9. STRAIN HARDENING

First principle

Figure 9.1 shows typical behaviour of a ceramic bar and a metal bar during tensile failure.

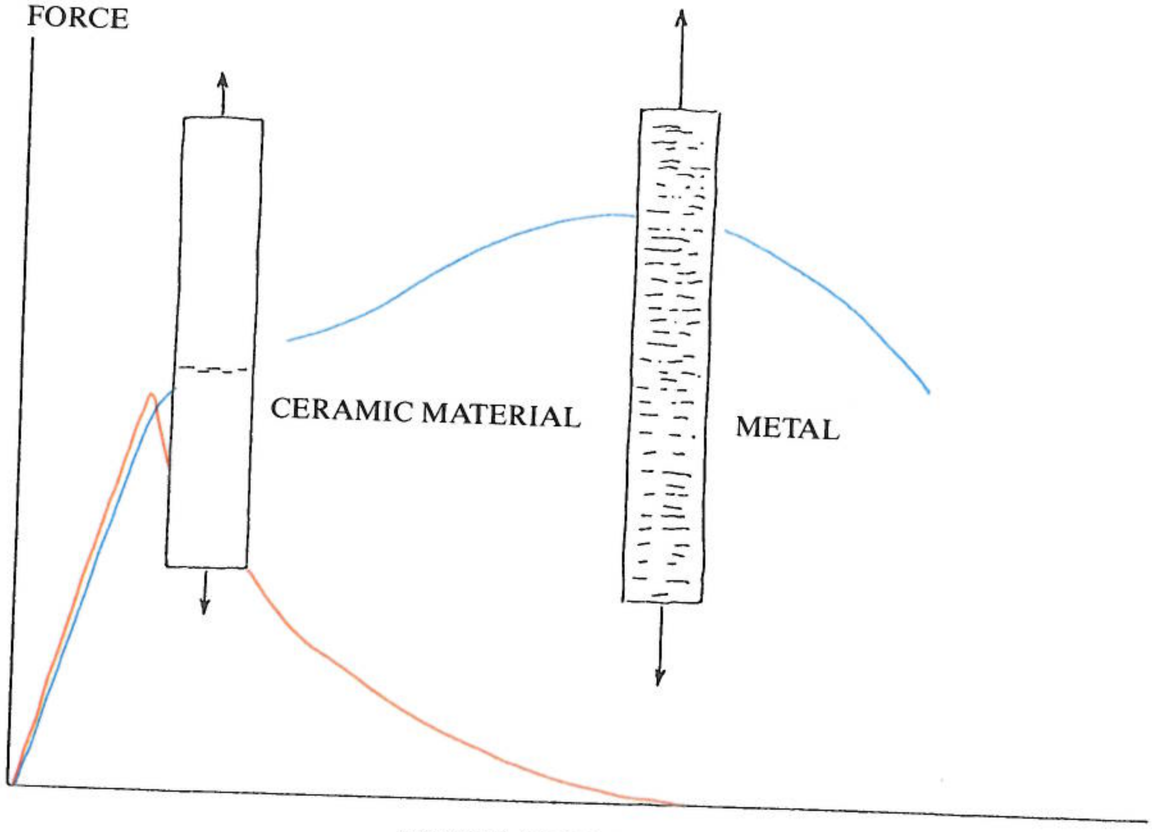


Fig. 9.1 Tensile behaviour of a bar of a "ceramic material" and a metal bar.

The ceramic bar fractures at the first "yield tendency" without yielding outside the narrow fracture zone.

The metal bar exhibits increased internal resistance during commencement of yielding, whereby the yielding spreads out over the volume - an effect that is termed strain hardening. (Sketch showing principle).

As mentioned in section 5, failure in brittle materials (here represented by the ceramic bar) takes the form of local deformation in a very narrow zone. The local deformation first becomes manifest after the maximum load (stress) has been reached.

In the metal bar, distinct yielding occurs, initially accompanied by a stress increase. The yielding spreads throughout the bar until maximum loading is reached, after which further yielding and failure occur in a single zone during relief of the remaining material. In the ceramic bar, on the other hand, where "yielding" is accompanied by a reduction of stress, only a single (narrow) yield zone develops and continues to develop up to separation failure.

In the metal bar, the initial stress increase causes the yielding to spread out over the volume of the bar and therefore causes large deformation before the bar finally breaks. In this case, we speak of "strain hardening". Strain hardening thus depends on local yielding being accompanied by an increase in stress.

The lack of ability of ceramic materials to exhibit strain hardening is, perhaps, the most serious, hidden, obstacle to structural utilization of cermaic materials in the same way as we use steel and other metals.

As mentioned in section 8, it is, however, possible - with a special fibre arrangement - to increase the crack load considerably beyond the tensile strength of the matrix material and thereby create strain hardening. What happens is that we reinforce the "yielding" crack zone material so effectively with fine, stiff, strong fibres that these take over loads considerably larger than the ultimate load of the matrix material during the crack zone deformation - long before a crack forms (see figure 9.2).

This important aspect, which is dealt with theoretically in section 8 and has previously been illumined by Aveston, Cooper and Kelly [9], is one of the two cornerstones of the new composite structures presented here - COMPACT REINFORCED COMPOSITE (CRC).

For example the "concrete" in the CRC-beams shown in section 2 was given strain-hardening reinforcing capacity with 6% (by volume) fine steel fibres.

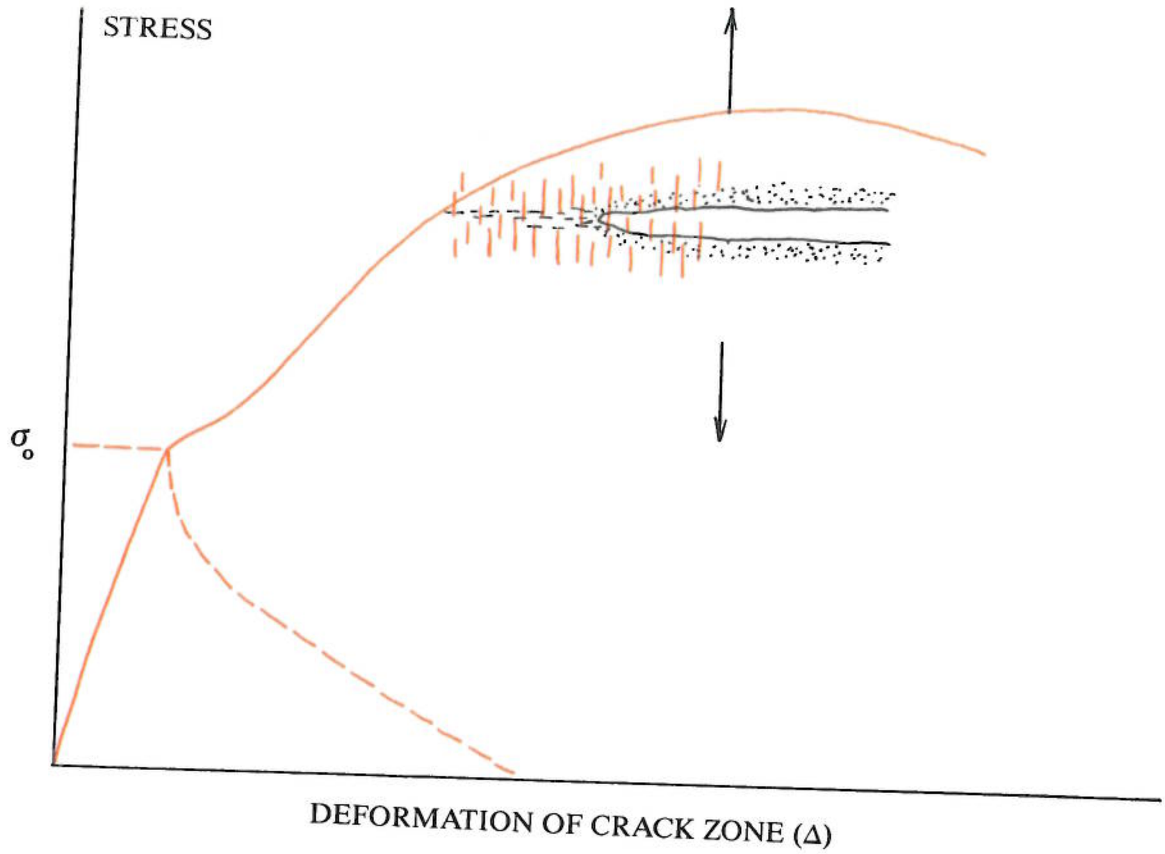


Fig. 9.2 Strain hardening of brittle material given "microductility" with fine, strong, stiff fibres.

At deformations beyond what corresponds to max. loading for unreinforced material (σ_o), the fibres immediately act so effectively that, together with the now more deformed matrix material, they transmit larger stresses than the tensile strength (σ_o) of the matrix material. The brittle material is thereby given the capacity to strain harden - in the same way as the metal bar in fig. 9.1.

Second principle

The second principle on which CRC is based is to use the main reinforcement to "divide" the body into small "sub-bodies and thereby increase the strain capacity in accordance with the principles of fracture strain of brittle materials, cf. section 6.

Let us consider tensile failure in a brittle material - with or without fibres (see Fig. 9.3A).

The material deforms largely elastically until local deformation starts in a narrow crack zone.

If the elastic deformations of the material outside the crack zone ($\mathcal{E}_0 L$) are much greater than the crack zone deformation (Δ_0), the ultimate strain of the bar will be largely equal to the ultimate tensile strain of the material:

$$\mathcal{E} = \frac{\mathcal{E}_0 L + \Delta_0}{L} \simeq \mathcal{E}_0$$

If, on the other hand, the crack zone deformation Δ_0 is much greater than the total elastic deformations, the ultimate tensile strain (determined as the total deformation divided by the total length) will depend mainly on the crack zone deformation:

$$\mathcal{E} = \frac{\mathcal{E}_0 L + \Delta_0}{L} \simeq \frac{\Delta_0}{L}$$

It is thus possible to increase the tensile strain capacity of "bodies" without altering the bulk strain capacity by establishing "small bodies".

