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Carl Bro Group A/S
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Results of an investigation on ultra high strength fibre reinforced concrete

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Abstract

Results achieved in the Brite/EuRam project MINI STRUCT (MINImal STRUCTures using ultra high strength concrete) are presented. Investigations have been carried out on CRC - a special high strength concrete - and comprise studies of structural analysis, mechanical properties, durability, production techniques and full scale tests. Results of tests on corrosion, fire resistance and anchorage have been selected for presentation in more detail.

Introduction

High strength concrete - defined as concretes with compressive strengths higher than 50 MPa - has been in use for the Iast 15 years, mainly to reduce column dimensions, but also for other structural applications, i.e. to increase the capacity of long span members. Most of these concretes - with strengths in some cases approaching 120 MPa - have been comparatively brittle, an aspect that has influenced design and applications, as brittleness prohibits the use of sufficient amounts of reinforcement to fully utilise the high strength of the concrete.

The use of fibre reinforcement has made it possible to achieve a ductile behaviour and limitations of number of cracks and crack widths, but in most cases the amount of fibres used has up till now been relatively low - usually less than 1°A by volume. In a few cases, as for Slurry Infiltrated Fibre reinforced CONcrete (SIFCON) and for CRC - the ultra high strength concrete investigated in the present project - it has been possible to incorporate fibre contents higher than **6%** by volume, thus achieving an extremely ductile behaviour. CRC - aIso known as Compact Reinforced Composite or Compresit - was developed in 1986 by Aalborg Portland /1/.

In CRC the extreme ductility obtained with fibre reinforcement is combined with closely spaced main reinforcement, yielding exceptionally high strengths and crack-free behaviour in bending. A load-deformation curve for a typical CRC beam is shown in fig. 1.

