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THE NEW STRONG CEMENTS: THEIR USE IN STRUCTURES

Hans Henrik Bache

Compact reinforced composites are the most exciting of several recently developed types of materials, with strength and toughness to rival steel, yet more usable than steel for large structures.

Within the last 10 to 15 years, a number of very strong cementitious materials have been developed, many of whose properties are closer to those of ceramics than to those of concrete. The new materials offer many interesting possibilities, partly because, unlike ceramics, they can be made at room temperature; since they have strengths 5–10 times that of conventional concrete, many people are tempted to regard them as alternatives to steel for structural use. However, the materials are typically very brittle, which makes their use for large objects doubtful.

This article gives a brief description of some of the newly developed strong cementitious materials and discusses the brittleness problems connected with their use. Lastly, a new class of extremely strong and at the same time extremely ductile composite materials developed in 1986, compact reinforced composite (CRC), is described. CRC is a kind of super-reinforced concrete with strength and ductility

more like those of structural steel and is specially suited for very large structures.

Conventional concrete and newer materials

Compared with structural steel, conventional concrete has a moderate compressive strength, a low tensile strength and poor ductility. Properly combined with reinforcement, the material forms reliable structures.

In reinforced concrete, the reinforcement (steel bars) resists tensile stresses, while the concrete resists compressive stresses and transmits forces to the reinforcement.

A severe drawback of reinforced concrete is that the concrete cracks under tension at strains that are only 2–5% of the yield strain of the reinforcement. That means that the reinforcement can only be effectively used at the cost of the internal coherence of the concrete in the form of cracks passing the reinforcement.

By following various rules of play concerning moderate quantities of reinforcement, good spacing between bars, large overlap length etc, design engineers ensure that reinforced concrete acts as intended, with moderate controlled cracks on the tensile side. Typical behaviour of good conventional reinforced concrete is shown in figure 1.

Within the last 10–15 years, a number of very strong cementitious materials have been developed based on new possibilities of creating far denser and stronger binder materials than previously known. Sophisticated tests on small cement specimens have shown the potential of cement-based binder materials to be far beyond those manifested in conventional concrete (see figure 2).

Theoretical considerations based on fracture mechanics and experience from ceramics indicated that it should be possible to increase the strength still further by using ultrafine cement particles – if the ultrafine particles could be arranged sufficiently densely and homogeneously.



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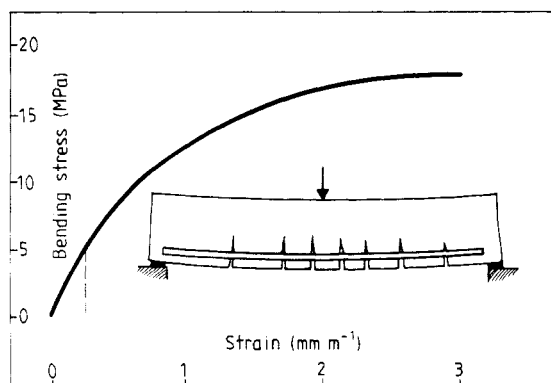


Figure 1. Typical behaviour of a conventional strong reinforced concrete beam in bending. The concrete resists compression, and the reinforcement resists tension. At tensile strains of about $0.1\text{--}0.2\text{ mm m}^{-1}$, the concrete cracks past the reinforcement, while the reinforcement deforms elastically up to $2\text{--}4\text{ mm m}^{-1}$ before yielding. The bending capacities are expressed as normalised bending stresses obtained by dividing the actual bending moment M by $\frac{1}{6}bh^2$, and the strains are normalised curvatures which correspond to the maximum strains in a similar homogeneous beam with linear elastic behaviour.

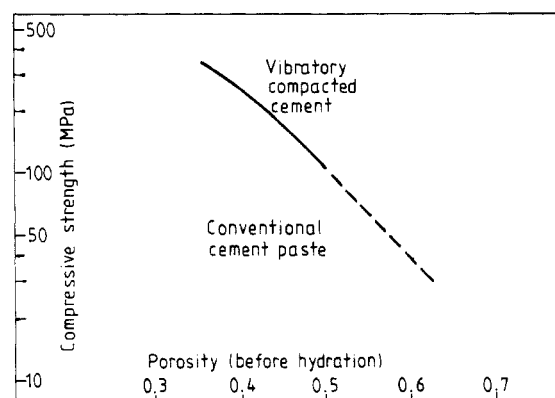


Figure 2. The curve shows the relationship between compressive strength and porosity of hardened cement paste in small-scale laboratory experiments under special conditions. The experiments were carried out with small cylindrical specimens (volume 1 cm^3) made by vibro-pressing with oscillating pressure up to 10 MPa for the densest specimens. In the experiments, considerably heavier compaction was used than in normal concrete production, resulting in paste strengths up to 350 MPa (Bache 1981). This strength is 5–10 times higher than the strength of the cement paste binding sand and stone in ordinary concrete, and the conditions under which the experiments were performed cannot be used in practice in the production of concrete. However, the curve shows the very pronounced effect of increasing the density to obtain very small porosity values, if this were possible in practice.

