High-Strength Fiber Reinforced Concrete Utilizing Closely Spaced Reinforcing Bars

by B. Aarup

Synopsis:

CRC (Compact Reinforced Composite) is the designation for a special type of fiber reinforced concrete with high strength (150-400 MPa) and closely spaced reinforcing bars. The dense matrix - with water/powder ratios of typically 0.16 - provide a good bond to fibers and reinforcing bars, and the large content of steel fibers provide the ductility necessary for utilizing reinforcement effectively. The steel fiber content is typically 2-6% by volume and the content of reinforcing steel is 2-10% by volume. The improved durability of the matrix - due to a high micro silica content - makes it possible to use a concrete cover to the reinforcement of only 10 mm in aggressive environments, improving the effectiveness of the reinforcement.

The CRC concept was developed in 1986 and aimed specifically for use in structures such as beams, columns and joints, but most of the applications so far have been in the security industry, for corrosion protection and in heavily loaded floors. However, in the last few years CRC has also been applied in structures.

One of these applications, production of 40,000 drain covers for a tunnel as a replacement for cast-iron covers, is described as an example of a project where the properties of high performance fiber reinforced concrete were utilised.

Keywords: fiber reinforced concretes; high-strength; precast; structural applications

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INTRODUCTION

High Strength or High Performance Concretes (HSC or HPC) are used increasingly for a range of structural applications and standards in a number of countries are being revised to accommodate these improved materials. As HSC are often more brittle than conventional concretes this can lead to the use of larger factors of safety for these materials and in order to provide these materials with improved ductility it is in some cases advantageous to incorporate fibers in the materials.

Fiber Reinforced Concretes (FRC) have mostly been used in non-structural applications such as slabs, floors, roads and architectural concrete, and typically less than 1% by volume of fibers are used. It is often prohibitive - for reasons of cost as well as in order to ensure acceptable workability and homogeneity - to include larger contents of fibers, but it has been tried with success in a few cases, usually by combining the advantages of fiber reinforcement and HPC, and in these cases other properties besides ductility can be improved as well (1). The high fiber contents have even been used in connection with considerable main reinforcement - as for Slurry Infiltrated Fiber CONcrete (SIFCON)(2) - or with prestressing - as for Reactive Powder Concretes (RPC)(3).

The improved ductility which can be obtained by using fiber reinforcement is necessary to utilize the high compressive strength which can be achieved in HSC in structures where tensile or bending loads are applied. If large contents of main reinforcement are used in brittle concretes, structures will exhibit large cracks at relatively small loads, whereas they will be able to show highly improved behavior if the necessary ductility is achieved. This has been the design philosophy behind Compact Reinforced Composite (CRC), which was developed at the Cement & Concrete Laboratory of Aalborg Portland in 1986 based on experience with DSP-concretes, a type of concrete developed in 1978 (4).

COMPACT REINFORCED COMPOSITE

CRC is the designation for a special type of Fiber Reinforced High Performance Concrete (FRHPC) with high strength (150-400 MPa). The matrix has a very large content of micro silica and water/powder ratios of typically 0.16. A typical composition is shown in table 1.

The binder contains cement, micro silica and a dry superplasticizer. As the cement and micro silica content is quite large there is considerable strength development after 28 days. The maturity curve also differs from that observed for conventional concrete as heat curing is more effective with CRC. One day at 80 ^{0}C corresponds to one year of curing at 20 ^{0}C.

The type of fibers used have a length of 12.5 mm, a diameter of 0.4 mm and a tensile strength of 1600 MPa. Other types of fibers have been used in earlier research projects with good results - especially brass coated fibers produced by Bekaert with 0.15 mm diameter, 6 mm length and a tensile strength of 2950 MPa. However, while a compressive strength of 180 MPa can easily be achieved with these fibers the price is so high that it would only be realistic to use these fibers for very special applications.

The combination of micro silica, a very low water content and steel fiber contents of 2-6% by volume provides CRC with a good bond as well as with a large ductility and has the effect of ensuring crack-free behavior in e.g. beams at tensile strains of up to 3 mm/m, more than 10 times the strain capacity of conventional concrete.

As an example of the behavior in bending a load-deformation curve for a CRC beam with 10% by volume of main reinforcement is shown in fig. 1. In this case prestressing wires with a yield strength of 1800 MPa have been used as main reinforcement. The wires have not been prestressed, but have been used as conventional reinforcement in order to utilize the high quality of the steel. Even at the very large deformations - 60 mm center deflection on a span of less than 2 meters - only very small cracks were observed. At this stage of loading the bending stress was 320 MPa.

