Mueller, U. et al., 2017. Textile Reinforced Reactive Powder Concrete and its Application for Facades. In HPC/CIC TROMSØ 2017. Tromsö, Norway.

Paper no. 53

Textile Reinforced Reactive Powder Concrete and its Application for Facades

Urs Mueller
CBI Betonginstitutet, Sweden
Natalie Williams Portal
CBI Betonginstitutet, Sweden
Mathias Flansbjer
SP Sveriges Tekniska Forskningsinstitut
Katarina Malaga
CBI Betonginstitutet, Sweden

Abstract

Reactive powder concrete (RPC) is a fairly novel material with extraordinary strength and durability properties. Due to these properties, it is increasingly being utilized also for external facade cladding thus enabling a considerable reduction in the thickness of concrete elements. Commercial RPC formulations on the market have drawbacks in terms of sustainability due to their high clinker content and heat curing which is often applied to increase final strength and material density. The presented study focusses on improved formulations with higher replacement levels of cement clinker by supplementary cementitious materials (SCMs). One different mix formulation was designed and tested in terms of mechanical properties. The formulation was combined with carbon textile reinforcements primarily to enhance the flexural and tensile behavior of the material. The results showed that even with clinker replacement levels of up to 33 % of the total binder amount, a satisfactory mechanical performance of the RPC mix could still be achieved. Fairly steep strength gains rendered heat treatment unnecessary. The incorporation of carbon textile fiber grids proved to be effective in improving the post peak performance of the RPC. However, their performance depended strongly on the bond between the carbon grid and the RPC. Higher moister contents in the concrete proved to reduce the bond strength between the carbon textile and the cement paste. This is maybe less relevant for facades but structural elements with textile reinforcement and RPC might perform less well in completely submerged environment.

Key-words: Reactive powder concrete, textile reinforcement, flexural behavior, mineral additions

INTRODUCTION

Since the 60’s and 70’s, pre-fabricated modular concrete buildings dominated the city landscapes in Europe. During this time demand for affordable housing increased drastically and the pre-cast production of standard steel reinforced concrete (RC) elements for buildings helped to mitigate this situation. Reinforced concrete has excellent load and durability properties. However, one disadvantage of RC is the thickness of elements, which measures usually around 80 mm for a single concrete panel and which is due to the necessary concrete cover on both sides of the reinforcement. The risk of corrosion of the steel reinforcement due to carbonation and to a lesser degree due to chloride ingress with subsequent spalling of the concrete cover is a frequent reason for limiting the durability of RC facades.

Over the last 15 years, advanced mineral based materials were developed enabling to drastically reduce the thickness and mass of pre-cast façade elements. This is accomplished by using alternative non-corroding reinforcement materials, enabling to minimize the concrete cover thicknesses. These new reinforcement options are used in with cement based high performance and ultra-high performance materials. Examples for such new materials are textile reinforced concrete (TRC) and fiber reinforced ultra-high performance concrete (FRUHPC). TRC and FRUHPC have had already applications in form of ventilated façade claddings [1] or as sandwich elements [2]. More and more

FRUHPC is used as façade material due to its extraordinary high strength and durability [3-5]. Prominent structures are the Jean Bouin football stadium in Paris, France or the MuCEM in Marseille, France. Both examples consist of perforated, partially structural, façade applications realized with FRUHPC.

Reactive powder concrete (RPC) is a variant of ultra-high performance concrete with a maximum aggregate size of 2 mm or below. Ultra-high performance concrete (UHPC) shows a maximum aggregate size of 8 mm. Both concrete types have compressive strengths above 120 MPa and a very low amount of capillary pores. Due to the high strength these materials behave strongly brittle. This brittleness is addressed by the incorporation of fibers or textile reinforcements, creating a quasi-ductile behavior (usually achieved by steel fibers) or to mitigate sudden failure by controlling cracking under strain hardening [6]. In façade applications steel fibers may cause brownish spots on unprotected concrete surfaces due to corrosion of the fibers. This is not a structural defect but an aesthetical impediment. To prevent this, additional coating of the concrete surface is required. Non-ferrous reinforcements such as carbon fiber textiles are therefore more suitable for façade applications. Glass fiber textiles seem to be less stable in alkaline environments, even with so called alkali resistant class fibers [7].

The goal of this paper was the investigation of the behavior of carbon fiber textile grids in reactive powder concrete. Furthermore, the replacement of the high cement clinker content of RPC by a partial replacement with supplementary cementitious materials (SCM) was explored. An important point was also to be able to mix the RPC in a standard forced action mixer for concrete with a minimum use of super plasticizer. The study was performed within the EC funded project SESBE “Smart Elements for Sustainable Façade Envelopes”. Textile reinforced RPC is used in this project as an outer and inner layer for innovative non-load bearing sandwich elements. Durability aspects were reported elsewhere [8]. One focus of the project was the functionalization of materials which will not be reported here.