Figure 3. Structure of strong binder material built from densely packed cement and ultrafine spherical silica particles arranged homogeneously in the spaces between the cement particles. The so called DSP material (densified cement ultrafine particle-based material) is described in Bache (1981).

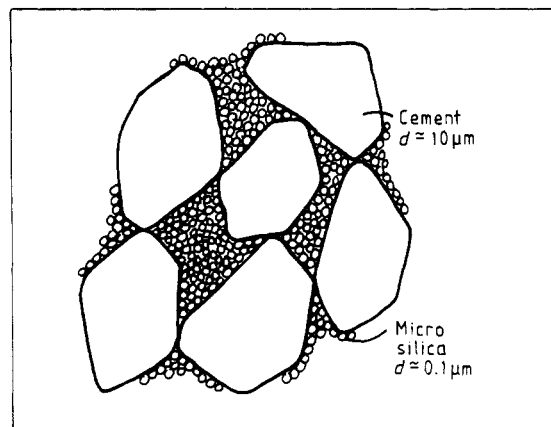
The reason why it is difficult to pack cement densely is that surface forces lock the fine particles in an open structure, and the finer the cement, the more difficult packing becomes. Until recently, this made it totally impossible to use ultrafine cement and cement with special particle-size distributions that are particularly suitable for forming dense structures.

With the appearance around 1970 of effective dispersants for cement systems, it became possible to establish far denser packing of cement in aqueous suspensions. This advance was primarily used to enhance the quality of conventional concrete with conventional cement, resulting in an increase in strength of 30–50%, corresponding to compressive strengths up to 120 MPa . However, the effective dispersants also made it possible to use cements with special particle geometries.

These possibilities were exploited in the so called DSP materials, which are new types of high-strength concrete (Bache 1981). DSP materials are based on very dense and strong binders with 70–80% cement and 20–30% microsilica having an average size of only 0.1 to $0.2\text{ }\mu\text{m}$. The use of effective dispersants ensures dense packing of the cement, with the microsilica placed homogeneously in the spaces between the particles of cement, as illustrated in figure 3. By using silica, which is far less reactive than cement, as the ultrafine particles, it became possible to create dense, homogeneous, sub-micrometre particle structures, which would have been impossible with corresponding ultrafine cement particles.

The amount of water needed to achieve a plastic-to-liquid consistency is as low as 14–16% of the weight of cement+silica, compared with 30–40% for conventional high-strength concrete.

The compressive strength of DSP concretes is typically between 120 and 250 MPa . DSP materials have been used commercially since 1978 for a variety of purposes, including machine components, cutting



tools, roads, safes, masts and quay walls. Other interesting developments include very dense and strong polymer-modified materials based on Portland cement or aluminate cement and water-soluble polymers. Thus 2–3 mm thin laboratory plates of these materials made by high-pressure rolling and curing under pressure have exhibited exceptional bending strengths of up to 150 MPa (Kendall *et al* 1983).

A characteristic limitation of most of these strong materials is their extreme brittleness.

Strength, brittleness and the Brittleness Number

The load capacity of a structure is governed by (a) the strength of the chemical bonds that are broken and (b) the degree to which the bonds act simultaneously at fracture. The theoretical tensile strength of concrete (assuming that all bonds in the fracture face act maximally at the same time) is of the order of magnitude of 10^3 MPa, whereas the real tensile strength of concrete is only about 3 to 5 MPa. The difference is due to cracks and pores and other inhomogeneities, which cause large stress concentrations that prevent the bonds from working together during fracture.

The problem of good and poor cooperation of bonds during failure is illustrated in the master graph in figure 4. In the range on the left (small values of the Brittleness Number) the bonds cooperated effectively at fracture, which here takes the form of yielding. The load capacity is high, and the objects are insensitive to sharp notches, stress concentrations, inhomogeneities etc. Fracture occurs plastically.

For large values of the Brittleness Number, on the other hand, the behaviour is brittle, and fracture is characterised by cracks peeling open, with the forces concentrated locally at the tips of the crack. The load capacity is low, the objects are sensitive to stress concentrations and local inhomogeneities, and fracture is sudden and brittle.

