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Rozvoj betonu s rozptýlenou výztuží a jeho aplikace v konstrukcích

Expansion of Fiber Reinforced Concretes and Their Application in Structures

Summary

Fibre-reinforced concrete is a contribution to the range of structural materials. Benefit of fibers in fiber-reinforced concrete is in improvement of the performance FRC in comparison to the plain concrete but also in application in RC and prestressed concrete. For application of fibre-reinforced concrete in structural members it is necessary to provide adequate methods for design.Within the last two decades extensive progress has been made in concrete technology. One of the breakthroughs is the develeopment of high-tec materials based on cementitious matrice with fibres (eg. concretes with its steel like compressive strength and a remarkable increase in durability). Novel materials following new technological rules regarding its composition, its production, the mechanical behaviour as well as regarding design and construction of structures were developed. Provisional technical recommendations for adequate design and construction of structures have been published in France, Germany and Japan. Some first applications in Canada, Europe and Asia have proven the assumed benefits of the new technology regarding costs, sustainabilty and service life. There is a need for further research and development to close existing gaps of knowledge, to come to a widespread regular application based on accepted technical regulations and to cost effective and highly efficient innovative construction systems.

The extensive experimental research programme of fiber concrete structures reinforced with conventional steel bars was performed. Steel fiber concrete and structural synthetic fiber concrete with polypropylene fibers have been investigated. The effect of a dosage and a type of fibres on load bearing capacity and service load behaviour with different types and amount of fibres was monitored. The programme was focused on finding of proper material model for structural analysis and assessment of material model influence on the structural analysis. The results will served as the input data for guidance for design of fibre-concrete structures with conventional steel bars. In addition, fibres generally favour improvements in first crack and ultimate member strength, impact resistance, and shear resistance. If properly designed, fibres can add to member structural performance even when used together with conventional steel main reinforcements (rebars). Special attention has been devoted to choise of suitable fiber concrete properties for improving performance of selected prefabricated elements and products. Prestressed beams with steel fibers concrete have been investigated to verify the possibility to decrease amount of of shear reinforment. Precast cornice plates, curbs and crush barriers were selected for application FRC in bridge accessories structures as a pilot project of tranfer of new concrete technologies into construction practice. The research also focuses on sustainability of construction, use of waste materials in specila fiber concrete production and applications.

Souhrn

Vláknobetony rozšiřují nabídku stavebních materiálů na bázi cementových kompozitů a jejich hlavní výhoda spočívá ve zlepšení působení konstrukcí ve srovnání s prostým betonem, ale také při použití v železobetonových a předpjatých konstrukcích.Pro širší použití vláknobetoů v konstrukcích je potřeba rozvinout vhodné metody pro jejich navrhování, které musejí být v souladu s navrhováním konstrukcí z běžného betonu a přitom využít výhod, které vláknobetony poskytují. V průběhu posledních dvaceti let byly vyvinuty nové materiály na bázi vláknobetonů a jejich technologie výroby vyznačující se nejen velmi vysokými pevnostmi v tlaku a zvýšenou , ale také zvýšenou duktilitou v tlaku i v tahu a dalšími výhodnými vlastnostmi včetně zvýšené deformační schopnosti a houževnatosti a také trvanlivostí. Nové poznatky byly ověřeny na aplikacích materiálů v konkrétních stavbách mostů a dalších konstrukcí a byla připravena předběžná doporučení pro zkoušení a aplikací těchto materiálů ve Francii, Japonsku a Německu. V našich podmínkách tato dopručení dosud neexistují a je to též jedním z důvodů, proč širší aplikace vláknobetonu mimo užití v půmyslových podlahách stále chybí.

V předložené práci je popsán rozsáhlý experimentální a teoretický výzkum vláknobetonů s ocelovými a syntetickými vlákny z polypropylénu v konstrukcích v kombinaci s běžnou prutovou ocelovou výztuží. Sledování účinku různých typů vláken a a jejich dávkování včetně synergie obou typů výztuže na výsledné působení konstrukcí z hlediska únosnosti a použitelnosti, vzniku, rozvoje a šířky trhlin. Jsou zkoumány též vlastnosti z hlediska dlouhodobého působení. Poznatky z experimentů jsou převedeny do materiálových modelů protřebných pro výpočtovou analýzu a návrhové metody. Materiálové modely jsou získány na základě experimentů inverzní analýzou a ověřeny numerickou simulací, která ve složitějších případech slouží také jako nástroj pro navrhování.Vytvoření databáze výsledků rozsáhlé palety materiálů a zkušenosti z oblasti technologie bylo využityopro praktické aplikace. Zobecnění získaných poznatků vedlo ke konkrétním aplikacím v prefabrikaci prvků a výrobků. Optimalizací složení vláknobetonu, vytipováním vhodného typu vláken a přizpůsobením technologie výroby byly vyřešeny konkrétní nedostatky výrobků nebo vylepšena jejich funkčnost, případně zajištěna úspora např. snížením tloušťky prvku, snížením potřeby konvenční výztuže, zvýšením houževnatosti, trvanlivosti a životnosti a dalších aspektů. Pro pilotní projekty byly vybrány doplňkové konstrukce mostního stavitelství jako jsou římsy, obrubníky, předpjatá svodidla, dále trouby velkých průměrů a oblasti konstrukcí s lokálním přetížením např. kotevní zóny u předpjatých prvků. Vlastnosti vláknobetonu s využitím recyklovaného stavebního odpadu jako kameniva byly též předmětem výzkumu a příprava speciálních aplikací s dosahem v environmentální oblasti se očekává v nejbližší době.

Klíčová slova:
vláknobetony, materiálové vlastnosti betonu výztuženého vlákny, experimentální výzkum, výpočtová analýza, numerická simulace, chování vláknobetonů,
zjišťování materiálových vlastností, inverzní analýza, ověření materiálových vlastností, technologie, optimalizace, návrhové metody vláknobetonových konstrukcí, aplikace vláknobetonu v prefabrikátech,
recyklované kamenivo

Keywords:
Fiber reinforced concrete, material properties of FRC, experimental investigations, numerical simulation, structural analysis, performance of FRC, determination of material characteristics, inverse analysis,
verification of properties, technology, optimization, design methods for fiber concrete structures, material parameters, recycled aggregate

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CURRRICULUM VITAE

1. INTRODUCTION

Concrete made with Portland cement has certain characteristics: it is relatively strong in compression but weak in tension and tends to be brittle. The weakness in tension can be overcome by the use of conventional rod reinforcement and to some extent by the inclusion of a sufficient volume of certain fibres. The use of fibres also alters the behaviour of the fibre-matrix composite after it has cracked, thereby improving its toughness. Cementitious composites reinforced by short, randomly distributed fibers began to gain in importance in concrete industry since 1960s. The benefits of fiber reinforcement in improving the fracture toughness, ductility, impact resistance, fatigue endurance and energy absorption capacity of concrete were quite clear arguments for their increasing use.

Toughness is defined as the area under a load-deflection (or stress-strain) curve. As can be seen from Figure 1, adding fibres to concrete greatly increases the toughness of the material.

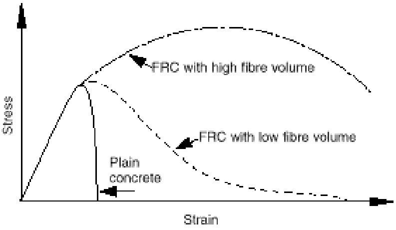


Figure 1: Typical stress-strain curves for fiber-reinforced concrete.

