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Reactive powder concrete for facade elements – A sustainable approach

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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. Within the project SESBE, funded by the European Commission, improved formulations with higher replacement levels of cement clinker by supplementary cementitious materials (SCMs) were developed. The work was carried out at two locations: ACCIONA in Spain and CBI in Sweden. In total three different mix formulations were designed and tested in terms of workability and mechanical properties. The formulations were combined with different types of reinforcements ranging from steel fibers to carbon fiber textile grids primarily to enhance the ductility and tensile strength of the material.
The results showed that even with clinker replacement levels of up to 40 %, a satisfactory mechanical performance of the RPC mixes could still be achieved. A fairly steep strength gain rendered heat treatment unnecessary. The materials also displayed good flow properties and a reasonably short initial setting time. The incorporation of carbon textile fiber grids proved to be less effective than expected due to their inherent smooth surface; nevertheless with the addition of random carbon fibers to the mix, the post failure performance of the materials increased multiple times. The results validated a more sustainable approach for RPC applied to thin facade elements.

1 Introduction

Precast concrete façade elements or claddings for housing projects were already used since the end of the 50ies in the last century. In Sweden pre-fabricated modular concrete buildings made the Million Program possible, a housing project realized between the 1960ies to the 1970ies [1]. The Million Program had equivalents in many other European countries during this time and established the concrete pre-cast technique on the housing market. Standard steel reinforced concrete (RC) elements were for a long time dominating the pre-cast market for cement based concrete building envelopes. From the 60ies to the 80ies of the former century they dominated the architectural landscape in many urban areas all around the world. The disadvantage of RC is the thickness of elements, which is given by the necessary concrete cover for the reinforcement. For a situation on a building façade the concrete standard EN 206-1 [1] would prescribe exposure classes XC3/XC4 with a minimum cover thickness of 30-35 mm (according to national application standards). This results in a total minimum thickness of a RC panel of around 80 mm including the thickness of the reinforcement. In fact many RC façade elements have this minimum thickness, which makes the elements particularly heavy and thick.

Over the last 15 years new cementitious materials emerged on the marked enabling to drastically reduce the thickness and weight of pre-cast façade elements due to the removal of standard steel rebar and steel meshes against other reinforcement concepts. Two of those are textile reinforced concrete (TRC) and ultra high performance concrete (UHPC) and reactive powder concrete (RPC), respectively. Both have usually no TRC has already been applied for façade elements in form of ventilated façade cladding [4] or as sandwich elements [4]. More and more RPC/UHPC is used as façade material since both show extraordinary high strength and durability [5][6][7].

The terms ‘reactive powder concrete’ and ‘ultra high performance concrete’ are often used synonym but RPC uses actually fine sand as aggregate (usually 0/2 mm) and UHPC can have coarser aggregate sizes (0/8 or 0/16). Both are defined as materials with compressive strength larger 120 MPa and with a strongly reduced capillary porosity. Heat curing of RPC/UHPC under ambient or water saturation pressure (steam curing) can considerably increase mechanical strength in the range of 20 to 30 % [8][9] and heat curing at 90 °C is an established process in pre-casting of UHPC/RPC elements [6].

An important point concerning RPC/UHPC is their high powder content, and to be more specific, high cement clinker content. The clinker content in RPC/UHPC is usually between 700 and 900 kg/m^3, which makes the material more expensive and seemingly less sustainable. The topic presented in this paper was therefore to explore how to reduce the high clinker content of a RPC mix by a partial replacement with other materials. The goal was to investigate the replacement of clinker by class F fly ash without loss of performance. 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 work was performed within the EC funded project SESBE in two locations, in Sweden at CBI and in Spain at Acciona with locally available starting materials. RPC is used in this project as an outer and inner layer for non-load bearing sandwich panels of a new type.

2 Conceptual approach for textile reinforced reactive powder concrete

The concept of RPC/UHPC is based on two main achievements: i) an optimized particle size packing including very small particles and ii) a greatly reduced water powder ratio, usually below 0.2. The theory of particle packing was already well investigated in many studies [10][11] and it is based on using specific components which complement each other to form a evenly distributed particle size curve which reaches from particles ≤ 0.1 nm to ≥ 1 mm. The optimization of the amount of the single binder and aggregate components will reduce the w/b ratio, the amount of super plasticizer and will enhance the workability of the fresh RPC mix. Within the SESBE project fibre and carbon textile fibre reinforcement were chosen to reinforce the reactive powder concrete.

