opening of a crack. σ_o is a material parameter (see fig. 2).

2.6 Characteristic length

The characteristic length l_{ch} is a material parameter that gathers the material parameters governing the brittleness of an object into a single number with the dimension length (3)

$$l_{ch} = \frac{EG}{\sigma_o^2}$$

where E is the modulus of elasticity. The greater the value of l_{ch}, the less brittle the behaviour will be. Brittleness is not a pure material property, but also depends on the size of the object. Therefore, it is only when l_{ch} is related to the size of the object that its real importance becomes manifest.

2.7 Brittleness Number

The parameter "Brittleness Number B" takes account of both material properties and object size (L) and unites all parameters in a single number

$$B = \chi \frac{L\sigma_o^2}{EG} = \chi \frac{L}{l_{ch}}$$

where χ is a dimensionless shape factor.

The greater the value of B, the more brittle the behaviour will be. B is a dimensionless quantity that classifies crack and fracture behaviour in the same way as Reynold's Number and Fourier's Number classify fluid flow and heat flow, respectively (1).

2.8 Stress intensity factor

The stress intensity factor K_I is a measure of the stresses in front of a crack tip in a loaded object, assuming linear elastic behaviour. K_I has the unit $N/m^{3/2}$. K_I depends only on the geometry and load of the object and is thus independent of specific material.

2.9 Critical stress intensity factor

The critical stress intensity factory K_{Ic} is the precise value of K_I at which sharp cracks in objects of a specific material peel open and propagate - i.e. the value at which the material fails locally at the crack tip. K_{Ic} is a pure material property.

2.10 Relations

For objects made of materials with linear- elastic behaviour up to failure, the following relation applies between the fracture-mechanical parameters:

$$G = \Delta_o \sigma_o \qquad l_{ch} = \frac{EG}{\sigma_o^2} \qquad B = \frac{L\sigma_o^2}{EG} \qquad K_{Ic} = \sqrt{EG}$$

Examples of fracture-mechanical properties are shown in table 1.

MATERIALS	E MN/m^2	σ_0 MN/m^2	G N/m	Δ_0 μm	l_{ch} m	K_{IC} $MN/m^{3/2}$
Cement paste	7.000	4	20	5	0.01	0.4
Dense silica cement paste	25.000	20	20	1	0.001	0.7
Concrete	30.000	3	60	20	0.2	1.3
Dense silica cement mortar 6% steel fibres	40.000	40	30.000	750	0.8	35
Glass	70.000	500	5	0.01	$1.4 \cdot 10^{-6}$	0.6

Table 1. Fracture mechanical data.
E is the modulus of elasticity, σ_0 the tensile strength, G the fracture energy, Δ_0 the characteristic crack tip deformation, l_{ch} the characteristic length, and K_{IC} the stress intensity factor. (1)

3. THEORIES FOR TENSILE FAILURE

Different theories can be used as basis for describing the criterion for tensile failure.

3.1 Theory of elasticity

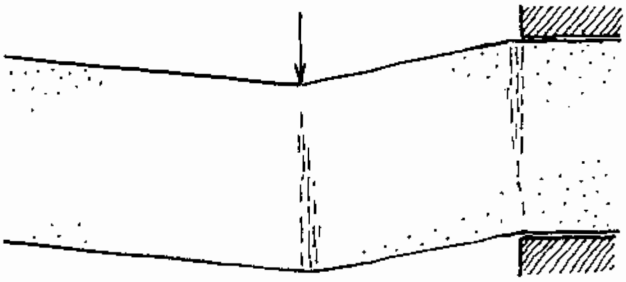
The theory of elasticity is based on the assumption of a unique relationship between strains and stresses up to an ultimate value, after which rupture occurs.

Rupture criteria based exclusively on the theory of elasticity imply "large" objects without "large", sharp initial cracks. The behaviour at rupture is brittle.

3.2 Yield-plane theory

This theory deals with tensile failure with yielding in narrow crack zones in the immediate proximity of geometrical planes - the later rupture planes (see fig. 4). The objects are assumed to be divided into sections by yield zones, the sections being regarded as rigid bodies so that deformations can only occur through opening of crack zones.

Yield-plane theory implies "small" objects (ductile behaviour).



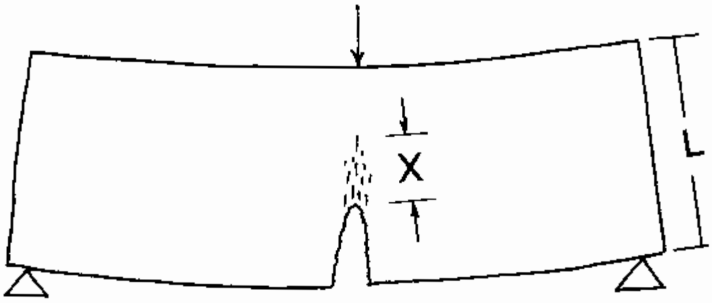


Fig. 4. Yield plane theory.
In tensile yielding the body is displaced as rigid bodies separated by narrow yield zones.

