Cement-based composites for structural use

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Abstract

Reactive Powder Concrete (RPC), with compressive strength higher than 200 and up to 800 MPa as well as flexural strength higher than 60 and up to 150 MPa, at the moment potentially represents a new material for structural use in building and engineering in general, even though its application fields have not yet been well defined. RPC can be also considered as the ultimate step in the development of high performance concrete, even though its classification as a concrete material may be not quite proper, based on its microstructure and mechanical behaviour. Also, its production technology for higher performance, by pressure moulding as well as extrusion, takes it even further from a common concrete. The wide range of achievable strengths for RPC requires careful design of the material, strictly related to the structural design and appropriate to the specific project, with maximum cooperation between materials engineering and structural engineering. For this, RPC can be used at best by developing new shapes and structural types specially designed for it. In this paper potential application of RPC for structural elements is exploited and discussed in comparison with other materials typically used for structural application, with an eye to sustainability.

Keywords: cement-based composite, reactive powder concrete, structural use.

1 Introduction

Historically, new materials are related to the shape and development of new structural concepts. One need only think of the megalithic structures, in which stone prevented a span higher than 5 m, until the introduction of pozzolanic cement, used to join bricks and stones, which allowed the building of high spanning arch structures, covering up to about 50 m, like the Pantheon's dome in Rome.

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Further evidence is provided by steel as a structural material, which became available between the eighteenth and the nineteenth century and whose high tensile strength permitted sweeping changes in building technology by allowing higher span beams, frame structures, truss girders, suspended structures, tall buildings, and so on.

In actual construction technology, structures are mainly built by concrete, timber or steel; however, new composite materials, reinforced by polymer, metal, glass, or carbon fibres, are in prospect of appearing, giving rise to new interesting practical applications owing to their improved mechanical performance [1].

A new general category of so-called CBC (Chemically Bonded Ceramics) materials resulted from recent research aimed at the attempt to reduce microporosity of cementitious materials. The term CBC attributed by Roy [2] to this new class of cementitious materials points out, beyond the chemical nature of the involved bond, the inorganic, non-metallic character of the material, which turns ceramic because of the particular processes involved in its manufacturing.

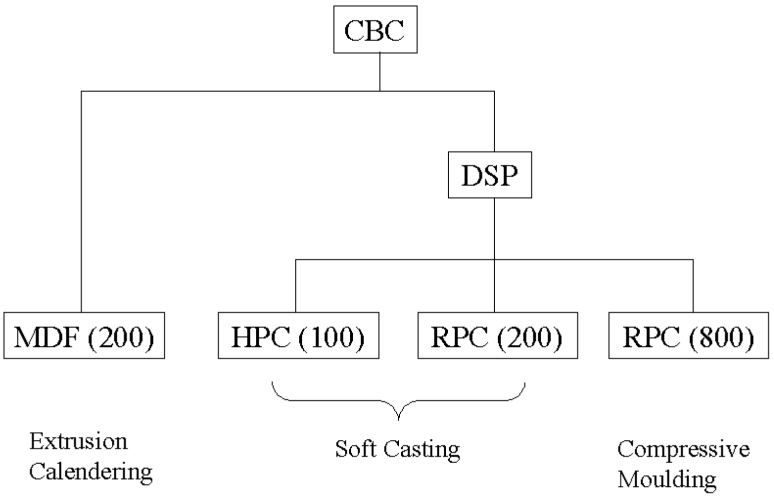

Figure 1: Outline of innovative cementitious materials and their related manufacturing process. Numbers enclosed in brackets, expressed as MPa, stand for compressive strength of HPC or RPC and flexural strength of MDF.

The CBC materials (Fig.1) can be grouped in two large categories [3]: MDF (Macro Defect Free) and DSP (Densified with Small Particles) materials, the main difference being the role played by the polymeric component in the manufacturing process. In MDF materials [4] fully hydrosoluble polymers play a very important role in order to significantly change the rheology of the cement paste and so to obtain a dough material, able to be extruded or rolled. In DSP materials, instead, sulphonated or acrylic polymers make possible either the compressive moulding of wet powders or the soft casting of flowable mixtures.

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Among the DSP materials, RPC (Reactive Powder Concrete), with compressive strength higher than 200 and up to 800 MPa as well as flexural strength higher than 60 and up to 150 MPa, at the moment represents potentially a new material for structural use in building and engineering in general, even though its application field has not yet been well defined. RPC can be also considered as the ultimate step in the development of HPC (High Performance Concrete), even though its classification as a concrete material may be not quite proper based on its microstructure and mechanical behaviour.