2.1 RPC mix design

Starting materials were based on components available on the market. They consisted of those listed in Table 1.

Table 1: Components of the RPC mixes

Components	Spain	Sweden
CEM II/A-V 52.5		X
CEM I 52.5	X	
Fly ash class F	X	X
Granulated blast furnace slag	X	
Silica fume	X	X
Quartz filler	X	X
Sand 0/600 µm	X	
Sand 0/1 mm		X
Sand 0/2 mm	X	
Super plasticizer	X	X
Tap water	X	X

The mix design was optimized by a particle packing model according to Andreasen [12] calculated with the software Emma by ELKEM [13]. The mix design was adjusted to locally available materials in Sweden (by CBI) and Spain (by ACCIONA). In total three final mixes were designed, two by CBI in Sweden (RPC-CBI1, RPC-CBI2) and one by Acciona in Spain (RPC-ACC). The Acciona mix had as a main constituent additionally ground granulated blast furnace slag as a main clinker replacement.

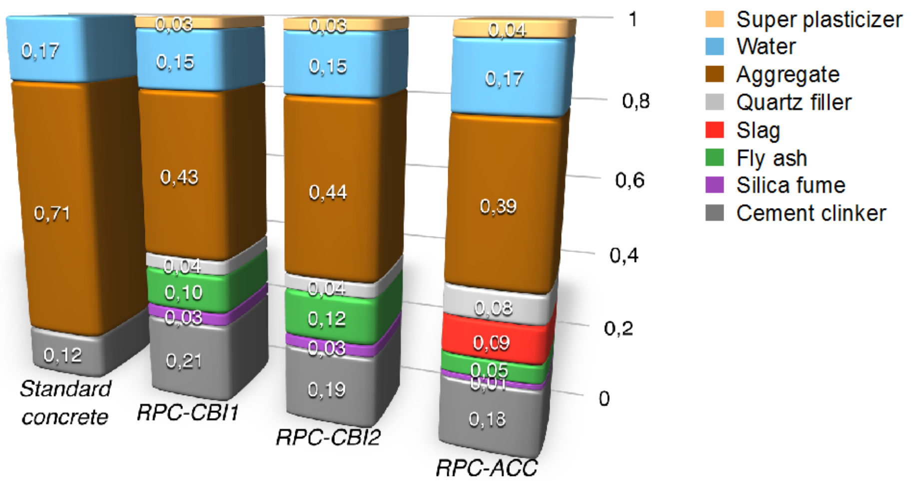

Figure 1: Composition of the RPC mix formulations compared to a standard concrete (in volu fractions).

Figure 1 illustrates the volume proportions of the three RPC mixes and shows also the differences in composition compared to a standard concrete. What is significant is the complexity of the RPC mixes. A RPC mix can have easily 6 to 8 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 optimized again. As a consequence, RPC and UHPC are considered as not very robust towards proportioning errors. This is the reason why for RPC mixes often commercial ready mixed products are used in order to avoid errors connected to wrong proportioning of the RPC components.

The mixes were blended in both, planetary mixes and in forced action concrete mixers. For the latter the mixing process lasted a little longer (around 20 minutes) due to the low water/binder ratios, which were below 0.2 for all three mixes. After blending the mixes behaved self-compacting. Bleeding was not observed. The slump flow of the mixes after 1 minute was 65 to 70 cm (RPC-CBI1, RPC-CBI2) and 90 cm (RPC-ACC), respectively. As reinforcement two types of carbon textile fiber grids were used. One of the two was a so-called 3d grid consisting of two grid sheets connected by PP fibers with a distance of 12 mm (Fig. 2).

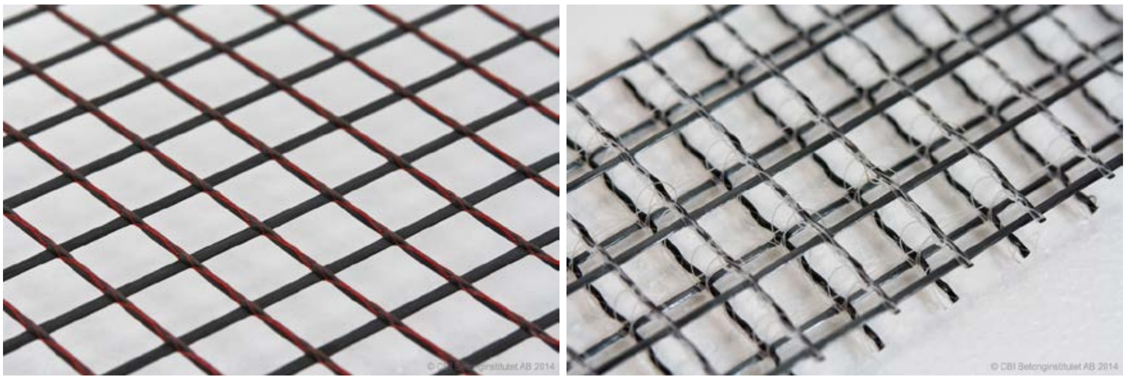

Figure 2: Types of carbon textile fibre reinforcement: 2d grid (left) and 3d grid (right).