Fig. 5. Non-linear fracture mechanics is typically used when the length of the crack zone x is not small in relation to the size of the object L.

3.3 Linear-Elastic Fracture Mechanics (LEFM)

LEFM deals with fracture in objects with "large", sharp cracks that peel open. The behaviour of the material outside the heavily loaded zone in front of crack tips is assumed to be linear-elastic, while special properties are attributed to the crack tip, this zone being regarded as a line singularity without physical extent.

LEFM implies "large" objects of elastic material with sharp cracks (brittle behaviour).

3.4 Non-linear-elastic Fracture Mechanics

This concept deals with an extension of LEFM to cover systems where crack zones are not dealt with as singularities but are assigned a physical extent. In analyses, deformations of both the crack zones and the material between these are taken into account, the latter usually being calculated by means of the theory of elasticity. Non-linear-elastic fracture mechanics encompasses the other theories as special cases and is used particularly for objects that are neither extremely small nor extremely large (semi-brittle or semi-ductile behaviour), see fig. 5.

4. EXPANSION OF BODIES IN ELASTIC MATERIAL

Many types of destruction of concrete are caused by the expansion of matter within the concrete - for example, the expansion of water through freezing, the expansion of aggregates due to alkali-silica reactions, and the expansion of reinforcing steel during corrosion.

For this reason it is natural to seek information about the mechanical aspects of the problems of durability by considering the expansion of bodies enveloped in elastic material.

4.1 Crack initiation

During the expansion, strains and stresses are induced that are uniquely determined by the expansion.

When local tensile strains reach the ultimate tensile strain of the material (determined on large specimens), local failure will occur in some cases, whereas in other cases, a far greater deformation is required to initiate a crack.

To initiate a tensile crack, the material as a whole must, of course, deform corresponding to the ultimate tensile strain of the material ε_o but it must, in addition, deform locally corresponding to the characteristic crack zone deformation Δ_o (see fig. 6).

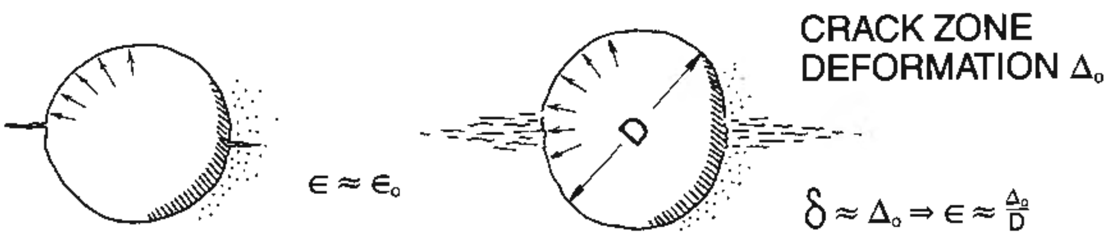


Fig. 6. Crack initiation by expansion of body in elastic solid.
Rupture criteria are shown for systems with big and small Brittleness Number $\left(\frac{\varepsilon_o D}{\Delta_o} = \frac{\sigma_o D^2}{EG}\right)$, respectively.

The crack initiation criterion can therefore typically be written in the form:

$$\varepsilon = \varepsilon_o + \alpha \frac{\Delta_o}{D}$$

where the constant α depends on the number of cracks initiated and the geometry of the system - in rough analyses we can often put $\alpha = 1$.

For large objects (large D) the first term predominates and crack initiation follows the theory of elasticity, local failure occurring when the tensile strain reaches the ultimate tensile strain of the material.

For small objects, on the other hand, the last term predominates; the crack initiation strain no longer depends only on the material (crack-zone deformation Δ_o), but also on the size of the object.

The governing parameter for the behaviour is the ratio $\varepsilon_0 D/\Delta_0$, which is identical to the Brittleness Number*.

This is illustrated in a master curve (fig. 7). The abscissa - the Brittleness Number - is a measure of the extent to which the object acts as a "small" object (exhibiting ductile behaviour) or as a "large" one (exhibiting brittle behaviour).

