Synthesis and Characterization of Reactive Powder Concrete for its Application on Thermal Insulation Panels

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Abstract. This paper describes the synthesis and characterization of a set of textile reinforced reactive powder concrete (RPC) mixes that have been prepared in the framework of the SESBE project which aims to develop façade panels for the building envelope. In order to reduce the environmental impact, high concentration of type I and II mineral additions were added to the mixtures (up to 40% of cement replacement). The mechanical properties of the materials were analysed showing high values of compression strength thus indicating no disadvantages in the compression mechanical performance (~140 MPa) and modulus of elasticity. In order to enable the use of these materials in building applications, textile reinforcement was introduced by incorporating layers of carbon fibre grids into the RPC matrix. The flexural performance of these samples was analysed showing high strength values and suitability for their further utilization.

1. Introduction

There is a vastly growing demand for increased energy efficiency of the buildings we live and work in, which is one of the great challenges of the European construction sector, including materials and processes. The EU has set ambitious energy-saving goals: to achieve a reduction 20% of the total energy consumption, a reduction of 20% of Green House Gases (below 2005 level) and for 2050 to ensure that most buildings and districts will be energy-neutral and have zero CO_2 emissions (Energy Policy set by the European Council in March 2007).

This work has been developed within the SESBE project, which aims to develop façade elements (sandwich and half sandwich) with high insulation ability and at the same time a reduced thickness in

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conjunction with superior mechanical and durability properties. Reactive powder concrete (RPC) has been chosen as the material for the outer layer of such façade elements. RPC is a cement-based material characterized by the property that its microstructure is optimized by a precise gradation of all particles in the mix to yield maximum compactness and a greatly reduced water/powder ratio, usually below 0.2. The theory of particle packing has been previously investigated in many studies [1,2] and it is based on using specific components which complement each other to form an evenly distributed particle size curve which reaches from particles ≤ 0.1 μm 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.

It uses extensively the pozzolanic properties of highly refined silica fume and other mineral additions. The superior properties are achieved by the optimization of the binder chemistry and by strongly reducing the binder porosity, in particular capillary porosity. In this context RPC should be more appropriately seen as a cold ceramic rather than a concrete [3]. Due to these properties, it is increasingly being utilized also for external façade cladding thus enabling a considerable reduction in the thickness of concrete elements. However, commercial RPC formulations on the market have drawbacks, the present work has been aimed to investigate and mitigate such barriers. In terms of sustainability due to their high cement content and heat curing which is often applied to increase final strength and material density. In this work, supplementary cementitious materials (SCMs) such as F class fly ash (FA) and ground granulated blast furnace slag (GGBS) have been used in order to partially replace the commercial cement. Moreover, in this work the RPC materials have been cured at room temperature.

Its toughness makes RPC a fairly brittle material, in order to improve this behaviour, fibre and textile reinforcement is typically incorporated in panels made of RPC. In this way, the reinforcement will prevent sudden collapse of the panel upon first cracking and would be activated under increased strain. In the present work, in order to enable a significant reduction of thickness and reduce the brittleness of these elements, panels of reactive powder concrete reinforced with carbon fibre textile grids have been developed. The composite behaviour of RPC reinforced by textiles has been investigated by uniaxial tensile and four-point bending tests.

The presented work has been carried out at two locations: ACCIONA in Spain and CBI in Sweden, in order to use local materials, being especially interesting in the case of SCMs which properties vary depending on the procedure. In total, three different mix formulations were designed and tested in terms of workability and mechanical properties. The matrices were reinforced with carbon fibre textile grids primarily to enhance the ductility and tensile strength of the material.

2. Materials and methods

This chapter describes the materials used for the synthesis of the RPC mixes, the mixing procedure and the analytic methods for their characterization.

2.1. Materials

Three RPC matrices were prepared with commercially available materials. The proportions of the components used in each of the cases have been collected in table 1. In total, three final mixes were designed, synthesized and characterized, two by CBI (C1 and C2) and one by ACCIONA (A1).

Table 1. Materials used for the RPC mix design. All the amounts are given in wt% except the water/cement ratio.

