CRC - A Special Fibre Reinforced High Performance Concrete

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Abstract

CRC (Compact Reinforced Composite) is the designation for a special type of fibre reinforced concrete with high strength (150-400 MPa) and closely spaced reinforcing bars developed in 1986. Properties are discussed with emphasis on durability and fire resistance. These properties are becoming increasingly important as high quality materials are utilised in making very slender structures. For the last 10 years CRC has been used in structural applications and typically for precast elements such as balcony slabs and staircases. A few examples of applications are shown and some of the considerations that were made in moving from the research phase to a marketing phase and finding applications are described.

1. 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. The use of these materials is not without problems, however, as HSC is often also more brittle than conventional concrete. This problem of brittleness can be solved in various ways, e.g. improvement in ductility can be provided by fibre reinforcement.

Fibre Reinforced Concretes (FRC) have mostly been used in non-structural applications such as slabs-on-grade, floors and architectural concrete, and typically less than 1% by volume of fibres 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 fibres, but it has been tried with success in a few cases, and in these cases other properties besides ductility can be improved as well. The high fibre contents have even been used in connection with considerable main reinforcement - as for Slurry Infiltrated Fibre CONcrete (SIFCON) [1] - or with prestressing - as for Ductal [2].

Compact Reinforced Composite (CRC), which was developed at the Cement & Concrete Laboratory of Aalborg Portland in 1986, combines large contents of fibres (typically 2-6 vol.%) and closely spaced reinforcement and was thus one of the first examples of the socalled Hybrid FRC [3]. CRC has been the subject of a number of international research projects but in the last 10 years CRC has also been used for a number of structural applications, however, mostly in Denmark. An example of a typical application – a cantilevered balcony slab - is shown in fig. 1.

Figure 1 Cantilevered balcony slabs produced in a dark CRC.

2. CRC properties

CRC is the designation for a special type of Fibre Reinforced High Performance Concrete (FRHPC) with high strength (140-400 MPa). The matrix has a very large content of microsilica and water/binder ratios of typically 0.16 or lower. Because of the large content of steel fibres the matrix is very ductile and that makes it possible to utilise rebars much more effectively without having large cracks under service conditions. Properties vary with fibre content and the type of aggregate used.
The size of the fibres and the largest grains of the matrix dictate the distance between reinforcing bars and the cover layer to the reinforcement, both of which have to be optimised in the slender structures, which can be produced with FRHPC. This is the reason for typically using a mortar composition for CRC and for using fibres with a length of 12 mm and a diameter of 0.4 mm. Often a cover layer of 10-15 mm and a similar distance between individual bars are used.

With the high fibre contents, CRC is especially suitable for precast applications, but in-situ cast concrete with 6% by volume of fibres has also been produced - for joints between slabs made in conventional concrete - using a poker vibrator for compaction [4]. In precast applications fibre contents will typically be from 2 to 4 % .

As recommendations that take the properties of FRHPC into account have only recently been introduced [5] – and were certanly not around in the late 1980’s when CRC was developed - it has been necessary to provide extensive documentation on the properties of CRC before the material could be considered for structural applications, and the material has been the subject of a number of research projects. These projects have investigated mechanical properties as well as durability and fire resistance – properties that become increasingly important for the slender structures designed in CRC [6-8].

3. Durability

The durability of HPC is usually superior to that of conventional concrete and in the case of CRC the matrix is so dense, that there are very few capillary pores. Measurements show a total porosity of 1.54% for the CRC-matrix, and only 14% of this porosity is in the capillary region, while the larger part of the porosity consists of gel pores. This means that there are no freezing and thawing problems, as there is no freezeable water available. Also carbonation has been demonstrated to proceed at an extremely slow rate.

Under normal exposure conditions there is little doubt that resistance to intrusion of chloride ions would also be higher than for conventional concretes. In the case of CRC there was another aspect which had to be considered, namely the effect of micro cracks induced by loading to chloride ion ingress.