As shown in figure 4, the degree of brittleness of an object depends on the properties of the material – tensile strength (σ_0), modulus of elasticity (E) and fracture energy (G) – and on the size (L) of the object. This is expressed by a single parameter designated the Brittleness Number:

$$B = \frac{\sigma_0^2 L}{EG}$$

The Brittleness Number is a dimensionless quantity that is used for classifying fracture behaviour in the same way, for example, as Reynold's Number in hydrodynamics and Fourier's Number in heating engineering. The greater the Brittleness Number, the more brittle will be the behaviour of the object.

The brittleness problems of the new very strong

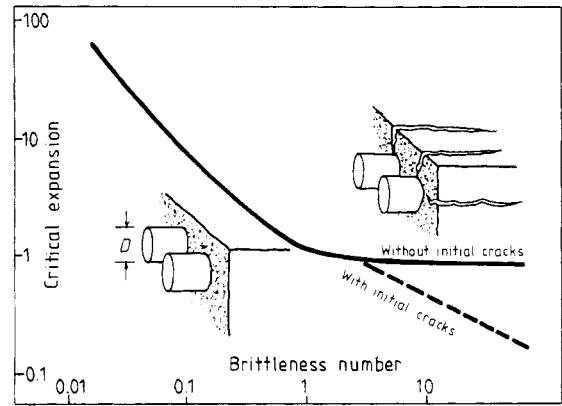


Figure 4. Classification of behaviour on basis of Brittleness Number ($\sigma_0^2 D / EG = \epsilon_0 D / \Delta$). Here exemplified by the behaviour of a body with an embedded cylinder (e.g. a reinforcing bar), which expands in relation to the matrix. The diagram shows critical values of the cylinder expansion, with crack formation/propagation when the strains exceed the critical strains. Critical strain is given as a function of the degree of brittleness – the Brittleness Number.

In the ductile range (small Brittleness Number), the strain capacity is high (increases in inverse proportion to the Brittleness Number) and the behaviour is insensitive to initial cracks and local stress concentrations. In the brittle range, the strain capacity is low and the behaviour is extremely sensitive to initial cracks and local stress concentrations. Sketch diagram valid for geometrically similar objects. Thus, the sizes of the initial cracks are assumed to be proportional to the diameters of the cylinders.

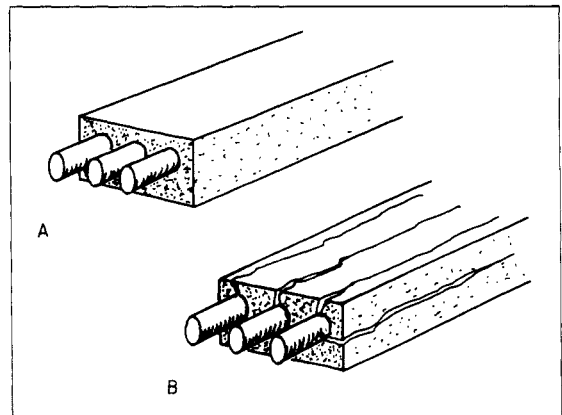


Figure 5. Reinforced concrete made with very strong – but brittle – concrete. Transferring experience from ordinary reinforced concrete (A) to reinforced concrete with very strong concrete materials (B) gave not the desired result but a brittle object that cracked along the main reinforcement.

materials are exemplified in figures 5, 6 and 7, which show unsuccessful use of very strong cementitious materials. The reason for the 'surprising' behaviour was that by increasing the strength (σ_0) or the size (L) of the object, we at the same time increased the Brittleness Number.

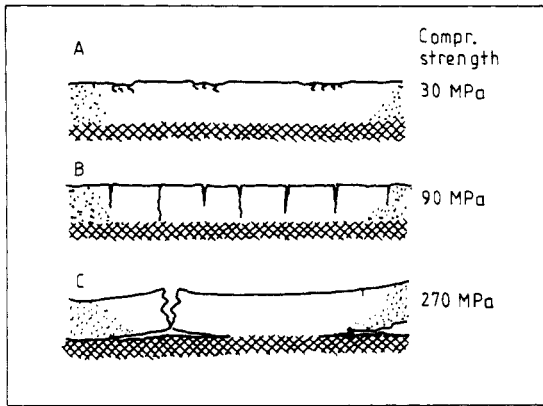


Figure 6. Strong wearing surfaces showing a high degree of brittleness. With normal quality (A), the wear was too heavy, so a material with higher strength was used (B). However, this resulted in a number of shrinkage cracks. To avoid this, much stronger materials (C) were used, but the result was disastrous destruction caused by peeling of the surface layer from the base.

For example, if the tensile strength σ_0 is increased by a factor of 5 without any appreciable alteration of the modulus of elasticity E and the fracture energy G , the Brittleness Number will increase by a factor of 25, and if the size L of an object is increased from millimetre size for a small test plate to an object 10–50 times the size, the Brittleness Number will increase correspondingly by a factor of 10 to 50.