Component	C1	C2	A1
Cement[a]	31	27	22
Silica Fume	3.1	2.7	1.1
SCM[b]	6.7	9.2	15.7
Aggregates + quartz filler[c]	51.6	53.3	52.5
Water	6.3	6.3	6.6
Superplasticizer	1.3	1.3	1.9
w/c	0.23	0.27	0.30

[a]For C1 and C2, CEM II/A-V 52.5 cement was used. For A1 CEM I 52.5R was used.
[b]F class FA was used in both cases, for A1 GGBS was also used (GGBS/FA 2.34)
[c]C1 and C2 were prepared with quartz filler and aggregates (0/0.2, 0.1/0.3, and 0.2/1 mm), A1 was prepared with quartz powder (0/100 µm) and aggregates (0/600 µm and 0/2 mm)

The mix design was optimized by a particle packing model according to Andreasen [4] calculated with the software Emma by ELKEM [5]. The mix design was adjusted to locally available materials in each location. Mix A1 had ground granulated blast furnace slag as the main cement replacement.
As it has been previously mentioned, reinforced RPC was also explored in this work. Carbon fibre textile grids were incorporated in the RPC matrices and their flexural behaviour was investigated by means of four-point bending tests. Two alternatives consisting of one or two layers of a 2D carbon grid (figure 1) have been analysed. Additionally, a 3D carbon grid composed of two layers interconnected by a low-modulus polyester (PET) spacer with a thickness of 12 mm (figure 2) was used. Initial works pertaining to the 3D carbon reinforcement have been initiated and will be published in a future paper. The grids are made of carbon rovings consisting of fibre bundles of 24K (thousands of fibres), the surfaces of which were initially coated by approximately 15 wt-% styrene-butadiene resin (SBR). The mesh sizes are indicated in figures 1 and 2 for both types of grids. In this work, the reinforced RPC panels have been denoted as RC1, RC2 and RA1, whereby R stands for reinforced followed by the matrix type. The inclusion of an additional polymer coating to the carbon grid surface was also investigated and is denoted with “-C”.

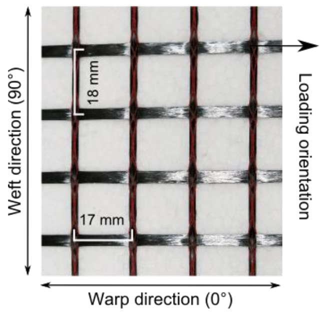

Figure 1. 2D carbon fibre textile grid.

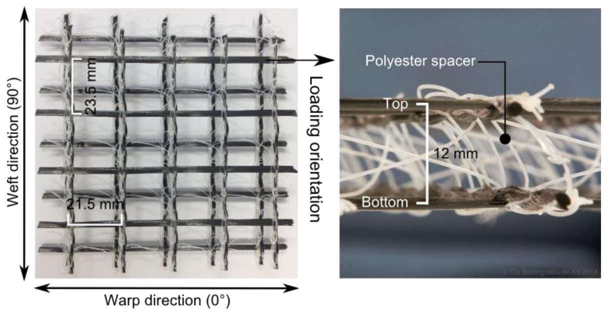

Figure 2. 3D carbon fibre textile grid.

2.2. Methods

2.2.1. Mix protocol.

In all cases, the RPC mixes were prepared according to the following procedure: firstly, the cement was homogeneously mixed with the supplementary cementitious materials (fly ash and blast furnace slag). Then, 75% of the previously mixed solution containing water and the superplasticizer additive was added and mixed for 4 minutes. After that, the aggregates, quartz powder and silica fume were incorporated into the mixture and all the components were mixed for 5 minutes. Finally, the remaining (25%) water/superplasticizer solution was added and mixed for 5 more minutes. All the mixtures were prepared in 50 L planetary concrete mixers and the mixing rate was set at 60 rpm. The rheology of the RPC fresh mortar matrixes was analyzed by a flow table test according to the European standard EN 1015-3. The result of the test consisted of the maximum diameter of the mortar mass measured after 60 s.