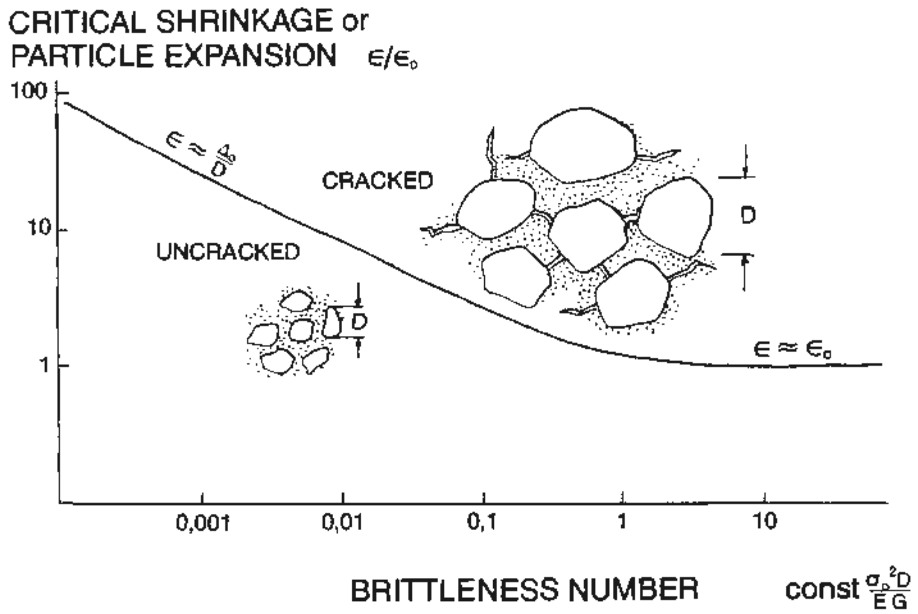


Fig. 7. Critical expansion of particles or shrinkage of matrix material in a composite with rigid particles as a function of the Brittleness Number. ε is the strain, D the particle size, σ_0 the tensile strength, E the modulus of elasticity, G the fracture energy, and Δ_0 the crack deformation, all referring to the matrix material.

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* The strain ratio is identical to the Brittleness Number. This can be seen from the relationship between stress and strain and between fracture energy, tensile strength and crack zone deformation:

$$\frac{\varepsilon_o D}{\Delta_o} = \frac{\sigma_o/E \cdot D}{G/\sigma_o} = \frac{\sigma_o^2 D}{EG}$$

4.2 Crack propagation - stability contra collapse

In some cases the initiation of a crack results in total fracture, whereas in others, the crack is stabilized. Instability is caused by release of energy, which is converted into fracture energy. The released energy may be elastic energy stored in the concrete, elastic energy stored in an expanding particle or fluid, or external potential energy such as gravity or fluid pressure from external sources.

If the released energy is insufficient to cause total fracture, the crack will stabilize.

The type of behaviour depends on the geometry of the object, the type and shape of the load, the material properties, and the size of the object. Examples are shown in figs. 8, 9 and 10.

Certain configurations will never result in total collapse. For example, "infinite" bodies loaded locally with a concentrated force, see fig. 8.

Other configurations will alsways result in total collapse, for example, crack systems with the crack loaded with steadily increasing fluid pressure, see fig. 9B.

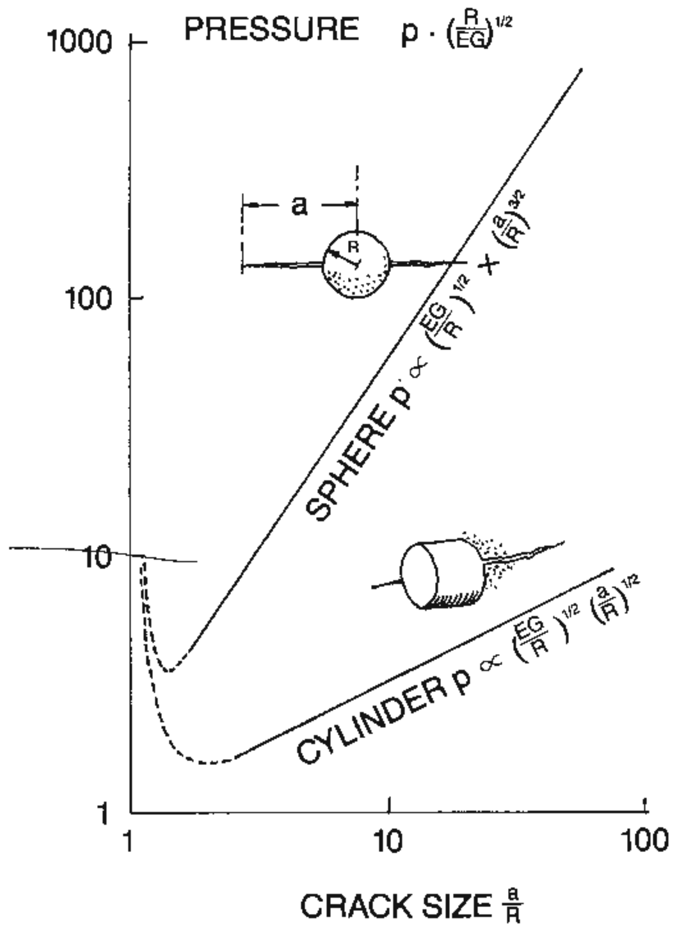


Fig. 8. Pressure versus crack size in stable crack propagation during expansion of a sphere and a cylinder in a large body. For both strain-loaded and stress-loaded systems the cracks grow steadily until they approach the boundaries of the object.
The extent of the crack (in relation to the size of the object) increases with increased Brittleness Number. The curves refer to systems with high Brittleness Numbers calculated according to LFEM.(1) The pressure is made dimensionless by dividing it by the fracture pressure corresponding to a sharp crack of size R.