Conventional fiber reinforced concrete is able to sustain load at deflections or strains much greater than those at which cracking first appears in the matrix. Fiber volume fractions varying from 0.5% to 1.5% by volume, increase of this volume improves the performance of the composite from the other side results in poor workability and non uniform fibers distribution. For the effective use of fibres in hardened concrete fibres should be significantly stiffer than the matrix, ie with a higher modulus of elasticity, fiber content by volume must be adequate, there must be a good fiber-matrix bond, fiber length must be sufficient, fibres must have a high aspect ratio, ie they must be long relative to their diameter. For the quantities of fibres typically used (less than 1% by volume for steel and about 0,1% by volume for polypropylene) the fibres will not have significant effect on the strength or modulus of elasticity of the composite. High volume concentrations of certain fibres may make the current type of plastic concrete unworkable. Fiber materials can be steel, glass, polypropylene, carbon, polyvinylalcohol, polyethylen, aramid and other tensile resisting materials.

2. CLASSIFICATION OF FIBER CONCRETES

The behavior of fiber reinforced cement concretes or composites (FRCC) can be described and quantified by a variety of parameters, such as strength and strain capacity, toughness index, and fracture energy, obtained from tests in tension or bending in a large number different configurations including varying specimen geometries and test setups. Depending on the details of the individual testing procedures, a particular composite may be characterized and classified (Fig.2). One distinguishing material characteristic is whether the response of the composite is strain-hardening or strain-softening in tension, and within this last category, whether it is deflection-hardening or deflection-softening. It is observed that a strain-hardening composite is considered to have performance of higher level than a strain-softening one, while a tension strain-softening material can be deflection-hardening or deflection-softening. Deflection-hardening materials are useful in structural applications where bending prevails, while deflection-softening composites cover a wide range of practical applications starting at the lower end by the control of plastic shrinkage cracking of concrete, to the higher end where they are used in concrete pavements and slabs on grade. As for strain-hardening FRC composites it is now generally accepted that their use can significantly improve the seismic resistance of concrete structures subjected to reversed cyclic loading as well as their impact and blast resistance.

For many years researchers have worked to increase the strength and ductility of concrete and cementitiuous composites. As a result high performance concretes (HPC) and ultra-high performance concretes (UHPC) were developed with the aid of water reducing agents, chemical admixtures and the addition of very fine fillers. HPC and UHPC are usually first characterized by their compressive strength. Initially HPC had compressive strength ranging between 60 to 100 MPa. For UHPC strength in excess of 200MPa have been attained. Such high strenght is expected to reduce the required section size of reinforced and prestressed concrete structural members such as bridge girders, beams and columns. However (U)HPC are extremely brittle in both tension and compression. Adding fibers to such matrices improves ductility and fracture properties. So far, ultra high performance concretes do not attain sufficient deformation capacity and toughness in tension without using high fiber contents (ranging from 5% to 11% by volume) such as in examples of SIFCON (slurry infiltrated fiber concrete, 1985), SIMCON (slurry infiltrated mat concrete, 1997) and CEMTEC$_{\text{multiscale}}$ (multiscale cement technical composites, 2005). The CEMTEC by using three different types of steel fibers with 11% total fiber volume fraction can achieve 50-58 MPA modulus of rupture in bending and more than 200 MPa compressive strength.

Recently several researchers reported on the mechanical , compressive, and time dependent behaviuor of UHPFRC and described many applications of

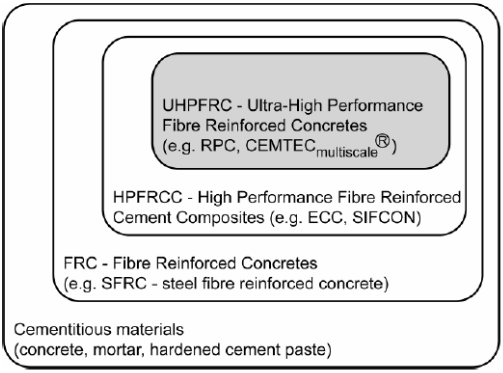


Figure 2 : Classification of cementitious composites, after Habel (2004)

Ductal®, a type of RPC (reactive powder concrete) with moderate fiber content, in bridges and footbridges and shoved that Ductal technology can achieve 200MPa compressive strength,45 MPa flexural strength and 11 MPa tensile strength. Since each 1% of steel fibres usually cost more than the entire concrete matrix, there is urgent need to minimize the cost of the composite for practical applications.

2.1 Conventional Fiber Reinforced Cementitious Composites (FRCC)

Fiber reinforced concrete composites are made by mixing short discontinuous fibers with concrete or mortar. Fiber types include steel, polymeric, glass, carbon, asbestos, and natural fibers. Due to their mixing process, fibers may not be uniformly distributed in the matrix, thus reducing their efficiency to resist tensile loads. The main applications of steel fiber reinforced concrete (SFRC) are in structures subjected to potentially damaging concentrated and dynamic load. FRC has been used in several areas of infrastructure and industrial applications such as airport pavements, industrial floors, overlays, blast-resistant structures, and tunnel and channel lining. A number of experimental highway and bridge deck applications using FRC showed the material can improve performance significantly enough to be economically justified. In most of these applications, the fiber content varies from 40 kg/m^3 to 120 kg/m^3. This is equivalent to fiber volume fraction between 0.5% to 1.5%. The second category is a high volume fiber composites containing between 5% to 15% fibers by volume. Figure 1 shows a typical stress strain curve of FRC compared to plain matrix and to high volume FRC composites.

2.2 High Performance Fiber Reinforced Cementitious Composites (HPFRCC)

Due to several advancements involving the matrix, the fibers, the fiber matrix interface and the composite production process the field of fiber composites has made significant advances in recent years.This includes commercial introduction of new generation of additives (superplasticizers) which allows for higher matrix strength without loss of workability, the increase use of micro-fillers such as silica fume and fly-ash and their effect of porosity and strength, the availability of different types of fibers, the use of polymers in concrete, and the innovations in production and mixing processes that allows for higher volume fractions and more uniform mixing of fibers. The larger the volume fraction of the fibers improves the mechanical properties such as toughness and ductility. There is a practical limit beyond which proper mixing of fibers is not possible and deterioration of mechanical properties may occur. HPFRCC are high-energy absorption materials that will be suitable for structures subjected to impact and blast loadings.

SIFCON which is SFRC with very high volume fractions of fibers ranging from 10% to 15% by volume has a significant increase in strength, toughness, and ductility over traditional SFRC. In SIFCON, the fibers are pre-placed in a mold to its full capacity and the corresponding fiber network is then infiltrated with a cement-based slurry. The fiber content depends on fiber type, fiber orientation, method of placement, and vibration. Fabrication of SIFCON requires preplacement the fibers prior to adding a special fine-grained cement slurry matrix with no coarse aggregates. Tensile strengths of SIFCON can reach 25 MPa and its compressive strength up to 100 MPa andwas used in special field applications and special locations in structures; it is not commercially used because of manufacturing techniques. A modified version called SIMCON has been evaluated for repair and rehabilitation of structures. In this composite, instead of infiltrating preplaced fibers, prefabricated fiber mats are infiltrated with slurry. The fiber content could be reduced to as low as 4% and still obtain good mechanical properties (Fig.3). This product also requires preplacing techniques and is not conducive for making complicated shapes.

Another type of HPFRCC is engineered cementitious composites (ECC) that has been microstructurally tailored based on micromechanics and the concepts of fracture mechanics. This very ductile FRCC can be used in large volumes.