2.2.2. Preparation of the carbon grid reinforced RPC samples.

The samples were cast in wood molds. The form consisted of a panel shape in the size of 700 x 100 x 20 mm^3, see figure 3. In the case of the 2D carbon grid, 2 layers were included in each sample to attempt to match the geometry and placement of the 3D grid. In samples with the 3D grid, only one layer was used as the 3D grid already incorporates two carbon textile layers. In order to position the textile grids properly within the samples, they were cut a little larger and fixed by the formwork sidewalls. Thereafter, the RPC paste was poured into the molds penetrating through the mesh and allowed to harden at room temperature, as per figure 4. The specimens were demolded after 24 hours and cured in a wet room at 20 ºC and 96% relative humidity.

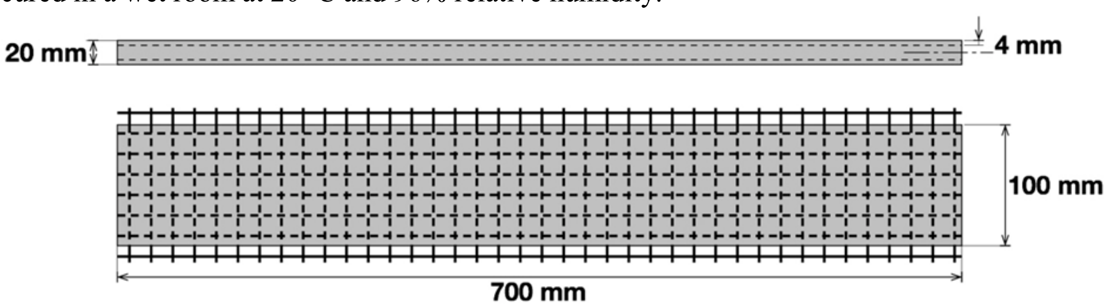

Figure 3. Schematic representation of the reinforced RPC panels.

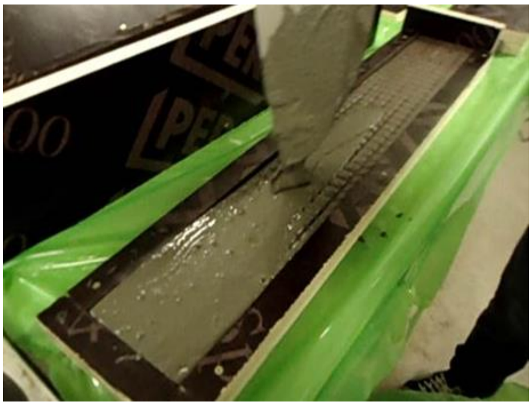

Figure 4. Photography of the RPC being cast with two 2D carbon grids as reinforcement.

2.2.3. Measurements.
The mechanical properties of the RPC materials with and without reinforcement were investigated by analysing different parameters. Compressive strength was measured on prismatic and cubic unreinforced specimens for screening purpose (160 x 40 x 40 mm^3 and 100x 100 x 100 mm, respectively) and on cylinders (Ø 54 x 100 mm and Ø 150 x 300 mm). Tensile strength, modulus of elasticity as well as Poisson's ratio were also measured in the latter specimens. The compressive strength and the elastic properties were measured according to standards EN 12390-3 and EN 12390-13, respectively. The uniaxial tensile test was performed according to the RILEM TC 232-TDT draft recommendations for textile reinforced concrete. Deformations in the tensile test were measured by a Digital Image Correlation System (DIC), while deflections in the flexural tests were measured by standard displacement transducers at midspan. The flexural behaviour of the reinforced RPC panels was measured using four-point bending tests according to standard EN 12390-5.

3. Results and discussion

3.1. Characterization of the RPC matrices

3.1.1. Rheology.
After blending the mixes, the mixes behaved as self-compacting and bleeding was not observed. The slump test was carried out on fresh concrete according to EN 12350-2. The maximum diameter reached was 65 to 70 cm (C1 and C2) and 90 cm (A1), respectively. The slump flow values evidence the suitability of the synthesized RPC pastes for their potential use at larger scale.

3.1.2. Mechanical characterization of the unreinforced RPC matrices.
The mechanical properties of the RPC samples were evaluated by measuring the compressive and tensile strength, elastic modulus, ultimate strain and Poisson's ratio. The values of these parameters, measured at 28 days of age, are summarized in table 2. The results show that the differences between the mixes are not significant. However, mix C1 showed a slightly higher value of compressive strength, attributed to the higher proportion of cement in its composition. The elevated value 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.