At first glance, the illustrated results seem depressing, but fortunately, the Brittleness Number also indicates ways in which these new very strong materials can be used effectively without the drawback of excessive brittleness – by increasing the product GE/L . In other words, objects made of strong materials can be given greater ductility by using stiffer materials and/or giving the materials greater fracture energy.

As the brittleness increases with the size of the object, it will also be seen that stronger materials with higher brittleness (higher values of σ_0^2/EG) are most suitable for small objects.

Fibre and particle modification

Incorporating fibres makes it possible to increase the tensile load capacity and provide ductility. However, in strong materials a very high concentration of fine strong fibres is required for the reinforcement to act as more than just safety reinforcement after the matrix material has cracked.

It is not easy to produce such structures. Special processes are required. For example, high-quality asbestos-cement pipes (cement+11% fine asbestos fibres) were fabricated by a spinning process, in which the pipe was built up from a large number of very thin layers of cement and fibres from an

aqueous suspension. The incorporation of fibres ensured a fivefold increase in the tensile strength without detectable cracks right up to failure.

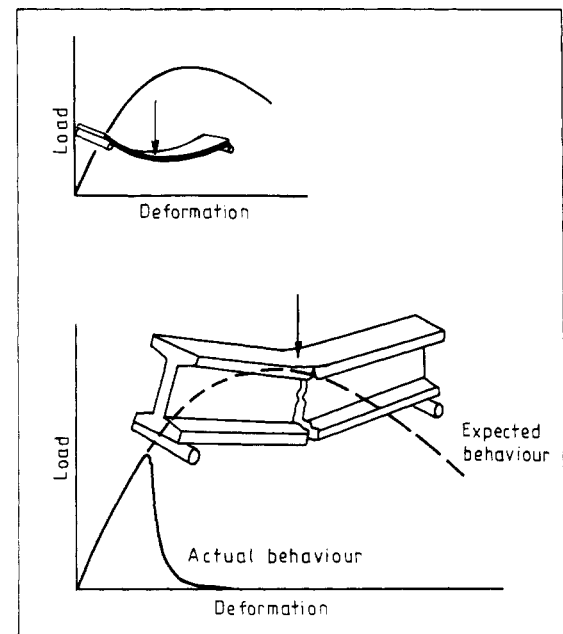
By using such special fine-fibre modification, one can typically increase the tensile strength from 10 MPa to 30–50 MPa, and the fracture energy from 10–100 N m⁻¹ to 5–15 kN m⁻¹. Such fibre-modified materials are highly suitable for small load-carrying objects (for example, millimetre-thin plates) but they are still far too brittle to be used as, say, a replacement for reinforced concrete in large load-carrying structures.

The brittleness can be reduced by incorporating strong stiff particles. That is what we experience when we transform extremely brittle cement paste into the far more ductile material, concrete, by means of sand and stone.

Working from the expression for the Brittleness Number, we can see what has happened when we have added sand and stone to pure cement paste by comparing the resulting concrete with a similar object made of pure cement paste.

- The fracture energy G has been increased (from about 10 to 100 N m⁻¹).
- The modulus of elasticity E has been increased (from about 10 GPa to about 40 GPa).
- The tensile strength σ_0 has not changed very much – probably just decreased slightly (for example, from 6 MPa to 4 MPa).

Figure 7. Large object showing a high degree of brittleness. The material exhibited ductile behaviour in very small objects but distinctly brittle behaviour in large structures.



These changes lead to a reduction of the Brittleness Number $\sigma_0^2 L/EG$ to about one-hundredth of its cement value.

Effective particle modification requires considerably stronger and preferably stiffer particles than the binder. For conventional concrete this requirement is met with good natural aggregates – as illustrated by the fact that fracture largely passes by, not through, the aggregates.

With the new very strong binders this condition is not satisfied with normal aggregates – fracture passes through the aggregates and we do not get the full benefit from the binder. Effective exploitation of strong binders is achieved by using correspondingly strong aggregates, whereby high fracture energy and high compressive strength are ensured.

For example, two types of cement-silica-based high-strength concrete are marketed, with compressive strengths of 120–160 and 200–250 MPa, respectively (Bache 1981). The binder is the same, but the second material is based on Al_2O_3 -rich aggregates, while the first is based on quartz.

Large members

A large value of the product of fracture energy (G), modulus of elasticity (E) and high tensile load capacity is needed in order to be able to use high-strength binders in large members. There seems to be no other way of achieving this than to apply the same basic principles as for conventional reinforced concrete, namely to use a main reinforcement in the form of large bars.