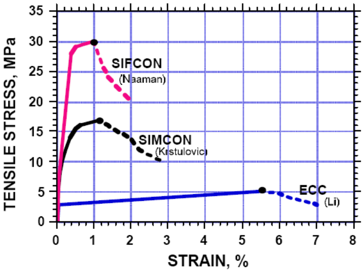


Figure3 : Comparison of the tensile response of three different strain-hardening FRC composites illustrating the trade-off between strength and ductility (strain is to peak point only), after Naaman

ECC typically has a tensile strain capacity of more than 3% with spacing between multiple cracks at saturation of less than 3 mm (Fig.4). The microstructure optimizations allow ECC to be made with fiber contents less than 2% to 3% with appropriate matrix design. This composition makes it a flexible material for processing. ECC can be cast, extruded, and sprayed. The advantages of high composite ductility in the hardened state and flexible processing in the fresh state make it attractive for a broad range of applications. The design of ECC is targeted at creating a fiber reinforced cementitious material with a deformation behavior analogous to that of metals, specifically at achieving pseudo strain - hardening and multiple cracking behavior. The combination of such a ductile cementitious composite with structural reinforcement in direct tension results in deformation compatibility of these components in the reinforced ECC composite, leading to a reduction of interfacial bond stresses and bond splitting cracks while maintaining composite integrity. ECC represents one particular class of HPFRCC, which are defined by an ultimate strength higher than their first cracking strength and the formation of multiple cracking during the inelastic deformation process (Fig.2) (Naaman and Reinhardt, 1995). In contrast to localized deformation in conventional FRC the deformation of ECC is uniform on a macro-scale and considered as pseudo-strain, which is a material property. ECC has typically an ultimate tensile strength of 5- 8MPa and a strain capacity ranging from 3% to 5% (Fig. 7b). The spacing between multiple cracks in a typical ECC is on the order of several mm, while the crack widths are limited to the order of 100µm. Besides common ingredients of cementitious composites such as cement, sand, fly ash, water and additives, ECC utilizes short, randomly oriented polymeric fibers (e.g. Polyethylene, Polyvinyl Alcohol) at moderate fiber volume fractions (1.5% - 2%). For structural applications in reinforced ECC members, processing of ECC requires conventional mixing equipment, such as a drum mixer, and can be adjusted to achieve regular consistency for casting and external compaction or a flowable consistency with self-compacting capabilities.

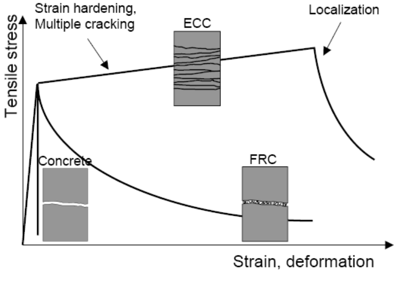


Figure 4: Tensile stress-strain behavior of cementitious matrices

2.3 Ultra-High Performance Fiber Reinforced Concrete (UHPFRCC)

The different UHPC currently marketed are: BSI "Béton Spécial Industriel" (special industrial concrete) developed by Eiffage, which technology is evolving in association with cement manufacturer Sika, to come to Ceracem®, different kind of Ductal® concrete, including BPR (reactive powder concrete), resulting from joint research by Bouygues, Lafarge and Rhodia, and marketed by Lafarge and Bouygues, BCV being developed by Vinci group in association with Vicat. Most cement manufacturers are developing products, and materials are being developed in the laboratories of EDF, LCPC (with CEMTEC® Multiscale technology) (Fig.5).

With in the past twenty years HPFRCC's with high tensile and compressive strengths, high strain capacity, and high-energy absorption capacity and impact resistance have been developed. Their matrix composition have low porosity and enhanced interfacial bond properties giving them high performance and more durability. The use of ultra-fine particles such as silica fume and microfillers with superplasticizers provide good dispersion within the mix which improves durability of these composites and new group of novel type of materials (UHPFRC) was developed.

UHPFRC refers to materials with a cement matrix and a characteristic compressive strength excceds 150 MPa, possibly attaining 250 MPa, and containing steel fibres in order to achieve ductile behaviour under tension and, if possible, to dispense with the need for passive (non-prestressed) reinforcement. They may also contain polymer fibres. UHPFRC differs from high-performance and very-high-performance concretes: by its compressive strength which is systematically greater than 150 MPa, by the systematic use of fibres, which ensures the material is not brittle and modifies the conventional requirements for passive and/or active reinforcement, by its high binder content and its special selection of aggregates. The aim of UHPFRC development is to achieve high tensile strengths through the participation of the fibres which provide tensile strength after the cement matrix has cracked. When the tensile strength is sufficiently high, it may be possible, depending on the way the structure works and the loads to which it is subject, to dispense with conventional reinforcement. If not, pretensioned or post-tensioned prestress will allow UHPFRC beams to span long distances since the fibres help take secondary tensile forces, making it possible to dispense with secondary passive reinforcement. The different UHPC currently marketed are: BSI "Béton Spécial Industriel" (special industrial concrete) developed by Eiffage, which technology is evolving in association with cement manufacturer Sika, to come to Ceracem®, different kind of Ductal® concrete, including BPR (reactive powder concrete), resulting from joint research by Bouygues, Lafarge and Rhodia, and marketed by Lafarge and Bouygues, BCV being developed by Vinci group in association with Vicat. Most cement manufacturers are developing products, and materials are being developed in the laboratories of EDF, LCPC (with CEMTEC® Multiscale technology).

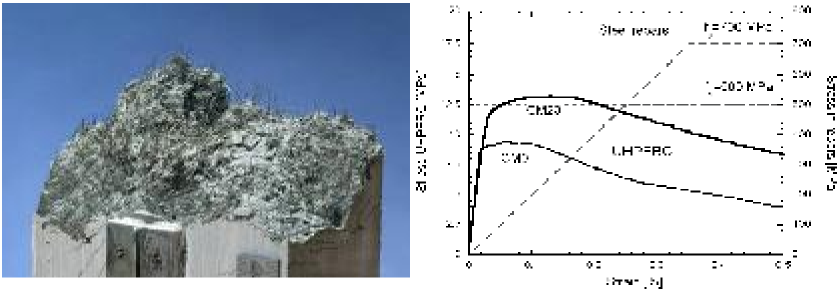


Figure 5: Fractured surface of UHPFRC (CEMTEC) with pulled-out steel fibres and typical stress-strain diagram of the CEMTEC

Some UHPFRCs undergo heat treatment (HT) which consists in raising the temperature of components to a relatively high level (about 90°C) a few hours after the concrete has set. It must be carried out only after the concrete has set in order to avoid any risk of Delayed Ettringite Formation. Heat treatment therefore requires good knowledge of the setting time and a means of checking it. The main effects of heat treatment are as follows: The concrete strengthens faster (compressive and tensile strengths), shrinkage and creep effects reduce substantially once the heat treatment is finished, durability is considerably improved. Example of heat treatment of the Ductal®: The Ductal® can be used in the same way as conventional concretes but it also benefits from heat treatment which can be optimized (duration and temperature), depending on the components to be made The most documented heat treatment (Fig.6). consists in raising the temperature of components to 90° C ± 10°C for 48 hours. It is traditionally performed with steam in a closed box. The treatment can start any time after the material has set.

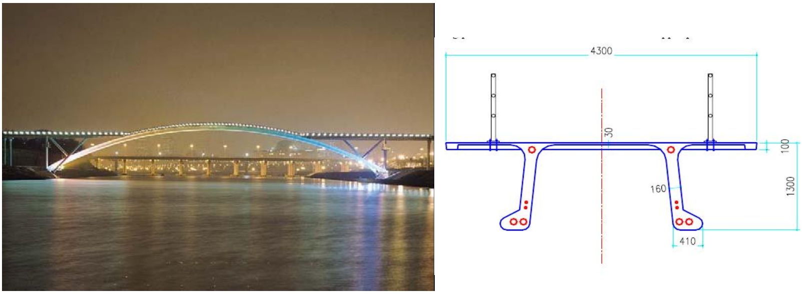


Figure 6 : General view and crosssection of Seoul footbridge from Ductal

UHPFRC can be produced from a concrete mix containing no coarse aggregate (i.e. stones). A high cement content and a special reactive silica sand, together with a very low water content and water-reducing and other admixtures, are used to produce concrete with a very high compressive strength, up to 5-7 times as strong as normal concrete. The addition of a large volume (2-4%) of short, fine steel fibres produces a concrete which is easy to produce and use and which has a very high tensile strength and toughness. This concrete can be made between 30-60 times as strong in tension as normal concrete and has a very high ductility.


