Fibre Reinforced High Performance Concrete for Precast Applications

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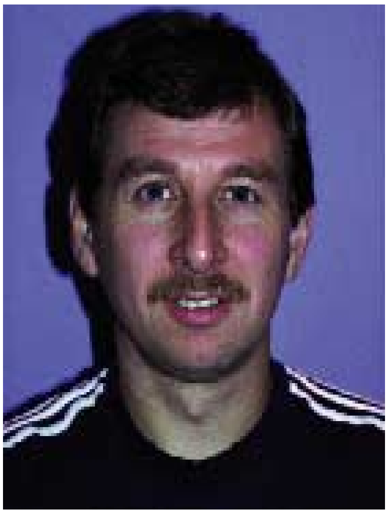

Abstract

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. In the last few years CRC has been used in structural applications and typically for precast elements such as balcony slabs and staircases. Durability and fire resistance is discussed. These properties are becoming increasingly important as sophisticated design methods and high quality materials are utilised in making very slender structures.

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) - or with prestressing - as for Reactive Powder Concretes (RPC).

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. CRC has been the subject of a number of research projects but in the last 4-5 years CRC has also been used for a number of structural applications.

Compact Reinforced Composite

CRC is the designation for a special type of Fibre Reinforced High Performance Concrete (FRHPC) with high strength (150-400 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.

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[1].

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 before the material could be considered for structural applications, and the material has been the subject of a number of research projects. The results on durability and fire resistance, which are briefly presented in this paper, are mainly taken from these projects, and reference is given to papers where results are reported in more detail.

An example of the type of applications, where the high strength in bending of FRHPC can be utilised is shown in photos 1 and 2. Photo 1 shows a cantilevered balcony slab used for a project near Copenhagen, while photo 2 shows a combined staircase and walkway produced in CRC. The cantilevered balcony slabs were used in a new building in Copenhagen, and as the slabs are very slender compared to slabs produced in conventional concrete, extensive documentation had to be provided before the slabs were approved by the building authorities. In another project using cantilevered balcony slabs, the loads were transferred into the building through a set of flaps. The largest moments appear where the flaps have a thickness of 65 mm. It was not so difficult to demonstrate that the slabs had sufficient strength, but as the cover to the reinforcement was only 10 mm in parts of the slab, the documentation should also demonstrate sufficient durability in an aggressive environment and at least 60 minutes of fire resistance in an ISO fire.

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[2]. 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[3]. 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. 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.

Thin section analysis has also been carried out to investigate whether there is an actual difference in level of micro cracking at the different loading levels, and the observations confirm that there is a relation between level of loading and number of micro cracks. However, this is observed on specimens, which have been exposed to salt water only for a short time. On older specimens, which have been exposed to chlorides for several years, mounted in the special rig, the number of micro cracks appears to have decreased. These investigations were carried out in a fellowship study sponsored by the European Commission in connection with a Brite/EuRam project. In a EUREKA project a similar effect was observed on beams that were deliberately cracked prior to exposure in order to obtain corrosion, but the cracks healed during exposure and no corrosion was observed.

Due to the low water/binder ratio in CRC the matrix contains a large number of unhydrated cement particles. These unhydrated cement particles react with the water in cracks and assist in healing of the cracks. In addition, the unhydrated cement particles appear to act as an effective barrier against carbonation and chloride penetration as there is almost no free water in the pores.

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 in these tests, as in all other tests carried out with CRC, it has not been 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.

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 as a remedy to this problem have suggested the use of polypropylene fibres, 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[4].

Beams of CRC and conventional concrete stored at ambient conditions for three months were exposed to 60 minutes of standard fire. Both materials showed surface spalling, but while conventional concrete could be crumbled by hand one week after exposure the residual strength of CRC specimens was 24 MPa.

CRC beams that had been dried at 45 or 80 ^{o}C showed no spalling after 30 minutes of exposure to a standard fire, and the residual strength measured on cylinders was 80 MPa, approx. 50% of the reference strength. The test, which was scheduled for 60 minutes, was discontinued after 30 minutes due to an accident in the furnace.

However, if young CRC specimens that had not been allowed to dry were exposed to fire conditions, they showed explosive spalling.

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. At high temperatures calcium hydroxide will decompose into water and CaO. While the water represents a possible danger of spalling, the CaO is more detrimental to the concrete. As the concrete is cooled, CaO will react with the humidity of the air and expand, which will lead to cracking. This is what is observed with the specimens of conventional concrete, while the CRC specimens exhibit a considerable residual strength.

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.

Discussion

CRC has higher strength than most of the concretes which are usually encompassed by the term HSC, and the structures are more slender, but the problems which are considered - such as durability and fire resistance - are not unique to CRC. The same type of problems will have to be addressed also for other types of high quality concrete as materials development and sophisticated design techniques makes it possible to utilise the materials more effectively.

The potential problems of explosive spalling are not restricted to very high strength concretes. Explosive spalling can occur at much lower strength levels as has been demonstrated in a recent Brite/EuRam project called HITECO[5]. But if a sensible design is carried out where spalling indicators such as water content, permeability, stress/strength ratio and heating rates are considered, also very high performance concrete can be used for structures without problems. Research on fire resistance has provided empirical guidelines, whereby CRC can be used with no special protection. Hopefully, further research will provide a fuller understanding of the behaviour of these very dense concretes under fire exposure, making it possible to further optimise design.

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Photo 1 Cantilevered balcony slabs in CRC.

Photo 2 Staircase and walkway in CRC.