This is, in fact, what is done in CRC, where the main reinforcement divides the matrix material into small, discrete sub-bodies. The principle is illustrated in figure 9.3. In A, tensile behaviour of a ceramic bar is shown. In B, the ceramic bar is firmly fixed in a very rigid but deformable "frame" that divides it into many small sub-bodies. We now subject the entire frame to tensile loading until tensile failure occurs in the ceramic material (not in the frame). In this system we will have crack zone deformation in each of the small sub-bodies before failure.

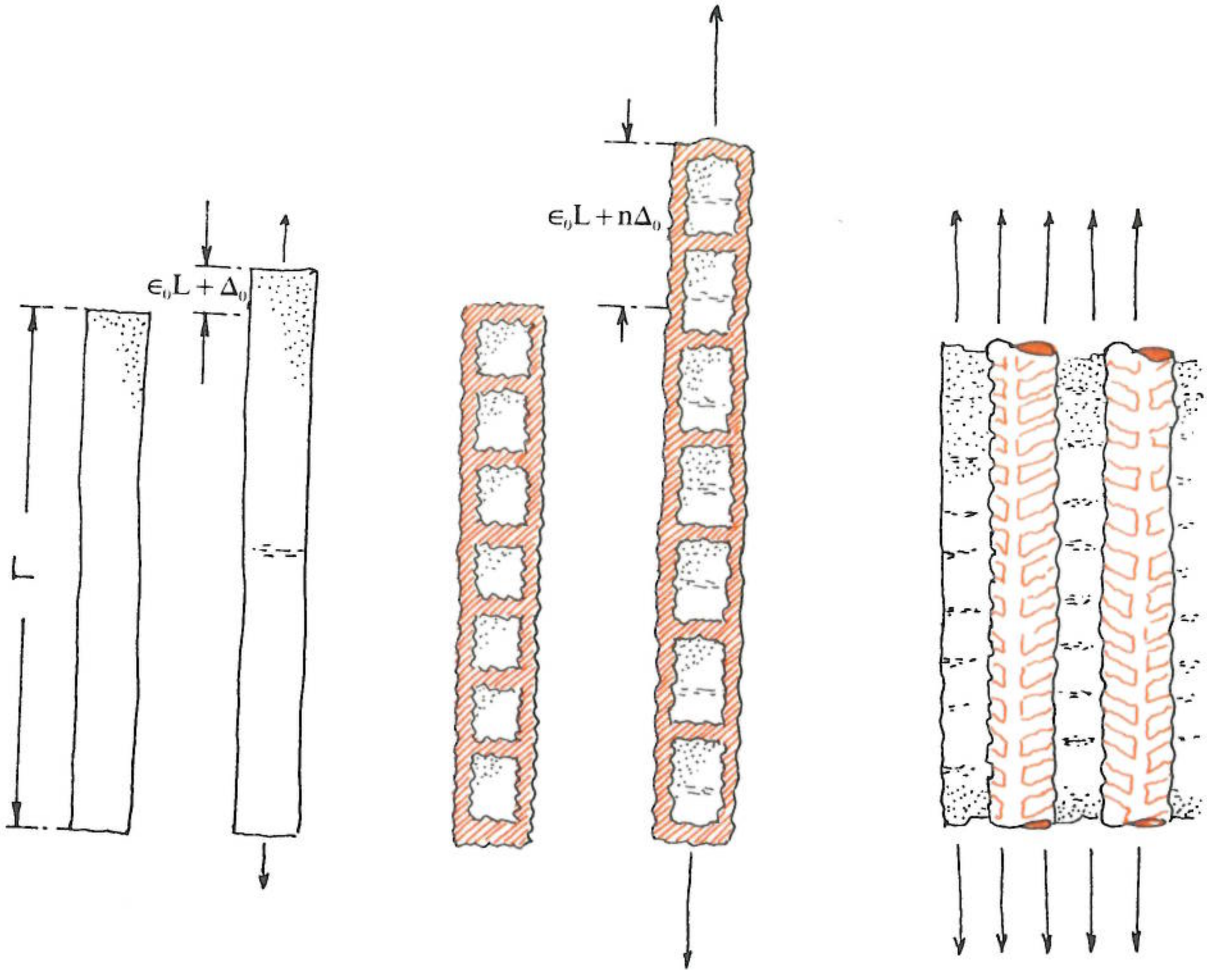


Fig. 9.3 Tensile deformation of bar of a ceramic material (A) and an identical bar divided into small bodies fixed to a stiff frame that undergoes tensile deformation (B).

By dividing the bar into n small bodies, the deformation required to create matrix cracks increases from $\delta = \varepsilon_0 L + \Delta_0$ to $\delta = {}_0L + n\Delta_0$.

In CRC (C), the densely arranged, profiled main reinforcing bars act as the stiff frame that divides the matrix material into small volumes and thus further increases its tensile strain capacity when the material undergoes tensile deformation together with the main reinforcement.

The total elastic deformation of the matrix material (outside the small crack zones) remains as before ($\varepsilon_0 L$). We now have n crack zones instead of one and therefore n times the total crack zone deformation ($n\Delta_0$).

That means that we have increased the total deformation and thus the mean strain of the system. In cases where $n\Delta_0 >> \varepsilon_0 L$, the strain is thus about

$$\varepsilon \simeq \frac{n\Delta_0}{L}$$

In CRC, the main reinforcement acts as the strong, rigid frame dividing the matrix into small, discrete sub-bodies (see figure 9.3C).

The densely arranged, spatially fixed main reinforcement, designed so that the matrix is intimately fixed, acts as a frame dividing the matrix into fixed volumes with linear dimensions of the order of magnitude of the transverse dimension of the reinforcement.

In order that the reinforcement may act as a rigid frame, spatial fixation of the main reinforcement is required in order to avoid internal fracture such as longitudinal splitting. In addition, firm fixation of the ductile fibre-reinforced matrix to the main reinforcement is required.

These essential factors are dealt with in the following section.

10. FIXATION OF REINFORCEMENT

For CRC to act as intended, it is essential for the matrix material to act in a ductile manner and to be intimately fixed to the main reinforcement, and also essential to ensure that the main reinforcement acts as a spatially stable, stiff frame.

The ductility of the matrix material is ensured by fibre reinforcement.

The fixation of the matrix to the main reinforcement is ensured by using strong, stiff matrix materials that are given high ductility, together with a useful shape of the main reinforcement (e.g. with circular cross section and deformed and rough-surfaced).

Spatial stability is ensured by geometrically arranged reinforcement held in place by the matrix material.

In order to transfer very large shear forces or large tensile forces perpendicular to the main reinforcement, it is desirable to make extensive use of transverse reinforcement. New, special, spatial arrangements of transverse reinforcement are made possible by the matrix materials' unique ability to fix reinforcement (see figure 10.1A).

In cases with less severe shear loading, transverse reinforcement can be omitted altogether because shear will then be totally absorbed by the strong, ductile, fibre-reinforced matrix (see figure 10.1B).

Good interaction between reinforcement and matrix depends on the matrix material being able to resist effects seeking to move the reinforcement relative to the matrix (see figure 10.2).

For systems with extreme brittleness, internal coherence requires that the strains in the matrix never exceed the ultimate strain of the matrix material in bulk:

$$\varepsilon < \varepsilon_o$$

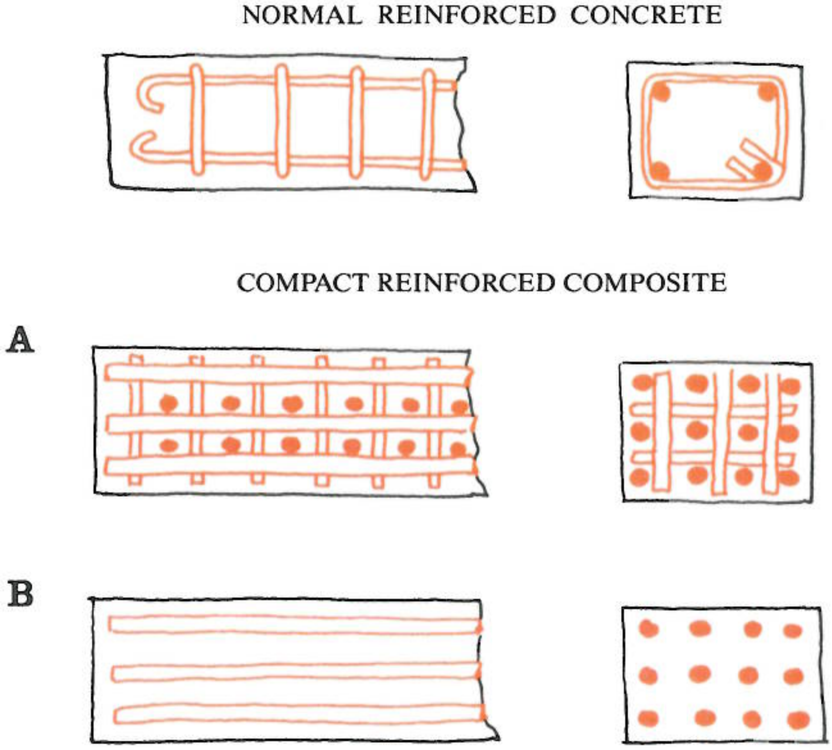
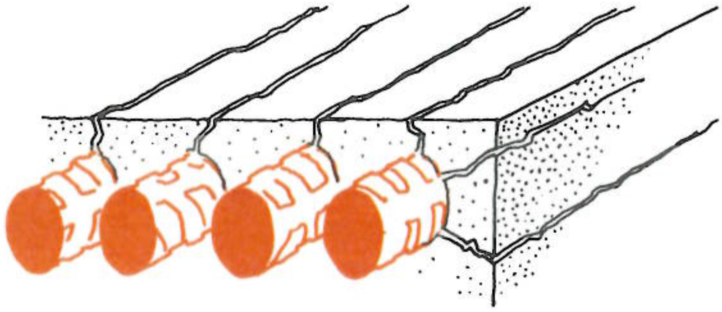


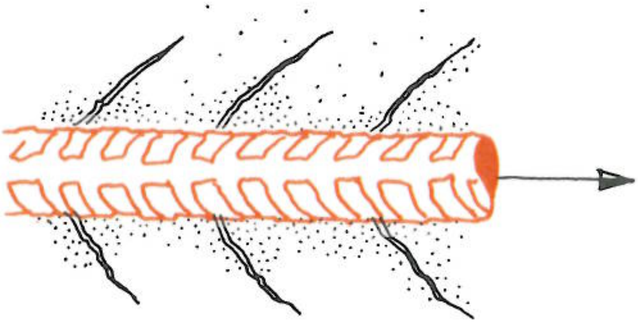
Fig. 10.1 Arrangement of main reinforcement in reinforced concrete and in CRC.