Figure 7:a)Shawnessy Light Rail Transit Station from Ductal, Canada
b)flexible concrete (ECC)

Densified cement ultra-fine Small Particle based material (DSP) is a form of HPFRCC produced by Aalborg Portland Cement in Denmark. In this material the grading of the cement and micro-fillers is controlled using high contents of microsilica. Fiber reinforced DSP has been used in producing CRC (Compact Reinforced Composite), where ductility is achieved through incorporation of a large content of short, stiff and strong fibers. This ductility combined with high strength (150-400 MPa) and exceptional durability makes it possible to utilize a large amount of reinforcement, thus giving new structural possibilities compared to conventional concrete. The composition of CRC can be varied using different types of aggregates and different types and contents of fibers, however, a typical composition using DSP with quartz sand, 4% to 6% steel fibers and a water/powder ratio of 0.16 . The fibers most often used have a length of 12 mm and a diameter of 0.4 mm. CRC was developed in 1986 and has been commercially available for 7-8 years. The first applications have been for in-situ cast joints, tunnel linings, balcony slabs, and very slender cross sections(Fig.8).

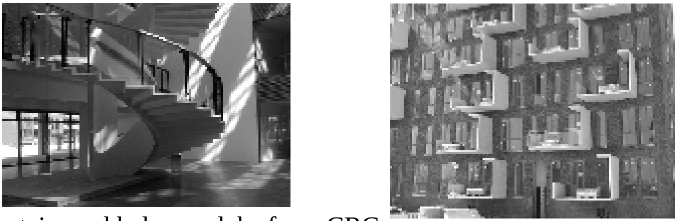


Figure 8: Spiral stairs and balcony slabs from CRC

Reactive Powder Concrete (RPC) is composite with enhanced mechanical properties, superior physical characteristics, excellent durability. RPC utilizes reactive powder material designed with optimal packing. The ultra-high strength cement-based material was first developed in the 1990 by researchers at the laboratories of Bouygues in Paris, France. The RPC microstructure has a very compact particle distribution enhanced by the presence of superior cementitious hydrates. RPC has precise gradation to produce maximum density, smaller size particles, highly refined silica fume, optimum chemistry, very low water/cement ratio, and hardening under pressure and increased temperature to produce very high strengths. The addition of steel fibers to RPC gives it high ductility, fracture energy, and toughness. RPC is characterized by high strength (200 MPa in compression and 45 in flexure), strain hardening, high flowability, and high durability. Ductal a commercially available product, is an inorganic high performance composite material based on the concept of RPC.

One example of UHPFRC mix used for rehabilitations of structures in extreme conditions (Fig.9): 1430kg/m^3 cement, microsilica, fine quartz sand with maximumgrain size of 0.5 mm, the microsilica/cement and water/binder ratio were 0.26 and 0. 125 respectively. The used fibers of this ultra compact matrix were a mix of microfibers(steel wool of 2 to 3 mm length) and microfibers of 10 mm length and an aspect ratio of 50, with total dosage of 706kg/m^3 ie. 9 vol. %.

The extremely low permeability of UHPFRC associated to their outstanding mechanical properties make them especially suitable to locally "harden" reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses. UHPFRC materials can be applied on new structures, or on existing ones for rehabilitation, as thin watertight overlays in replacement of waterproofing membranes, as reinforcement layers combined with reinforcement bars, or as prefabricated elements such as curbs. Tailored composite UHPFRC-concrete structures promise a long-term durability which helps to avoid multiple interventions during the service life of structures.

Figure 9 : UHPFRC for rehabilitation- easy application with usual tools

3. EXPERIMENTAL INVESTIGATIONS

The purpose of the research in laboratory testing was to investigate effect of dosage and type of fibres on load bearing capacity of concrete beams, service load behaviour related to cracking and deflections, and then on the basis of experimental testing to verify possibilities of material modelling for design of FRC beams including finding proper models, evaluating influence of the selected material model on the structural analysis, verification of the model for behaviour and analysis of FRC elements in combination with steel bars and to formulate simple recommendations for practical design of fibre reinforced members. Generally, the FRC characteristics for tension largely influences the bending resistance and the shear resistance properties of the structure. By estimating tension characteristics adequately, it is encouraged to produce the structure with efficient safety and also with the economical rationality. Fibre concrete beams with longitudinal steel bar reinforcement were investigated in this period. Three mixtures were prepared to compare benefit of fibres in the concrete matrix: a conventional concrete and two corresponding fibre concretes with polypropylene fibres (1% and 0.5% of volume dosage). Beams 1800 x 150 x 100 mm reinforced by two steel bars of 6, 8 and 10 diameter both from concrete and fibre concrete were produced. To determine basic material properties specimens recommended by RILEM were cast from above mentioned mixtures - cubes 100x100x100 mm and beams 100x100x400 mm. In a compressive test of cubes compressive strength was taken.

3.1 Material characteristics

The basic material properties were adjusted, further material properties needed for finite element analysis were determined and a suitable material model was verified by means of an analysis. The inputs to such an analysis were compressive and tensile strength from laboratory tests and load – deflection curve registered in a four point bending test. Flexural bending test of a 100x100x400 mm beam was simulated in a finite element analysis, suitable material model was specified and material characteristics were determined and refined until the load - deflection curve from the FE analysis acceptably agreed with the curve from experiment.

Material models for a fibre concrete with polypropylene fibres with 0,5% and 1% volume dosage of fibres was determined and evaluated. It was looked for by means of inverse analysis. The found material model was used for a structural analysis of beam behaviour in a FE numerical analysis and results of this numerical simulation was compared with real behaviour recorded in a laboratory experiment

3.2 Testing of beams with combination of reinforcement

Six sets of beams were prepared and tested in a flexural laboratory test. Setup of the test is depicted in the Fig.10-11. Dimensions and load scheme of the beam for the case study were selected for the reason of separation of various parameters on structural behaviour in bending.

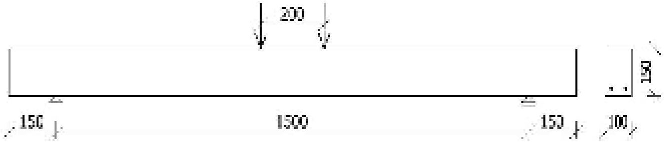


Figure. 10 Load arrangement of the beam in the bending test

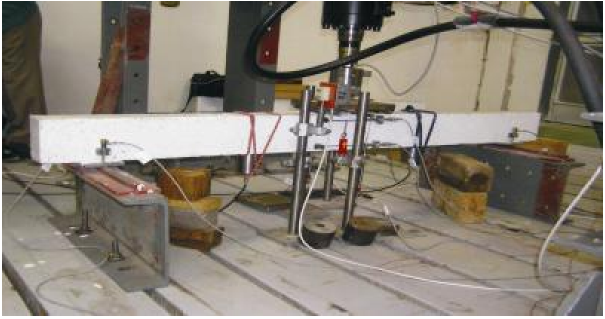


Figure. 11 Setup of the concrete beam test in the laboratory

he beams with effective span of 1500 mm were loaded with two local forces in the distance of 200 mm. The reason of such a setup was preventing of potential shear failure of the beam and also the application range of the strain gauges used for monitoring longitudinal strains in compression and tension regions of the cross-sections in the middle part of the beam. Mid span deflections and strains were registered by measuring device. In each step formation and developments of cracks were visually monitored and graphically signed on one side of the beam. Crack spacing, crack developments and crack widths were measured and registered in all load steps.