BASIC RPC MIX DESIGN

The starting materials consisted of those listed in Table 1. A first initial step in the design was to optimize the mix proportion based on the particle size properties of the materials. The optimization was carried out according to the Modified Andreasen model for fine particles [9]. The model is based on minimizing the packing density by a continuous distribution of the particle sizes. Andreasen assumed that an array of particles around every particle is similar regardless the size of the particles. The model was later modified by Dinger and Funk [10] by introducing the smallest particle size in form of the Modified Andreasen model.

Table 1 – Starting materials for the RPC mixes.

Components
CEM II/A-V 52.5
Fly ash class F
Silica fume
Quartz filler
Sand 0/1 mm
Super plasticizer
Tap water

The actual modeling was performed with a publicly available software (Emma by Elkem AS). As input data the particle size distribution of the single materials have to be provided. The program calculates the Modified Andreasen size distribution curve for a multi particle size fraction mix based on the minimum and maximum particle size as well as the distribution modulus. By adjusting the relative amounts of the given material size distributions the cumulative RPC size distribution can be adjusted towards the Andreasen model curve.

In a second step, the mix proportions were fine adjusted by determining the optimal particle packing via Puntke-tests [11]. The test refines the packing density since particle size optimization alone still allows fairly large variations in the amounts of the single components. With the Puntke-test the minimum water demand is measured from where a granular material starts to flow. The test can be performed for single materials or for mixtures of different materials. The determined minimum water demand, however, is not reflecting the amount of water being later used for mixing the reactive powder concrete but barely an indication for the optimal particle packing and mix proportions.

Figure 1 illustrates the volume proportions of the RPC mix and also shows the differences in composition compared to a standard concrete and a common UHPC mix. The complexity of the RPC mixes is significant, such that a RPC mix can easily consist of six to eight different components and the fine adjustment of those components is essential. If one component changes (e.g. type of cement) the entire mix may need to be re-optimized. As a consequence, RPC and UHPC are considered as not very robust concerning proportioning errors. The industry provides therefore commercial ready mixed RPC/UHPC products for easier use in daily production.

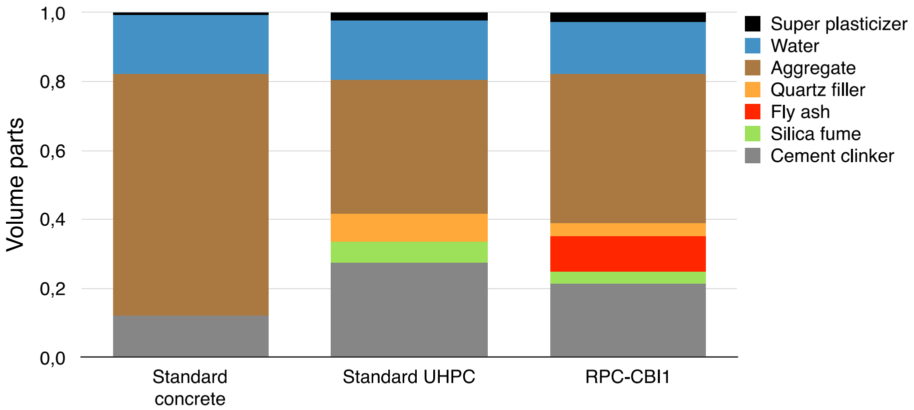

Figure 1 – Volume proportions of the reactive powder concrete mix compared to a standard concrete and UHPC. The illustrated fly ash content of mix RPC-CBI1 includes also the fly ash from the cement.

The mix CBI1 was blended in both, planetary mixers and in forced action concrete mixers. For the latter method the mixing process lasted a little longer due to the lower mixing energy and low water/binder ratios, which were below 0.2. After blending, the mix behaved self-compacting and bleeding was not observed. The slump flow of the mixes after one minute was > 80 cm.

The RPC reinforcement consisted of two types of 2d carbon fiber grids. One grid was manufactured by SGL and had carbon roving of fibers bundles of 24K (thousands of fibers), which were coated by a styrene-butadiene rubber (SBR). The other grid was a 2d carbon fiber grid impregnated with epoxy resin (EP) manufactured by Solidian GmbH (Solidian GRID Q85/85-CCE-21) with the same grid geometry and a similar fiber bundle number. Additionally, grids manufactured by SGL were additionally coated by a composite polymer in order to investigate the bond behavior between reinforcement and the RPC matrix. The composite polymer was developed within the SESBE project.