However, a very large quantity of main reinforcement is needed to achieve effective utilisation of the very high compressive strengths of the concrete. This is not directly feasible because of the brittleness of the concrete materials and the high concentration of main reinforcement, giving an increasing tendency towards local fractures along the reinforcement.

The brittleness problems can be greatly reduced by using concretes that are modified with fibres. An example of a member made of high-strength concrete reinforced with steel bars and modified with fibres is shown in figure 8. However, the quantity of fibres and main reinforcement is moderate.

Really effective exploitation of the potential of ultrastrong binder materials combined with a high concentration of main reinforcement means that we have to be able to combine:

- (1) a very dense binder material – for example, based on cement and microsilica, with a water/powder ratio of about 0.18,
- (2) a high concentration of fine strong fibres, say above 5% by volume of steel fibres with diameter of about 0.1 mm,
- (3) a high concentration of strong stiff particles,

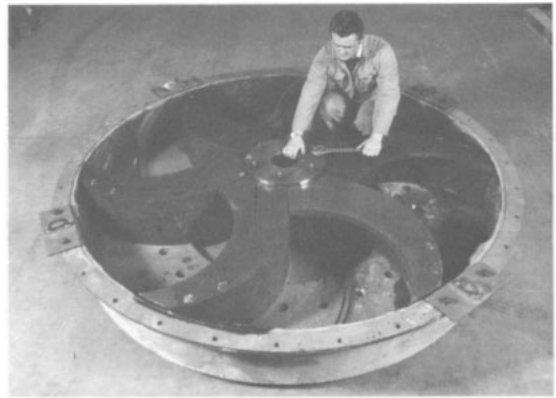


Figure 8. Scoop feeder for revolving cement mills. It lifts cement clinker from the feed of the mill to the grinding chamber. The exchangeable scoops are made of concrete (they are traditionally made of cast iron). It has been in service since 1982. The concrete is very strong, with a compressive strength of about 200–250 MPa. The component was given ductility and increased tensile load capacity by about 3% steel fibres by volume and main reinforcement. The binder was made from well dispersed mixtures of densely and homogeneously arranged cement and microsilica with an extremely low water/cement+silica ratio (only about 0.16–0.20 by weight; and an Al_2O_3 -rich sand was used to secure high strength and high abrasion resistance.

(4) joining such modified materials together with densely arranged main reinforcement, with a volume concentration of, say, 10 to 20%.

It is this that has been done in the new type of composite designated compact reinforced composite (Bache 1987).

Compact reinforced composite (CRC)

CRC is a new type of composite structure having a very high strength not only in compression but also in tension, combined with great stiffness and a high strain capacity in tension, with retention of very high internal coherence.

The structure is built up of a strong base matrix, typically very brittle in itself, which is heavily reinforced with fine fibres, thereby forming a stronger and more ductile material. This heavily fibre-reinforced material in turn acts as matrix in a composite reinforced with a high concentration of main reinforcement such as steel bars. The new class of material or structure has a superficial similarity with reinforced concrete. It has, however, a much higher load capacity, not only in compression, but also in tension – for example, a bending capacity corresponding to a formal bending stress of about 150 to 300 MPa, compared with 20 MPa for good conventional reinforced concrete, and it performs with retention of substantial internal coherence also in the tensile zone, showing crack-free behaviour at tensile strains above 3 mm m^{-1} , as compared with

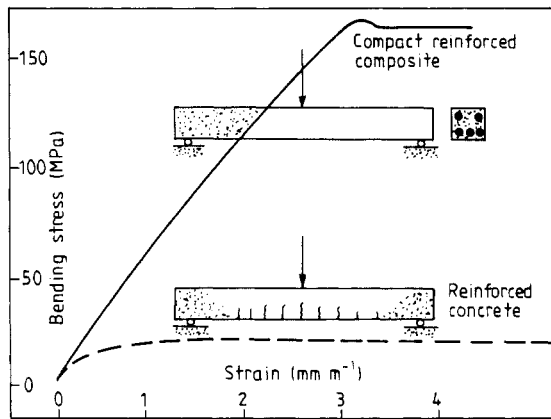


Figure 10. When a brittle material in the form of a large rod fractures in tension, the fracture occurs very suddenly after a substantially elastic deformation of the rod. If, however, the deformation is measured over a narrow zone in which the actual separation takes place, we see a different picture. The zone first deforms elastically up to maximum load and then undergoes larger deformation as the load decreases, exhibiting a kind of plastic yielding.

This so called crack zone deformation is 20–50 μm in concrete, 2–10 μm in conventional cement paste, 0.5–1 μm in high-strength cement paste, and only about 0.001–0.01 μm in glass. Whereas the larger crack zone deformation (Δ) of concrete has been measured directly, the values for the more brittle materials have been estimated from measurements of the tensile strength (σ_0) and the fracture energy (G), assuming that the work of fracture is predominantly due to fracture zone deformation: $G \approx \Delta \sigma_0$.

