INTRODUCTION TO COMPACT REINFORCED COMPOSITE

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ABSTRACT

Compact Reinforced Composite - CRC - is a new type of composite structure.

In its cement-based version, CRC is built up of a very strong and brittle cementitious matrix, toughened with a high concentration of fine steel fibres and further reinforced with a high concentration of larger steel bars.

CRC has structural similarities with reinforced concrete, but is much more heavily reinforced and exhibits mechanical behaviour more like that of structural steel, having almost the same strength and extremely high ductility.

The article describes this new type of structure and presents estimates of the ranges of properties to be expected.

Key-words: Brittleness, Composite, Cracks, Ductility, Fibres, Fracture mechanics, High strength concrete, Reinforced concrete.

1. INTRODUCTION

The last 10-15 years have seen the development of ultra-strong, cement-based matrix materials. A major factor here has been the appearance of efficient dispersants.

It has, for example, become possible to produce concrete and mortar, with compressive strengths of about 200-270 MPa. An example is shown in FIG. 1.

However, the very strong matrix materials are extremely brittle, which makes it difficult to utilize them effectively for load-carrying structures.

These brittleness problems are far greater with the new, high-strength matrix materials than with conventional, cement-based matrix materials because 1) the new materials are far more brittle and 2) the reinforcement is much more densely arranged (as a far greater quantity of reinforcement is needed in order to exploit their higher compressive strengths), which increases still further the risk of local cracking close by the reinforcement.

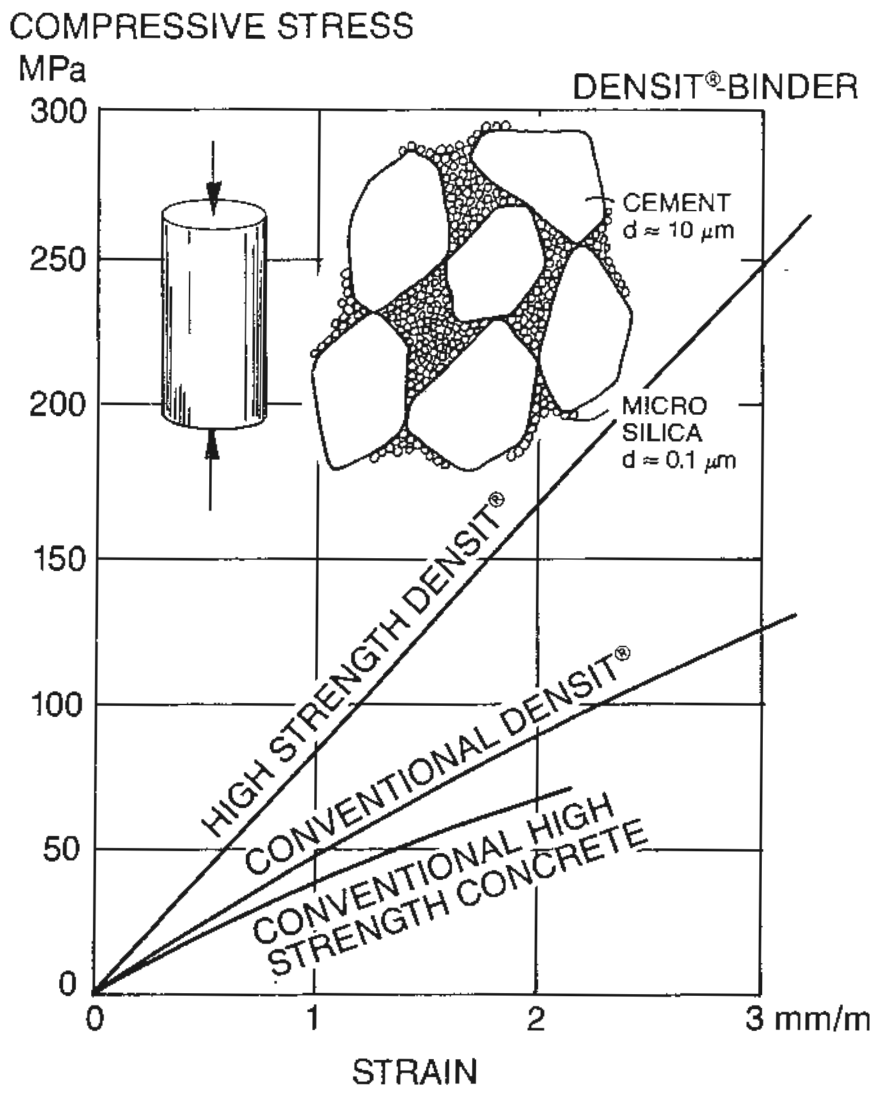

FIG. 1. Behaviour of Densit®-materials and conventional high-strength concrete under compression.
The high-strength Densit®-materials are made with strong Al_2O_3-rich aggregates (calcinated bauxite).
The Densit®-binder is formed from a structure built up of densely packed cement with microsilica placed in the spaces between the cement particles /1/.

In order to utilize the high compressive strength of the matrix materials really effectively, we need a correspondingly high concentration of strong, stiff reinforcement (e.g. 10-20%-vol., compared with 1-3%-vol. in conventional, good-quality reinforced concrete).

Materials with very fine main reinforcement - fibre-reinforced materials - can only be used in the form of very small (thin-walled) objects because they are totally incapable of providing large objects with sufficient ductility.