TEST-SETUP

Some of the mechanical properties were measured without any reinforcement in order to determine the pure material characteristics. This was done for routine screening of the concrete properties (in case of compressive strength) and for gathering input parameters for modeling. The testing program for some of the test included different curing conditions: Curing under water at 20 °C until day of test; curing at 20 °C and 65 % r.h. Table 2 summarizes the test program. The two sizes for panels emerged during the project. It was seen, that to have a double layer of reinforcement grids large scale panels are much more difficult to realize in a thickness of 20 mm such that a thickness of 25 mm was deemed most suitable.

Table 2 – Test program of mechanical tests performed on the mix CBI1.

Test method	Specimen size (mm)	Reinforcement (double layer grid)	Extra polymer coating	Curing under water	Curing at 20 °C, 65 % r.h.
Development comp. strength	40x40x40	-	-	X	
Comp. str., E-modulus, Poison ratio, tensile str.	Ø54x100	-	-	X	
Flexural strength	700x100x20	2d grid with SBR	X	X	X
	700x100x25	2d grid with EP	-		X
Tensile strength	700x100x20	2d grid with SBR	-	X	-
	700x100x25	2d grid with EP	-		X

The strength development was measured by determining compressive strength on cubes at different curing ages of the RPC mix. The test setup followed the standard EN 1015-11 [12] on a servo hydraulic testing machine (ToniComb III, Toni Technik) with a 300 kN load cell. The test was run load controlled and the loading rate was adjusted so that failure of the sample occurred within 60 and 90 s of loading. Tested were 4 to 6 specimens for each age. The compressive strength and the stabilized secant modulus of elasticity were evaluated from compression tests on cylinders according to EN 12390-3 [13] and EN 12390-13 [14] (method B) respectively at an age of 7 days and 28 days. The axial strain was calculated from the axial deformation measurements with a gauge length of 50.5 mm. The direct tensile strength of RPC samples without reinforcements was determined on a universal servo-mechanical testing machine with a load cell of 100 kN (Instron 1195) under load-controlled conditions.

In order to investigate flexural properties of textile fiber reinforced RPC panels, 4-point bending tests were performed. In the tests, at least four panels for each sample were subjected to the test. The tests were performed with a servo mechanical testing machine (Instron 1195). The sample panels were placed on roller supports, which were 600 mm apart (Fig. 2). The samples were then loaded by two upper point loads each applying a load of P/2, which were 200 mm apart. The loading was applied using displacement control with a loading rate of 0.5 mm/min and a pre-load of 100 N. On opposite sides of the panels two linear displacement transducers (LVDT) were placed at midspan. A mean value of displacement was calculated from the two LVDTs.

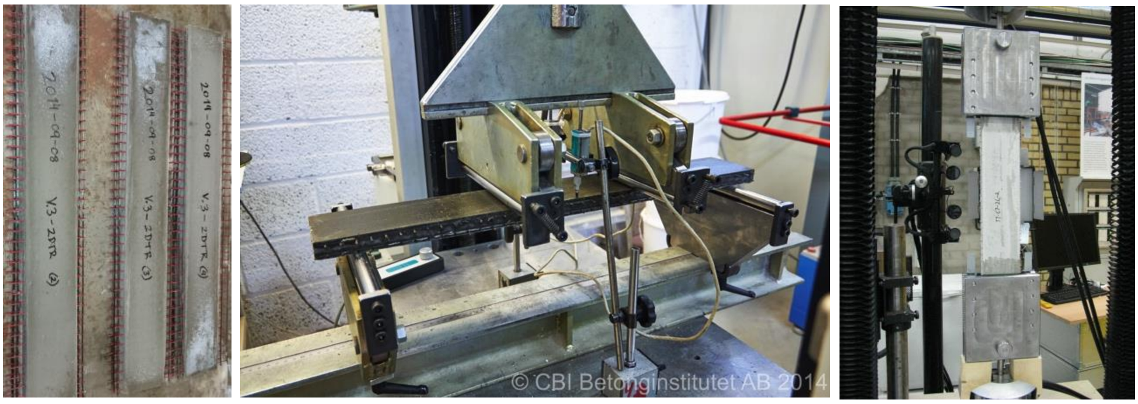

Figure 2 – Panels with carbon fiber grids for bending and tensile tests. Set-up of the 4-point bending test (left) and for the tensile test on panels (right).