Table 2. Results of the mechanical properties of unreinforced RPC matrices tested at 28 days of age.

	Compressive strength (MPa)	E-modulus (GPa)	Ultimate strain (‰)	Poisson ratio	Tensile strength (MPa)
C1	147.2 (2.3)	49.7 (1.7)	3.9 (0.2)	0.22 (0.02)	5.1 (0.5)
C2	135.7(4.3)	49.9 (2.4)	4.1 (0.3)	0.22 (0.01)	3.9 (0.7)
A1	135.0 (2.4)	48.3 (0.1)		0.21 (0.02)	

The development of the compressive strength of the three different final RPC mixes is shown in figure 5. All three strength curves showed a similar course. After 28 and 56 days of age, respectively, the differences in strength were only marginal for all three mixes. However, mix C2 showed a lower strength within the first 24 h of hydration but still well above 20 MPa. It is important to note that after only a short time period compressive strength was significant. Initial setting time was determined for C1 at 5.5 h and C2 at 7 h. The slower setting and lower initial strength of mix C2 was attributed to the higher content of fly ash in the mix.

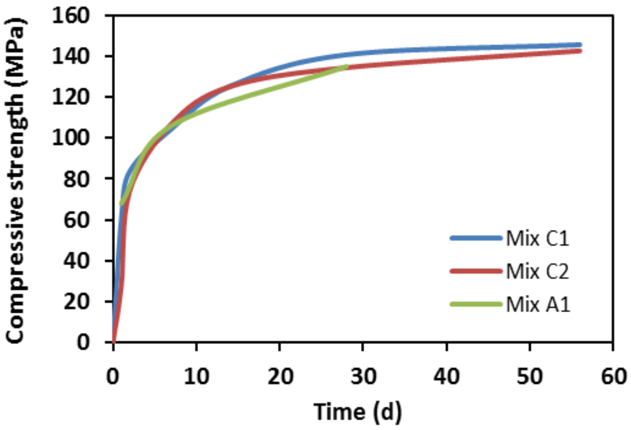

Figure 5. Development of compressive strength for three different mixes.

3.1.3. Characterization of the reinforced RPC materials.

The RPC mixes with one and two layers of textile reinforcement grid were tested. Figures 6 and 7 show the load versus deflection of the specimens composed of A1 and C1 matrices reinforced with one layer and two layers of carbon grid, respectively. In both cases, during the initial stage it was possible to appreciate the contribution of the RPC matrix until its brittle failure, reaching load values between 1000 and 1400 N. In the case of RA1 specimens, after the first load drop, it was possible to observe the contribution of the reinforcement, represented by an increment of the load/deflection curve, reaching a value close to that shown in the failure peak. After this stage, the specimens showed a gradual loss of their flexural capacity until a final failure of the reinforcement occurred after large deflections. In the case of RC1, the contribution of the reinforcement and the so-called increase in flexural capacity after first cracking of the matrix was not observed and the test was terminated due to the continued pull-out of the reinforcement. It is thought that the observed behaviour for RC1 could result from poor bond at the interface of the reinforcement grid and matrix, which should be further investigated.

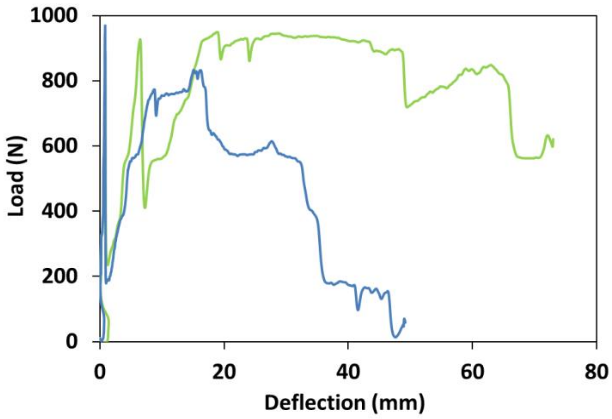

Figure 6. Flexural test results of RA1 with one layer of carbon grid reinforcement (lines correspond to independent tested specimens).