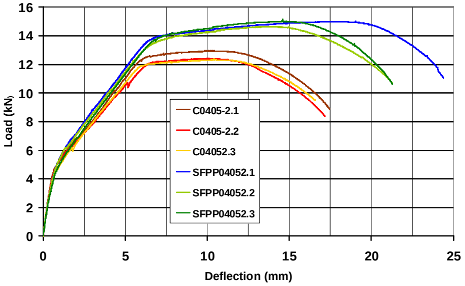


Figure 12: Load – deflection curves for concrete beams (C) and fibre concrete beams (SFPP)

First set of polypropylene fibre concrete beams with longitudinal steel bar reinforcement and a comparative set of beams from common concrete reinforced with identical steel bar reinforcements were prepared. Material properties confirmed by the inverse analysis were used for FE analysis of a fibre concrete beam with conventional reinforcement. Comparing results of bending test of reinforced concrete and reinforced fibre concrete beams from experiment proved benefits of fibre concrete (Fig.12).

Record of load-deflection relation is depicted in Figure 11. The lines in dark grey are load-deflection curves of fibreconcrete beams (SF PPx), the light grey lines are for concrete beam (Cx) load-deflection relation. Until a first crack arises the load-displacement curves are practically identical, also behaviour of fibreconcrete beam and concrete beam was similar. Several cracks were created then one main crack developed. Crack spacing was measured for concrete and fibreconcrete beams. A fibreconcrete beam had more cracks than a concrete beam. That implies more favourable layout of cracks of a fibreconcrete beam. A mean value of crack spacing was 63mm for the fibreconcrete beam and 80mm for the concrete beam.

The failure of a concrete beam came on with a fracture of steel reinforcement. The beam was broken into two pieces. Compared to it fibreconcrete beam remained whole even after the steel rebar reinforcement was broken thanks to the fibres bridging a crack. A higher load-bearing capacity of comparable fibreconcrete beams is evident from the picture (Fig. 10).

4. MODELLING AND SIMULATION

The basic material characteristics were obtained from laboratory tests on prisms in four or three point bending and by an inverse analysis procedure the load-deflection relation were transformed into constitutive relations used in simulation. The test was simulated by means of non-linear program FEM using various constitutive relations, which enable to model fibre concrete. The advantages and possibilities of different material models for fibre concrete available are discussed.

4.1 Effect of FRC on load-bearing capacity of the beam in flexure

Favourable results were obtained in all the series. The increase of the ultimate load ranging 10 -14% were observed in fibre concrete beams in comparison with concrete beams (both with steel rebars of the same amount, volume of pp was the same). A positive effect of ductile behaviour at the failure was apparent in all cases. It depended on the area of steel rebars which differed in series - after rupture of the rebars, the dominant crack kept opening continuously, no sudden collapse occurred - even in the case when deflections were enormous in all cases. It depended on the area of steel rebars which differed in series - after rupture of the rebars, the dominant crack kept opening continuously, no sudden collapse occurred – even in the case when deflections were enormous

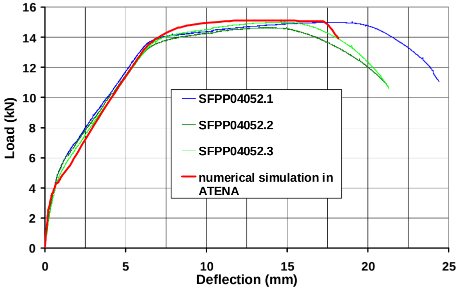


Fig.13 Load –deflection curves of fibre concrete beams (SFPP - measurements) and numerical analysis

and wide crack opening exceeded length of fibres (Fig.10). After failure of the beams failure surface was visually checked. Pull out of fibres from concrete was not observed, fibres were broken (Fig.11).

Figure. 14 a) Detail of the failure mode of the tested beam with fibres and steel bar reinforcement and b) crack patterns of the tested FRC beams

4.2 Effect of FRC on cracking of the beam in flexure

Crack patterns of FRC beams (Fig. 14b) exhibit more cracks with smaller spacing and with smaller crack widths, it means that fibre reinforced structural elements have more favourable response from point of view of serviceability limit state considering cracking and deflections.

Increase in enegy-absorption capacity due to fibres leads to improvement in cracking characteristics. Cracks may be more uniformly distributed resulting in reduction of the maximum crack width. Cracking behaviour is effected by the amount of longitudinal reinforcement. Design codes and recommendations generally control the minimum amount of reinforcement. Benefit of combining conventional reinforcement with steel fibres may be assessed. Combining conventional reinforcement with polypropylene fibres FF result in economic solutions, especially to control crack width and to ensure more favourable crack distribution, which was observed from test results (Fig.12). The values of crack widths measured at the limited value of deflection equal to 10 mm proved that amount of 0,5 % of polypropylene fibres have such synergistic effect on the beam, that average values of crack width are below limiting value of 0,2 mm. Quantification of this effect can be done by similar procedure, but it is necessary to carry out extensive experimental program for statistical evaluation.

4.3 Inverse analysis from flexural tensile tests on prisms

The experimental procedures can be used to characterize the tensile performance of FRC by means of flexural tests. Several types of test are used: firstly, four point flexural tests for determining the tensile strength following correction for scale effect, centrepoint flexural tests using notched prisms, both to determine the contribution of fibres as reinforcement of a cracked section, after application of the so-called inverze-analysis method. At least six tests are required to get a statistically significant mean response. Results are conflated as follows: In the absence of direct tensile-strength testing to determine the performance of FRC, the tensile strength can be approximated from four-point flexural testing by extracting from the flexural test results the value of the force (F_{fiss}) corresponding to the loss of linearity of elastic behaviour. This point is easily identified on force-actual deflection curves. The strength (R_{fl}) attained at the moment of flexural cracking can then be easily calculated using the following formula:

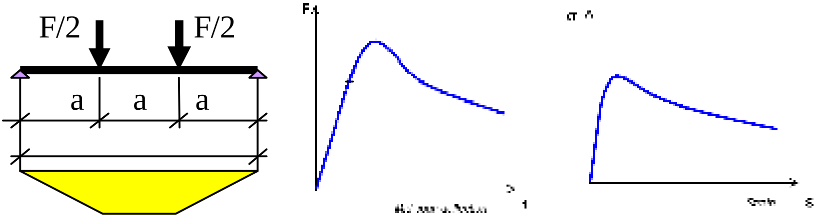


Figure 15: Set–up of flexural test, load –deflection diagram, stress-strain

$$R_{fl} = \frac{6F_{fiss}a}{bh^3}$$

To estimate the tensile strength, the cracking strength must be corrected for scale effects (or gradient effect). The approach adopted is derived from research into this point and corresponds to that adopted for the CEB-FIP structural design code:

$$R_r = R_{fl} \cdot \frac{2.0 \cdot \left(\frac{h}{h_0}\right)^{0.7}}{1 + 2.0 \cdot \left(\frac{h}{h_0}\right)^{0.7}} \qquad h_0 = 100 \text{ mm}$$

To take account of elastic deformation of the measurement base, it is necessary to correct the direct measurement of crack opening. This correction can be carried out only before initiation of the crack; subsequently, the stress release caused by propagation of the crack results in negligible elastic deformation of the measuring base. The simplest way to make this correction is to identify the end of the initial elastic range (loss of linearity) and to note the deflection values (f_o) and corresponding crack openings (w_o). The crack opening of interest is then obtained directly be subtracting w_o from the values measured when cracking started. This simply changes the coordinate system and puts the new origin of the curves at the time the crack is assumed to initiate. In the case of tests where the crack opening is not recorded, it must be estimated from measurement of the actual deflection. Although the relationship is not direct, and depends on the depth of cracking, a good estimate can be obtained as follows. If the deflection f_o at the end of the elastic range is known, the crack opening (w) can be estimated using the following equation:

$$w = 4/3 * 0,9 * (f - fo)$$

where f is the actual deflection as measured. This expression is derived from the assumption of a perfect hinge mechanism at the crack, modified by a correction factor taking account of the fact that the crack does not go right through the section. It is therefore not valid in the initial phase of crack propagation. However, this phase is relatively short and the depth of the crack quickly stabilizes between 80% and 90% of the depth of the section.