2.2 Methods for mechanical properties

The early age and hardened properties of the RPC mixes were characterized by different methods. Here only the mechanical properties will be reported. Strength measurements consisted of tests without and with reinforcement. Strength testing without reinforcement was done on mortar bars for screening purpose (compressive strength, 160 x 40 x 40 mm^3) and on cylinders for compressive, tensile strength and modulus of elasticity as well as poison ratio (∅ 54 x 100 mm).

RPC is a fairly brittle material and tests with reinforcement should demonstrate if the brittle behavior can be controlled by the incorporation of a textile grid. In praxis load on panels is introduced in form of bending forces due to lift-out of the panels from the formwork and due to wind load (under pressure and in suction). In case of material failure the textile reinforcement will prevent sudden collapse of the panel and under increased strain be activated. How the textile reinforcement is activated was investigated by the tensile and bending tests.

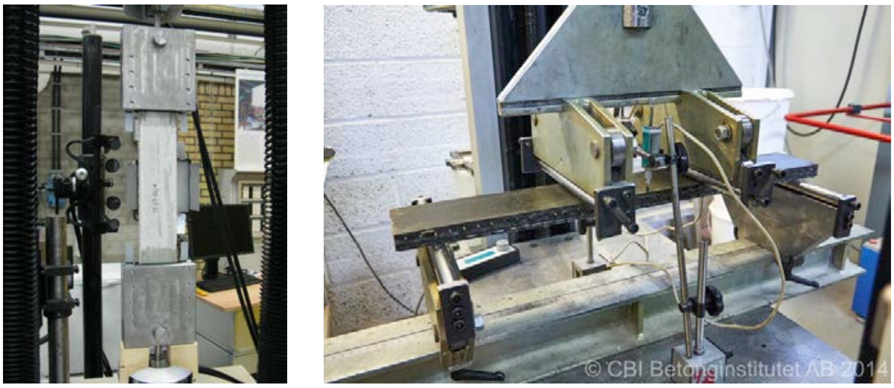

Figure 3: Setup for tensile (upper left) and flexural strength testing (upper right).

RPC with reinforcement was tested in tensile and flexural mode, the latter in a 4-point bending test. The samples consisted of panels of the size 700 x 100 x 20 mm^3, which included two layers of 2d-grid with a distance of 12 mm and 1 layer of 3d grid, respectively. Used were two different electro mechanical universal testing machines. Figure 3 shows the setups for both tests. The tensile test was performed according to the RILEM TC 232-TDT draft recommendations for textile reinforced concrete [14]. Extensions in the tensile test were measured by a Digital Image Correlation System (DIC), deflections in the flexural tests by standard displacement transducers.

3 Results and discussion

3.1 Without reinforcement

The development of the compressive strength of the three different final RPC mixes is shown in Figure 4. All three strength curves showed a similar course. After 28 d and 56 d, respectively, the differences in strength were only marginal for all three mixes. However, mix RPC-CBI2 showed a lower strength within the first 24 h of hydration but still well above 20 MPa. Important was that after only a short time period compressive strength was significant. Initial setting time was determined for RPC-CBI1 with 5.5 h and RPC-CBI2 with 7 h. The slower setting and lower initial strength of mix RPC-CBI2 was due to the higher content of fly ash in the mix.

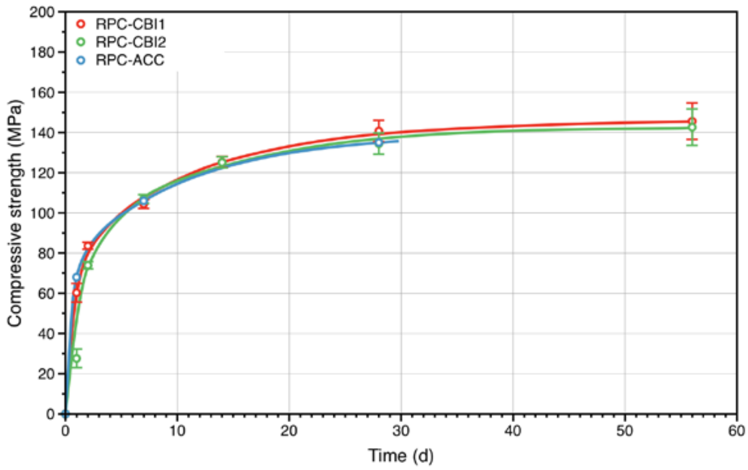

Figure 4: Development of compressive strength for the three different mixes.