Therefore, in order to utilize the strong matrix materials effectively in large load-carrying structures, it is absolutely essential to have thick main reinforcement (at least several millimeters), so successful use of the matrix materials depends entirely on the degree to which the matrix can be given ductility.

However, with CRC, we have gone a step further than simply ensuring the necessary degree of matrix ductility. By effectively exploiting the ability of the strong matrix materials to fixate very high concentrations of fine fibres, we have created matrix materials with extremely high ductility, which, together with densely arranged main reinforcement, thereby forms the new ultra strong and ultra ductile material: COMPACT REINFORCED COMPOSITE - CRC.

2. CRC-STRUCTURE

CRC is built up of a base matrix toughened with fibres and further reinforced with densely arranged main reinforcement (see FIG. 2).

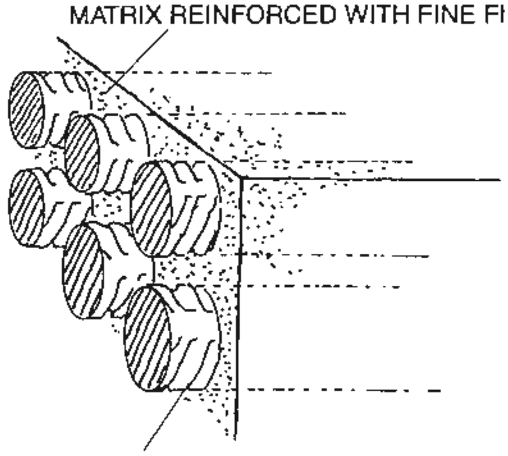

FIG. 2. Typical CRC structure with a brittle, strong matrix toughened with fibres and provided with high tensile load carrying capacity through a high concentration of main reinforcement. The matrix may be a cement/microsilica-quartz sand mortar, reinforced with 6%-vol. of fine steel fibres (0.15 x 6 mm) having a compressive strength and fracture energy of 225 MPa and 13000 N/m, respectively. Such a matrix was used in the first CRC experiments (with small beams, 50 x 50 x 500 mm). A very similar - slightly weaker - matrix was used in the later experiments with larger beams. The amount of main reinforcement is typically 10-25% by volume, but may be even higher (see FIG. 9).

Typical bending behaviour is shown in FIGS. 3, 7 and 8. Portland-cement-based CRC beams exhibited load capacities almost equivalent to those of structural steel and remained substantially uncracked right to the yield limit of the main reinforcement (about 3 mm/m), where conventional reinforced concrete typically cracks at about 0.1-0.2 mm/m.

The concept of CRC is not restricted to cement-based, reinforced-concrete-like structures, but as this publication concerns "concrete", the description is limited to the Portland-cement-based structures.

3. FRACTURE-MECHANICAL PRINCIPLES

The development and design of CRC is based on fracture-mechanical principles, which are applied to ensure ductility and internal coherence. They are based on the fact that tensile failure in brittle materials occurs by a single crack developing after a local crack-zone deformation has arisen in a narrow zone along the later separation face (see FIG. 4). The strategy used in CRC is to increase the toughness of the matrix in general and specifically to provide it with the ability to form multiple crack-zone deformation by:

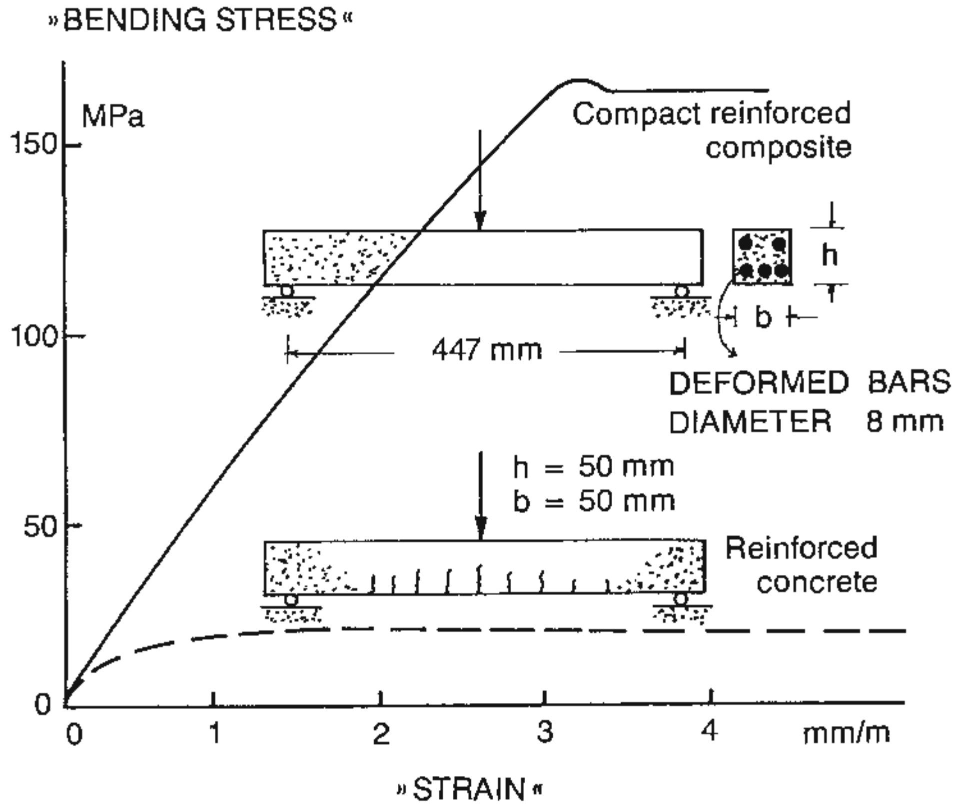

FIG. 3. Behaviour of CRC-beam (plate strip) in bending.