To determine the tensile behavior of carbon textiles reinforced RPC panels, uniaxial tensile tests were performed according to the draft recommendations given in RILEM TC 232-TDT [15]. The specimens had the same panel dimensions as for the 4-point bending test. The ends of the specimen were clamped between two stiff steel plates (Fig. 2). The specimen and the clamping devices were aligned in a frame to ensure centric loading. The tests were carried out in a Sintech 20D electro-mechanical universal testing machine with a rated load capacity of 100 kN (Fig. 2). The accuracy of the load measurement is within 1%. The grips were hinged connected to the testing machine. The specimens were preloaded with a force of 500 N. The tests were controlled by the cross-head displacement of 0.5 mm/min until the first crack appeared 1.0 mm/min until the second crack and after that 2.0 mm/min for the remaining test. The load and cross-head displacement were recorded in a data acquisition system with a sampling rate of 10 Hz. The temperature at testing was approximately 22 °C. The deformations and crack developments were registered at one side of the specimen during testing by the use of the optical full-field deformation measurement system ARAMIS™ 12M by GOM (Fig. 2). The system uses a measurement technique based on Digital Image Correlation (DIC) with a stereoscopic camera setup, consisting of two CCD-cameras with 12 Mega pixel resolutions. The basic idea of DIC is to measure the displacement of the specimen during testing by tracking the deformation of a speckle pattern in a series of digital images acquired during the loading. This is done by analyzing the displacement of the pattern within discretized facets of the image.

RESULTS AND DISCUSSION

Specimen without reinforcement

The strength development between 1 and 56 d measured on cubes is shown in Figure 3. The strength gain was rapid: After 1 day ca. 60 MPa, after 7 days over 100 MPa were reached. The difference in strength between 28 d and 56 d were below 5 %. Table 3 gives the results for modulus of elasticity, deformation, Poisson's ratio and measured on cylinders. The modulus of elasticity is high as expected. Between 7 d and 28 d, however, there is not much change in E-modulus anymore.

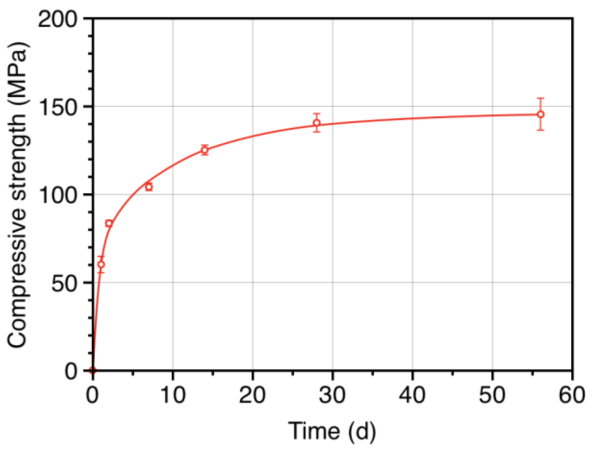

Figure 3 – Development of compressive strength of mix CBI-RPC1. Results are mean values; error bars are standard deviations.

Table 3 – Results for compressive strength, modulus of elasticity, strain and Poison ration. Mean values with standard deviation in parenthesis.

Age (days)	Modulus of elasticity (GPa)	Compressive strength (MPa)	Ultimate strain (‰)	Poisson's ratio (-)	Tensile strength (MPa)
7	46.4 (1.2)	97.2 (6.9)	-	-	-
28	49.7 (1.7)	141.4 (2.8)	3.89 (0.16)	0.216 (0.021)	5.9 (0.3)

Flexural behavior of reinforced panels

Preliminary tests were performed on the mix with sample specimens which were stored submerged in water until the testing age of 28 d and the 2d grid with SBR coating. Results from the flexural strength tests are given in Figure 4. Minimal crack propagation took place, such that one crack appeared and the sample essentially failed. The initial part of the load versus midspan deformation was relatively stiff for the un-cracked specimens. The crack formation was brittle and a clear load drop in the load-deformation relation characterized the onset of a crack. Some smaller load drops could be attributed to minor cracking within the clamping length (Fig. 4). The observed behaviour is different to test results from textile reinforcement in standard or high strength concrete, wherein the textile reinforcement increases the ductility of the material to a certain level by distributing the load along the textile grid [6] resulting in a multitude of small cracks within one panel. The fact that the load does not increase past the first cracking load in the RPC panels indicates that an insufficient level of stress for causing further cracking was present within the RPC. This was due to the insufficient bond length between the carbon grid and RPC matrix.