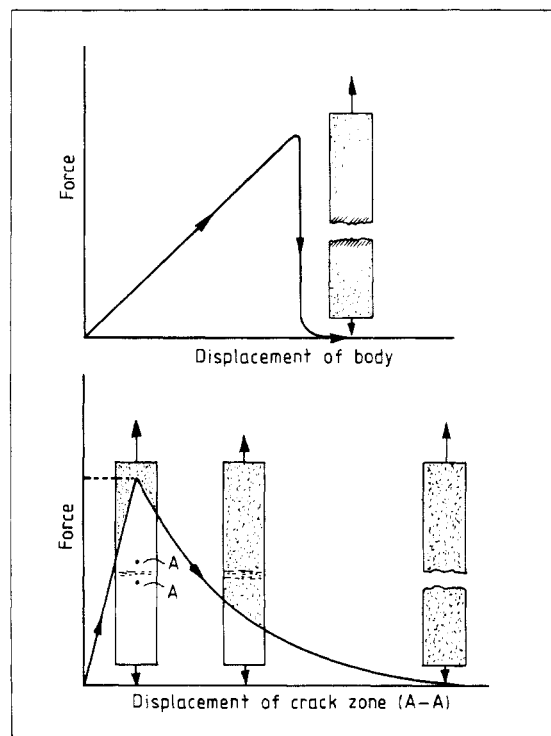


Figure 9. Behaviour of a small CRC beam (50×50×500 mm) in bending. The matrix is based on Portland cement and reinforced with 6% by volume of steel fibres (length 6 mm, diameter 0.15 mm), and the reinforcement was 8 mm deformed steel bars. In the test, the relationship between force and deflection was recorded (maximum force 31 kN). For comparison, the results have been normalised (expressed by stresses and strains, respectively). The bending stress is obtained by dividing the moment by the section modulus ($M/\frac{1}{6}bh^2$). The strains correspond to the maximum strains in a similar, homogeneous beam with ideal linear elastic behaviour (Bache 1987).

tensile strains of only 0.1–0.2 mm m^{-1} before cracking of the concrete material in reinforced concrete (see figure 9).

The strength of the material is almost like that of structural steel, not only in compression, but also in tension, bending and shear. At the same time, however, the material has the advantage of being a composite material, with all the possibilities such a structure offers for tailoring specific (often directional) properties.

The new composite is *the* hitherto non-existent composite – or, for that matter, non-existent material in general – that can give very large, massive structures very high rigidity, ductility and strength.

High-quality conventional fibre-reinforced composites, such as carbon-fibre-reinforced plastics, are well suited for small bodies to be loaded in tension, but are unable to resist large loads in shear and compression and are absolutely unsuitable for large structures.

Structural steel, on the other hand, is obviously a very useful material, also for structures of great overall size and weight, but it cannot realistically be used effectively in massive structures of thickness greater than about 200–400 mm, because the available methods of processing steel (rolling, welding, casting, etc) cannot be used for thicker steel structures.

With respect to massive structures that are able to resist large forces, also in tension, conventional reinforced concrete has hitherto been the only candidate material, but its strength, especially in tension, is inferior to that of high-strength fibre-reinforced composite and structural steel.

CRC can be used effectively in massive structures of sizes that have hitherto only been possible with reinforced concrete, but its mechanical properties are more like those of structural steel. This exceptional behaviour of CRC is obtained by applying novel principles of mechanical design based on