In example A, the reinforcement, consisting of longitudinally and transversely arranged bars, forms a spatial lattice held together by strong, ductile, fibre-reinforced matrix material.

In example B, the longitudinal reinforcement alone forms the spatial lattice, the matrix material ensuring the spatial fixation.



A



B

Fig. 10.2 Cracking around main reinforcement.
In CRC, cracking around very dense, heavily loaded main reinforcement is counteracted by effective fibre reinforcement.

For systems with ductility, the requirement concerning internal coherence is that the local deformation of the matrix is smaller than the material's crack zone deformation:

$$\varepsilon_o D < \Delta_o$$

In CRC, high concentrations of main reinforcement are used, arranged parallel - a configuration involving a high risk of splitting along the reinforcement, especially as the binder materials are usually extremely strong and brittle. These tendencies are counteracted by inducing great ductility by effective fibre reinforcement. (See figures 10.3 and 10.4).

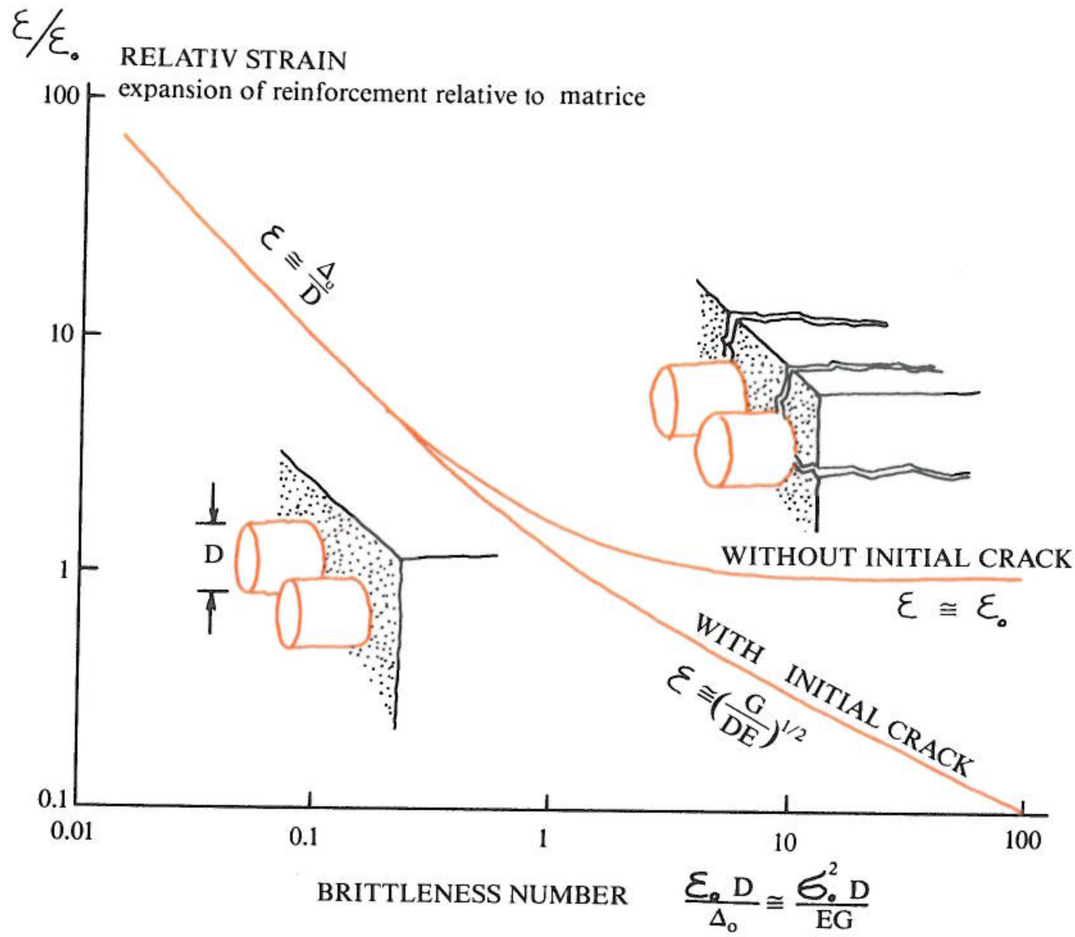
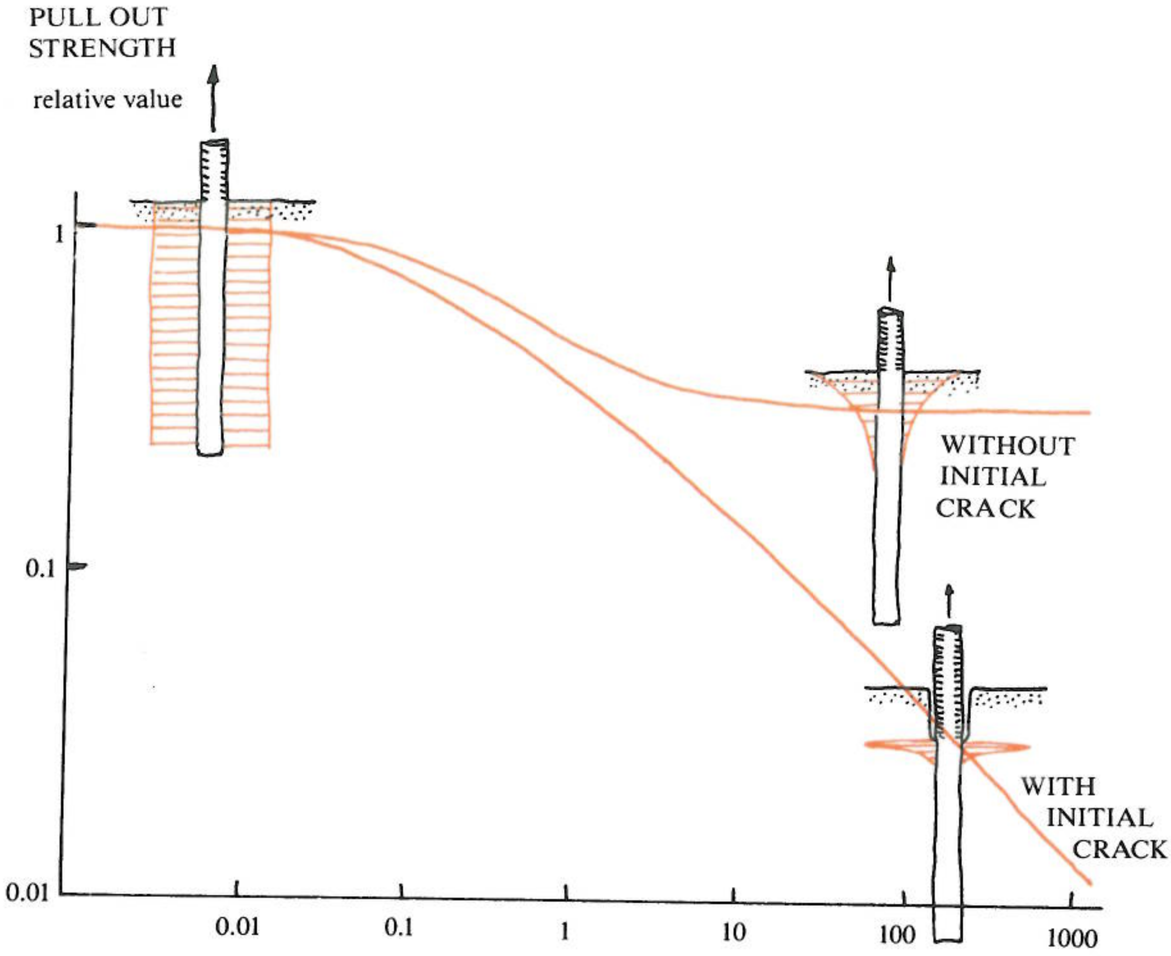


Fig. 10.3 Ultimate strain of the matrix when the reinforcement expands relative to the matrix.

In CRC, great ductility - low brittleness numbers - is ensured in connection with fixation of the main reinforcement by means of very effective fibre reinforcement, whereby the fracture energy of the matrix (G) is increased by a factor of 100-1000 compared with that of unreinforced material.

(For further explanation of this figure, see fig. 6.3).



$$\frac{\tau_0^2 D}{E\,G}$$

Fig. 10.4 Resistance to pulling-out of reinforcement as a function of the brittleness number. (Sketch showing principle).

τ_0 is the shear stress during sliding between reinforcement and matrix, G the fracture energy of the interface between reinforcement and matrix, E the modulus of elasticity of the reinforcement, and D the diameter of the reinforcement. (Sketch showing principle).

In CRC, great local ductility in connection with fibre pull-out - low brittleness number - is achieved by using fine fibres (small D) in a matrix-fibre system with a relatively high fracture energy (G) and fibres with a high modulus of elasticity (E).

(For further explanation of this figure, see figure 4.2).

The expression for the brittleness number ($\frac{\sigma_0^2 D}{E\,G}$) shows that the brittleness can be reduced (ductility increased) by using smaller reinforcement dimensions (D), increasing the stiffness (E), and increasing the fracture energy (G).

In CRC, ductility in connection with fixation of main reinforcement is primarily obtained by substantially increasing the fracture energy of the matrix material through a high concentration of fine, strong, stiff fibres. The fracture energy (G) is thereby increased by a factor of 100-1000.