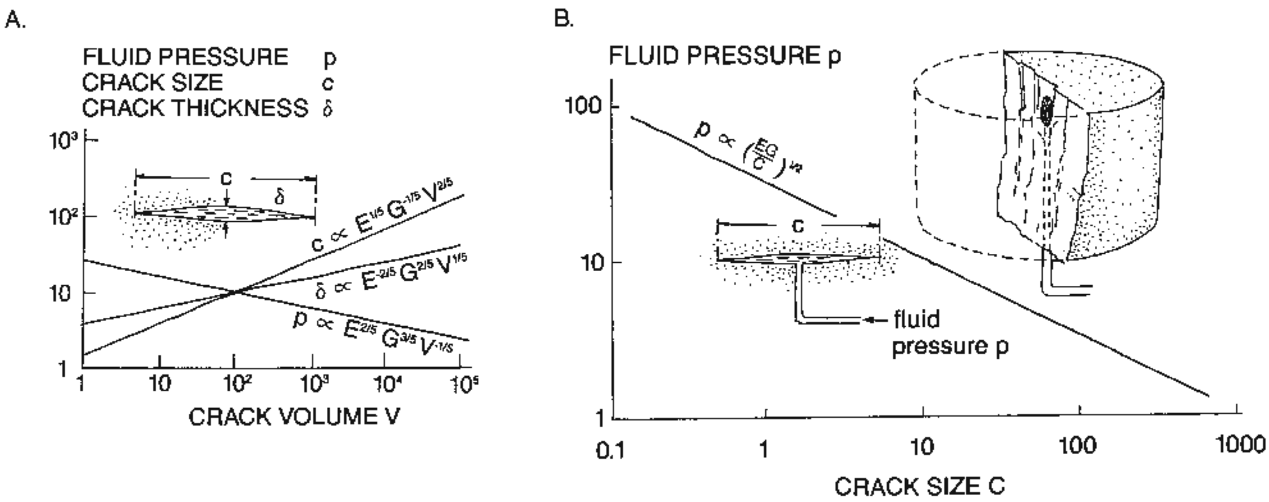


Fig. 9. Crack propagation in large objects caused by fluid expansion in the crack. The propagation is stable for strain-loaded systems, where the volume increases slowly (A), and unstable for stress-loaded systems, where the fluid pressure increases (B). The curves refer to systems with high Brittleness Numbers calculated according to LFEM.(1)(5)
The sketch shows undesired cleavage due to leakage of oil from a rubber ball during pop-out tests at low oil pressure.

The size of the cracks developing after local crack initiation increases with increasing Brittleness Number $\sigma_0^2 L / EG$. The increase in the relative crack size with increase in object size occurs because the stored elastic energy at crack initiation (W_E) is proportional to the volume and specific stored energy of the object, whereas the energy required to create a characteristic crack (W_G) is equal to a characteristic area multiplied by the specific crack energy.

$$W_E = \text{constant } \frac{\sigma_0^2}{E} L^3$$
$$W_G = \text{constant } GL^2$$

If the energy ratio W_E/W_G is very large, plentiful elastic energy will be relased to form the characteristic crack - so a considerably larger crack will form.

If, on the other hand, the energy ratio is small, insufficient elastic energy will be released to form the characteristic crack, so a corresponding very small crack will form.

The ratio W_E/W_G, which thus governs the crack size, is proportional to the Brittleness Number

$$W_E/W_G = \text{constant } \frac{\sigma_0^2 L}{E G}$$

In the example in fig. 10, we considered a system in which the elastic energy was stored only in the concrete.

In many cases, the expanding particles have lower moduli of elasticity than the surrounding concrete material and make a larger contribution to the stored elastic energy.