The bending stresses have been normalized by dividing the actual moments (M) by the section of modulus (1/6 b h^2). The normalization is made in order to facilate comparison with beams or plates made of other materials - such as massive steel.

The CRC beam remained uncracked right up to yielding.

The matrix was a Densit[®]-mortar with properties as indicated in FIG. 2.

1. reinforcing the brittle base matrix with a very high concentration of fine, strong, stiff fibres, which provides great toughness and has the additional effect of increasing the tensile strain capacity of the base matrix because the fibres take over the loads effectively in zones with incipient crack-zone deformations before real cracks develop in the matrix; this results in incipient crack-zone deformations spreading out over the material (see FIG. 5);

2. further increasing the strain capacity through very firm fixation of the matrix material to densely arranged, uniformly distributed main reinforcement; multiple crack-zone deformations thereby form, uniformly distributed throughout the object when the matrix, in tension, is forced to follow closely the elongations of the main reinforcement (see FIG. 6).

As mentioned, the fracture-mechanical principles are applied to provide the composite with the necessary ductility and internal coherence. The actual design of the reinforcement with a view to ensuring the desired load capacity is based on classic continuum mechanics for reinforced composites (theory of elasticity, theory of plasticity). By ensuring the great internal coherence and high ductility, it has at the same time been ensured that the criteria for using continuum-mechanical design are in order.

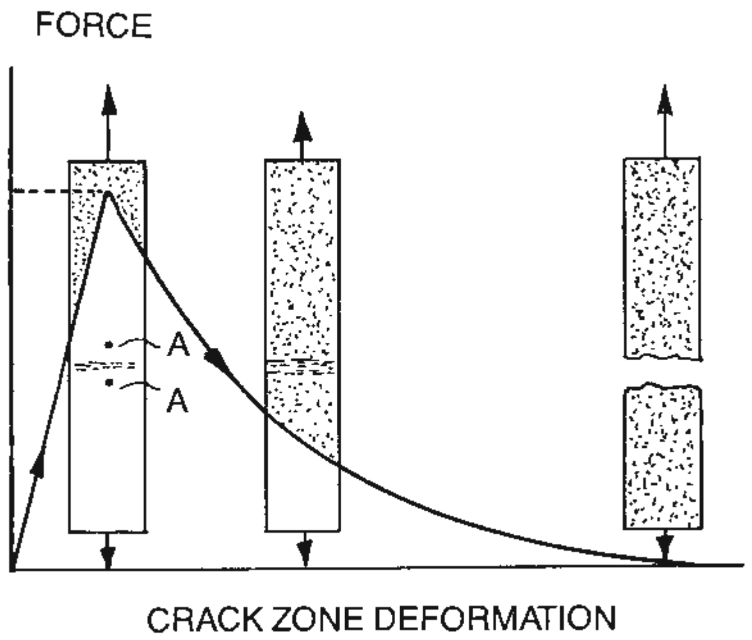

FIG. 4. Tensile failure in brittle materials occurs through the development of a single crack. The cracking is accompanied by a small deformation in the zone around the later separation face (A-A) after maximum loading has been reached.
The magnitude of this "crack zone deformation" is about 20 µm for concrete, 5 µm for cement paste, 1 µm for Densit[0]-paste, and 0.01 µm for glass.