Extraction of the tensile-strength law using back analysis The figure below shows a cracked section of a bent prism. Two different parts are distinguished: the uncracked part where the stress distribution corresponds to linear elastic behaviour, and the cracked part where stress distribution depends directly on the effectiveness of the fibres. It is the latter distribution which is of interest here, and which can be determined by back analysis

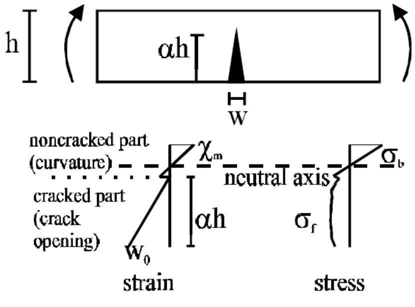


Figure 16: Strain and stress in the cracked section

The mechanical equilibrium of the section results in the following equations, where index b means the contribution of the uncracked part and index f the contribution of the cracked part:

$$N_b = \frac{E.\chi_m.b.h^2}{2}\left[(1-\alpha_n)^2 - (\alpha - \alpha n)^2\right]$$

$$N_f = \frac{\alpha.h.b}{w_0}\int_0^{w_0}\sigma_f.dw$$

$$M_f = \alpha h.N_f - \frac{(\alpha.h)^2.b}{w_0}\int_0^{w_0}\sigma_f.w.dw$$

$$M_b = \frac{E.\chi_m.b.h^3}{3}\left[(1-\alpha_n)^3 - (\alpha - \alpha_n)^3\right] + h.\alpha_n.N_b$$

i.e. resistance moment: $M = M_b + M_f$

normal force: $N = N_b + N_f = 0$

with: α ..... relative depth of the crack (see Figure...)

α_n .... relative height of the neutral fibre, given by:

$$\sigma_t = E.\chi_m.h.(\alpha - \alpha_n)$$

χ_m ..... curvature of the uncracked part

σ_t ..... tensile strength of the matrix

E .... modulus of elasticity

b, h ..breadth and height of the section

To link crack opening to the curvature of the uncracked part, a kinematic relationship of the following type is used:

$$w_0 = \left[\chi_m + 2.\chi_e\right]\frac{2.(\alpha h)^2}{3}$$

where: χ_e is the equivalent elastic curvature, given by $\chi_e = M/EI$ and I is the inertia of the rectangular section.

Iterative procedure

Since the tensile stress-crack opening relationship is complex, couples of points (w_i, σ_{fi}) defining it discretely are sought. Considering that the discretization of the horizontal scale (crack opening) is sufficiently fine, the integral of the stresses can be expressed by a trapezoidal approximation such as: Subsequently, the previous expressions of the normal force and moment of the cracked part can be expressed incrementally:

$$\int_0^{w_{i+1}}\sigma_f.dw = \int_0^{w_i}\sigma_f.dw + \left(\frac{\sigma_{f_i} + \sigma_{f_{i+1}}}{2}\right)(w_{i+1} - w_i)$$

$$N_{f_{i+1}} = N_{f_i} \cdot \frac{\alpha_{i+1}}{\alpha_i} \cdot \frac{w_i}{w_{i+1}} + \alpha_{i+1}.b.h.\left(\frac{\sigma_{f_i} + \sigma_{f_{i+1}}}{2}\right)\left(1 - \frac{w_i}{w_{i+1}}\right)$$

$$M_{f_{i+1}} = M_{f_i} \cdot \left(\frac{\alpha_{i+1}}{\alpha_i} \cdot \frac{w_i}{w_{i+1}}\right)^2 + \alpha_{i+1}.h.N_{f_{i+1}} \cdot \left(1 - \frac{w_i}{w_{i+1}}\right) - \frac{(\alpha_{i+1}.h)^2.b}{2} \cdot \left(1 - \frac{w_i}{w_{i+1}}\right)^2 .\sigma_{f_{i+1}}$$

Thus, considering that the stress-crack opening relationship is known to iteration i, the two unknowns—stress and relative depth of the crack at iteration i+1—can be calculated with the equations of the previous model so as to obtain zero normal force and a resistance moment of the section equal to the test moment.

Initialization of the process and stabilization of convergence

To start the incremental process, take as starting values the point defined as the

$$M_b^0 = M_{ext} = \frac{-bh^2.\sigma_f^0}{6}$$

$$\text{with } M_f^0 = 0 \; ; \; N_b^0 = 0 \; ; \; N_f^0 = 0$$

Since the description of the test results is discrete, the inverze analysis method using a sort of derivative of the moment curve, oscillation of the stress-crack opening relationship often occurs. It has been shown that it can be stabilized by correcting iteration i after calculating iteration i+1. In practice, it is sufficient to reposition the stress of iteration i by determining a moving average of the following type:

$$\sigma_i = (2^* \sigma_i + \sigma_{i+1})/3$$

If the stress does not vary suddenly—which is the case in practice—this correction does not affect the response of the method and leads to much more realistic results. It should be observed that this stabilization operation must be carried out at the end of each iteration in order to be taken into account in the calculation of the following iterations.

In some cases the test with crack opening cannot be used and only deflections are measured. The objective is therefore to characterize the material by carrying out tests on specimens of the same thickness as the actual structure concerned. Inverse analysis can be obtain as follows:

The first step of the inverse analysis is to derive the relation between the curvature of deflection line and the corresponding (the bending moment – curvature diagram) from the load – deflection diagram obtained by a laboratory test. In a bending test of a beam (Fig.15) we obtained load F(z) – deflection z diagram. Flexure of the central part of a beam is defined by increasing curvature of a deflection line k_s. If the effect of shear on deflection is taken into account (equation (1)), the deflection of a centre of the rectangular beam (width *b*, height *h*) is given by

$$z = \frac{5}{8} a^2 k_s + \frac{F(z) a^3}{3EI} + 1.44 \frac{F(z) a}{Ebh} \qquad (1)$$

where I is moment of inertia of the beam.
The initial modulus of elasticity E is determined from the early stage of the bending test.
This formula allows to express the curvature of deflection line of the central part of the beam

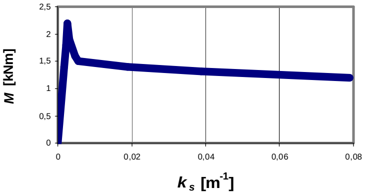
$$k_s = \frac{8}{5a^2} \left(z - \frac{F(z) a}{Es^2} \left(4 \frac{a^2}{s^2} + 1.44 \right) \right) \qquad (3)$$

where the dependent variable F(z) is load and ***z*** is a span of the beam.

Corresponding bending moment in the central part of the beam is

M(z) = F(z) a (4)

By combining equations (3) and (4) we obtain demanded bending moment M - curvature k_s diagram.