Local ductility around the individual fibres is ensured by using fine, very stiff fibres in a stiff matrix with a high fracture energy (see figure 10.4).
The fibre dimension will often be a compromise between the desire for fine reinforcement for the purpose of ensuring the abovementioned local ductility and the desire for large fibres to ensure ductile macro-failure and for production reasons.

The possibility of achieving a matrix of great stiffness is limited since this can seldom be increased by more than a factor of 1.5 to 2. The stiffness is increased by increasing the volume of aggregate and by using aggregates of materials with a higher modulus of elasticity. Increasing the volume of strong aggregates has a beneficial effect besides increasing the stiffness in that it reduces the quantity of binder material required, whereby the material becomes less sensitive to deformation and gets a higher fracture energy.

In accordance with the foregoing, a high concentration of coarse quartz particles was used in the cement-based CRC-beams, which gave the matrix material a high modulus of elasticity ($E \simeq 50{,}000$ MN/m^2) and a relative high fracture energy ($G \simeq 100$ N/m).

The stiffness - and probably also the fracture energy - can be increased still further by using stronger particles such as refractory bauxite (rich in Al_2O_3) [2].

Seen in a broader perspective, CRC is an example of a new design strategy to exploit very strong, dense binders in order to incorporate high ductility and thereby increase the quality far beyond that afforded by the increased strength (see figure 10.5). In CRC, there is, in fact, a revolutionary improvement in behaviour as regarding giving bodies ductility and great strain capacity. The new design philosophy is based on fracture-mechanical principles:

1. creating, with fibres, a matrix material capable of exhibiting strain-hardening,

2. further increasing the strain capacity by effectively fixing the matrix material to densely arranged, spatially fixed main reinforcement,

3. ensuring global and local ductility by means that reduce the brittleness number.

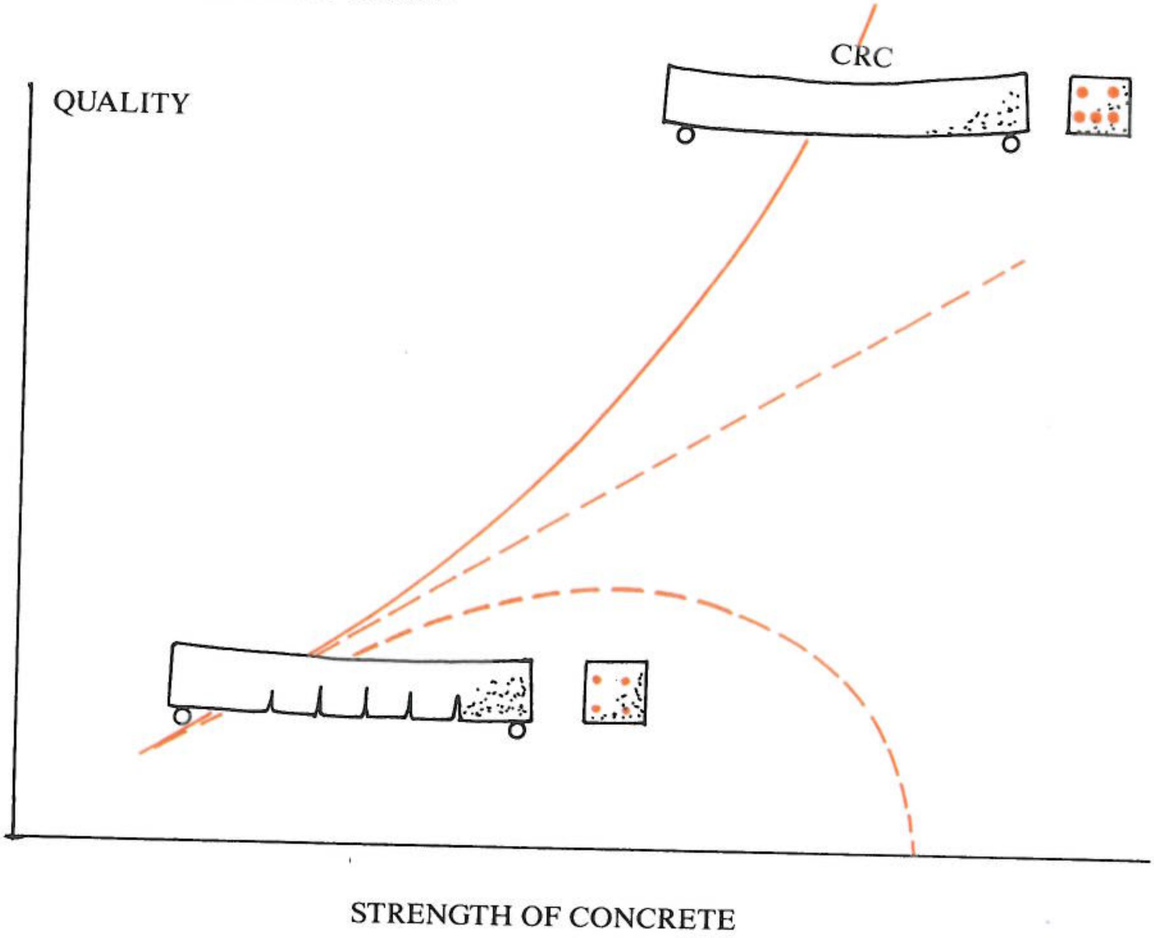


Fig. 10.5 Quality reinforced "concrete" as a function of concrete strength - CRC design.

CRC is based on new, very strong and at the same time very brittle binders that are given a high degree of ductility by means of a combination of fibre reinforcement and fixation to the main reinforcement.

In CRC, the ductility is increased considerably beyond what is needed to compensate for the increased brittleness of the very strong binders.

The quality is therefore increased considerably more than corresponding to the increased strength of the binder.

The behaviour is actually fundamentally different from the behaviour of known reinforced brittle materials. It is changed from showing tensile cracks at very small strains to ductile, crack-free behaviour right up to yielding of the main reinforcement.

11. PRODUCTION OF COMPACT REINFORCED COMPOSITES

As CRC structures are extremely dense, with a complicated internal structure (comprising fibres, large particles, ultra-fine particles, etc.), it is vitally important to ensure that the components are correctly placed in relation to each other.

In this section the production principles are discussed, using as an example the production of the cement-silica-based test beams mentioned in section 2.

Various production methods can be used, such as soft casting, extrusion, pressure or vacuum-assisted injection moulding, etc.

The technology used in connection with the production of the CRC test beams mentioned in section 2 was based on some general principles which are discussed in the following.

Principles of dense packing

Dense packing of the "particles" (sand, cement and ultra-fine silica) together with the fibres is essential for achievement of the desired mechanical behaviour.

Familiar geometrical principles are applied to achieve this - for example, gap grading, where small particles are packed between large ones, selection of suitable particle shapes (where possible), etc. (See figure 11.1).

These principles are also applied to the fine components, special precautions being made to ensure that the fine particles can be physically arranged in accordance with this geometry. For example, the cement particles (particle size 5-10 μm) were very densely packed, and the space between them was additionally filled with a high concentration of microsilica (particle size 0.1-0.2 μm), secured by an efficient dispersing agent. See figure 11.2.

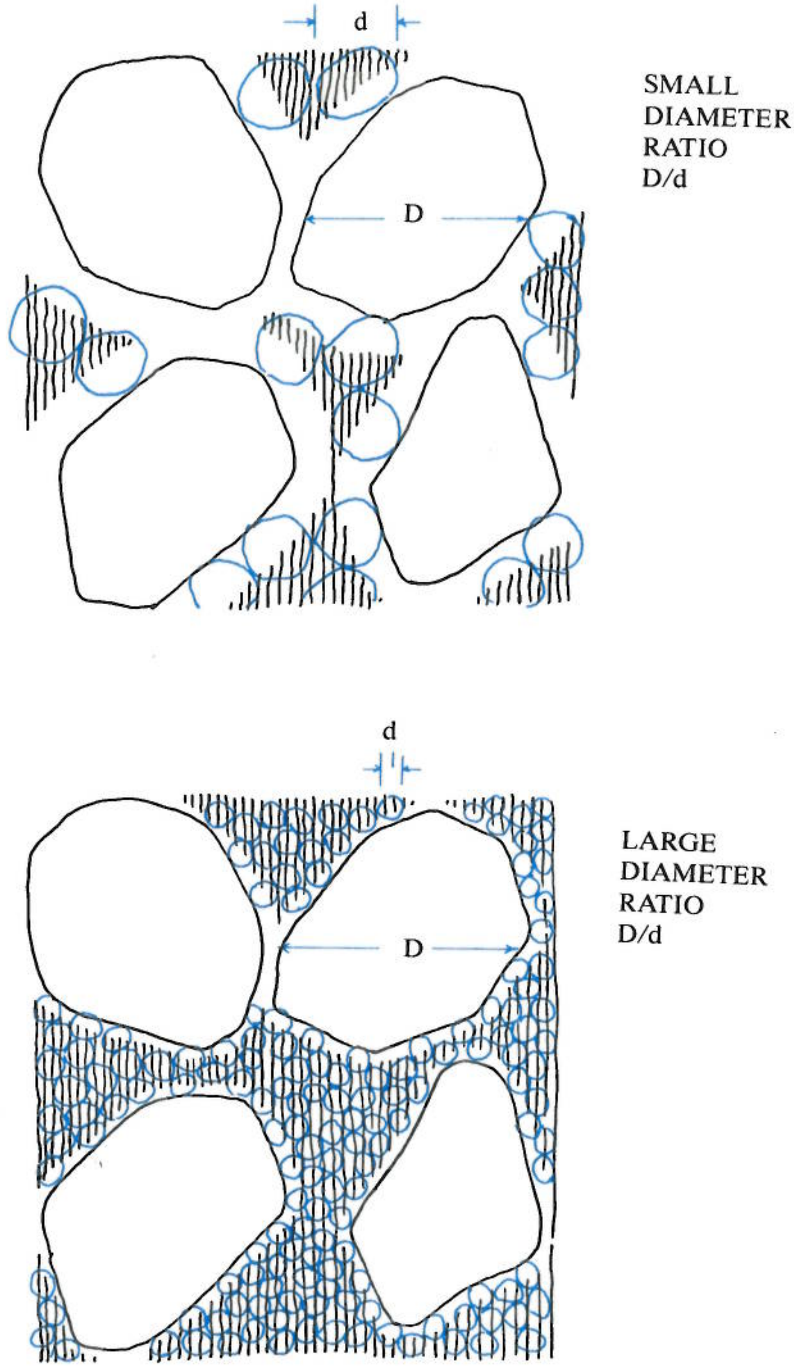


Fig. 11.1 Sketches showing principle of use of gap grading in order to achieve high packing density.