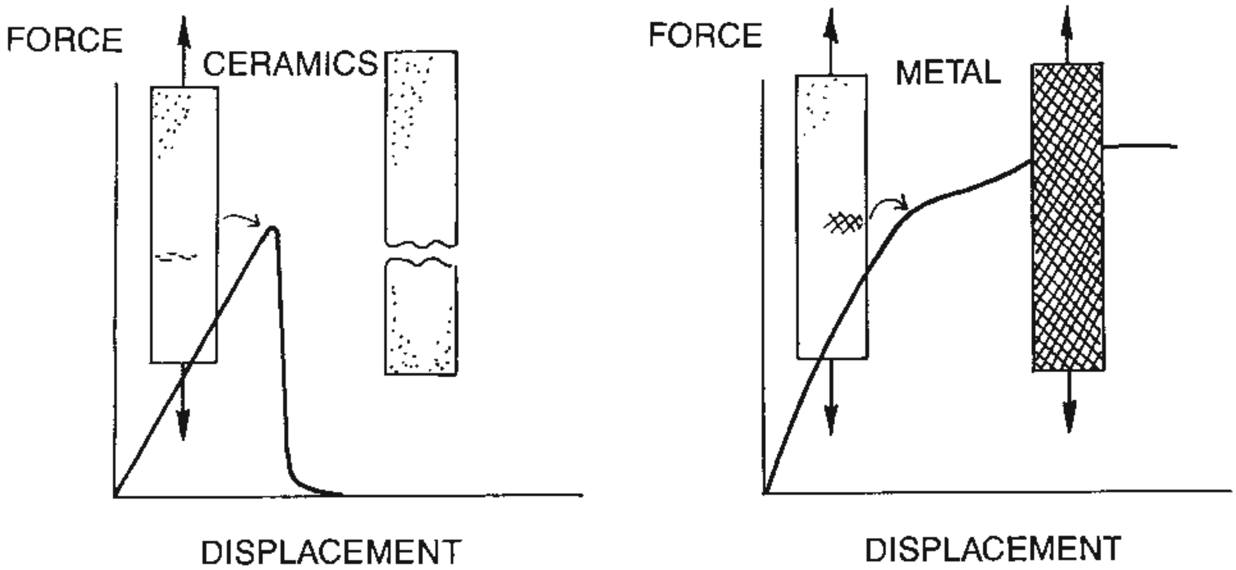

FIG. 5. Tensile behaviour of a bar of a "ceramic material" and a metal bar.
The ceramic bar fractures at the first "yield tendency" without yielding outside the narrow fracture zone.
The metal bar exhibits increased internal resistance during commencement of yielding, whereby the yielding spreads out over the volume - an effect that is termed strain hardening.
A ceramic material can be made to exhibit strain hardening by reinforcing it so effectively with a high concentration of fine, stiff, strong fibres that, on commencement of cracking in the matrix, these - together with the locally weakened matrix - resist a higher load than the ultimate load of the matrix /3/. This is exploited in "advanced CRC".

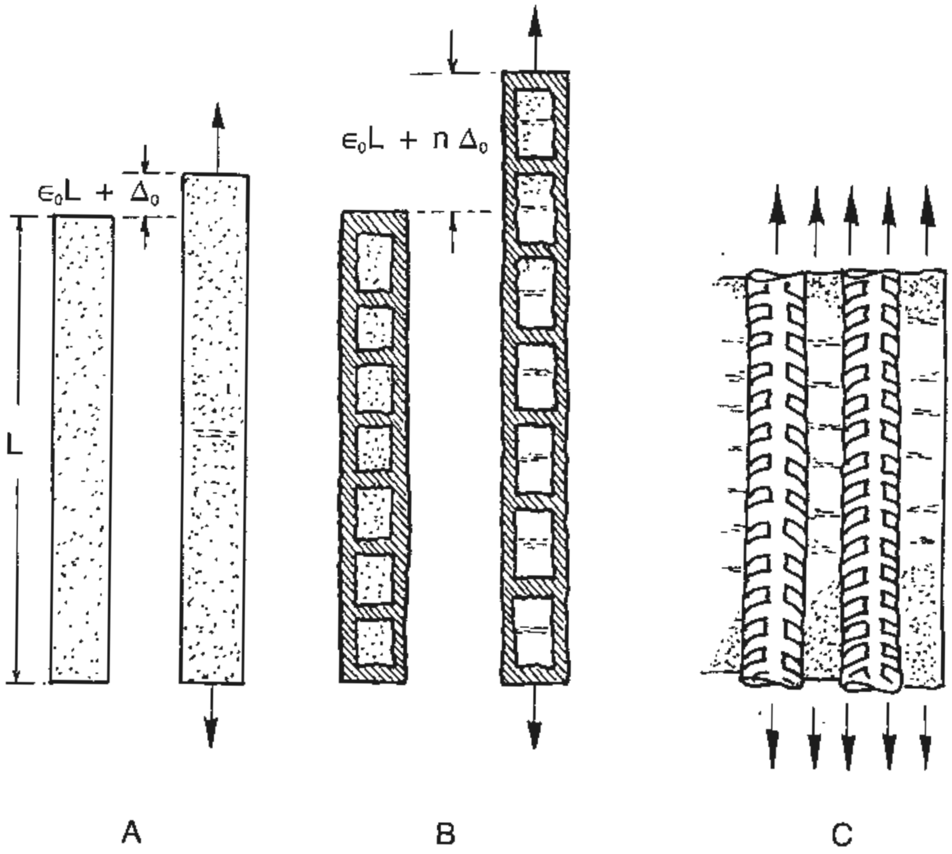

FIG. 6. Tensile deformation of a bar of a ceramic material (A) and an identical bar divided into small bodies fixed to a stiff frame that undergoes tensile deformation (B).

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

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.

4. MECHANICAL BEHAVIOUR

In the following the mechanical behaviour of CRC is discussed in the light of experiments performed on small and large beams, and estimates are given of the anticipated ranges of properties that can be achieved with CRC.

CRC objects of the type dealt with here are typically reinforced with 10-20%-vol. of main reinforcement in the form of steel bars of diameter from about 5 mm to perhaps 40 or 50 mm and 5-10%-vol. fine fibres. The fibre-reinforced "concrete" typically has compressive strengths from 150 to 270 MPa and fracture energy from 5,000 to perhaps 30,000 N/m.

4.1 Bending strength

Typical bending behaviour of a CRC-beam (plate strip) is shown in FIGS. 7 and 8. The beams deformed substantially crack-free up to the yield limit of the main reinforcement, after which plastic deformations occured while a high loading level was maintained. In the beam tests, the yield loads (expressed as formal bending stresses $M/(1/6\ bh^2)$) varied between 140 and 260 MPa.