One key factor in utilizing the high quality matrix in FRHPC is to be able to use large contents of reinforcement - and also reinforcement of higher quality - without experiencing large cracks. Another important factor is to be able to place the reinforcement to full advantage. In CRC the size of the fibers and the largest grains of the CRC matrix dictate the distance between reinforcing bars and the cover layer to the reinforcement. This is the reason for typically using a mortar composition for CRC. Often a cover layer of

10-15 mm and a similar distance between individual bars are used. Especially the durability has been the subject of a number of research projects because of these small cover layers, but it has been demonstrated on a number of occasions that 10 mm of cover layer will provide sufficient protection of the reinforcement in an aggressive environment (5).

With the high fiber contents CRC is most suitable for pre-cast applications, but in-situ cast concrete with 6% by volume of fibers has also been produced - for joints between slabs in conventional concrete - using a poker vibrator.

As the properties of FRHPC are not taken into account in existing standards and recommendations, it has been necessary to provide extensive documentation on the properties of CRC, and the material has been the subject of a number of research projects. These have often been carried out in cooperation with universities in Denmark, but CRC has also been the subject of international research projects, such as COMPRESIT, a EUREKA project with partners from Denmark and England and sponsored by the two national Departments of Trade and Industry (6), and MINISTRUCT, a BRITE/EURAM project with partners from Denmark, France and Spain and sponsored by the European Commission (7).

APPLICATIONS

CRC was developed with applications in bridges and tall structures in mind, but some of the first applications of this combination of large fiber contents and closely spaced reinforcement were non-structural, as the concept was used in the security industry, for machine components and in heavily loaded floors where limited space was available.

It was anticipated that CRC could be used as a replacement for steel or cast-iron due to the favorable strength/weight ratio of the material, and this had also been the subject of the first international research project on CRC - COMPRESIT - in which design, production and testing was made of segmental tunnel-linings to be used as replacement for cast-iron linings. The project was concluded in 1993, at the same time as a major infrastructure project was carried out in Denmark - a joint bridge-tunnel project linking the two major islands of Denmark under the name of the Great Belt Link. As problems were anticipated with availability of the cast-iron linings, an inquiry was made to Aalborg Portland as to the availability of CRC-linings. This contact did not lead to the use of CRC-linings as the problems with availability of cast-iron were solved and the designers could maintain the original design, but the contact lead to the application of CRC in another part of the two tunnels, a part which may seem of limited significance in the larger scale, but a part which was nevertheless well suited as a demonstration of the advantages of FRHPC, and an application which will be used as an example in the following in an attempt to describe the properties which can be of interest to the designers.

DRAIN COVERS FOR THE GREAT BELT LINK

The covers placed over the drain channels in the Great Belt tunnels were originally designed in cast-iron, but it was discovered that this could cause problems with stray currents for the electrical installations in the tunnel. The drain channels were an integrated part of the lining design, so the dimensions of the covers were fixed with a thickness of 40 mm and a span of 500 mm. As the covers were to be placed under the rails, they had to sustain an ultimate static load of 47 kN/m which would necessitate the use of reinforcement. The small thickness, however, was not compatible with the requirement for a cover of at least 45 mm to ensure a design life of 100 years in the aggressive environment.

A cross-section of the design made to suit these criteria is shown in fig. 2. The covers have the dimensions 590x412x40 mm. The reinforcement - 8 mm bars with a specified yield strength of 550 MPa - is closely spaced and the cover to the reinforcement is 10 mm. Compressive strength of the matrix was 150 MPa with 6% of fibers with dimensions 12.5x0.4 mm.

With regard to resistance to intrusion of chloride ions, measurements had been made on specimens under load exposed to chlorides, and these investigations show that the diffusion coefficient for chloride ions measured after two years of exposure under accelerated conditions was only 8×10^{-15} m^2/s, in which case corrosion should not be a problem. Tests performed later indicate that the chloride threshold value is also considerably higher for these very dense concretes.

Production of a total of 40,000 covers were carried out by a pre-cast manufacturer and the covers were installed in the tunnel in the spring of 1995. As the design was not exactly according to the current standards, it was decided to adhere to a rather strict program of quality control, which included testing of 1% of the covers produced in three-point bending after 7 days, after which a control was made of the cover to the reinforcement. Also compressive strength was measured on 100x200 cylinders cured at 80 ^{0}C for one day. Average compressive strength of the reference specimens tested during the production was slightly above 150 MPa, while average strength of the more than 400 drain-covers tested was 216 kN/m. This strength was considerably higher than necessary for the static case, but the high strength was used to ensure the capacity in fatigue as well, as $3.2x10^8$ load cycles had to be considered in the design life of 100 years.

DISCUSSION

The application of CRC for the drain-covers of the Great Belt Link is an example of an application of FRHPC where properties of durability and fatigue as well as bending strength have been utilized.