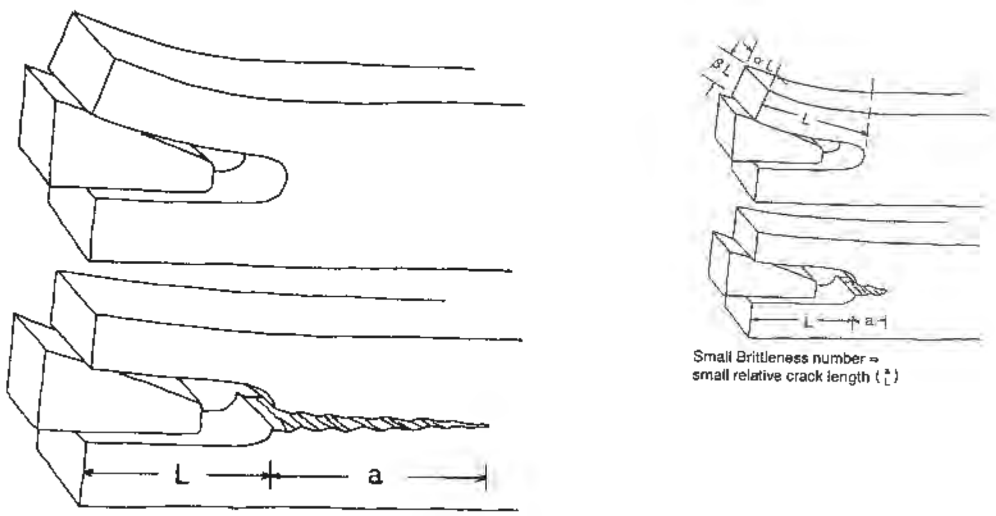


Fig. 10. Instability after crack initiation, illustrated by the size of the instantaneous crack.
The crack size - in relation to the size of the object - is determined by the relationship between stored elastic energy (some of which is released during crack initiation) and the energy required to create a characteristic crack. The larger the ratio, the bigger the crack. The energy ratio is identical to the Brittleness Number $L \cdot \sigma_0^2/EG$.

5. INTERNAL COHERENCE OF CONCRETE

Roughly speaking, concrete can be characterized as consisting of rigid particles - sand and stone - held together by a brittle binder - cement paste - which is extremely sensitive to tension and exhibits great contraction during hydration and drying.

Since the presence of sand and stone substantially hinders free contraction of the paste, concrete should crack and disintegrate because the prevented contraction is about 10 times the ultimate tensile strain of the paste.

That this does not happen and that the concrete stays together as a coherent, strong material is due, as described section 4.1, to the fact that the cement paste in small systems actually exhibits distinct ductility.

The fact is that the crack zone deformation in cement paste, which is about 2 to 5μm, is big in relation to the total shrinkage of small systems of size about 1 mm or less. For example, the restricted contraction of cement paste around an 0.5 mm grain of sand must be as high as 0.4 to 1% to cause cracking, against 0.03% for similar systems with larger particles.

The effect of particle size on critical free matrix contraction - or on critical particle expansion - is shown in fig. 7.

Concrete is normally constructed as a multi-component system.

By adding sand to cement paste we get a new binder - the mortar - with which to glue the larger aggregates together. Mortar shows less free contraction and higher ductility than the pure paste and can therefore bind the large aggregates firmly together without cracking and destruction during hydration and drying.

6. POP-OUT FORMATION

An expanding particle near the surface can cause a so-called pop-out, where a conical body is pushed out.

Twenty years ago, Isen and I determined the pop-out pressure and presented a model which we claimed had general validity (4):

$$p = 10(h/d)\,\sigma_c \qquad \text{range: } 0.07 < h/d < 0.9$$

where σ_c is the tensile strength of the mortar.

The pop-outs were created by building up oil pressure in 30 mm dia., thick-walled rubber balls emedded in cement mortar. The depth was varied from 2.4 to 30 mm (see fig. 11). By means of dimensional considerations we generalized the model to cover arbitrary particle sizes and qualities of mortar.

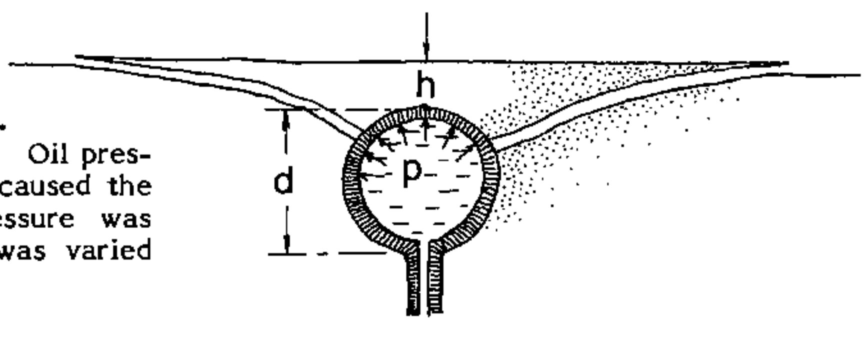


Fig. 11. Creation of pop-outs.
Model test on cement mortar. Oil pressure in 30 mm rubber balls caused the pop-outs. The pop-out pressure was measured and the depth h was varied between 2.4 and 30 mm. (4)

Unfortunately, the assumptions for these dimensional considerations were incorrect because σ_c, h and d were not, as had been assumed, the only parameters that were significant for resistance to pop-out. Therefore, the model is not generally valid and can only be used as a case story telling about the behaviour of a specific system.

Seen in the light of fracture mechanics, the situation looks entirely different. Failure can occur in at least three different ways, depending not only on the locations of the spheres, but also on the tensile strength σ_o of the matrix material, the modulus of elasticity E and fracture energy G, and the size D of the spheres. This is shown in fig. 12, where the effect of σ_o E G D is united in the Brittleness Number.