Expected range: 100 - 300 MPa.

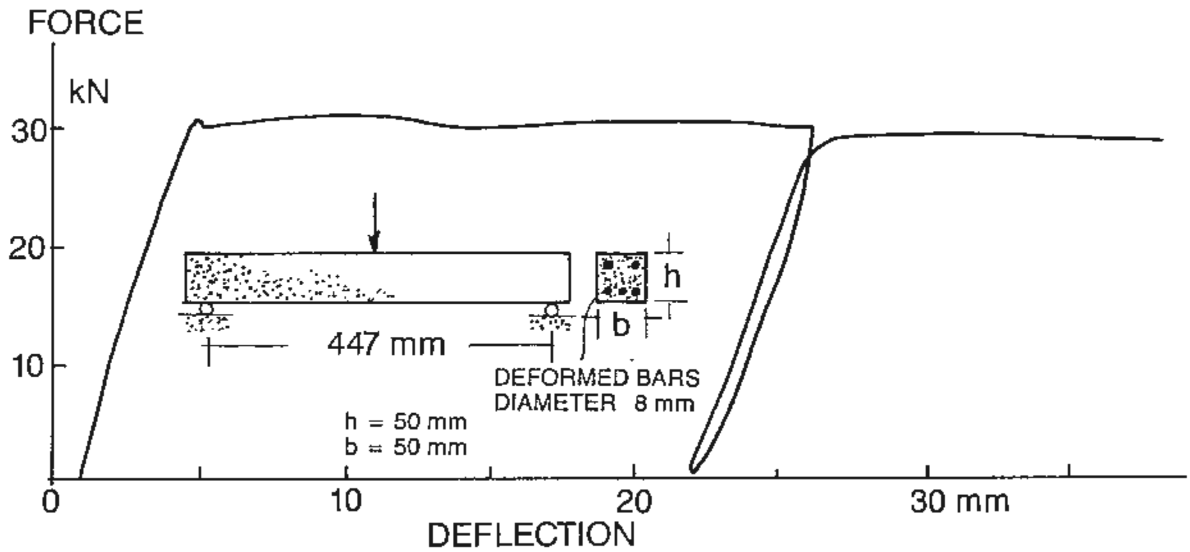

FIG. 7. Behaviour of a CRC beam (plate strip) in bending. After a pronounced yielding at a deflection of about 25 mm the load was released whereafter the beam was reloaded. The first part of the curve is shown in normalized form in FIG. 3.

4.2 Shear strength

Objects - plates, for example - that are designed to resist very great shear stresses can be provided with special shear reinforcement, as shown in FIG. 9.

With the very densely arranged shear reinforcement that can be utilized in CRC, formal shear strengths of up to 100 and perhaps even 150 MPa are anticipated.

Even without special shear reinforcement, CRC is able to resist large shear loads. Thus, in experiments on beams without shear reinforcement, shear yield loads corresponding to formal shear stresses of about 15 MPa were recorded. It should be noted that the shear stresses were accompanied by large bending moments.

4.3 Tensile strength

CRC's tensile yield value is expected to range from 100 to 200 MPa (formal tensile stress - force/area), and it should be noted that the tensile strength can be further increased by prestressing or posttensioning the entire CRC structure with high-quality wires.

4.4 Compressive strength

Through different combinations of matrix materials and reinforcement, CRC is expected to be able to have a compressive strength in the range approx. 150 MPa til approx. 400 MPa. Thus compressive yield stresses of about 260 MPa and 300 MPa were achieved in tests on a beam (see FIG. 8) and a plate (see FIG. 9), respectively.

4.5 Fatigue

Fatigue tests on large beams have shown that the structure and behaviour of the matrix material remain substantially unchanged after repeated tensile loading (100,000 to 5,000,000 times) up to the fatigue strain of the main reinforcement. Fatigue tests on the fibre-reinforced matrix material under oscillating compressive loads indicates a behaviour like that of concrete, with long-term stability (over 5,000,000 load cycles) if the loads are less than about 65% of the compressive strength determined in a static test /5/ /7/.

The experiments give ground for optimism with regard to the use of CRC in objects that are exposed to prolonged, repeated loading. However, it has not, for example, been investigated how the matrix material behaves under heavy, repeated loading with alternative compression and tension.

4.6 Safety - toughness

CRC exhibits distinct toughness at several structural levels. Firstly, the fine fibres ensure local toughness of the matrix material, secondly, the main reinforcement ensures that the cracks do not propagate over larger areas and, through its high yield strength, ensures very great overall ductility. This makes CRC extremely suitable for large objects/constructions for which an extremely high load capacity is required, together with a very high yield strength, while retaining a high degree of internal coherence.

4.7 Reliability

CRC exhibits considerably greater reliability than conventional reinforced concrete - illustrated by much greater uniformity of deformation behaviour up to yielding in bending tests on large beams than normally found for reinforced concrete. This is due to the great internal coherence of the material, which results in very uniform distribution of stresses and strains - without the brittleness and cracking that characterize conventional reinforced concrete /5/ /7/.