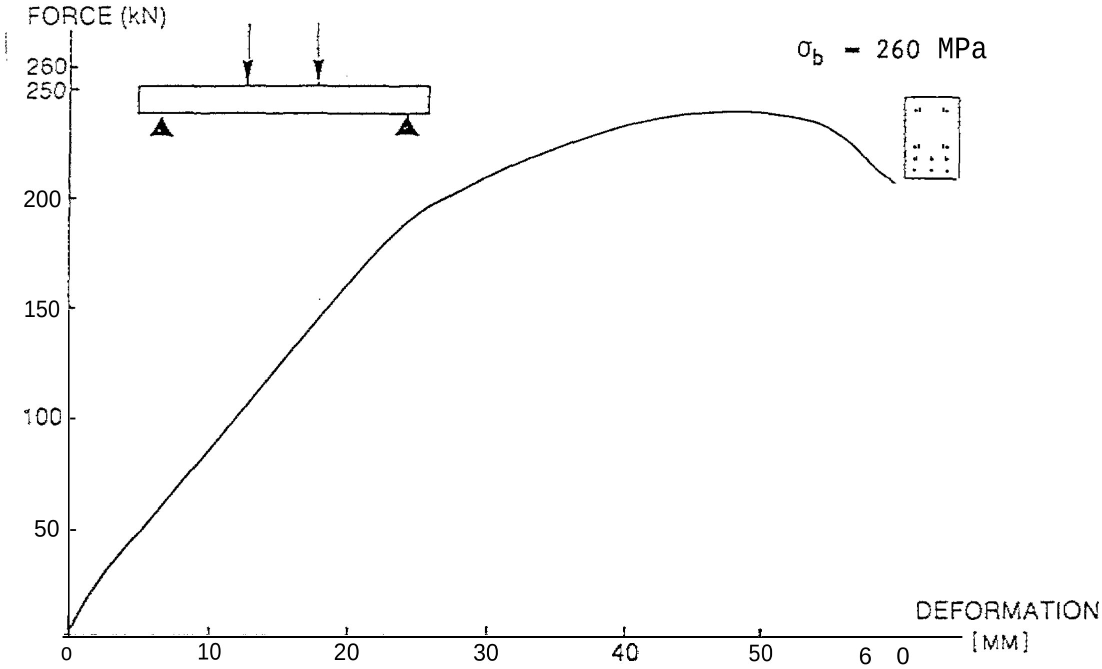

Figure 1 Load-deformation curve for a typical CRC beam,

High strength concrete has become a viable alternative to lower grade concretes. By reducing water/powder ratios and using additives, conventional concrete mixtures are enhanced to produce higher strength - step by step - making it possible to stay comfortably close to the range of the present codes and standards. CRC, however, with a compressive strength up to 300 MPa and a capacity in bending approaching that of steel - by deserting the step by step approach - is a material well outside the range of present codes and standards. This does not prohibit the use of CRC for special applications, but with some further effort it would be possible to gain a large advantage by using a ductile ultra high strength concrete for many structural applications where conventional concrete or structural steel is used today.

The MINISTRUCT project (MINImal Structures using ultra high strength concrete) is an attempt to provide the experimental documentation, the technical basis and the production methods necessary for the introduction of the concept of Minimal Structures, where the higher quality of materials is used to produce more slender structures with less use of materials.

Technical description

The project partners were **Aalborg Portland,** Denmark - a cement factory and research laboratory with special expertise *in* high performance concretes, which acted as co-ordinator of the project and was in charge of modifications to the matrix and determination of mechanical properties, **Carl Bro Group,** Denmark - consulting engineers and planners - performed the structural analysis and established a design guide for CRC, **Bouygues**, France - a major contractor - handled large scale production and full-scale tests, and **Instituto Eduardo Torroja,** Spain - leading European specialist on corrosion - investigated durability of the CRC material.

In the following will be given a short description of each of the technical tasks undertaken.

Mechanical properties

CRC has been the subject of a number of research projects since the material was developed in 1986, and most of the mechanical properties had already been described in a manner suitable for the structural analysis. However, three areas were defined where further analysis would be of special value. The areas investigated were:

- Effect of fibres - with the objective of establishing a better link between choice of fibre type and content and structural behaviour.
- Anchorage -as the exceptional bond between CRC and reinforcing bars had already been established, an attempt was made to analyse this sufficiently for setting up guidelines. This included varying the type and size of reinforcing bars, concrete cover and amount of transverse reinforcement.
- Creep and shrinkage - parameters which are of special importance in connection with prestressed structures and columns in high-rise. buildings.

Durability

Durability studies included investigation of chemical resistance, the possibility of embrittlement of high yield steel, the effect of carbonation and the effect of chloride intrusion. Special emphasis was placed on the studies of chloride intrusion, as the concrete cover to the reinforcement is typically as low as 10 mm in CRC. As earlier investigations in other projects had demonstrated a very low permeability in CRC all tests were carried out under accelerated conditions.

Production technique

Investigations on production technique consisted of an attempt to modify existing production methods - which were based on laboratory scale production - to large scale production. One of the first issues looked at was minimizing the time required for mixing, where the mixing time of one batch was typically 18 minutes at the beginning of the project. **Also,** the correlation between workability and requirements for vibration were studied in more detail as well as mixer requirements, vibration requirements, in-situ production etc.

Structural analysis

Based on the considerable information already available - and additional information to be obtained in the present project - an effort was made to gather this information in a design guideline. The guidelines were to be set up in a similar manner as international codes for concrete structural design and the design methods were to be tested in connection with the final task of the project - the full scale tests.

Full scale tests

To evaluate the results achieved in the other tasks, a final task was added, where full scale structural members were designed, produced and tested. These full scale members consisted of a number of slender columns with a height of three meters, two large I-beams with a length of 13 meters, and two column-beam joints.

Results

Production methods have been refined to allow large scale production of CRC, including a reduction in mixing time from 18 to 8 minutes. Design rules have been established for CRC and confirmed by tests on full scale structures. The columns tested were designed without stirrups, but they behaved satisfactorily and according to predictions. One of the 13 meter beams tested was designed without shear reinforcement, and also in this case behaviour was highly satisfactory, as the fibre reinforced matrix adds ductility as well as improved tensile capacity.

During the three years of the project a number of tests have been carried out, and in the following three of these tests will be described in more detail, namely investigations of corrosion, fire resistance and anchorage. For a more detailed description, information can be found in ref. 2-4.