As CRC can sustain much higher loads than conventional structures in reinforced concrete, stress under service loads will also be considerably higher for CRC structures, which could possibly cause micro cracking, the effect of which with regard to chloride diffusion was not quite clear. For this reason investigations of exposure to chlorides for CRC were carried out in a special way. Small reinforced beams with a cover to the reinforcement of 10 mm were loaded in a special rig during exposure to the chlorides. The beams were subjected to a range of deflections, corresponding to bending stresses - calculated as modulus of rupture - as high as 75 MPa to investigate whether the micro cracks that were likely to be present at these stresses would affect the rate of chloride penetration. During exposure - a period of 4 years - a wetting-drying cycle was maintained, where specimens were placed for 2 days in 3.5% NaCl in saturated $Ca(OH)_2$, after which they were dried for 5 days.

No relation was observed between the loading of the beams and the rate of chloride diffusion and no corrosion was observed in any of the tests – not even in cases where the beams were intentionally loaded to create visible cracks before exposure. For un-loaded reference beams as well as for the beams where a centre deflection corresponding to 75 MPa stresses was induced, the diffusion coefficients measured were in a range from $2x10^{-14}$ to $1x10^{-15}$ m^2/s.

For another set of tests chlorides were introduced in the mixing water (3.2% NaCl by weight of cement), to investigate whether the resulting high chloride content would lead to corrosion, but also in these tests it was not possible to observe corrosion. This indicates that the limiting factor for corrosion to occur is not so much presence of chlorides, but rather availability of oxygen and water.

4. Fire Resistance

The low porosity, which is an asset with regard to durability, may in some cases present a liability with regard to fire resistance, as the risk of spalling will typically increase in proportion to a decrease in permeability of the concrete. The combination of low porosity and a considerable water content can lead to large pressures as water turns to steam inside the concrete. Severe spalling of HSC has been observed in several tunnel fires including the Great Belt Link tunnel in Denmark and the Channel Tunnel between France and England. Several researchers have suggested the use of polypropylene fibres as a remedy to this problem, as the melting fibres should provide the necessary space for the steam to expand during heating, thus avoiding explosive spalling.

As CRC has a very low porosity research has also been performed with regard to its fire resistance. This research showed that the residual behaviour of CRC - the behaviour determined one week after the fire test - was better for CRC than for conventional concrete. One of the reasons for the improved performance with CRC compared to conventional concrete is that CRC has a very high microsilica content and the content of calcium hydroxide is thus negligible.

The tests also demonstrated that the rate of increase in temperature in CRC was similar to conventional concrete - despite its large content of steel fibres - and conventional calculation methods can thus be used in design for fire resistance.

5. Structural applications

Based on the high strength and ductility of CRC the material was originally designed for applications in heavily loaded sructures such as long span bridges, structures exposed to seismic loads or columns in high rise buildings. However, it was soon evident that even with extensive documentation few owners appreciated the distiction of being the first to use a new type of material in a critical structure. So an approach was taken where CRC was used for more "humble" applications – initially smaller elements such as drain covers, staircases and balcony slabs. The reasoning behind this was as follows:

- If there is any doubt about safety, structures can easily be tested in full scale. No matter how much information you have regarding structural properties this can often seem more appealing to a developer.
- It is often possible to have a back-up solution. If the spiral staircase shown in fig. 2 should have a problem for some reason, it could be replaced with an alternative in steel at a late stage of the project.
- These types of structures were "sold" to architects rather than engineers, and architects are often more motivated to accept new types of materials.
- CRC is not promoted as a special material that can be used for any type of application, but rather as a third option – an alternative to steel and conventional concrete that can sometimes be used if a satisfactory solution can not be achieved in steel or concrete, increasing the likelihood of achieving the right – and most cost-effective – solution to a particular project.
- The use of CRC is encouraged in every-day products that utilize some of the properties of CRC so that contractors, architects and engineers can see applications in a range of projects and get used to the material. With this familarity the chance of people getting bright ideas and finding new applications is expected to increase.