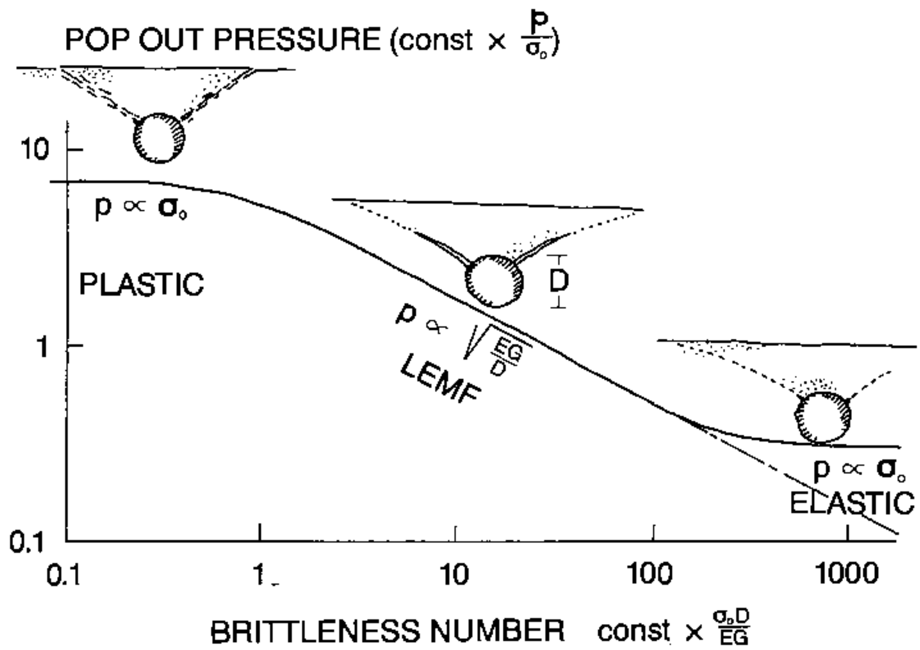


Fig. 12. Pop-out pressure as a function of the Brittleness Number.
Master curve for geometrically similar systems (sketch). The sketches illustrate the situation just before rupture.

1. In systems characterized by high Brittleness Numbers, failure occurs suddenly directly after the maximum tangential tensile strain reaches the material's ultimate tensile strain. The failure pressure p is proportional to the tensile strength σ_o and can be calculated on the basis of the theory of elasticity. The pop-out pressure increases with increasing depth, approaching a final value $p = 2\sigma_o$ (corresponding to infinite depth).

2. Systems characterized by extremely small Brittleness Numbers exhibit ductile behaviour, with the whole of the rupture zone actively force-transmitting at the same time. The failure pressure is proportional to the tensile strength and the pop-out fracture area of the pop-out cone's yield plane. The pressure can be calculated in accordance with the yield plane theory. The pop-out pressure increases considerably with increasing depth, following a second power law:

$$p = \text{constant} \cdot \left(\frac{H}{D}\right)^2$$

Thus, at great depths, the pop-out pressures are several orders of manitude larger for system with plastic behaviour than for systems with elastic behaviour (for materials with identical tensile strength σ_0).

3. In the big intermediate range, rupture occurs through stable crack growth in step with the load (up to a critical size). The transitional range from unstable to stable behaviour requires analysis that takes account of released elastic energy after the crack initiation. The continued crack growth can be determined by means of LEFM for systems with comparatively high Brittleness Numbers, while less brittle systems require the use of non-linear elastic fracture mechanics. In the range in which LEFM is applicable, the rupture load is proportional to $\sqrt{EG/D}$.

Rough calculations on the results from the old pop-out experiments show that the behaviour at rupture - despite a visual impression of great brittleness - was not distinctly brittle, evaluated for example on the basis of the fact that the fracture pressure was 3-5 times that corresponding to unstable elastic failure for systems with very high Brittleness Numbers. This view is also substantiated by the fact that the actual Brittleness Number was most likely about 0.5, which is not "very large" in the present context. This figure was calculated on the basis of estimates of E and G ($3 \cdot 10^{10}$ N/M^2 and 30 N/m).

In the tests we found a rupture pressure of about 40 MPa for deeply bedded spheres - about 10 times the tensile strength of the mortar, which was about 4 MPa.

If we were to transfer this experience to identical systems with high-strength mortar (tensile strength 20 MPa), we would expect the material to be able to resist pop-out pressures of about 200 MPa.

However, fracture-mechanical evaluations lead to far lower values. The reason for this is that the brittleness has been drastically increased.

If, for example, the Brittleness Number is increased by a factor of 12 (assuming that E ·G is increased by a factor of 2) and the systems can be described by LEFM (sloping section of curve), the estimated pop-out pressure will be only about 60 MPa, not 200 MPa.

If the high-strength mortar were to resist 200 MPa pop-out pressure, EG/D would have to be increased by a factor of at least 12. This could, for example, be done by increasing the fracture energy G of the mortar by means of fibres (1). With the original high-strength mortar, a 200 MPa pop-out pressure must be expected in systems with small spheres (diameter D less than 2.5 mm).

7. RUPTURE AND CRACK CONFIGURATION

Local overloading of concrete is often accepted even though it results in cracking, just as long as the cracks are harmless.