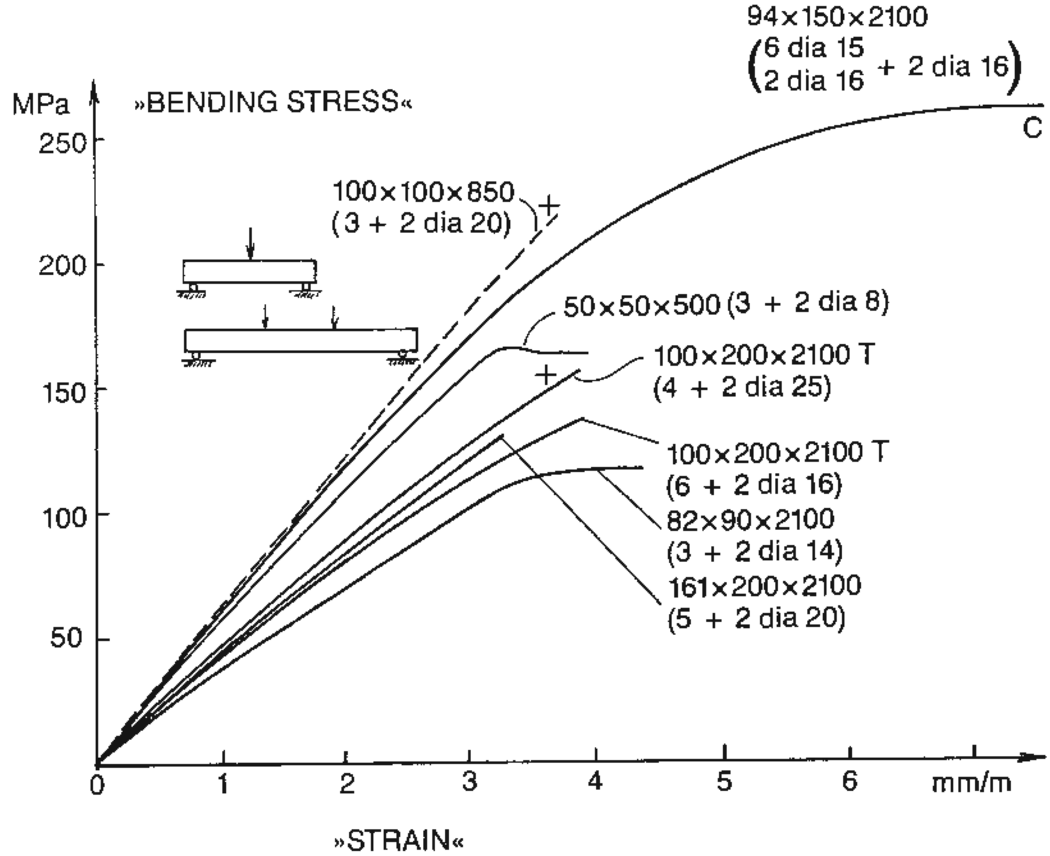

FIG. 8. Bending behaviour of six different types of CRC-beams, expressed by formal bending stresses and formal maximum tensile strains.

The dimensions of the beams (height, width, length) and, in brackets, the number of reinforcement bars at bottom and top and their dimensions (diameters) are given by each curve. All lengths are in mm. The beams marked T are T-shaped with a top width of 161 mm and top bar thickness of 50 mm, and the width of the bottom is, as indicated, 100 mm.

The beams were reinforced only in the longitudinal direction.

The bending behaviour of the beam 100 x 100 x 850 mm up to the shown maximum load (shortly before occurrence of shear failure) is not known and is therefore indicated with a stippled line. The reinforcement in all beams except the top one consisted of deformed bars: KS 600, KS 410 (505), KS 550(599), KS 550(580), KS 550(587), KS 410/472), referring to the curves from the top downwards; the figures in brackets indicate measured yield stresses in MPa. The strongest beam was reinforced with 6 15 mm DYWIDAG bars 885 and 2 16 mm KS 550 at the bottom side and 2 16 mm KS 550 at the top side.

The two smallest beams were loaded with a centrally acting concentrated force, while the remainder were loaded with two identical concentrated forces. The beams designated by + (at max. loading) failed in shear, and the beam designated by C failed by yielding in compression.

The behaviour of the beams (except the strongest) is only shown up to incipient yielding.

The behaviour of the smallest beam (second curve from top) - including yielding - is shown in FIG. 7.