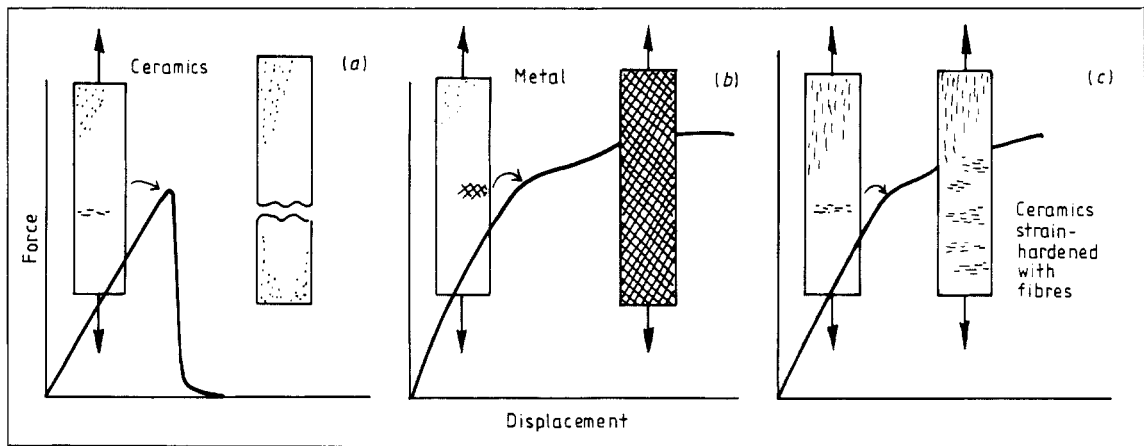


Figure 11. Tensile behaviour of a bar of a 'ceramic material' (a), a metal bar (b) and a ceramic material provided with strain hardening capacity (c). The ceramic bar fractures at the first 'yield tendency' without yielding outside the narrow fracture zone. The metal bar exhibits increased internal resistance during commencement of yielding, whereby the yielding spreads out over the volume – an effect that is termed strain hardening (sketch shows principle). The ceramic material with a high concentration of fine, strong, stiff fibres behaves like the metal bar. At deformations beyond what corresponds to maximum loading for unreinforced material (σ_0), the fibres immediately act so effectively that, together with the now more deformed matrix material, they transmit larger stresses than the tensile strength (σ_0) of the matrix material. The brittle material is thereby given the capacity to strain harden – in the same way as the metal bar.

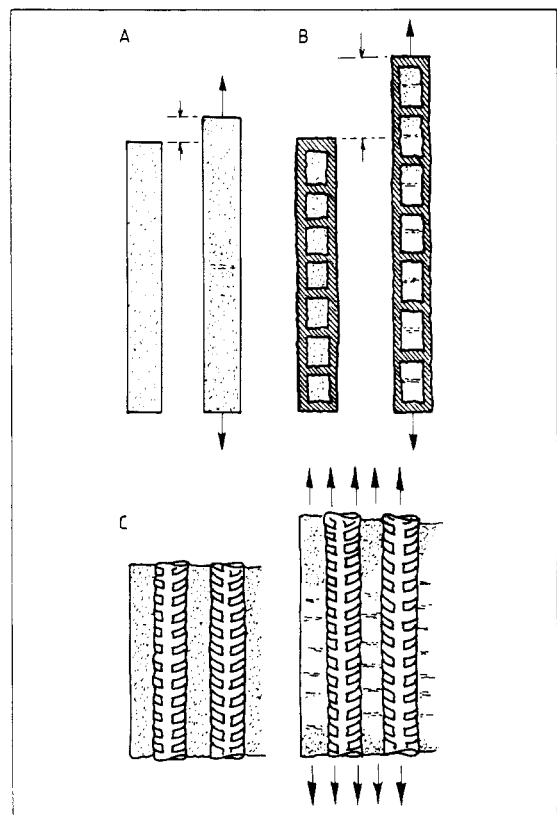
material behaviour; these aim to benefit from the almost neglected knowledge of the fact that strong brittle materials fracture in tension *after having shown a very small deformation in a narrow zone after maximum stress has been reached* (see figure 10).

By reinforcing the strong brittle matrix with a high concentration of fine fibres, so that the fibres carry a heavy load during crack zone deformation, and by using the main reinforcement for distribution of crack zone deformations over the entire body, the

Figure 12. Strain capacity increase by use of main reinforcement. This figure shows a body, A, made from a brittle material in unloaded condition and then in strained condition just before fracture. In the strained condition, a single crack zone has developed. The total deformation of the body is equal to the ultimate strain multiplied by the length of the body plus the crack zone deformation of the single crack zone.

In B, the brittle material has been fixed to a rigid frame which divides the material into several smaller domains. When the frame with the smaller domains is strained, several small crack zones develop (one crack zone in each domain) before any crack opens. This means that the total deformation before a crack is developed is increased.

This is what is obtained in CRC materials (as in C), where the densely arranged main reinforcement acts as a stiff frame that subdivides the matrix material into small domains and thus increases its strain capacity when the material undergoes tensile deformation together with the main reinforcement. This behaviour requires a matrix having large internal coherence. In CRC this is ensured by incorporating a large content of very fine rigid and strong fibres (Bache 1987).