Table 2: Summary of results mechanical strength (28 d) of RPC mixes without reinforcement given as mean values and standard deviations in parenthesis (nt = not tested).

Mix	Comp. str. MPa	E-modulus GPa	Ultimate strain ‰	Poison ratio 1	Tensile str. MPa
RPC-CBI1	147.2 (2.3)	49.7 (1.7)	3.89 (0.16)	0.216 (0.021)	5.14 (0.48)
RPC-CBI2	135.7 (4.3)	49.9 (2.4)	4.07 (0.30)	0.223 (0.014)	3.96 (0.74)
RPC-ACC	135.0	48,3	nt	0,209	

In Table 2 results are listed of specimens without reinforcement. The results show that the differences between the CBI mixes are not significant. The high values of 50 GPa for the E-modulus and the post peak behaviour indicate the extreme brittleness of the material with a sudden and almost explosive failure. Even though for the mix RPC-ACC tensile strength and modulus of elasticity were not tested, similar values can be assumed as for the CBI mixes due to similarities in the strength development.

3.2 With reinforcement – tensile and flexural behaviour

Tested were the mixes RPC-CBI1 and RPC-CBI2. Both mixes showed, independent from the textile reinforcement (2d or 3d) a similar failure mode. Both, under tensile and bending forces there were only between 1 (bending) and 3 cracks (tensile) appearing (Fig. 5, left). The initial part was relatively stiff for the un-cracked 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 could be attributed to minor cracking within the clamping length. The observed behavior is different to test results from textile reinforcement in standard or high strength concrete, wherein the textile reinforcement increases to a certain level the ductility of the material by distributing the load along the textile grid [15]. As a consequence the post peak performance is signified by a smaller drop in load and a much quicker gain of the original maximum load resulting in a multitude of small cracks within one panel.