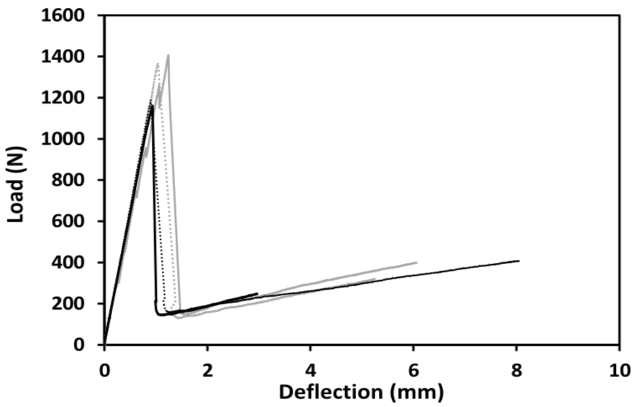

Figure 7. Flexural test results of RC1 with two layers of carbon grid reinforcement (lines correspond to independent tested specimens).

Figure 8 depicts the flexural characterization of the RC1-C specimens reinforced with two layers of carbon grid additionally treated by the aforementioned polymer coating. It can be seen that the three specimens showed a rather similar behaviour, however particularly the initial pre-cracking stiffness differed slightly due to material variability. The first peak corresponds to the contribution of the stiff RPC matrix followed by a series of multiple cracks and so-called crack stabilization, which is a favourable behaviour for this type of reinforced matrix. Compared to RC1 (figure 7), the first cracking load was slightly lower despite the fact that the same matrix is applied in RC1-C. The failure load was also lower than in the case of RC1, which could be explained by the fact that multiple cracking took place causing the matrix to subsequently lose stiffness. In this case, the RPC matrix did not undergo a brittle failure and it was observed that far from losing its flexural capacity, the additionally coated reinforcement led to a continuous increment of the flexural strength to around 80-100% with respect to the unreinforced matrix. It is worth highlighting that the scatter of the results is relatively low, compared to the typical scatter values characteristic of the discontinued fibre reinforced concrete materials.

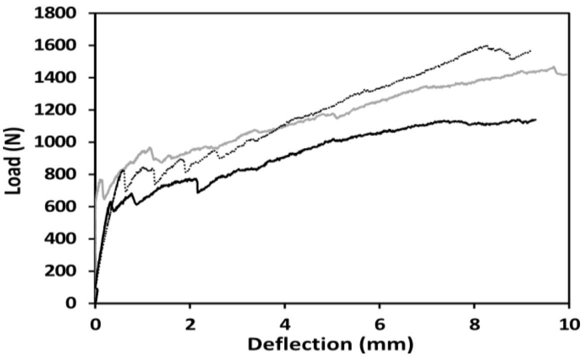

Figure 8. Flexural test of RC1-C with two layers of additionally coated carbon grid reinforcement (lines correspond to independent tested specimens).

4. Conclusions

The presented work has been developed in the framework of a project which has as an ultimate goal to produce panels for the building envelope and improve energy efficiency of the buildings in Europe. For this application, RPC has been chosen as the material to form the external layer of the panels and three sets of RPC mixes have been designed, prepared and characterized at two different locations (CBI and ACCIONA). In order to reduce the environmental impact of the materials, high amounts of mineral additions have been used to replace the cement.

The mechanical analyses evidenced the superior mechanical properties of the RPC matrices, characterized by high values of compressive strength (135-147 MPa) and modulus of elasticity (~50 GPa). In order to counteract the brittleness of the RPC and improve the flexural behaviour, textile reinforcement has been used in the form of one or two layers of carbon fibre textile grids. The flexural behaviour of the resulting panels was studied by four-point bending tests revealing the positive contribution of the reinforcement. This effect was especially evidenced when using two layers with additional coating, whereby the brittle first cracking was followed by multiple cracking and an increment of the flexural load resistance of about 80-100% with respect to the value of the unreinforced matrix.

5. References

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Acknowledgments

This project has received funding from the European Community's Seventh Framework Programme NMP.2013-1 under Grant agreement no: 608950