Figue17: Diagram relating bending moment M to curvature k_s of the central part of the beam (simplified)

The second step of inverse analysis is finding a stress – strain diagram which fits in tests discovered behaviour in flexure defined by bending moment - curvature diagram (Fig. 17).For structural analysis, the input of stress – strain diagram is reduced to an idealized form given just by several parameters e.g. as in Fig. 18, where the idealized stress - strain diagram of the material in tension is determined by five depicted parameters. Calculation of ordinates of the stress – strain diagram is carried out for a layered model: for strain ε stress σ is determined according to the diagram in the Fig.17. The procedure consists of repeated computation of bending moment – curvature relation with varying combination of input parameters from the Fig.17.: the reasonable ranges of parameters are set, these ranges are divided into a suitable number of intermediate values, computational runs are performed with combinations of intermediate values. Application of the least-square method leads to the computational run that approximates the bending moment – curvature relation obtained from the laboratory test.

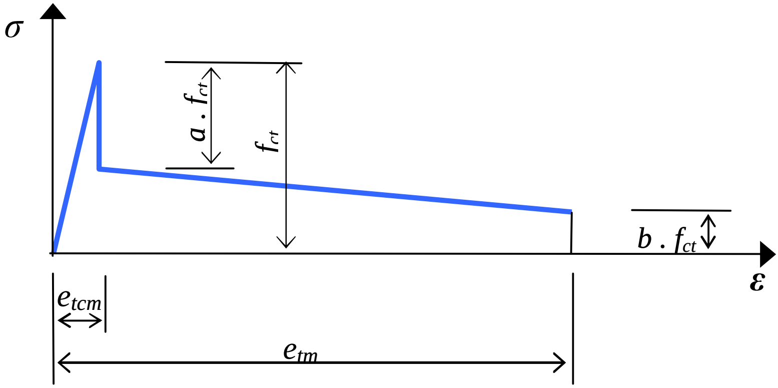


Fig. 18. Stress - strain diagram of the material in tension

5. APPLICATIONS OF FIBER CONCRETE IN STRUCTURES

Assertion of fiber concrete in prefabrication has these main advantages: The application of FC is profitable if homogeneity of FC is assured. Experience shows that homogenous mixture by adding of fibers into concrete agitator (truck-mixer) is impossible. Control of manufacturing in a precast-plant ensures proper fiber distribution in the mixture.The choice of a fiber type is determined by demanded properties of the resultant FC: Synthetic fibers provide ductility and fire safety. In case of big profiles of longitudinal reinforcement and thus high cover synthetic fibers prevent spalling of cover layer and ensure sufficient durability of a structure. Synthetic fibers usually do not enhance physical-mechanical properties of the material. Steel fibers enhance physical-mechanical properties and ductility.

5.1 Fiber concrete in prefabrication

Research findings clearly establish that ductility of certain structural members can be greatly enhanced with the use of fibres. In addition, fibres generally favour improvements in first crack and ultimate member strength, impact resistance, and shear resistance. If properly designed, fibres can add to member structural performance even when used together with conventional steel main reinforcements (rebars). Precast cornice plates and crush barriers were selected for application FRC in bridge accessories construction, circle sewer pipes of big diametre as an example of common concrete products of industrial manufacturers and prestressed girders as an application for building construction. Structural analyses of fiber concrete members of different levels were performed to choose a convenient type of fiber concrete for particular members and to verify the way and procedures of analysis of fiber concrete structural element. Some highlights of these findings and experience are summarized in the section below.

5.2 Choice of suitable type of fibre concrete

In a pilot study conducted within a project supported by the ministry of industry and trade of the Czech Republic in cooperation with construction industry concerning design methods and practical application of various types of fibre concrete two types of simple precast elements for bridge accessories in the sphere of bridge construction were tipped for testing in the production plant. For both groups of precast concrete members intended for application of FRC it is necessary to choose different efficient type of fibre concrete with suitable mix composition. The reasons are differences in loadings and conditions acting on members during their service life. Precast elements of bridge cornices - covering plates are auxiliary elements without load-bearing function, but crash barriers have to resist impact loads of vehicles and safety of their design is very important. On the other hand both elements have in common that they are usually designed only according to constructional provisions so that they should resist mechanical damages caused by traffic and various environmental exposures including areas subject to freeze thaw. The result of the study was that concrete with structural synthetic fibres is the best solution for cornice plates and concrete with steel fibres is the most suitable material for barriers due to its greater toughness and increased tensile strength in comparison to plain concrete. Both selected fibre concrete materials have good ductility needed for elements exposed to severe conditions on bridges concerning changes of temperature and humidity. This testing is on-going and recently surpassed.

5.3 Bridge cornice plates and curbs

The cornice is not a load-bearing part of the bridge; nevertheless it can be subjected to substantial strain, salts treatment and atmospheric effects. Cracking due to volumetric changes must be prevented for this element. Because of aesthetic requirements on cornice, to provide bond of anchors and prevent corrosion and pull-out of anchoring elements. fiber concrete may be a contribution to better service, behaviour and durability of the element. Other problem that may be solved by use of fiber concrete is cracking and failure during transport and resulting fall of the element and injure of pedestrians and damage of passing vehicles. With respect to demands on durability of the cornice and risk of corrosion SSFRC with polypropylene fibers was chosen for the manufacturing of this fiber concrete element. Bridge curbs are similar elements with posibly more complicated and variable shapes and one type is also intended FC production.

5.4 Production of selected FRC elements

Transition from an intention of an FRC application to the actual production of an element is very demanding process. Therefore only simple elements were tipped for the first phase of production. Operating conditions in a production plant are different from conducting laboratory studies. Harmonized components of concrete mixture had to be adjusted and technological process should be verified for selfcompacting type of concrete. By concreting of plate elements real applicability of production for cornice plates was proved. The procedure of production of fresh fibre concrete and casting concrete into the form is documented on the following photos the (Fig. 1 a 2)

Figure 19 Filling of the forms

Figure 20. Manufactured bridge cornice plate, location in the bridge

5.5 Sewer pipes

The aim of the joint work is finding out members, where use of fibers will be a contribution, determination of a convenient type of fiber concrete and verification of manufacturability of the fiber concrete element. Sewer pipes are made in two shapes: one from plain concrete, second from reinforced concrete. Pipes made from plain concrete have satisfactory load-bearing capacity, but after the first crack is formed a brittle failure of the pipe follows. Reinforcement which consists of main spiral reinforcement and secondary longitudinal reinforcement avoids brittle failure of the pipe, but anyway after forming of the first crack the use of the pipe is restricted on account of wide cracks and lost of watertightness of the sewer pipe. Fiber concrete may solve both problems mentioned; fiber concrete members fail in a non-brittle mode and cracks have more favourable lay-out and may satisfy demands on water-tightness. Four types of fibers (steel and polypropylene) were investigated in pipes of two diametres and by means of structural analysis and testing optimal solution was found for both types of pipes (plain and RC)

Figure 21. Structural analysis and testing of a sewer pipe

5.6 Prestressed precast beams

Analysis and tests were performed with prestressed beam from self-compacting concrete (SCC) with dispersed steel- fiber reinforcement. The beams had no conventional shear reinforcement. Experiments proved that the fiber concrete beam had considerably high ductility and sufficient shear resistance even without the stirrups. Advantage is that eventual holes for service equipment may be drilled additionally without essential decrease of the load-bearing capacity. This is important point for economy of production because big series of identical beams may be manufactured.

5.7 Preparing procedure of new applications of FC in prefabrication

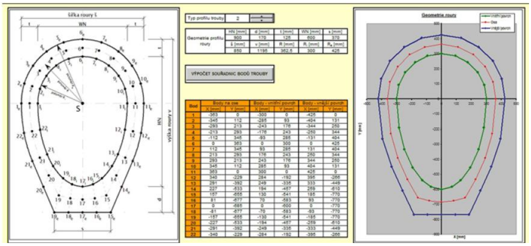
In several research projects new possibilities of fiber concrete exploitation in precast elements is analysed. In the process usually the stress-state of the loaded element is calculated. The complexity levels are various from the simple

Figure 22.a) Experimental beam loaded with concrete sleepers, b),anchorage zone

calculation based on elastic analysis to more sophisticated analysis by means of nonlinear FEM. After determination of the element behaviour a suitable fiber concrete is sought. The laboratory specimens with different fiber types are tested and analysed to optimise material with properties corresponding with the structural element behaviour.