By using distinct gap grading (large diameter ratio), dense particle packing is achieved because the boundary space with loosely packed fine particles near the surfaces of the large particles is small[2].

In CRC, this principle is applied both in the concrete (coarse sand/cement binder) and in the binder system (cement/ultrafine microsilica).

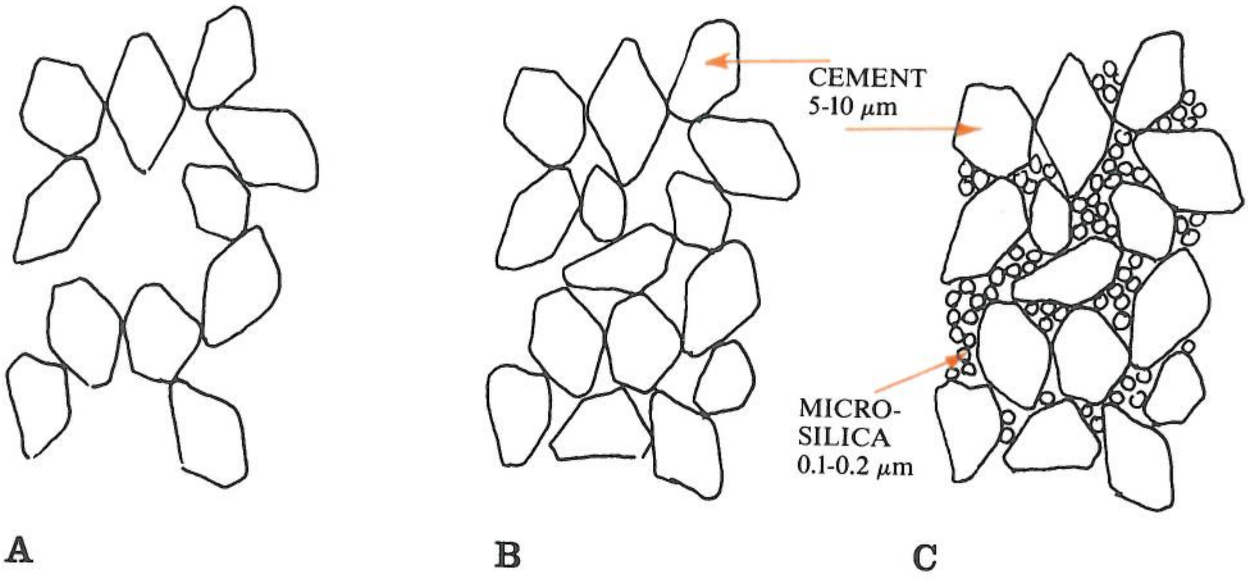


Fig. 11.2 Principle of dense packing by using gap grading in the binder.
Surface forces prevent dense packing of cement in cement/water mixtures (A), but with the advent of effective dispersants that eliminate the locking effect of surface forces, it became possible to pack fine particle systems densely on the basis of purely geometrical principles. In the 1970s, this was applied to make denser and stronger concrete (B).
The geometrical possibilities were exploited really effectively by introducing in well-dispersed systems 20-30% microsilica in the spaces between densely packed cement (C). This resulted in very dense, extremely high-strength concrete[2].
Binders of the latter type were used in the CRC test beams.

Overcoming surface forces

The greatest difficulty in arranging small particles in a dense and homogeneous pack resides in surface forces interlocking neighbouring particles, thus counteracting mutual particle movement during mixing and shaping.

The above situation is of special importance to systems with very small particles because the internal cohesion resulting from locking surface forces between neighbouring particles increases with decreasing particle size (the cohesion is inversely proportional to the particle size). Thus, the cohesive resistance against mixing and shaping a particle system with submicron particles with a particle size of 0.01μm is 1,000 times that for a geometrically similar particle system built up of micron size particles with a particle size of 10μm and 100,000 times that for a corresponding millimetre-size system (d = 1 mm).

The combined effect of surface forces and compaction stresses on the densities to which specific particle systems can be packed is shown in the master curve (figure 11.3).

It is possible to overcome the locking effect by mechanical effects (pressure, shear, etc.) or by reducing internal resistance by means of surface-active agents.

Viscous processing

It is desirable to create deformation throughout the casting mass during the processing (mixing, casting and compaction). This is achieved by imparting substantially viscous behaviour to the casting mass. In order to avoid internal locking, the viscosity-dominated resistance should dominate over the cohesive and frictional resistance (figures 11.4 and 11.5).

Viscous-cohesive systems

For systems containing fine and ultrafine particles, locking surface forces between the particles may contribute significantly to the total cohesive resistance. The surface force contribution to the cohesive resistance for geometrically similar particle systems, cf. the section "Overcoming surface forces", will be proportional to the inter-particulate surface tension γ and inversely proportional to the particle size (d):

$$c \propto \frac{\gamma}{d}$$

Accordingly, in order to have viscous resistance dominate over particle-caused cohesion, it is required that

$$\frac{\eta \dot{\varepsilon} d}{\gamma} > \text{constant}$$

where η is the viscosity and $\dot{\varepsilon}$ the rate of strain. This means that for a given particle system (characteristic particle size d) with interparticulate surface tension (γ) to be shaped at a given strain rate ($\dot{\varepsilon}$), the following requirements to the viscosity of the fluid matrix should be fulfilled:

$$\eta > \frac{\gamma}{\dot{\varepsilon} d} \times \text{constant}$$

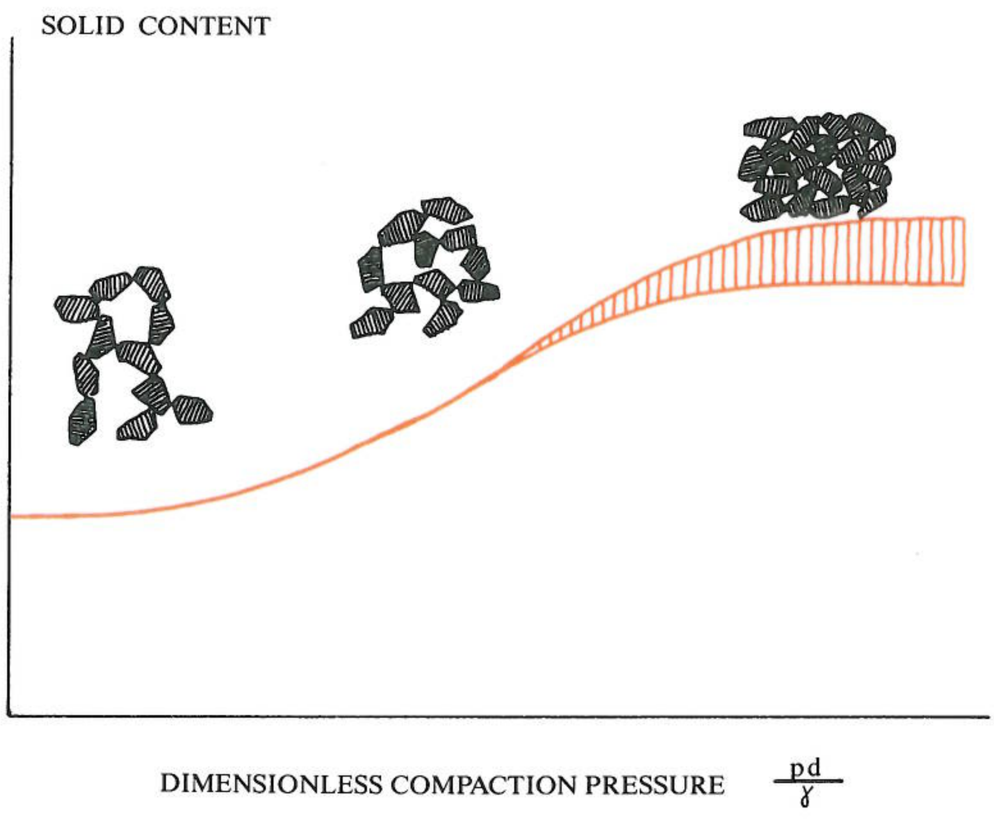


Fig. 11.3 Density of particle material as a function of dimensionless compaction load. In zone 1, the surface forces keeping the particles locked predominate. The compaction pressure is too small to achieve any appreciable compaction. In zone 2, the external loads and internal cohesion balance so that internal yielding toward a denser packing takes place with increased pressure. In zone 3, the external loads dominate the surface forces between the particles. In this zone, the packing depends on the particle geometry and the type of compaction.

In connection with CRC, we try to overcome the surface forces (zone 3) and to exploit the geometrical possibilities thereby created to establish very dense packing by means of a good particle-orienting vibratory compaction process (top curve).

which shows the important fact that the viscosity should be increased in inverse proportion to the particle size. This is illustrated in the master graph, figure 11.4.

The above expression shows that a reduction of the inter-particulate surface tension (γ) will reduce the requirement to the viscosity (and consequently also the requirement to the shaping stress). Therefore, the use of a fluid that can reduce the inter-particulate surface tension (that is, a fluid that acts as a dispersing agent) is an important way of improving the rheology of the system. For submicron particle-based systems, the shaping fluid is required in almost all cases also to act as an efficient dispersing agent. In order to eliminate locking surface forces from internal liquid-gas interfaces, it is important that the liquid fill the pore space completely.

