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APPLICATION OF INNOVATIVE MATERIALS IN PRECAST CONCRETE STRUCTURES

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Construction industry contributes essentially to Germany's gross domestic product (GDP). In 2015 construction investments amounted around 300 billion Euro corresponding to a share of 10% of total GDP. Because of the essential importance of construction industry there are many activities aiming on reduction of construction costs and improvement of durability and sustainability. Recent tendencies in precast concrete industry include application of innovative materials like self-compacting concrete, fiber reinforced concrete, textile reinforced concrete, carbon concrete composite and strain hardening cementitious materials. The report describes the material developments and first applications for precast concrete members. By the application of non-metallic reinforcement, such as carbon meshes and carbon bars, there is no corrosion risk for the reinforcement resulting in an essentially lower concrete cover and depth of structural members. However, the use of carbon reinforcement requires new design concepts and new construction methods. By solving these problems there is a big chance for precast concrete industry to enhance their market share.

Keywords: Precast concrete, Self-compacting concrete, Fiber reinforced Concrete, textile reinforced concrete, Carbon concrete composite, Strain-hardening cementitious composites.

1 INTRODUCTION

Construction industry is one of the big players in Germany's economy. In the year 2015, construction investments amounted nearly 300 billion Euro. It is corresponding to a share of 10% of the total gross domestic product of the country. Germany's cement consumption is a little more than 30 million tons per annum. Because of the obvious importance of construction industry, there are numerous activities aiming on reduction of construction costs, improvement of durability and better sustainability.

The sales of Germany's precast concrete industry have been 5.6 billion Euro in 2015. This is only a small part of total construction investments but precast concrete industry traditionally is open-minded for implementation of innovations. So many new trends in civil engineering have been started in precast concrete industry. Recently, new innovative construction materials like self-compacting concrete, fiber reinforced concrete, textile reinforced concrete, carbon concrete composite and strain hardening cementitious materials were applied for production of precast members. Steel mesh and bar reinforcement is partially substituted by non-metallic materials. This tendency is motivated by the fact that a non-metallic reinforcement does not need protection from corrosion. So, the concrete cover can be reduced and durability is improved. The dimensions of the cross section can be limited to values that are necessary for load bearing. This allows to design and to construct light and resource-efficient members suitable for large spans. In the following chapters, some of the new developments are reported.

2 INNOVATIVE CONCRETES FOR PRECAST CONCRETE INDUSTRY

2.1 Self-Compacting Concrete

Self-compacting concrete (SCC) was developed at the turn of the millennium. There are no statistical data available about the applied amount of SCC in Germany's precast concrete industry. But there is no doubt that SCC is the preferred solution for architectural concrete and other members with high demands on surface quality. It is one of the main advantages of members made of SCC that their surface is uniformly colored and widely without any pores or other defects. Even complicated surface geometries with sharp edges can be produced easily. This benefit is mainly used for façade, stair, slab and wall elements. An outstanding example for the high technical performance of SCC is the façade of the Vorarlberg Museum in Bregenz, Austria. Though it is not precast but in-situ concrete there is an excellent surface quality of the exterior wall made of SCC, see Figure 1.

Other issues are the high durability of SCC and the improvement of working conditions in the precast concrete plant as a result of noise reduction (Holschemacher *et al.* 2017).

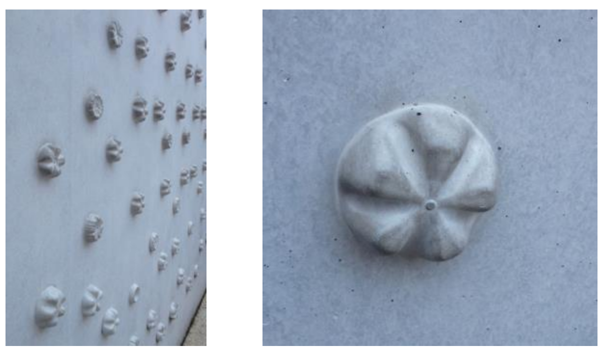

Figure 1. SCC-wall of the Vorarlberg Museum in Bregenz, Austria.

2.2 Fiber Reinforced Concrete

For production of fiber reinforced concrete (FRC) short fibers of different materials (e.g. steel, polymer, glass, basalt, carbon) are used. FRC offers a better ductility, cracking behavior and fire resistance in comparison to ordinary reinforced concrete. By application of fibers it is possible to reduce the steel mesh and bar reinforcement or to replace them. Because of its advantages, FRC is an often-utilized construction material in precast concrete industry for many years.