This has been relatively successful, as CRC was used for 2500 tons of structural elements in 2003 . The bulk of applications was in balcony slabs and staircases – a type of product that was introduced 5 years ago, but new products are introduced regularly. At the moment there is a growing number of requests for CRC beams and columns – a type of product that was originally envisioned for CRC. The elements are produced by 3 precast producers, one of which only produces CRC. However, most of the applications are still in Denmark and only a few projects have been carried out aboad - in Spain and the UK.

6. Discussion

For the first few applications a rather extensive documentation had to be provided for the authorities, but as CRC has now been used on a number of projects, a simple overview of properties is usually sufficient. One reason for this is that a standard matrix is invariably used, where only the content of steel fibres is changed from one project to another, providing a good quality control. Another reason is that the design of CRC structures is modeled after conventional design methods, so that any engineer can do the design. The tensile strength of the matrix is not taken into account in the design, but the fibres ensure ductility, control cracking, allow a very short anchorage length and closely spaced reinforcement and if shear stresses are below typically 10 MPa they are carried by the fibres so that shear reinforcement is not needed. Other modifications that have been made are to allow for: a higher compressive strength and a cover to the reinforcement of 10 to 15 mm in an aggressive environment.

Figure 2 Spiral staircase with cantilevered steps produced in CRC.

In most applications it is relatively easy to achieve the strength needed, even without taking the tensile strength of the matrix into account, so some of the factors that determine the design of the typically slender structures are behaviour under service loads and fire resistance. While the failure load of the balcony slab shown in fig. 3 may be much higher than necessary, it is also important that it is sufficiently stiff for comfort, something not so easily achieved with long spans and small thickness.

This represents some of the reasoning behind moving from research to applications for CRC. Other venues may have worked as well or better but an advantage of this approach - where CRC has competed on market terms with other products - is that it has been possible to achieve with very limited ressources. CRC is still being developed further and is currently the subject of a research project on innovative jointing systems together with the Building Research Establishment in the UK as well as a column project together with a Danish precast company and two Danish universities. Current projects, however, are closely linked to specific applications.

CRC was developed in 1986 and as such is a relatively old concept, but it is expected that CRC will still have a place among the new types of Hybrid FRC that are being developed – and perhaps some of the applications of CRC will help facilitate finding applications for these new materials when researchers are met with the demand for examples of long term experience.

Figure 3 Cantilevered balcony slabs in CRC.

7. References

1. **Namaan**, A.E. & **Reinhardt**, H.W. & **Fritz**, C., “Reinforced Concrete Beams with a SIFCON Matrix”. ACI Materials Journal, November-December 1991, pp. 595-601.

2. **Richard**, P & **Cheyrezy**, M.H., “Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength”. Concrete Technology: Past, Present and Future, SP-144, American Concrete Institute, Detroit, 1994, pp. 507-518.

3. **Bache,** H.H., “Compact Reinforced Composite, Basic Principles”. CBL Report No. 41, Aalborg Portland, 1987, 87 pp.

4. **Aarup**, B. & **Jensen**, B.C.,”Bond Properties of High-Strength Fibre Reinforced Concrete”. ACI-publication SP-180, Bond and Development of Reinforcement, 1998.

5. “Ultra High Performance Fibre-Reinforced Concretes, Interim Recommendations”, January 2002, AFGC/SETRA, France.

6. **Andrade**, M.C. & **Frias**, M. & **Aarup**, B, "Durability of Ultra-High Strength Concrete: Compact Reinforced Composite". BHP96 Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, 29-31 May 1996, Paris, France.

7. **Jensen**, B.C. & **Aarup**, B., "Fire resistance of fibre reinforced silica fume based concrete". BHP96 Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, 29-31 May, 1996, Paris, France.

8. **Juvas**, K. & **Jumppanen**, U.-M. & **Aarup**, B.,”High Performance Concrete at High Temperatures”. Proceedings of Nordic Concrete Research Meeting, 3-6 August 1999, Reykjavik, Iceland.