Viscous-friction systems

When the dominating internal resistance is due to friction between the solid particles (i.e. the resistance to shear (τ) caused by a normal compressive load (stress p) conforms to the expression, $\tau = \mu p$, where μ is the coefficient of friction), the following requirement to the viscous resistance must be satisfied in order to achieve viscous dominance:

$$\eta \mathring{\varepsilon} > \mu p \quad \text{or} \quad \frac{\eta \mathring{\varepsilon}}{p} > \mu$$

The flow behaviour of viscous-frictional governed particle fluid systems is shown in figure 11.5.

This means that the larger the coefficient of friction and the confining pressure and the smaller the strain rate, the greater must be the viscosity of the fluid.

In addition to requirements concerning the degree of viscosity, it will be seen that the shaping process is also aided by reducing the coefficient of friction. Therefore, it is also desirable to use lubricating additives - or to use a shaping fluid that in itself acts as a lubricant.

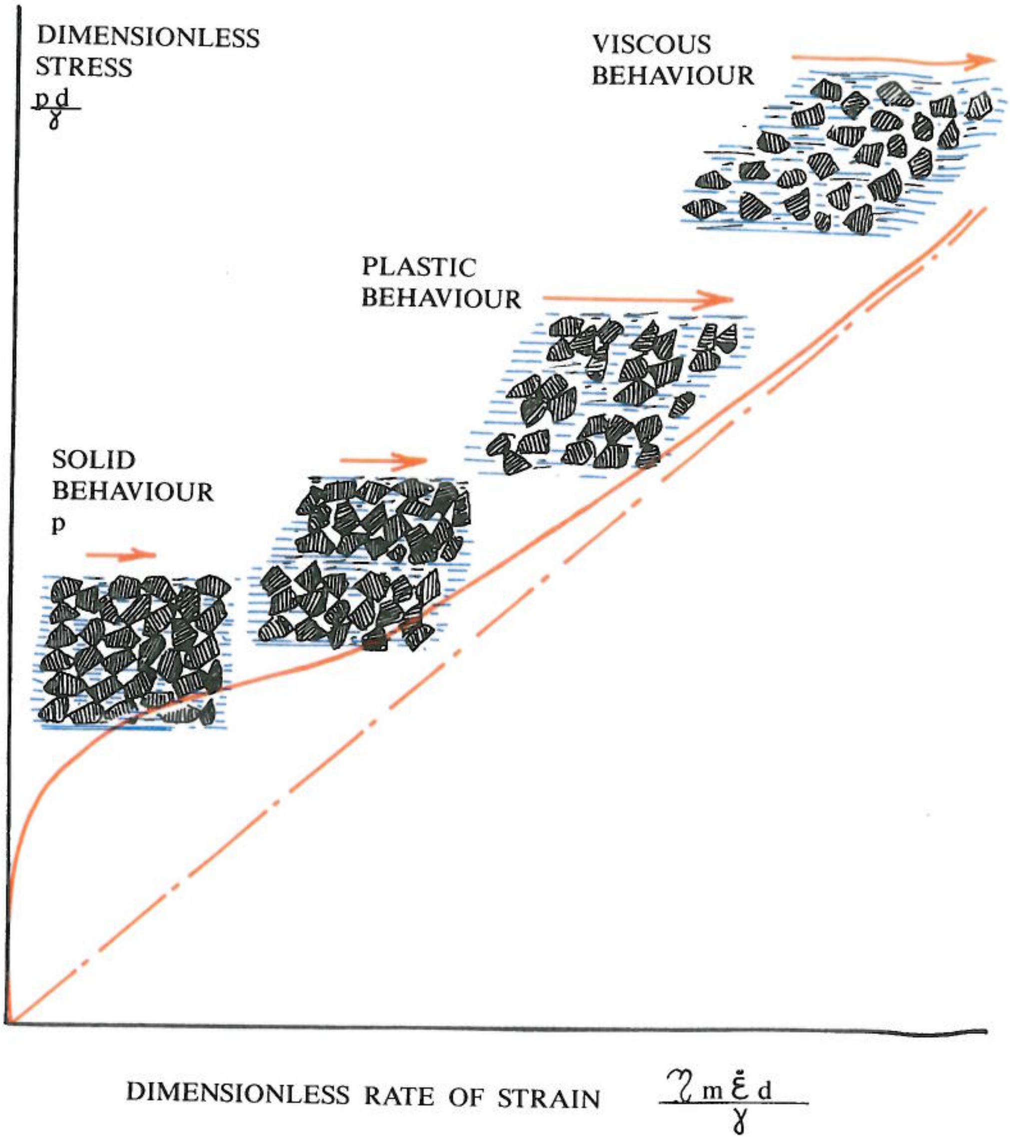


Fig. 11.4 Stress (p) versus rate of strain ($\mathring{\varepsilon}$) for a system of particles in mutual attraction in zones of contact by surface forces (γ)embedded in a viscous matrix. Master graph for systems with geometrically similar particle structures [11], [12].

In CRC systems with complex internal structure, we aim at shaping during substantially viscous flow behaviour achieved primarily by eliminating the locking effect of surface forces (small γ) and by using a matrix with a reasonably high viscosity (not too small η_m).

In the preparation of the cement-based CRC-beams, the viscosity-dominated resistance of the fibre-rich mix was established by incorporating a high volume of microsilica particles and using a very small amount of water, corresponding to a water/cement + microsilica ratio of 0.18 by weight. The surface forces were eliminated by using a sufficient quantity of an effective surface-active agent.

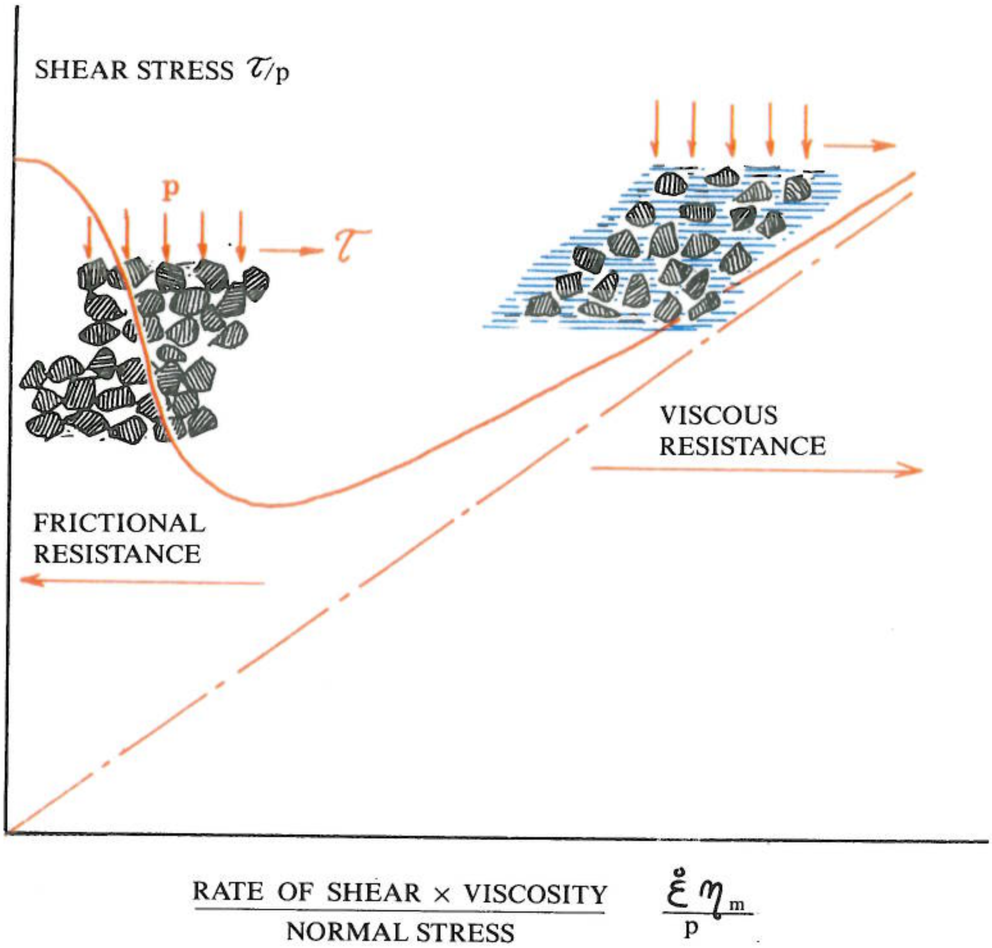


Fig. 11.5 Resistance to shear flow as a function of the rate of shear for particle - fluid systems in which the resistance is governed by friction and viscous forces only. Master graph for systems with geometrically similar particle structure [11], [12].
In CRC processes, we aim at viscous flow behaviour by "incorporating" viscous resistance (η_m) of such a magnitude that it dominates over the frictional resistance ($p{\cdot}\mu$).

Vibratory processing

In connection with the production of CRC, vibratory processing plays a vital role in ensuring the very high packing density of the particles and fibres under geometrically complicated conditions, typically with very densely arranged main reinforcement [12].

It is outside the scope of this article to explain all aspects of vibratory processing, but a few should be particularly noted:

Vibration can be used to help promote viscous flow in connection with mixing and casting, making it possible to perform these operations with a substantially higher particle concentration than in normal production practice.

With heavy main reinforcement, it is difficult to transfer the oscillating load deep into the body because there will be extensive damping due to sliding between the material and the reinforcement.

The disadvantage of heavy reinforcement can be turned into an obvious advantage by using the stiff reinforcement to transfer the oscillating stresses.

This method is contrary to normal practice in reinforced concrete, where vibration applied to the reinforcement causes separation of the concrete adjacent to this. However, in a high-viscosity system, especially one with a high content of fine fibres, practically no separation occurs.

Fabrication of CRC test beams

Test beams (5x5x50 cm) and supplementary test specimens of cement-based CRC were fabricated and tested [1]. Some of the test results are shown in section 2.

The mix proportions and method of fabrication are described below.