A new development is the use of alkali-resistant macro glass fibers for construction of load bearing members. In past, glass fiber reinforced concrete was almost exclusively applied for non-structural members like façade elements or concrete products. In a recent research project, it was found out that the hardened properties of structural glass fiber reinforced concrete are comparable to those of steel fiber reinforced concrete (Löber *et al.* 2015, Heiden *et al.* 2015). The used macro glass fibers had a length of 36 mm and an aspect ratio of 67, see Figure 2. Typical load-deflection curves were investigated in four-point bending tests with specimens measuring 15 x 15 x 70 cm according to Germany rules for steel fiber reinforced concrete (Figures 3 and 4).

Figure 2. Alkali-resistant macro glass fibers.

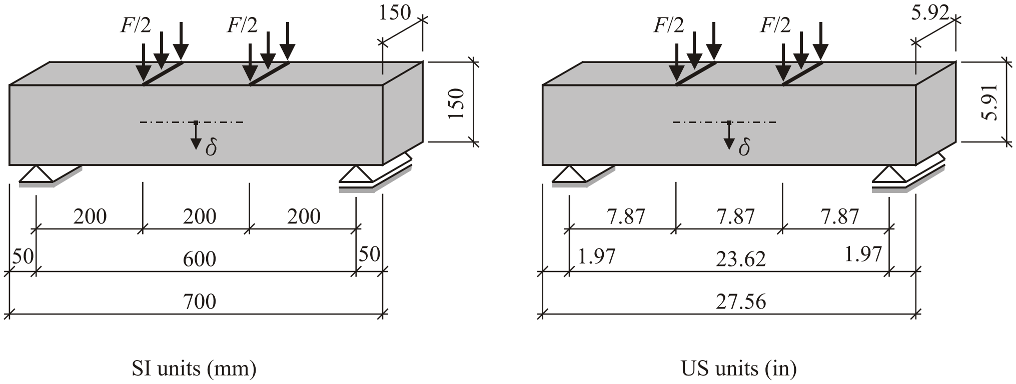

Figure 3. Specimen for four-point bending tests.

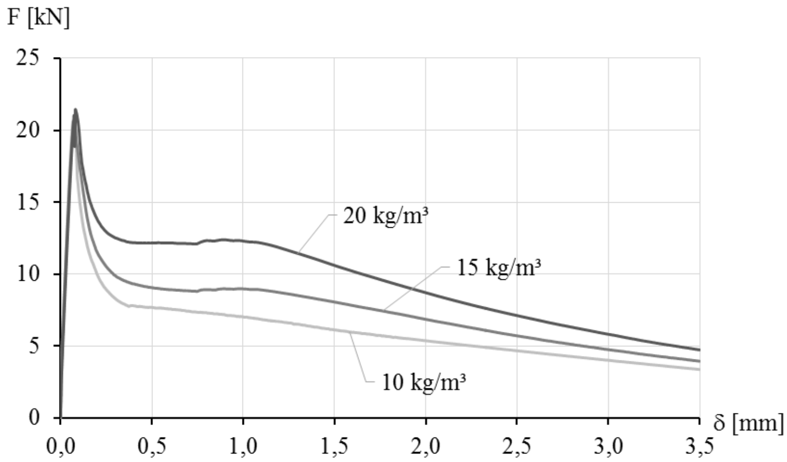

Figure 4. Load-deflection curves of structural glass fiber reinforced concrete members for different fiber amounts.

Results of the four-point bending tests indicate clearly that structural glass fiber reinforced concrete is a suitable material in highly statically indeterminate systems like slabs on ground. But it is also appropriate for precast concrete members predominantly under compression like walls. Therefore, first applications of structural glass fiber reinforced concrete in precast concrete industry are expected soon.

2.3 Textile Reinforced Concrete

Textile reinforced concrete (TRC) consists of a textile mesh and a special high strength fine grading concrete with a maximum grain size of 2 mm. First investigations about TRC were carried out in Germany in the 1990s. It was tried to establish textile meshes as non-metallic reinforcement whereby yarns made of alkali-resistant glass fibers were mainly applied.

The development of TRC started with high expectations. But it became obvious very soon that some problems are arising when TRC is applied in practice. In this context are to count the following facts:

- Because of the poor stiffness and low density of textile meshes it is difficult to fix the mesh position during casting the concrete.
- It is necessary to develop a new production technology for members of TRC. Adapting the traditional methods suitable for steel bar or mesh reinforcement is not possible. Precast concrete technology is traditionally adjusted on materials with magnetic properties like steel. If non-metallic materials are used, new ideas for transportation and assembling of textile meshes are needed.
- The bond between yarn and surrounding concrete is a quite complicated issue. Only the outer filaments of the yarn are in direct contact to the concrete matrix and have a good bond. The inner filaments have only direct contact to other filaments but not to the matrix resulting in a non-uniformly strain distribution over the section of the yarn. Consequently, there is a significant gap between the ultimate strength of one filament and the design strength of the yarn.
- The cross-sectional area of usual textile meshes is relatively low because the mesh with must not be to low for sure casting of concrete. Especially for structural members, often more than one layer of textile reinforcement is necessary. But then there will be difficulties in the production of the members. In such cases a very flowable concrete is needed otherwise the probability of imperfections in the concrete structure are quite big.