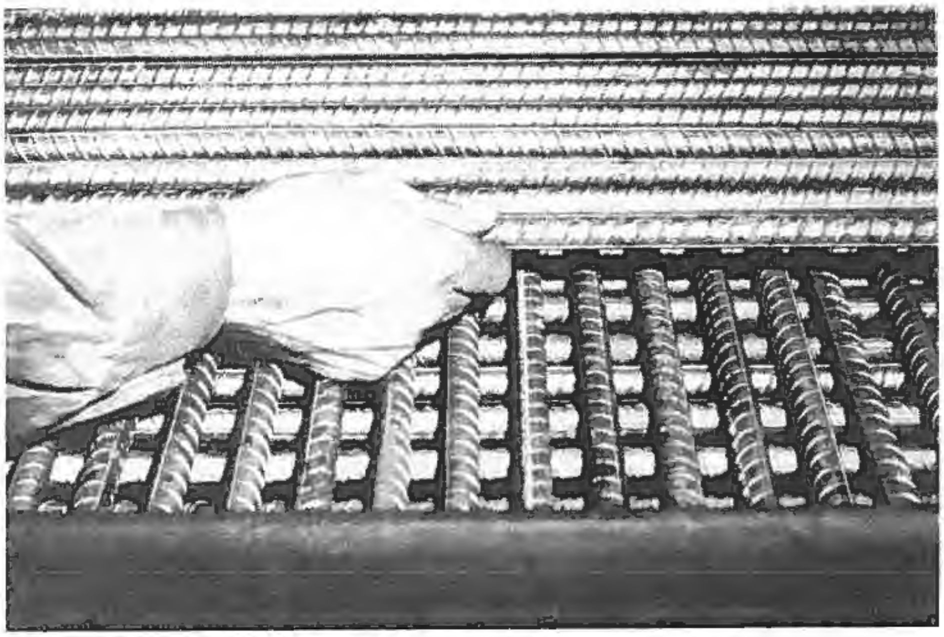

FIG. 9. Installation of reinforcement in 120 mm thick CRC plates (1100 x 1100 mm). The main reinforcement in the plane of the plate consists of 4 layers of 16 mm diameter bars at a distance of 32 mm (center to center). Shear reinforcement (not shown) in the form of bars (100 mm long, 10 mm dia.) arranged at right angles to the plane of the plates is inserted in each of the meshes in the reinforcement mats (16 x 16 mm).

Reinforcement in the plane of the plates: total 21% by volume. Reinforcement at right angles to plane: 8% (section area of reinforcement/total area).

The plates were cast with Densit$^{\circ}$-mortar based on strong Al_2O_3 rich sand with a water/cement- silica ratio of 0.18, 6%-vol. of steel fibres, 6 x 0.15 mm.
The material completely filled out the narrow space between the reinforcement (air content less than 1%).

In a punching test a plate (120 x 600 x 600 mm on a circular support with diameter 500 mm) failed at a load of 340 tons concentrated on a circular area of 113 cm^2 (punch-diameter 120 mm) - corresponding to a contact pressure of 300 MPa.

4.8 Stiffness

Objects made of CRC typically exhibit very great stiffness right up to yielding, typically corresponding to formal modulii of elasticity from around 30,000 MPa to 100,000 MPa. (The formal modulus of elasticity is defined as the formal stress divided by the strain).

4.9 Density

With reference to cement-based materials with steel reinforcement, CRC objects will typically have densities in the range 3,000 to 4,000 kg/m^3.

5. EXPERIMENTAL BACKGROUND

A series of tests have been carried out with CRC objects. The first tests were performed on small beams (50 x 50 x 500 mm) in spring 1986.

Following the establishment of facilities for producing and testing large objects, series of lager beams (35 nos measuring about 160 x 200 x 2000 mm) have been manufactured and most of them have been tested.
Heavily reinforced plates (for example 120 x 1100 x 1100 mm with 27%-vol. reinforcement) have also been made but only two have been tested as by december 1987.

Most of the beam tests have been performed as static loading tests, with registration of forces, displacements, and strains, and observation of cracks.

Fatigue tests have also been performed (on beams 89 x 90 x 2100 mm) loaded from almost zero to values between about 45% and 90% of the statical yield value. The number of loadings before failure were recorded. In the case of the beams with the smallest load, which did not fail, the experiments were stopped after about 5,000,000 load cycles. During the testing, related values of strains, loads, and deflections, measured at short intervals, were recorded.

These tests have been accompanied by a series of supplementary investigations of the matrix materials (compressive strength, fatigue in compression, fracture energy, transverse expansion under compression, etc.), and of the fixation of the reinforcement in the strong ductile matrix (pull-out tests).

The experiments have substantiated the ideas behind CRC and demonstrated that it is possible, in practice, to make large CRC objects with the anticipated high quality.

The introductory tests on the larger beams were primarily aimed at testing methods - the materials were far from optimal from a function point of view.

Preparations are in hand for tests aimed at producing more advanced CRC and at studying the basic mechanisms (matrix strain hardening etc.).

6. PROCESS TECHNOLOGY

The development of process technology has played a vital role in the development of CRC and is a prerequisite for industrial production. Some important process technological factors must be emphasized:

CRC objects, e.g. 1100 x 1100 x 120 mm plates, reinforced with 27%-vol. main reinforcement and 6%-vol. fine fibres, shown in FIG. 9, are cast under vibration like conventional reinforced concrete.

However, compared with conventional concrete, CRC structures are incredibly complex and simply cannot be created with conventional techniques:

1. The water/cement-silica ratio is extremely low (0.18).

2. The content of fine fibres (steel fibres 6 x 0.15 mm) is 6%-vol., which is 2-3 times higher than can normally be incorporated in conventional concrete.

3. The fibres are incorporated in a coarse mortar with a high concentration of sand with particle size between 2 and 4 mm.

4. The spaces between the very dense reinforcement consists of narrow "channels" of irregular shape that are very difficult to fill - even with conventional concrete (mortar) without fibres.

Production of the very dense and homogeneous CRC structures is ensured by, for example,

1. effective elimination of locking surface forces by selection of specially suitable combinations of cement-microsilica and a dispersant;

2. ensurance of viscous flow behaviour during mixing and casting by i.a. using a high concentration of microsilica, which "holds the water";

3. promoting flow by high-frequency vibration (70 to 150 Hz), where impulse transmission to the viscous vibration-damping mass is achieved by transmitting the effects from external vibrators through the main reinforcement (contrary to conventional practice, where this leads to separation);

4. prolonged process time - for example, a mixing time of 15-20 minutes - to ensure effective particle wetting and a high degree of microhomogeneity.