Materials used:

Quartz sand
Density 2,630 kg/m^3

Cement (White Portland cement from Aalborg Portland)
Density (estimated) 3,150 kg/m^3)
Specific surface (estimated) approx. 400-450 m^2/kg

Microsilica
Fine SiO_2-rich powder with spherical particles produced by condensation from a gaseous phase as a by-product from the production of silicium metal in electrical furnaces. Specific surface about 25,000 m^2/kg, corresponding to an average particle diameter of about 0.1 μm. Estimated density: 2,220 kg/m^3.

Dispersing agent (powder)

A so-called concrete superplasticizer - a sodium salt of highly condensed naphthalene sulphuric acid formaldehyde condensate. Density of powder: about 1,600 kg/m^3.

Water

Common tap water, density 1000 kg/m^3.

Steel fibres

Cylindrical brass-coated steel fibres "Dramex" from Bekaert, Belgium, diameter 0.15 mm, length 6 mm. The material is declared to have a tensile strength of 525 MPa.

Reinforcing steel

Deformed steel bars, diameter 8 mm - KS 410-S "Kamstål".
Yield stress 500-510 MPa.

The composition of the mix is shown in Table 1.

	g[1)]	Litres[2)]
Cement	7750	236
Microsilica	1850	80
Dispersing agent (powder)	230	14
Quartz sand 0-0.25 mm	1727	
0.25-1 mm	3492	446
1-4 mm	7001	
Water	1740	167
Fibres	4710	58

1) mix composition of one batch of approx. 10 litres
2) mix composition in litres/m^3

The structure and mix composition are shown in figure 11.6.

TABLE 1. Mix composition*)

*) It should be noted that the principles and compositions described here are subject to pending international patent applications [14] and that products manufactured on the basis of these principles are marketed under the trade name "Densit®".

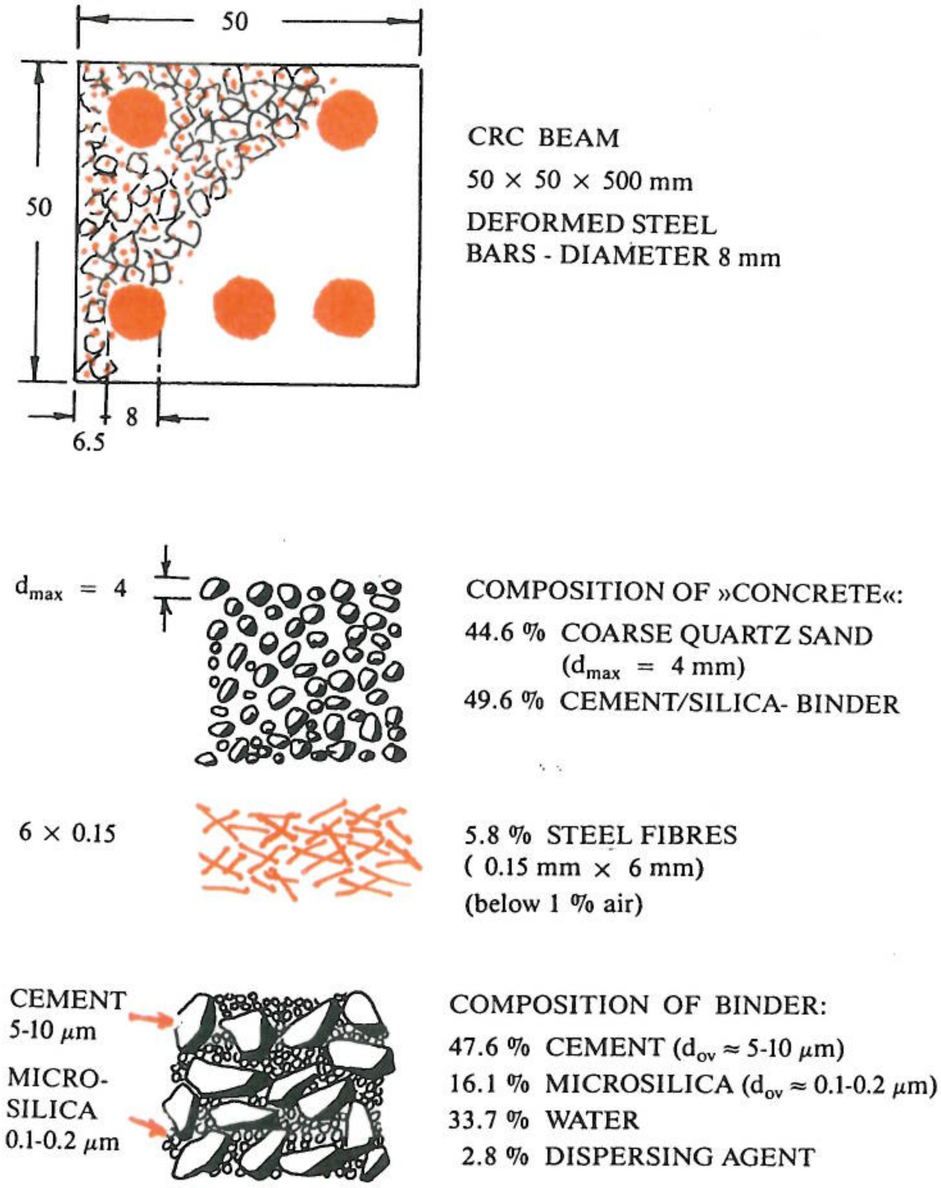


Fig. 11.6 The structure and mix composition of the CRC test beams. Here, the mix composition is given as volume proportions related to the arrangement after placing and compaction of the "concrete".

Preparation

The mixing was performed in a planetary mixer as follows:

The cement, microsilica, dispersing agent and sand were dry-mixed for two minutes. Water was then added, and mixing continued for a further 10 minutes. Fibres were then added, and mixing continued for another 5 minutes.

The mass had a dry appearance for the first few minutes of mixing after water had been added. It then underwent a rather sudden change into a doughy mass which gradually changed into a softer, glossy, viscous mass, indicating complete saturation of the system.

The texture remained the same after the addition of fibres, but there was far greater resistance to shear during the mixing.

Test specimens (cylinders of diameter 45 mm, length 90 mm and cylinders of diameter 100 mm, length 200 mm, unreinforced beams with the dimensions 50 x 50 x 500 mm and reinforced beams of the same dimensions) were cast under vibration on a standard vibrating table with a frequency of 50 Hz and an acceleration of about 30-50 m/sec^2. Each of the reinforced beams contained 5 deformed bars (length 500 mm, diameter 8 mm) arranged as shown in figure 11.6 and fixed in position in the mould prior to casting.

The cast specimens were covered with plastic and stored at 20°C and 100% humidity for 24 hours. They were then cured in water at 80°C for 24 hours.

Density

After curing, the density was determined by determining the weight in air and the weight submerged in water.

The density of the fibre-reinforced material when placed in the final position between the main reinforcement was 2,720 kg/m^3, whereas the "theoretical" values calculated on the basis of the mix composition (assuming no air) was 2,730 kg/m^3. This indicates that the packing of the "concrete" is very dense (air content below 1%), despite the extremely high fibre content and the arrangement in narrow spaces with heavy reinforcement. It also indicates that the binder itself consists of particles (cement and silica) in a very dense packing.

As the dispersing agent was dissolved in the water, the concentration of the solid particles (cement plus microsilica) in the binder (cement + silica + liquid + air) is 63.6%, and the porosity is 36.4%.

This is a very high volume concentration of solid for a cement binder. In fact, it is so high that it corresponds to the densities obtained by high pressure vibratory compaction of well-graded dry cement powder (optimal grading from a density point of view prepared in the form of small cylinders, diameter 11 mm, height approximately 10 mm) [13]. In this reference the compaction was performed with an oscillating pressure of about 5 MPa at a frequency of 100 Hz for about 2 minutes. The experiments were made to illustrate what was at that time (1968) believed to be an upper limit only to be achieved with pure cement powder specimens of very simple shape and small size at high-pressure, vibratory compaction.

In the CRC-experiments the high degree of packing of the cement-silica powder was realized under the condition of soft casting of a mass with a complicated internal structure (binder material + coarse particles + fibres) and with a complicated external structure with very slender beams (50 x 50 mm), with a high concentration of main reinforcement (five 8 mm. dia. deformed bars).

Comments

In order to achieve the desired structure, a high content of relatively large sand particles and a very high fibre content were desired. From a geometrical and kinematical point of view, large particles are normally regarded as undesirable because of interference with the main reinforcement and the fine fibres. However, in the present case, a very high fibre content (6% by volume) was used and, in addition, quartz particles up to 4 mm in diameter. These must be considered large particles compared with the diameter of the reinforcement (8 mm) and compared with the available space between the reinforcing bars and between the bars and the sides of the mould (6.5 mm). The following precautions were taken to secure the necessary fluidity (viscous shaping) of this complex mix:

1. The fine particle part (cement + microsilica) was converted into a fluid system (in spite of its extremely dense packing) by saturation with a very small amount of water (0.18% by weight).

2. An appropriate quantity of a type of dispersing agent found suitable for ensuring good dispersion of the cement and silica particles was used.

3. The cement-water mix was given increased viscosity and internal coherence (no water separation) and low frictional resistance by incorporating a high concentration of microsilica.

4. The desired viscous consistency of the mass (sand, cement, microsilica, plus liquid) made it possible to incorporate a large quantity of fine steel fibres.

5. The casting was performed under vibration substantially without internal separation.

6. The mixing time was much longer than used in ordinary concrete practice (17 minutes as opposed to 1-2 minutes).

In many respects this strategy differs from and is to some extent in conflict with traditional reinforced concrete technology.

Re.1. It is contrary to the teaching in many textbooks on concrete technology to add ultrafine powder to the cement/water mix in order to reduce the water requirement, the normal, traditional teaching being that fine particles will increase the water requirements (this new approach of replacing water with fine particles is explained in [2]).

The water/(cement + microsilica) ratio is low (about 0.18% by weight), thereby securing a high quality of the final product and the desired viscous behaviour. This low ratio is not conventional in reinforced concrete, where a water/(cement + other fine particles) ratio of 0.30% by weight is normally considered very low and is considered exceptionally low when such a mix has to have a high content of fibres.