Even though the properties of FRHPC are well documented for a number of compositions, the first applications are probably going to be similar to this case, where CRC was considered due to a problem encountered after the design was made - for trouble-shooting. Another solution for the owner could have been to electrically isolate the cast-iron covers. However, the risk of using a new material in this application was moderate, as the design allowed for full-scale testing of the individual covers, a strict quality control was maintained and failure of the covers would - while very costly - not lead to dangerous situations. Finally, the cost of the CRC covers was only about 60% of the cost for the cast-iron covers which could also have been of some significance in the considerations.

In the last few years CRC has been used for other structural applications, mostly as pre-cast components such as balcony slabs, manhole covers and facade elements, and as the components are increasing in size the results from these applications - combined with results from the joints which are cast on-site and results from applications of other types of FRHPC such as SIFCON, SIMCON and RPC - should provide designers with the references necessary for considering the use in columns and large beams where the properties of FRHPC can also be utilised.

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TABLE 1—TYPICAL CRC COMPOSITION AND PROPERTIES MEASURED AT 28 DAYS.

binder	940 kg/m^3
quartz sand 0-0.25 mm	170 kg/m^3
0.25-1 mm	340 kg/m^3
1-4 mm	680 kg/m^3
water	150 kg/m^3
steel fibers	475 kg/m^3
compressive strength [MPa]	140
bending strength [MPa]	20
Young's modulus [GPa]	47
density [kg/m^3]	2750

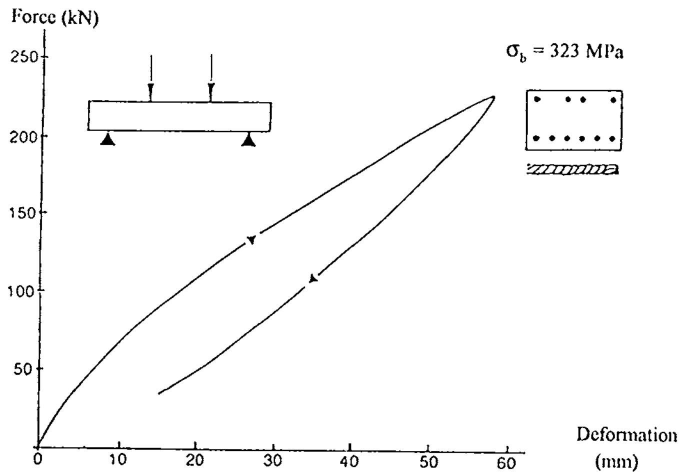

Fig. 1—Load-deformation behavior of CRC beam with prestressing wires as main reinforcement.

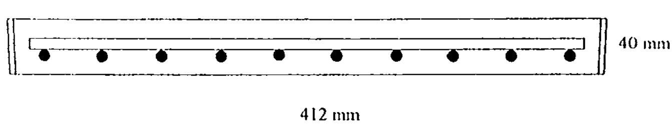

Fig.2—Cross section of CRC drain covers used for the Great Belt Link.

SP 182-2

Structural Behavior of Steel Fiber Reinforced Concrete Beams in Shear

by B. Oh, D. Lim, K. Hong, S. Yoo and S. Chae

Synopsis: The structural behavior of steel fiber reinforced concrete beams in shear is studied. A comprehensive experimental program has been set up and several series of reinforced concrete beams with steel fibers have been tested. The test variables include the volume contents of steel fibers and stirrups. The fiber contents varies from 0% to 2% by volume. It is seen from these tests that the cracking and ultimate shear strengths increase as fiber contents increase. The present study indicates that fiber reinforcement can reduce the amount of shear stirrups to obtain same strength. The combination of fibers and stirrups may accomplish strength requirements as well as ductility requirements.
A theoretical approach is proposed to predict the shear strength of reinforced concrete beams containing steel fibers and good correlation is obtained with test data. The present study allows more efficient structural application of steel fibers for shear reinforcement in reinforced concrete structures.

Keywords: cracking shear strength; fiber reinforced concrete; shear analysis; shear reinforcements; steel fibers; ultimate shear strength

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INTRODUCTION

The brittle nature of concrete causes collapse in unreinforced beams shortly after the formation of the first crack. The addition of steel fibers aids in converting the brittle characteristics to a ductile one. The principal role of fibers is to resist the formation and growth of cracks by providing pinching force at the crack tip. In addition, a marginal improvement in tensile strength also results and fiber reinforced concrete have higher ultimate strain than plain concrete (1-12).

Many studies have been conducted to determine the flexural behavior of steel fiber reinforced concrete beams. The authors recently published a paper concerning the flexural analysis of reinforced concrete beams containing steel fibers as Ref.1. However, only a few studies (5,10,11) are available on the shear behavior of reinforced concrete beams with steel fibers and the shear behavior of those beams is not well established yet. The purpose of the present study is therefore to explore the mechanical behavior of steel fiber reinforced concrete beams in shear for structural