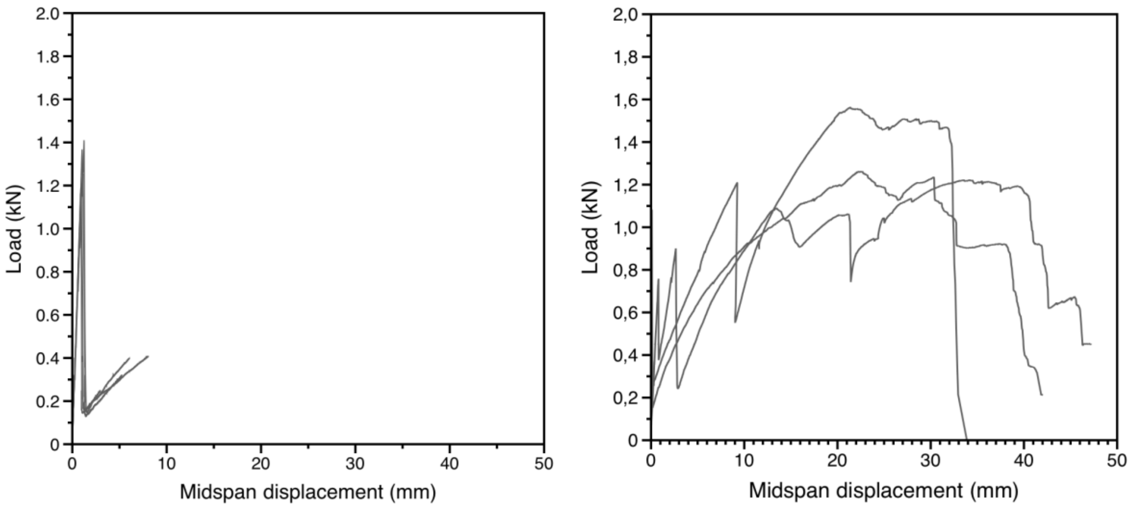

Figure 4 – 28 d results from 4-point bending tests of 20 mm thick panels with a 2 d carbon fiber grid with SBR coating. Specimen stored in water at 20 °C (left) and in air at 20 °C, 65 % r.h. prior to the test.

The results of specimen stored at 20 °C and 65 % r.h. for 27 d showed improved different results (Fig. 4). Here, even though similar maximum loads were achieved, displacement values were much higher and the panels showed multiple cracks after the tests. This indicated that the water content is important towards the bond between the cement paste and the carbon grid. It was clear in the case of the styrene butadiene rubber (SBR) coating that the bond behavior between the carbon grid and the matrix in water saturated RPC was significantly weakened. In order to see if the bond behavior of the SBR can be improved an additional polymer clay nanocomposite (PCN) was applied to the grid in two coating layers. The PCN was developed within the SESBE project and consisted of a polyvinyl alcohol smectite composite [16]. The PCN is hydrophilic and the thickness of the layer was below 0.5 mm.

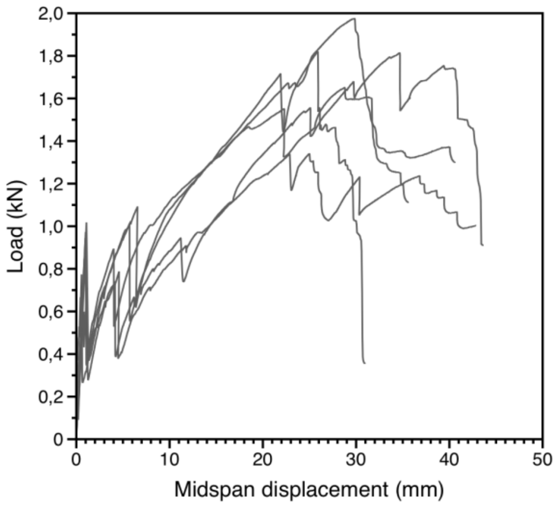

Figure 5 – 28 d results from 4-point bending tests of 20 mm thick panels with a 2d carbon fiber grid with SBR and PCN coating. Specimen stored in air at 20 °C, 65 % r.h. prior to the test.

Figure 5 shows the results of 4-point bending tests with PCN coated carbon grid reinforcement. Though the midspan displacement range is almost the same as in Figure 4 (right), an overall increase in load capacity could be observed.

RPC specimen with the epoxy coated 2d grid from Solidian showed different behavior. The main results from the four-point bending tests are shown in the Figure 6. First cracking of the specimen should take place upon reaching the tensile strength of the concrete matrix, which in this case was in general considerably lower than in Figure 4 and 5. It is thought that the cause of the apparent lower bending strength at first cracking could be due to: presence of initial shrinkage cracks, curing method in a climate room (20°C, 60% RH). Following initial cracking, tensile stresses were transferred to the textile reinforcement allowing for the formation of multiple cracking (marked by load drops) accompanied by a minimal increase in load. The crack formation eventually stabilized and was marked by a noticeable gain of stiffness said to be governed by the properties of the textile reinforcement. Certain specimens failed according to textile rupture, while all other specimens remained intact with notable surface spalling particularly in the central loaded region. These results with the EP coated reinforcement grid revealed a significant improvement of the flexural behaviour compared to the SBR grid. This is due to the improved bond between the matrix and reinforcement leading to the efficient use of the embedded textile fibre grid.