Re. 2. The amount of dispersing agent used was considerably higher than in traditional reinforcement and was of a type that proved very effective in dispersing the system in question.

Re. 3. It is not conventional in reinforced concrete technology to assist the incorporation of fibres by increasing the viscosity (here, by using a low water content and adding a large amount of microsilica). The conventional strategy would be the opposite, i.e. to make the mix flow more easily by adding water to facilitate the incorporation of the fibres. This, however, would result in low viscosity and thus in a friction-dominated resistance, which would, in fact, result in bad intermixing and therefore possibly a lower maximum fibre concentration.

Re. 4. The quantity of fibres (6 mm x 0.15 mm) incorporated and arranged in the test beams is very high - up to 6% by volume (20% by weight).

In ordinary reinforced concrete technology, it seems impossible to incorporate more than 1% or at most 2% by volume of fine steel fibres in a mortar with about 50% coarse sand without creating a loose packing, and it would seem almost impossible to cast such a mass so that it would completely fill the narrow spaces between the densely arranged main reinforcement.

Re. 5. The long mixing time (approx. 20 min.), compared with 1-2 min. for ordinary concrete, is needed to secure effective wetting of the ultrafine particles and a high degree of microhomogeneity.

12. CRC - A NEW TYPE OF COMPOSITE

COMPACT REINFORCED COMPOSITE can be regarded as a new type of advanced composite, being a counterpart of advanced fibre composite based on ultra-strong fibres in ductile matrices. CRC can transmit big tensile loads, but not as well as the most advanced fibre composites. However, unlike the traditional, advanced fibre materials, which are only really effective in tension, CRC is able to transmit any type of load (tension, compression, shear, bending, torsion) very efficiently.

CRC makes it possible to benefit from the good properties of the strong, brittle matrix materials (hardness, thermal resistance, chemical resistance) in heavily loaded, large structures, because the brittleness and low tensile strain capacity which have hitherto prevented the production of large, high-performance, composite structures based on brittle matrices are eliminated.

Conventional, Advanced Fibre Composites

It is in advanced, fibre-reinforced materials that the most fascinating utilization of the concept of composite materials has taken place.

These are typically built up of very thin fibres, thinner than 100 μm and often thinner than 10 or 5 μm, embedded in a ductile matrix material such as plastic or ductile metal.

These composite materials make effective use of materials held together by strong, chemical bonds, such as carbon, glass, steel, silicon-carbide, and silicon-nitride, which can only be fully exploited with the materials in the configuration of ultra-fine fibres.

Advanced composite materials with ductile matrix materials are primarily suitable for resisting tension and less suitable for resisting compression, shear, and loads acting perpendicular to the direction of the reinforcement (see figure 12.1).

A

B

C

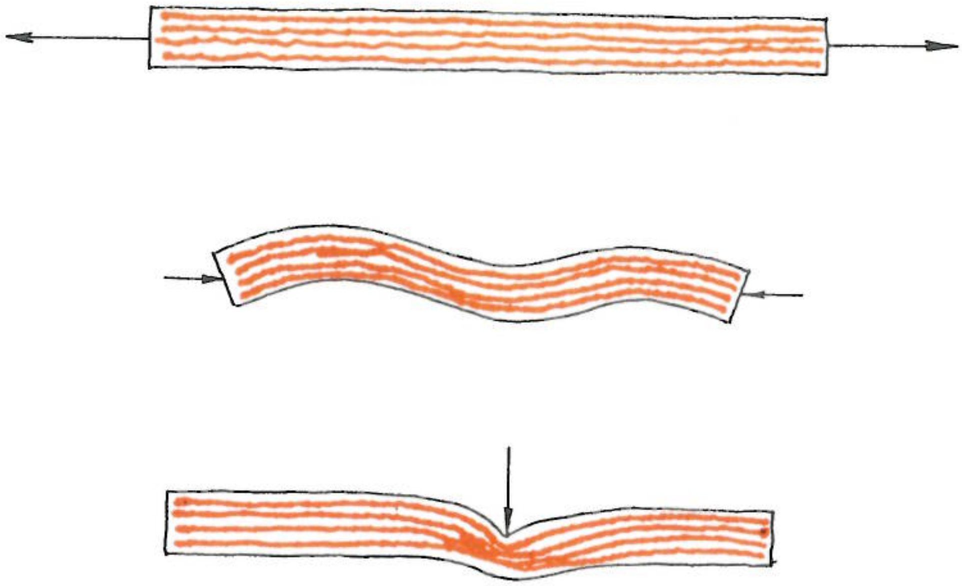


Fig. 12.1 Traditional, high-performance composite materials with strong fibres in a ductile matrix.

The composite materials are suitable for resisting tensile forces but not compression, shear or loads acting perpendicular to the direction of the reinforcement, or for acting in the form of very large objects. These drawbacks are eliminated in CRC.

Efficient utilization of the very strong fibres requires arrangements of fibres parallel to the direction of the tensile load (one-dimensional structure).

Two-dimensional structures obtained by a random orientation of fibres may give reasonably good structures. However, the maximum obtainable strength is considerably smaller than with parallel fibres. The optimum fibre concentration in two-dimensional random arrangements is considerably lower than the fibre concentration that can be obtained in one-dimensional arrangements. However, two-dimensional bodies - such as thin plates - may perform almost as well as one-dimensional bodies through cross-lamination of one-dimensional substructures (tapes).

In three-dimensional structures with randomly oriented fibres, it is only possible to utilize the potentials of the fibres to a very moderate extent. This is because the maximum possible fibre concentration is far lower than in two-dimensional and one-dimensional arrangements. Although it is geometrically and kinematically possible to build up three-dimensional, compact bodies by cross lamination of one-dimensional substructures, this is technically difficult and has hardly any major practical significance.

Advanced fibre composite structures can be characterized as

1. one-dimensional structures
2. two-dimensional structures
3. "never" three-dimensional structures
4. perfect for transmitting tensile forces
5. not suitable for transmitting compression, shear, bending, or torsion
6. sensitive to loads transverse to the fibre orientation
7. normally have a moderate working temperature range
8. are only suitable for small articles.

Points 5 and 6 above are due to the ductility of the matrix materials. The moderate temperature range is also related to the ductility of the matrix material, which is incompatible with structures built up of the type of bonds (strong chemical bonds) that are stable at high temperatures. Furthermore, ductile materials often give rise to brittleness at low temperatures.

The inability to function in large structures (8) is not only a practical problem, but also a fundamental limitation dictated by physical/mechanical laws.

Large bodies, for example beams - in the range of, say, 30 to 100 metres - prepared from ultra-strong fibre composite materials with, say, 10 μm dia. carbon fibres, would be useless in practice. In theory, they would be perfect, but a slight crack would be disastrous and would make the beam fracture as brittle glass. This is due to fundamental fracture-mechanical facts, namely:

A. that the crack sensitivity (the brittleness) is not a purely material-related property but increases with the size of the body,

B. that the "stabilizing" property of the material (fracture energy G) is very small in fine fibre systems compared with the fracture energy of systems reinforced with large bars (G is in many cases approximately proportional to the transverse dimension of the reinforcement) and

C. that the tensile strength σ_0 of the material, which promotes brittle fracture, is extremely high (cf. the expression for the degree of brittleness: $\sigma_0^2 L/EG$).

Consequently, advanced fibre composite materials are unsuitable for transmitting large forces between large components in a compact structure.

Known art

Broadly stated, the known art provides:

1. thin, high-performance, reinforced composites based on strong fibres and ductile matrices that are primarily suitable for tension performance (see figure 2).

2. large, low-performance, reinforced composites for transmitting also shear, bending, and torsion, like reinforced concrete (typically with a bending capacity of not more than 5 MPa or, at best, 15 MPa before the crack), or three-dimensional reinforced plastic with moderate strength and stiffness.

Compact Reinforced Composite

CRC thus provides a new category of composites, with hard, strong, brittle matrices that have been given "ductility" and high tensile strain capacity. The new composites are able to transmit tension, shear, bending, and torsion, at very high performance, typically with a bending capacity in excess of 100-200 MPa without matrix cracking and showing high, three-dimensional rigidity, typically with a modulus of elasticity of more than 50,000 MPa and even more than 70,000 MPa.

In addition, the new, compact reinforced composites typically show high resistance to transverse loads and can be designed with high chemical resistance and the ability to function in a very broad temperature range.

13. NOTATION

b	width of beam or plate	m
B	Brittleness number $B = \frac{\sigma_o^2 L}{E G}$ or $\frac{\varepsilon_o L}{\Delta_o}$	
c	cohesion	N/m^2
d,D	diameter of reinforcement	m
	size of compact shaped particle	m
E	modulus of elasticity	N/m^2
E_m	refers to the matrix material	N/m^2
E_f	refers to the reinforcement	N/m^2
G	fracture energy	N/m
G_m	refers to the matrix material	N/m
L	characterize size (length)	m
l_c	thickness of anchorage zone	m
M	bending moment	Nm
p	pressure/normal stress	N/m^2
w	work required to open a unit area of a crack	N/m
γ	inter-particular surface tension: work required to separate two parallel plates of units area (of the specific materials) from the closest particle distance to infinity	N/m
δ	crack opening	m
Δ	crack zone deformation	m
Δ_o	critical value ($_o$ = G/ $_o$)	m
ε	strain	
ε_o	ultimate tensile strain of matrix material	
	formal bending strain: normalized curvature of deformed beam (corresponds to maximum strain in a beam of identical size made of a homogeneous, linear-elastic material and subjected to identical deflection)	
$\mathring{\varepsilon}$	rate of strain	sec^{-1}

φ	volume concentration of reinforcement	
η	viscosity	sec N/m^2
η_m	refers to the matrix fluid	sec N/m^2
μ	coefficient of friction	
σ	stress	N/m^2
σ_o	tensile strength	
	formalized flexural strength: normalized bending moment for rectangular beams $M/\frac{1}{6}bh^2$	N/m^2
τ	shear stress	N/m^2

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