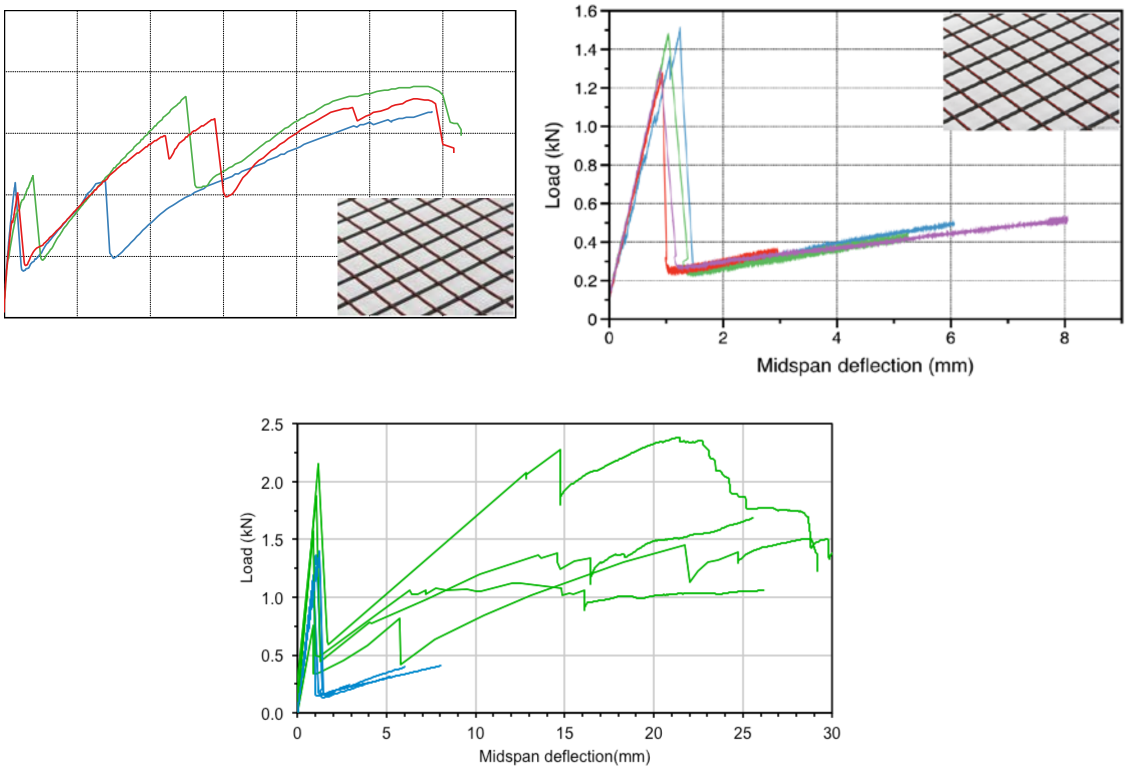

Figure 5: Results from tensile (upper left) and flexural (upper right) tests with mix RPC-CBI1 with 2d carbon textile fibre reinforcement. Lower graph: Results flexural tests with mix RPC-CBI1 with 2d carbon textile grids and additional carbon fibres. Blue: textile grid only, green: textile grid and carbon fibres.

If the bond could be improved, the load transfer length would be shorter hence allowing for the formation of multiple cracks along the sample. Accordingly, a stiffer behaviour of the panel and more closely spaced cracks with small crack widths would be observed, yet at the expense of a decrease in deformation capacity. RPC is a brittle material having poor ductility, which could cause inefficient flexural capacity if the incorporated tensile reinforcement ratio is so-to-say insufficient. Random fibres can be incorporated in RPC to primarily increase the toughness. This is demonstrated in test results in shown in Figure 5 (lower graph), were 0.5 mass-% carbon fibres were added additionally to the carbon grid. The results show a much higher strain hardening and increase in capacity (green curves) compared to the panels without fibres and only carbon textile grid (blue curves).

4 Aspects of sustainability

Both approaches, from CBI and ACCIONA, have shown that it is possible to create a reactive powder concrete with a high replacement level of clinker. The mechanical properties lay within 135 to 150 MPa, which are more than enough for the envisaged panel applications. The replacement levels of both approaches are high, thus lowering the cement clinker content of RPC considerably (Fig. 6).
However, designing a RPC mix is more challenging compared to a standard concrete mix since there are a lot more components, which needs to be adjusted toward each other. Also, workability and setting is of prime importance for the production process of the panels and this is strongly related to the type and amount of RPC's constituents. If setting is delayed too much because of too high amounts of clinker replacements, form-stripping times will be too long and the production process will not be profitable. Also, it is desirable to reduce the amount of super plasticizer as much as possible in order to reduce total m^3-costs of the concrete. By utilizing industrial waste products such as fly ash and slag sustainability and costs can be further adjusted. However, it has to be kept in mind that these so called waste products have become by itself a desired raw material for cement and concrete production. In practice this means their availability is also limited.

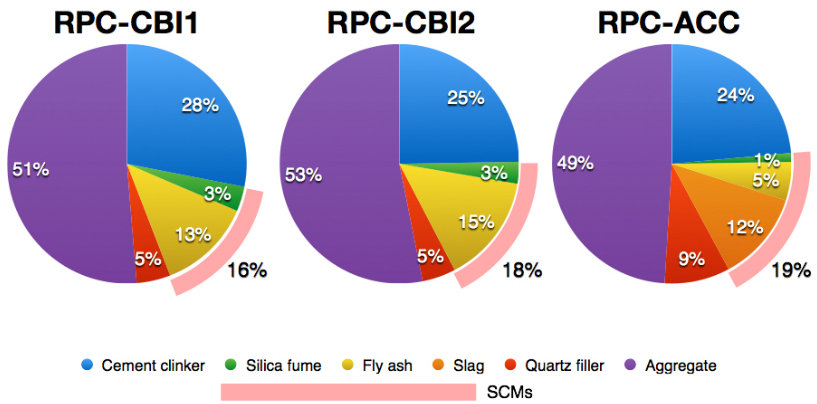

Figure 6: Comparison of clinker replacement levels (on the solid content) by supplementary cementitious materials (SCMs) for the RPC mix approaches of CBI and ACCIONA.

It was shown that with reactive powder concrete the bond between textile grid and cement matrix is of prime importance and this will be investigated further. Better results can be achieved by mixing a certain amount of fibers additionally to the textile grid. However, this has also limitations. Additional fibers increase costs and influence workability, in particular with carbon fibers, which make the fresh RPC mix less flowable.

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