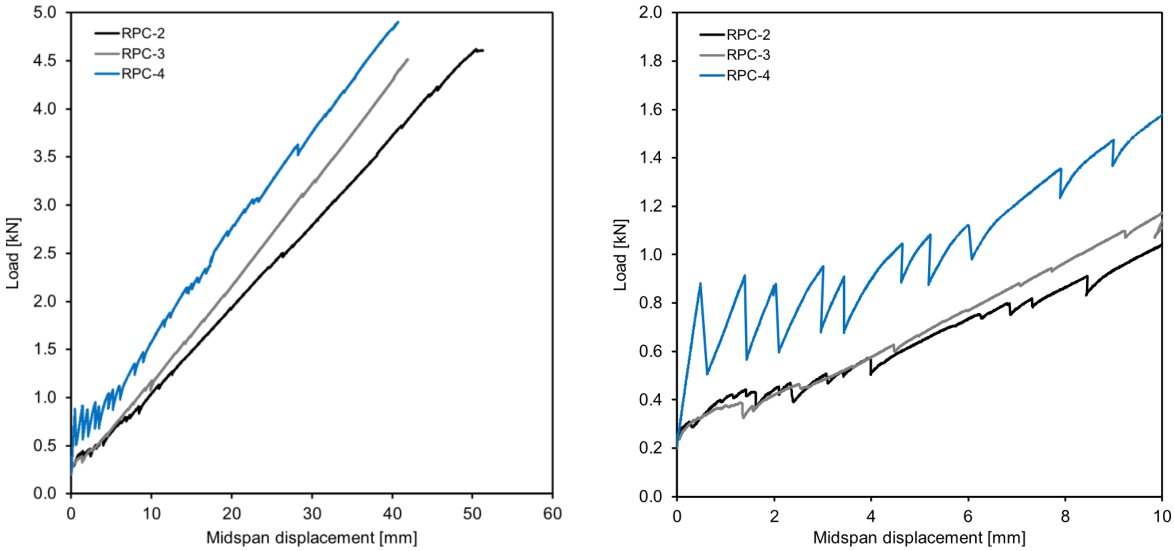

Figure 6 – 28 d results from 4-point bending tests of 25 mm thick panels with a 2d carbon fiber grid with epoxy resin (EP) coating. Specimen stored in air at 20 °C, 65 % r.h. prior to the test. The left graph shows the entire range, the right one shows a detail.

Tensile behavior of reinforced panels

Figure 7 shows the tensile test results of the 20 mm panel specimen, which were stored 27 d under water prior to the tests. The initial part is relatively stiff for the uncracked specimen. The crack creation was very brittle and a clear load drop in the load-deformation relation characterized the onset of a crack. Some smaller load drops can be attributed to minor cracking within the clamping length. There were only two cracks in total for all specimens, except for one specimen where three cracks appeared. All cracks were initiated at a cross yarn, except one crack that was initiated at the position of the clamping edge. This is natural, since the cross yarn causes a stress concentration as a result of a reduced cross section area and local higher shear force transfer.

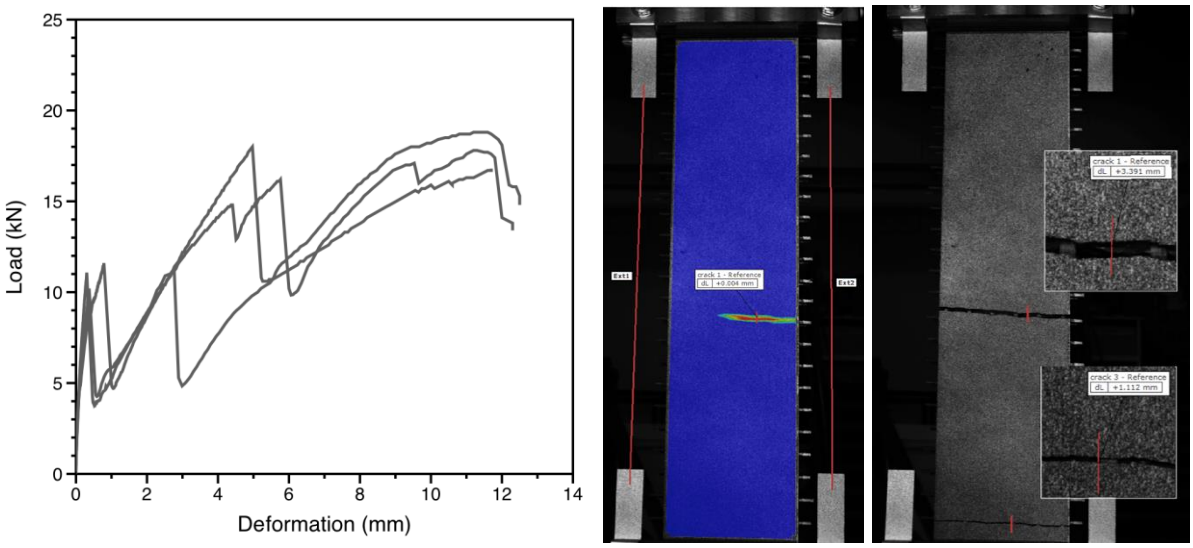

Figure 7 - 28 d results from tensile tests of 20 mm thick panels with a 2 d carbon fiber grid with SBR coating (left). Specimen stored in water at 20 °C prior to the test. Results from the DIC measuring system (middle and right). Middle: major strain overlay on the specimen showing the initiation state of the first crack.