5.8 Oval sewer pipes

For application of fiber concrete in a precast element an oval egg-shaped sewer pipes were chosen. The reason was a crack that occurred in the lower part of the pipes usually after some time mainly during storage of pipes. A first task of analysis was determination of the stress-state of the pipe. A spreadsheet was prepared for calculation of the section. The spreadsheet is linked to the computer program HUTEM for analysis of stress and strain due to drying and shrinkage. The further tasks are determination of suitable fiber concrete and verifying of the fiber concrete manufacturability and workability in the producers manufacture and optimising of the fiber concrete mixture in test and a pilot-plant.



Typ profilu trouby: 2

Geometrie profilu roury	HN [mm]	d [mm]	t [mm]	WN [mm]	s [mm]
	900	170	125	600	370
	š [mm]	v [mm]	R [mm]	R_i [mm]	R_e [mm]
	850	1195	362,5	300	425

Bod	Body na ose		Body - vnitřní povrch		Body - vnější povrch	
	X [mm]	Y [mm]	X [mm]	Y [mm]	X [mm]	Y [mm]
1	-363	0	-300	0	-425	0
2	-345	112	-285	93	-404	131
3	-293	213	-243	176	-344	250
4	-213	293	-176	243	-250	344
5	-112	345	-93	285	-131	404
6	0	363	0	300	0	425
7	112	345	93	285	131	404
8	213	293	176	243	250	344
9	293	213	243	176	344	250
10	345	112	285	93	404	131
11	363	0	300	0	425	0
12	340	-229	284	-192	395	-266
13	291	-392	249	-335	333	-449
14	227	-533	194	-457	259	-610
15	157	-655	130	-541	185	-770
16	81	-677	70	-583	93	-770
17	0	-685	0	-600	0	-770
18	-81	-677	-70	-583	-93	-770
19	-157	-655	-130	-541	-185	-770
20	-227	-533	-194	-457	-259	-610
21	-291	-392	-249	-335	-333	-449
22	-340	-229	-284	-192	-395	-266

Figure 23. Spreadsheet – input form

5.9 Anchorage zone

The aim of this research is substitution of rebar reinforcement with dispersed reinforcement (SFRC – Steel fiber Reinforced Concrete) and simplifying of the anchorage zone reinforcement. In the preliminary analysis a stress distribution and cracking behaviour of anchorage zone was solved. To predict behaviour of an experimental specimen simulation was performed in finite element program. A fiber concrete block 450x450x900mm with an anchor VSL CS 2000–6-12 which provides loading of the specimen was investigated in the FE analysis. Three types of reinforcement were assumed: spiral reinforcement, minimal stirrups´ reinforcement and without reinforcement. The limiting width of crack 0.2 mm was the followed-up criterion. Results of the FE analysis on Fig.22 : the layout of crack for three types of specimens; left – with spiral reinforcement, centre – without conventional rebar reinforcement.

6 CONCLUSIONS

Significance of FRC is not only in improvement of the performance of FRC in comparison to the plain concrete but also in synergic behaviour in RC and prestressed concrete structures. For application of FRC in structural members it is necessary to ensure not only appropriate material and production technology but also adequate methodology for design. In experimental program several sets of beams have been tested to investigate the influence of polypropylene fiber reinforcement and steel fiber reinforcement on the mechanical behaviour of conventionally reinforced concrete beams in bending. The test results showed that the flexural crackig (crack formation, crack patterns and crack propagation) varied significantly as fiber content increased and improvement in ultimate resistance and ductility of the beams was also achieved. The present study indicates that steel fiber reinforcement and polypropylene fiber reinforcement either can reduce crack width and deflections and improve defomation capacity and toughmess of beams and that the combination of polypropylene fibers, longitudinal steel bars (without stirrups) may meet strength and ductility requirements. However steel fibers are more efficient. Data from simple experiments are used for determination of material model by inverse analysis. A numerical simulation with the material model by nonlinear FE method is used to predict behaviour of reinforced concrete beams containing polypropylene fibers and comparisons are made with the present test data. The results from measurements are accompanied by discussions of parameters affecting flexural behaviour of tested beams. Some recommendation for limit values of deflections of the beams considering different amount of fibers are proposed. Submitted results from the case studies are directed to preparation of recommendations and regulations for design of structural members considering post-peak behaviour in dependence on crack width and limit of deflections and discussing consequences of different values of such limits on ultimate resistance and service life.

The future of cementitious composites with fibers lies primarily in production of subtle, thin-walled or lightened structures where ultra high performance concrete is exploited. For conventional FC of common classes the benefits of fiber reinforcement must be thoroughly analysed and proved in each case.

The actual expansion of fiber concrete utilisation is affected by many aspects of present situation in construction industry and depends on the the interest of contractors, ie.especiallly on the cost of such a structure. Therefore the application of fiber concrete in precast elements must be assessed from many points of view and optimized not only for production cost but for the entire service life. In particular, proper fiber type must be chosen, suitable mixture shall be designed according to the loading, stress-state of the structural element, its exposure and other conditions including production technology. for appropriate application. Some applications can contribute to sustainable construction and environmental requirements.

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Curriculum vitae

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Professional Positions:

1978 – 83 Postgraduate research student, Czech Technical University, Civil Engineering, Prague
1983 - 92 Designer - analyst, PÚ VHMP (Design Institute of Prague Construction)
1992 - 1994 Research fellow, Klokner Institute, CTU, Prague
1995-2003 Assist. Professor, Dept. of Concrete Structures and Bridges, Civ. Engrg., CTU, Prague
since 2004 Associated Professor, Dept. of Concrete and Masonry Structures
since 2004 Head of the Dept. of Concrete and Masonry Structures

Education:

MSc. (Ing.) June 1978, Czech Technical University, Civil Engineering, Prague
Ph.D. (CSc.) November 1985, Czech Technical University, Civil Engineering, Prague
Assoc. Prof. (doc.) 2004, Czech Technical University, Civil Engineering, Prague

Awards:

2000 price of the Dean of he faculty for outstanding results in education
2005 price of the Dean of he faculty for outstanding results in research
2006 price of the Dean of he faculty for outstanding results in research

Publications:

Author or coauthor of 4 monographs, 4 paper in international reviewed journals, 40 contributions in the proceedings of the international conferences, 20 papers in the czech journals, 85 contributions on the international conferences, 12 invited lectures at the universities in the USA, G.Britain, Germany

Teaching activities

Concrete structures, design, technology and construction, also in English in the courses of Concrete Structures 2, Concrete Structures 3, Concrete Structures 4, Modelling and reinforcing of concrete members, supervising of the Bachelor thesis, advisor of 27 defended diploma thesis, advisor of the doctoral students (5 defended doctoral thesis)

Research activities

Analysis of reinforced, prestressed, composite concrete structures, design of fibre reinforced structures, serviceability models of bridges, excessive deflections of prestressed bridges, material modelling, concrete creep and shrinkage, FEM analyses, computational mechanics, identification of materials, recycling of concrete, estetics in concrete design properties and behaviuor of composite materials with cement matrix reinforced with fibers, leader of the research teams of 9 contracted research projects of the Czech Science Foundation, Ministry of Industry, Ministy of Education and ESF

Membership in International Associations:

fib, TG 4.1, Serviceability models, SEFI, IABMASS

Membership in National Associations:

Czech Concrete Society

Visiting Positions:

National Technical University of Athens, short courses in 1999, 2000, 2001
University of Wales, College of Cardiff , September 2004
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Selected publications

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