Corrosion

Typically tests with respect to corrosion of reinforcement are carried out on un-loaded specimens. In order to take advantage of CRC in structures it is likely that service loads will be in a range where microcracks could develop, and it was thus highly relevant to test specimens under high loads and determine whether this would accelerate the intrusion of chloride ions.

This was accomplished with a test rig as shown in fig. 2. Specimens with a 400 mm span were mounted in a flexure rig and loaded to constant center deflections of 0.2, 1 and 2 mm. Then specimens were exposed to alternating wetting and drying in a sodium chloride solution for a period of several years. Deflections of 0.2, 1 and 2 mm correspond *to* bending stresses of approx. 10, 30 and 55 MPa.

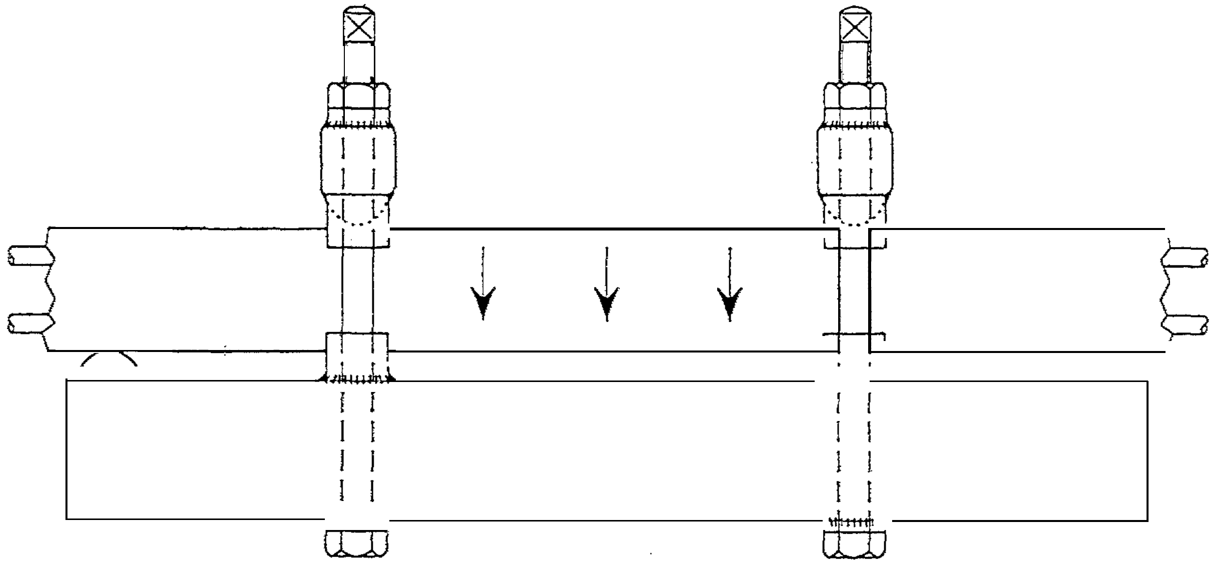

Figure 2 Mounting rig, where specimens are loaded to a constant center deflection before being exposed to chlorides.

Tests on this type of specimen have been carried out at the Danish Force Institutes, where specimens have been exposed for more than five years with no sign of corrosion being initiated. As the tests were initiated at the Instituto Eduardo Torroja it was decided to perform a number of accelerated tests in addition to the comparative tests. These accelerated tests included adding 1.6 or 3.2% NaCl by weight of cement in the mixing water when the specimens were cast or exposing specimens in a salt spray chamber. Also, in a few cases specimens were deliberately cracked before exposure to study whether this would lead to corrosion.

It was not possible to observe corrosion on any of the specimens tested. There was literally no effect of carbonation, and as reinforcing bars were removed from the specimens exposed to chloride, only superficial corrosion stains were observed. These stains, however, had nothing to do with active corrosion, as the corrosion had not been removed from the bars before they were used in production of specimens. This was done to simulate a typical production procedure as closely as possible.

Fire resistance

A total of 24 cylinders and 8 reinforced beams have been tested in a standard fire. The tests were carried out in the furnace of Dansk Brandteknisk Institut in Denmark. The residual strength of the cylinders and the reference strength of companion cylinders which have not been exposed to the fire are shown in table 1. The residual strength for conventional concrete is not included in the table, as the specimens could literally be taken apart by hand, with very little effort.