However, this implies that the concrete is able to rupture in an acceptable manner and that it is not made so strong that failure occurs in other, more harmful ways.

For example, increasing the strength of a surfacing can result in a change in rupture mode from harmless surface cracking to unacceptable peeling from the base (see fig. 13).

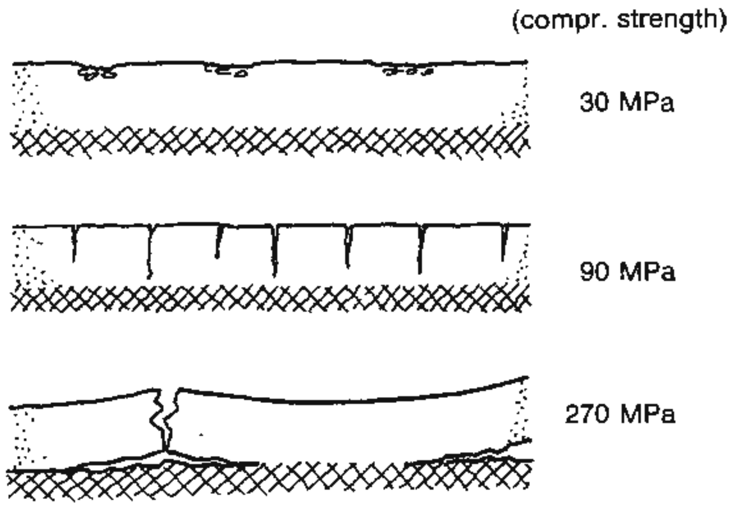
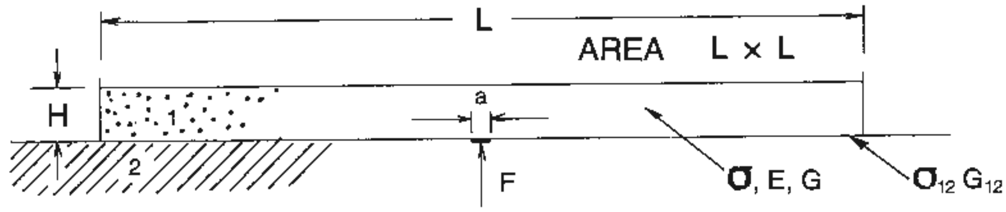


Fig. 13. Strong wear surfacings. With normal quality (A), the wear was too heavy, so a higher quality was used (B). However, this resulted in a number of shrinkage cracks. To avoid this, much stronger materials (C) were then used, but the result was disastrous destruction caused by the surface layer peeling off the base.

In connection with durability problems, changes in rupture modes play a decisive role, often in the form of unwelcome surprises as illustrated above. However, it is often very difficult to predict changes in rupture modes.

We can take as an example 2-layer structures, which often give rise to durability problems because of destruction caused by expansion of matter in the interface between the two layers (see fig. 14).



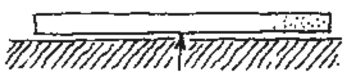
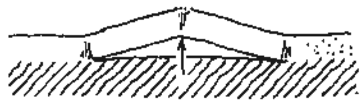
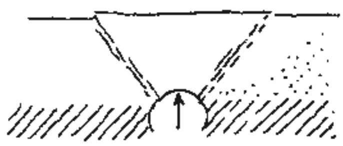
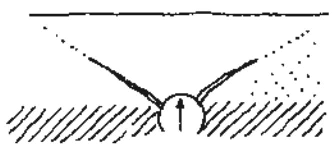
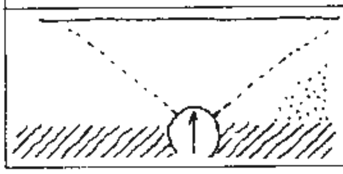
RUPTURE MODE		FORCE MODEL	THEORY
	RIGID PLATE parallel separation	$\sigma_{12} L^2$	Plasticity
	PEELING FROM BASE	$E^{1/2} G_{12}^{1/2} H^{3/2}$	L.E.F.M.
	CLEAVAGE sudden failure	$\sigma_{12} a^2$	Elasticity
	BENDING plastic failure	σH^2	Plasticity
	BENDING elastic, sudden faulire	σH^2	Elasticity
	PUNCHING plastic failure	σH^2	Plasticity
	PUNCHING	$E^{1/2} G^{1/2} H^{3/2}$	L.E.F.M.
	PUNCHING elastic, sudden failure	σa^2	Elasticity

Fig. 14. Rupture in an elastic plate on a rigid base subjected to a concentrated force in the interface.

As shown in fig. 14, several types of rupture can occur. The problem is how to treat such complex systems in a meaningful way. One approach is to describe the various types of behaviour by simple first-order models expressing the rupture force as a product of some signifant parameters, raised to different powers, as shown in the last column in fig. 14.