Nevertheless, TRC is a product for special application cases today. TRC is well suitable for light façade elements. Furthermore, some bridges were constructed using TRC and finally, there are numerous applications in the context of strengthening of existing structures.

2.4 Carbon Concrete Composite

The basic idea for development of carbon concrete composite in Germany was to combine the existing TRC experience with application of carbon fibers and the implementation of new design concepts. Based on these requirements the development of carbon concrete composite is a special challenge for researchers. One of Germany’s biggest research projects called C^3 is dedicated to the investigation of construction with carbon concrete composite.

Carbon fibers have outstanding material properties. A comparison to other building materials is given in Table 1. There is a wide diversity of available carbon fibers (Figure 4). For application in carbon concrete composite meshes, bars and short fibers are taken into consideration. Beside the new design concepts this mix of reinforcement is one of the main differences between TRC and carbon concrete composite.

Table 1. Material properties of different fiber materials (Holschemacher *et al.* 2017).

	Density	**Modulus of elasticity**	**Tensile strength**	**Ultimate strain**
	g/cm^3	GPA	GPa	%
Steel fibers	7.85	160-210	0.3-3	1-10
Polypropylene fibers	0.9	1.3-10	0.2-0.4	5-15
Alkali-resistant glass fibers	2.68-2.70	72-80	1.5-3.7	1.5-3.6
Basalt fibers	2.6-2.8	90-110	4.8	<4.0
Aramid fibers	1.44	30-130	0.6-2.9	1.8-4.4
Carbon fibers	1.8	240-600	3.0-5.0	0.5-2.5

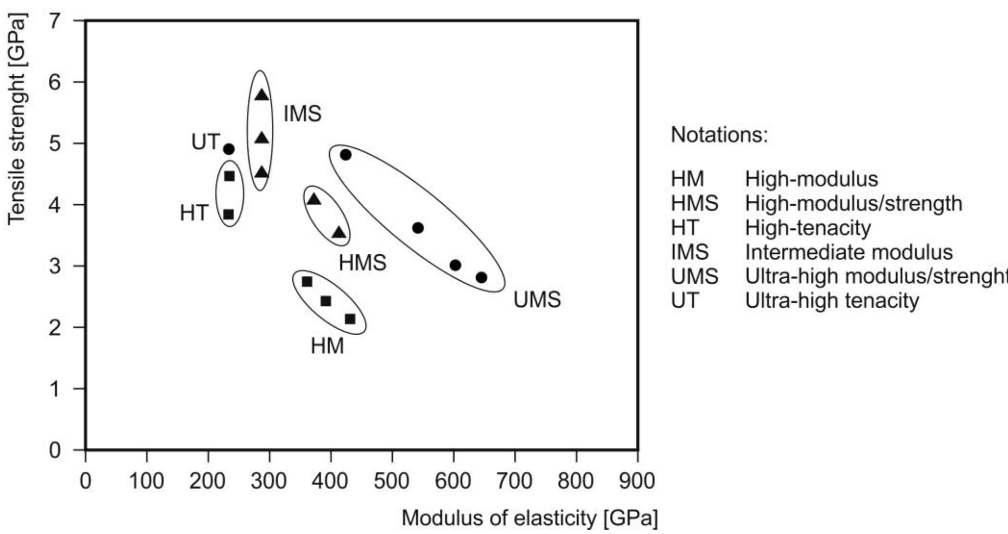

Figure 4. Diversity of carbon fibers (Ehrenstein 1992).

Though the research about carbon concrete composite has taken just the first steps, there are already notable applications in practice. These include Frenzel *et al.* (2014), Scholzen *et al.* (2016), and Helbig *et al.* (2016):

- Precast balcony slabs
- Single curved barrel-vault shells
- A bicycle and pedestrian bridge with a span of 15 m and a width of 3 m
- Numerous examples for strengthening and repair of old shell and vault structures, reinforced concrete slabs, silos and bridges.

Even very exceptional constructions are possible when using carbon concrete composite. At HTWK Leipzig, students constructed a canoe where this material was applied for the boat hull. The students were very successful with this boat. In 2016, they won 6 of 9 races while the Netherlands Concrete Canoe Competition in Arnhem (Figure 5).

Figure 5. Successful HTWK Leipzig students' canoe team with their canoe from carbon concrete composite.

3 SUMMARY

In Germany's precast concrete industry, the application of innovative building materials becomes more and more popular. Especially, carbon concrete composite opens new possibilities in the construction of precast concrete members. The usage of the new and innovative materials is undoubtedly a progress but new design concepts are needed as well. By the erection of first carbon concrete composite structures, the high potential of this construction method could be already demonstrated. But the complete possibilities connected with carbon concrete composite are not conceivable yet. The future of carbon concrete composite has just begun.

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