Table 1 Specimens tested in exposure to 1S0 fire.

Description	Reference strength		Residual strength	
	mean	variation	mean	variation
Conventional concrete, cured for 2 months in lab, then wrapped in plastic until testing	58.9 MPa	5.4'?"0		
CRC, cured for 2 months in lab, then wrapped in plastic until testing	156.7 MPa	2.5%	24.1 MPa	14.3%
CRC, cured for 1 month at 45 ^{0}C, then wrapped in plastic until testing	150.1 MPa	4.7?40	84.5 MPa	12.5?4,
CRC, cured for 1 month at 80 ^{0}C, then wrapped in plastic until testing	182.3 MPa	7.5%	80.3 MPa	5.2?4

No cases of explosive spalling were observed, as has been reported in the literature after other types of tests, but the specimens cured only in the lab were damaged after fire exposure. The CRC beams showed severe spalling, but in no cases was the reinforcement - with a cover layer of 10 mm - exposed. The reference concrete showed severe cracking and had lost most of its strength as shown in table 1. The CRC beams dried at elevated temperatures showed minor surface cracking. Specimens cured at 45 and 80 ^{0}C were, however, only exposed to the ISO fire for 30 minutes due to a mistake during testing. The other specimens were exposed for 60 minutes.

The beams were equipped with a number of thermocouples, and the readings were similar for CRC and conventional concrete.

It is very significant, that the CRC specimens maintained a considerable portion of their strength after fire exposure. This is possibly due to the fact, that in conventional concrete, a large amount of CaO is created when calciumhydroxide is dewatered. When the specimens cool off, CaO absorbs water and expands, causing extensive cracking in the surrounding matrix in a short period following the fire. Thus, the strength of a concrete structure is considerably lower one week after the fire, than immediately after.

Only a small amount of calciumhydroxide is present in the CRC-matrix, where the structure is mainly calcium-silicate-hydrates. The large amount of microsilica prevents formation of large amounts of CaO and the integrity of the matrix is much better preserved.

Anchorage

An extensive test programme was undertaken in order to investigate anchorage of reinforcement in CRC, where an assessment was made of the effect of varying the type and diameter of reinforcement, the thickness of the CRC cover to the reinforcement and the amount of transverse reinforcement perpendicular to the anchored bar.

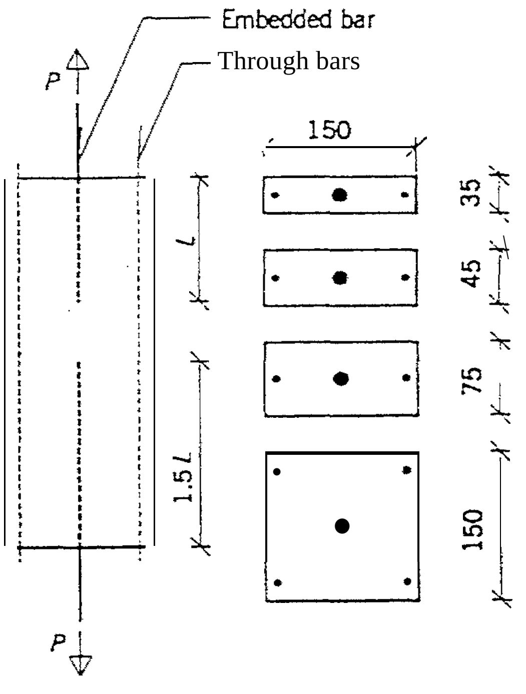

Figure 3 Concrete prisms used for investigations of anchorage length.

Ribbed bars K8, K12 and K16 and prestressing strands L13 and L15 were assessed in a pull-out test carried out with test specimens as shown in fig. 3 and performed on an Instron universal test machine.

For the investigations on larger embedment lengths of the prestressing strands it was not possible to obtain the necessary grip on the strands which were to be tested, and this led to either failure of the individual strands or slip at high loads. For this reason the results for the strands are not as extensive as the ones obtained on ribbed bars.