The two force models for peeling fracture are developed by means of LEFM. (1) The two force models for bending come from the classic theory for bending of plates under the action of a concentrated load F. Both for elastic and plastic behaviour the load is equal to a constant x the maximum bending moment m (per metre).

$$F = \text{constant} \cdot m$$

With the well-known moment/stress relationship for bending of plates with thickness H(m = const. $\sigma_o H^2$), we get the force model

$$F = \text{constant } \sigma_o H^2$$

The two force models σa^2 and $\sigma_{12} a^2$ express the contact stress, the force being proportional to the contact area x the contact stress.

The problem is to decide where the various models are applicable and where it is necessary to compare two or more of them. This can be done by systematically compare the different models two and two.

As an aid in such an analysis it may be useful to set up force ratios (or energy ratios) in a matrix as shown in Table 2.

	$\sigma_{12} L^2$	$G_{12}^{1/2} E^{1/2} H^{3/2}$	$\sigma_{12} a^2$	σH^2	$G^{1/2} E^{1/2} H^{3/2}$
$G_{12}^{1/2} E^{1/2} H^{3/2}$	$\frac{\sigma_{12} L^2}{G_{12}^{1/2} E^{1/2} H^{3/2}}$				
$\sigma_{12} a^2$	$\frac{L^2}{a^2}$	$\frac{G_{12}^{1/2} E^{1/2} H^{3/2}}{\sigma_{12} a^2}$			
σH^2	$\frac{\sigma_{12} L^2}{\sigma H^2}$	$\frac{G_{12}^{1/2} E^{1/2}}{\sigma H^{1/2}}$	$\frac{\sigma_{12} a^2}{\sigma H^2}$		
$G^{1/2} E^{1/2} H^{3/2}$	$\frac{\sigma_{12} L^2}{G^{1/2} E^{1/2} H^{3/2}}$	$\frac{G_{12}}{G}$	$\frac{\sigma_{12} a^2}{G^{1/2} E^{1/2} H^{3/2}}$	$\frac{\sigma H^{1/2}}{G^{1/2} E^{1/2}}$	
σa^2	$\frac{\sigma_{12} L^2}{\sigma a^2}$	$\frac{G_{12}^{1/2} E^{1/2} H^{3/2}}{\sigma a^2}$	$\frac{\sigma_{12}}{\sigma}$	$\frac{H^2}{a^2}$	$\frac{G^{1/2} E^{1/2} H^{3/2}}{\sigma a^2}$

Table 2. Force ratios for qualitative force models in fig. 14. For example, the first force ratio ($\frac{\sigma_{12} L^2}{G_{12}^{1/2} E^{1/2} H^{3/2}}$) express the fact that the ratio between the two forces required to destroy the system by parallal displacement ($\propto \sigma_{12} L^2$) and peeling ($\propto G_{12}^{1/2} E^{1/2} H^{3/2}$), respectively, is directly proportional to the force ratio shown.

To simplify matters, all three types of behaviour described in the form $F \propto \sigma H^2$ are collected under one heading. That implies a reduction in the number of force ratios from 28 to 15, but also means that the aspects of separating the three types of behaviour mentioned are not included.

Let us, as an example, take a look at the conditions under which failure occurs through bending (not differentiating here between plastic and elastic behaviour).

Bending failure will occur if the system has a lower resistance to bending than to any other effect. That means that we are going to compare the bending force systematically with all the other types of forces.

For example, the system will fail in bending and not by peeling if

$$\frac{\sigma \ H^{1/2}}{G_{1.2}^{1/2} \ E^{1/2}}$$

is lower than a critical value. In other words, bending failure is promoted in this case by all changes that reduce the Brittleness Number $(\sigma^2 H / G_{1.2} E)$.

Quite often we face the situation where the behaviour cannot be described by a single model, as is the case in fig. 12. Here we have complex behaviour. The type of behaviour is uniquely classified by the Brittleness Number in the same way as Reynold's Number classifies types of fluid flow.

It should be mentioned that simply setting up force ratios cannot replace physical insight. It is therefore necessary to warn against slavish use of the above-mentioned method. For example, it is not always the type of rupture corresponding to the smallest rupture force that predominates - locking failure for instance, either through slow crack opening or spontaneous elastic failure, will occur corresponding to the largest rupture force (see fig. 12).

The force ratios are not just figures - in modified form, for example, by raising to a power or by regrouping the various factors, they give greater clarity and provide much useful information..

For example, a modification of the force ratio at top left in Table 2 to the more informative form

$$\left(\frac{\sigma_{12}^2 L}{G_{12} E}\right) \left(\frac{L}{H}\right)^3$$

Brittleness Number   Shape factor

tells us that the rupture behaviour (peeling or displacement) is a unique function of the Brittleness Number for geometrically similar systems (identical L/H) and that the effect of the specific geometry shown (plate) is described by the shape factor $(L/H)^3$.

9. CONCLUDING REMARKS

The purpose of this article has not been to present solutions to durability problems but to introduce fracture mechanics to colleagues working in concrete durability - and to inspire them and others to research into the micro-fracture mechanics of concrete.

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