The stress at first crack was 4.9 MPa. This value was lower than the tensile strengths evaluated for the plain RPC (Tab. 3). However, the actual concrete section was between 10 to 15 % lower than the nominal area due to the cross yarns, hence, the true stress is 10 to 15 % higher. In most of the tests, it required a higher stress level to create the second crack indicating insufficient bond strength. Low bond strength results in a longer load transfer length. If the load transfer length is longer than the free length of the specimen, the actual nominal tensile force in the reinforcement at the first crack cannot be transferred into the concrete within the free length, which corroborates the results of the flexural tests of the same specimen series.

The load versus deformation relationship obtained for 25 mm thick specimens with a EP coated carbon grid reinforcement, cured for 27 days in air at 20 °C and 65 % r.h. is presented in Figure 8.

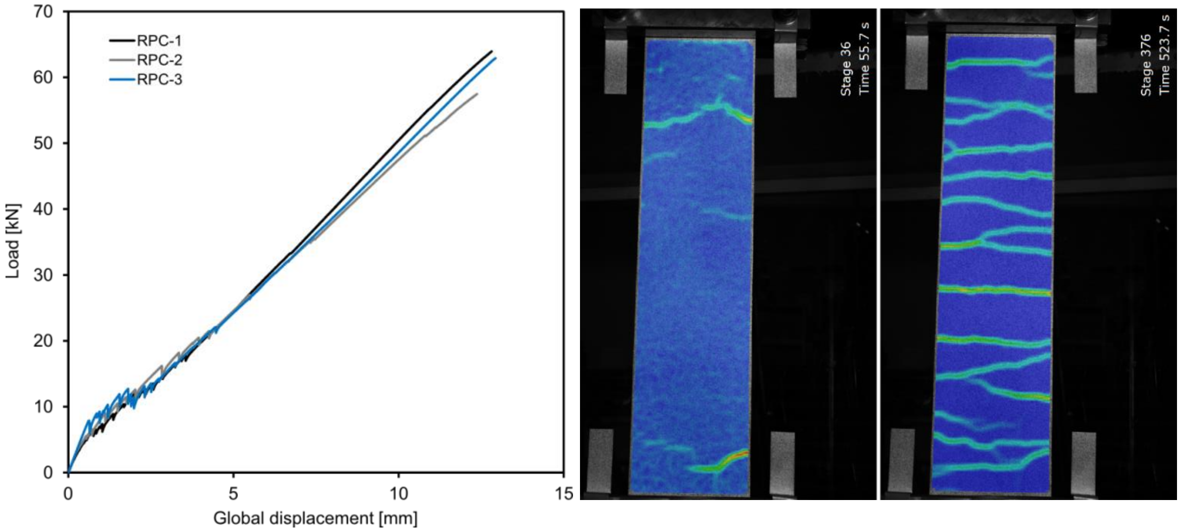

Figure 8 - 28 d results from tensile tests of 25 mm thick panels with a 2 d carbon fiber grid with EP coating (left). Specimen stored in air at 20 °C and 65 % r.h. prior to the test. Major strain overlay showing the crack initiation (middle) and final crack propagation (right).

First cracking appeared upon reaching the tensile strength range of the RPC at an approximate load of 5-7 kN amounting to a tensile strength of 2-3 MPa. This is, compared to the original tensile strength lower and can be attributed to the cross section reduction of the panels by the yarn. In case of the EP coating the grids were much thicker as the SBR coated ones. Moreover, after first cracking a series of multiple-cracking marked by load drops with minimal load increase took place. As before, crack initiation generally occurred at cross-yarns. The crack formation eventually stabilized and was marked by a noticeable gain of stiffness said to be governed by the properties of the textile reinforcement; which is often described as a form of strain hardening. When comparing to the results of RPC panels cured under water and reinforced with a SBR coated grid, it is clear that these new results showed a significant improvement of tensile behavior for the composite.

CONCLUSIONS

The results on the mechanical properties of textile reinforced reactive powder concrete showed the influence on several parameters on its flexural and tensile behavior. Pure carbon fibers are hydrophobic and very smooth. To increase the bonding behavior towards cement paste polymer coatings are applied. Styrene butadiene rubber is a fairly inexpensive coating material, which forms thin layers on the carbon textile. However, the bond behavior in reactive powder concrete is much less effective compared to a much thicker (and also more expensive) epoxy resin coating. The modification of the SBR coating with another layer of coating consisting of a polymer clay nanocomposite improves the flexural behavior but does not match the results of the epoxy coated grid.