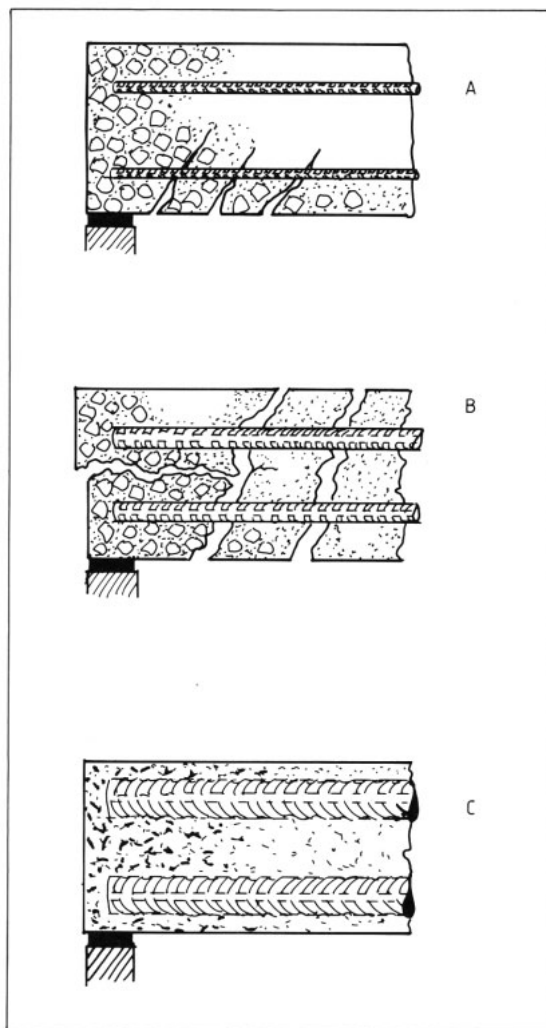


Figure 14. Detail of a section of a 120 mm thick CRC plate after a punching test. The plate failed at a concentrated load of 340 ton acting on a circular area of 113 cm² (punch diameter 120 mm, ring-support diameter 470 mm), corresponding to a contact pressure of 300 MPa. The ultrastrong 'concrete' cuts 16 mm diameter high-quality steel bars in shear almost like scissors cutting paper.

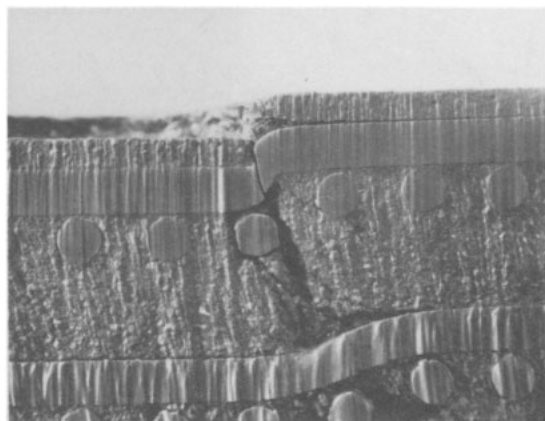


Figure 13. Behaviour under loading of reinforced concrete (A), a too heavily reinforced concrete (B) and CRC (C). In normal reinforced concrete (with a moderate amount of reinforcement) the concrete cracks past the reinforcement, which resists the tensile stresses but retains acceptable inner coherence. If we try to use more reinforcement, the 'concrete' cracks and splits, and the inner coherence is lost. With CRC, an extremely large quantity of reinforcement is used without losing inner coherence and without cracking for loads right up to the yield limit of the steel (Bache 1987).

strain capacity of the body before cracking and the coherence of the entire structure are considerably increased (see figures 11 and 12).

The high ductility thereby obtained makes it possible to benefit from a very high concentration of main reinforcement, for example, 10–30% by volume, to carry the main part of the load. This is not possible with conventional reinforced concrete, where the brittleness and low strength of the concrete prevents the use of a high concentration of main reinforcement and thereby limits the obtainable performance (see figure 13).

Future prospects

With the latest recognition of the brittleness problems in connection with the new strong cement-based binders and of how the materials can be given a large tensile load capacity and high ductility, the way is open for the development of entirely new high-performance cement-based structures.

Note added in proof

Since this manuscript was delivered, a large number of experiments have been carried out on metre-sized CRC objects which have fully confirmed our earlier experience and expectations.

For example, 2100×150×94 mm beams exhibited 60% greater specific bending capacity than those shown in figure 9 (bending stresses of about 260 MPa), and a 120 mm thick plate resisted a concentrated load of 340 tons transmitted via a 120 mm diameter steel cylinder. A detail of a section of the plate is shown in figure 14.

Further reading

- Bache H H 1981 Densified cement/ultrafine particle-based materials *Paper presented at 2nd Int. Conf. on Superplasticizers in Concrete, Ottawa, Canada, 10–12 June, 1981* (Available as CBL Report No 40 from Aalborg Portland, PO Box 165, DK-9100, Aalborg, Denmark)
- Bache H H 1987 Compact reinforced composite basic principles *CBL Report no 41* (Aalborg Portland Juli 1987)
- Kendall K, Howard A J and Birchall J D 1983 The relation between porosity, microstructure and strength, and the approach to advanced cement-based materials *Phil. Trans. R. Soc. Lond. A* **310** 139–53