Analysis of the results show that the bond strength consists of three contributions. One contribution depends primarily on the cover thickness and this contribution is observed to be identical for ribbed bars and strands. The second contribution - which is constant - is based on adhesion due to the roughness of the bar, and this contribution is practically non-existent for the smooth strands. The third contribution to the bond strength is obtained from the presence of transverse reinforcing bars, which prevent splitting cracks from developing. Again, this contribution was not observed for the strands as the effect of transverse bars is in part connected to the contribution from adhesion, and especially the deformations which are necessary to overcome the adhesion,

Finally there will of course also be a contribution from stresses induced in the anchorage zone, i.e. when placed over supports, but this effect has not been investigated in the present project.

The significance of the adhesion contribution is demonstrated in fig. 4 where the anchorage length in a 75 MPa concrete is compared to the necessary anchorage length in CRC. As shown the effect is most pronounced for small covers and full anchorage for ribbed bars can be achieved with an embedment length of only 5-10 diameters. With transverse reinforcement anchorage length can be decreased even further.

For ribbed bars the best performance is obtained with the small bars, where the relative size of the ribs is the largest.

For prestressing strands a relatively large anchorage length - or a large concrete cover - is necessary from the test results found in this investigation, but it is expected that a moderate confinement pressure will have a large effect, as the prestressing strands have been used with success in several test beams produced in connection with full scale tests and investigations on effect of shear in beams. Anchorage failure was not observed in any of the beams even though the strength of the strands is well above 1700 MPa.

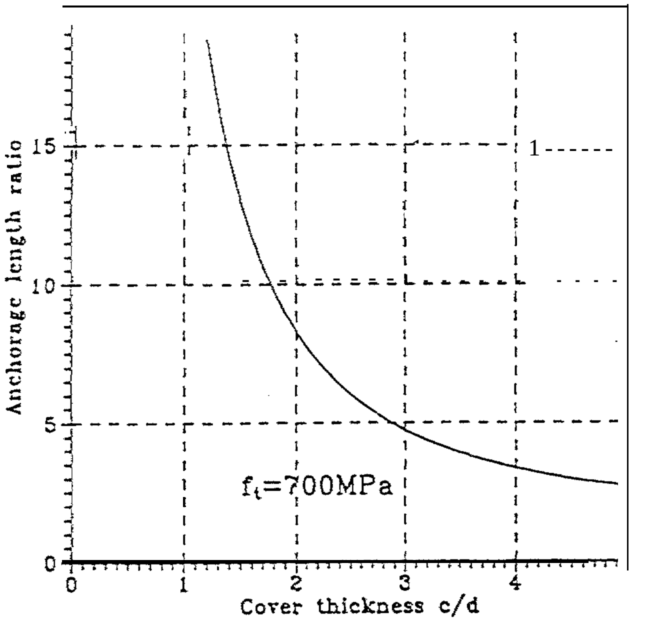

Figure 4 Ratio between anchorage length in 75 MPa concrete and CRC.

Conclusions

The investigations carried out in the MINISTRUCT project have prepared CRC well for use in Minimal Structures, providing design guidelines, experimental documentation and production methods for large scale production.

The results obtained show that CRC is well suited for a number of applications, and this technical assessment is supported by full scale demonstrations and field applications. The most likely applications are:

- structures where high durability is required
- structures where low dead load is an advantage
- joining of structural elements
- any structural purpose where there is a demand for high strength
- structures exposed to seismic loads

During the project period CRC has been used for a few applications where the experience achieved has also been of benefit in the project.

CRC has been used successfully for 40,000 drain covers (thickness 40 mm) for the Great Belt Tunnel in Denmark, where there was a strict requirement for documentation of the resistance to chloride intrusion, freeze-thaw and fatigue loads. In addition it was necessary to obtain high strength - comparable to that of cast iron drain covers.

In 1995 construction work was completed on a new building for Aalborg University in Denmark, where CRC was used for joining structural elements. This type of application is possible because of the high anchorage capacity of CRC.

Apart from these special applications, it will be necessary - for a broad application of results - to have CRC accepted in international codes and standards. This will be facilitated by the applications made and by the full scale prototype structures developed in the project.

Acknowledgements

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