The fundamental principles of CRC process technology are described in /2/.

7. APPLICATIONS

As a new class of material, with unique properties, CRC will undoubtedly find its own applications, just as concrete, for example, developed into more than just a replacement for brickwork.
CRC will probably be used especially in the form of large plates or shells - designed, for example, to resist very large local loads with unknown attack position (from explosives, say, or mechanical impact) or to resist uniformly distributed pressure, either as pure compression or pure tension (e.g. large pressure tanks). A comparison with steel and conventional reinforced concrete is shown in FIG. 10.

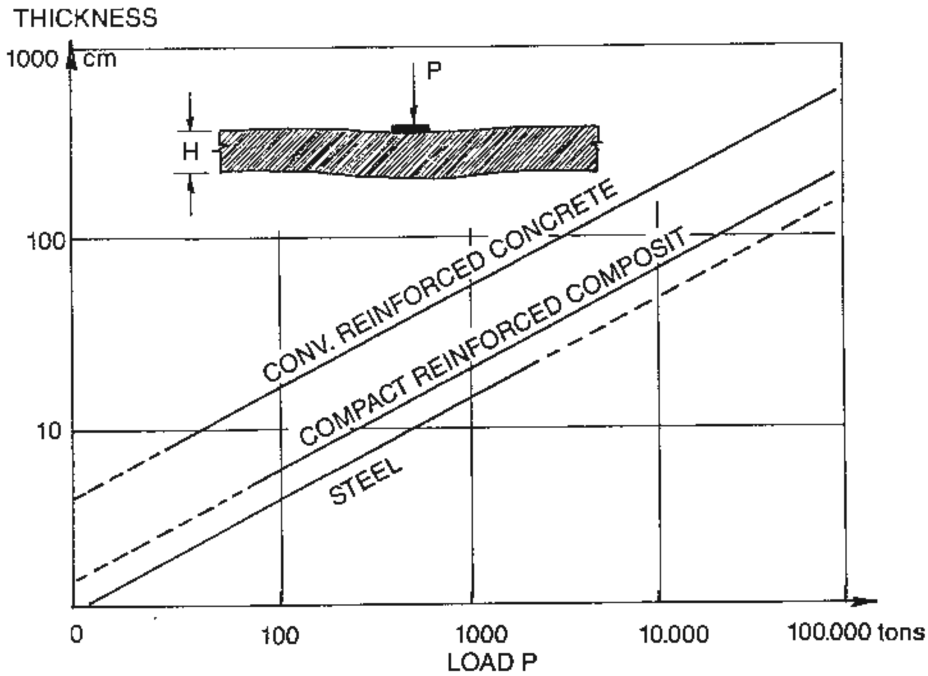

FIG. 10. Critical thickness of large plates loaded with a concentrated force.

The curve show critical plate thicknesses corresponding to the yield stage (with fully developed moments in top and bottom) as a function of the load (concentrated force).

The CRC plates are calculated on the basis of the following assumptions:

formal bending yield stress = 150 MPa
formal compressive strength > 230 MPa
formal shear strength > 50 MPa (for radius of the loaded area equal to the thickness of the plate)

(for example, obtained by reinforcement arrangements similar to that shown in FIG. 9).

It is assumed that the reinforced concrete plates are relatively heavily reinforced in both directions at top and bottom (volume concentration of reinforcement: slightly more than 7%), with formal bending stress about 20 MPa.
(The top and bottom reinforcement correspond to that used at the bottom of the most heavily reinforced plates treated in K. W. Johansen's doctoral thesis /4/).

The steel plates are assumed to have a formal bending yield stress of 300 MPa. The curve for steel plates over 200 mm in thickness are stippled to show that it is hardly possible to produce very large steel plates thicker than, say, 200 to 300 mm.

The calculations were performed in accordance with the yield line theory ($P = 4\pi m$, where m is the yield moment per length /4/).

Compared on a weight basis CRC behaves even better than steel having 30-40 % less weight.

Because CRC has very high strength/density ratios (often greater than those of structural steel), it offers particularly interesting possibilities for members, where weight and inertia loads are decisive. It could, for instance, be used for different forms of transport (ships, vehicles, etc.), where low weight is essential, or for rapidly rotating large machine parts, where the performance is limited by the capacity of the materials to resist their own inertia loads.

The materials' great ductility, even at very low temperature, will make CRC very interesting for large objects that have to resist large loads at low temperatures, where steel will fail due to brittleness. At low temperature, the steel reinforcement in CRC naturally also becomes brittle, but local fracture in individual bars will not spread as it does in bulk steel. The behaviour of CRC at very low temperatures is expected to be very similar to that of glass-fibre-reinforced composites - typically showing good strength and ductility despite the fact that the fibre material (glass) exhibits extreme brittleness in bulk members.

Because of the far better possibilities of forming CRC and combining the structure with other components than are afforded by steel, it may find its principal use in hybrid constructions - for example, load-carrying parts in large machines or special high-performance joints in conventional steel and concrete structures, typically where large forces have to be concentrated in small volumes.

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