Another influential factor is the moisture content. It could be clearly seen that panel specimen with SBR coated fiber grids are sensitive towards curing conditions and moisture content. Curing under water/water saturated specimen showed inferior flexural and tensile behavior, indicating insufficient bond length of the grid along the overall length of the specimen. A reduced moisture content by curing the specimen in air at 20 °C and 65 % r.h. resulted in a much improved flexural behavior of textile reinforced RPC panels. The impact of curing on an EP coated grid was not yet investigated.

For practical purposes the use of epoxy resin coated carbon fiber textile grids in conjunction with reactive powder concrete seem to be the most suitable solution for façade applications. Due to the stiffness of the grid caused by the epoxy coating large areas of grids are easier to handle and to incorporate in layers. SBR coated grids tend to deform more and are more difficult to layer.

ACKNOWLEDGEMENTS

The SESBE project was supported by the European Commission within the Framework Programme 7 under the Grand Agreement no. 608950. The authors would like to thank the European Commission for funding the project and making this work possible.

REFERENCES

1. Engberts, E. Large-size facade Elements of textile reinforced concrete. In 1st International RILEM Conference on Textile Reinforced Concrete, (2006), (pp. 309–318). RILEM Publications SARL.
2. Hegger, J., Horstmann, M., & Scholzen, A. Sandwich Panels with Thin-Walled Textile-Reinforced Concrete Facings. In C.-M. Aldea (Ed.), Design and Applications of Textile Reinforced Concrete, (2008), (pp. 109–123). American Concrete Institute.
3. Ghoneim, G., El-Hacha, R., Carson, G., & Zakariasen, D. Precast Ultra High Perfromance Fibre Reinforced Concrete Replaces Stone And Granite On Building Façade. In Proceedings of the 3rd fib International Congress – 2010, (2010). (pp. 1–15).
4. Rebentrost, M., Wight, G., & Fehling, E. Experience and Applications of Ultra-high Performance Concrete in Asia. In E. Fehling, M. Schmidt, & S. Stürwald (Eds.), 2nd International Symposium on Ultra High Performance Concrete (2008). (Heft 10., pp. 19–30). Kassel, Germany: Kassel University Press.
5. Müller, U., Meng, B., Kühne, H.-C., Nemecek, J., Fontana, P., & Fehling, E. Micro texture and mechanical properties of heat treated and autoclaved Ultra High Performance Concrete (UHPC). In E. Fehling, M. Schmidt, & S. Stürwald (Eds.), 2nd International Symposium on Ultra High Performance Concrete, (2008). (Heft 10., pp. 213–220). Kassel, Germany: Kassel University Press.
6. Hegger, J. & Voss, S. Investigations on the bearing behaviour and application potential of textile reinforced concrete. Engineering Structures **30,** 2008, 2050–2056.
7. Williams Portal, N., Flansbjer, M., Johannesson, P., Malaga, K. & Lundgren, K. Tensile behaviour of textile reinforcement under accelerated ageing conditions. Journal of Building Engineering **5**, (2016), 57–66.
8. Mueller, U., Williams Portal, N., Chozas, V., Flansbjer, M., Larazza, I., da Silva, N., Malaga, K. Reactive powder concrete for façade elements – A sustainable approach. Journal of Facade Design and Engineering 4, (2016), 53–66.
9. Andreasen, A. H. M., 'Über Die Beziehung Zwischen Kornabstufung Und Zwischenraum in Produkten Aus Losen Körnern (Mit Einigen Experimenten)', Kolloid-Zeitschrift, 50 (1930), 217–28.
10. Funk, James E., and Dennis R. Dinger, Introduction to Predictive Process Control - Predictive Process Control of Crowded Particulate Suspensions. Boston, MA: Springer US, (1994).
11. Puntke, Wolfgang, 'Wasseranspruch von Feinen Kornhaufwerken', *Beton*, 2002 (2002), 242–48
12. EN 1015-11: Methods of test for mortar for masonry – Part 11: Determination of flexural and com-pressive strength of hardened mortar. (1999).

13. EN 12390-3: Testing hardened concrete. Compressive strength of test specimens. (2009).
14. EN 12390-13: Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression. (2013).
15. RILEM TC 232-TDT. Recommendation of RILEM TC 232-TDT; Test methods and design of textile reinforced concrete – Uniaxial tensile test: Test method to determine the load bearing behavior of tensile specimens made of textile reinforced concrete. Materials and Structures 49(12), (2016), 4923-4927.
16. Carrado, K.A., Thiyagarajan, P., Elder, D.L., Polyvinyl alcohol-clay complexes formed by direct synthesis. Clays and Clay Minerals 44, (1996), 506–514.