Also, its production technology, by pressure moulding as well as extrusion, takes it even further from a common concrete. The wide range of achievable strengths for RPC requires careful design of the material, strictly related to the structural design and appropriate to the specific project, with maximum cooperation between materials engineering and structural engineering. For this, RPC can be used at best by developing new shapes and structural types specially designed for it.

As for any new building material, one of the main issues in RPC initial use is represented by its high production cost, even if economy can be achieved in the long term by lower maintenance cost and longer service life, as a consequence of the extraordinary durability of RPC.

Another obstacle to remove is to consider RPC as an ordinary concrete by measuring its performance on traditional structures in which RPC strength levels are not required. This means that new shapes and structural typologies must be developed for this material in order to maximize its performance.

Within this framework, the paper presents the experimental results obtained by the mechanical characterisation of RPC prepared in the laboratory, and, based on these data, exploits its use for structural applications in comparison to other typical structural materials.

2 RPC mixture proportions and experimental approach

The achievement of DSP materials is based on combined use of water-soluble polymers and ultra-fine ($\leq$ 0.1 μm) solid particles, which mainly consist of amorphous silica. The role of water-soluble polymers is to improve the rheological behaviour of cement mixtures with a very low amount of water. The role of ultra-fine silica particles is to reduce interstitial porosity among cement grains and to ensure the formation of calcium hydrosilicates by reaction with hydrolysis lime from cement hydration.

The ultimate goal is to produce easily formable materials through the soft casting technique in addition to the compressive moulding technique. By this method, even large sizes and complicated shapes may be produced, also by using extremely flexible reinforcing fibres (polymeric or amorphous cast-iron-based), instead of ordinary steel fibres.

In Table 1, typical mixture proportions of differently prepared RPC [5] are reported together with the achievable mechanical performance. However, being satisfied with not an ultimate performance, in this work a different aim was pursued: to obtain typical performance of RPC 200 by using in the mixture easily

Table 1: RPC mixture proportions, processing treatment and related mechanical performance.

Ingredients [kg/m³]	**RPC**	**RPC 200**	**RPC 600**	**RPC 800**
Portland Cement	955	1000	1000	1000
Silica Fume (18 m²/g)	229	230	230	230
Fine Aggregate (150-400 μm)	1051	1100	500	-
Very Fine Quartz Sand (diameter 10 μm)	-	-	390	390
Amorphous Silica (35 m²/g)	10	-	-	-
Superplasticizer	13	19	19	19
Steel Fibres (L = 13 mm, d = 0.18 mm, L/d = 72)	191	175	-	-
Micro-Fibres (L = 3 mm)	-	-	630	630
Metal Aggregates (diameter < 100 μm)	-	-	-	490
Water	153	190	190	190
Treatment	**RPC**	**RPC 200**	**RPC 600**	**RPC 800**
Compressive Stress (on the fresh mixture, MPa)	-	-	50	50
Curing Temperature, °C	20	90	250-400	250-400
Mechanical Performance	**RPC**	**RPC 200**	**RPC 600**	**RPC 800**
Compressive Strength [MPa]	200	230	680	810
Flexural Strength [MPa]	50	60	45	140
Elastic Modulus [GPa]	50	60	65	75
Fracture Energy [J/m²]	20000	40000	12000	20000

available raw materials as in common practice for precast concrete. In this way, a cement type CEM II/A-L 42.5 R was used instead of CEM I 52.5 R as usual in RPC mixtures. Moreover, a limestone instead of quartz aggregate was used, which was also coarser (0.15-1 mm) than usual (150-600 μm). Finally, a lower quality black type silica fume was added. In this way, mechanical performance will remain a bit lower while promoting higher sustainability, in any case much higher than ordinary concrete.

According to this approach, the influence of an easily attainable thermal treatment, such as 24 hours air curing at 160°C, on the mechanical performance of this mixture was also evaluated. The thermal treatment was applied on de-moulded H-shaped specimens after 1 day's casting. The two RPC materials in this way obtained are later on labelled RPC 200-a (without thermal curing) and RPC 200-b (thermally cured) respectively, notwithstanding that a compressive strength of 170 MPa was achieved instead of 200 MPa because of the change in the specification of the raw materials.

The mixture proportions of the RPC materials prepared for this work are reported in Table 2 together with the experimental results of the tests performed on them.

Table 2: Mixture proportions, processing treatment and related mechanical performance of laboratory prepared RPC 200 materials.

Ingredients [kg/m^3]	**RPC 200-a**	**RPC 200-b**
CEM II/A-L 42.5 R Cement	960	960
Silica Fume (18 m^2/g)	250	250
Limestone Aggregate (0.15-1 mm)	960	960
Acrylic-based type Superplasticizer	96	96
Brassed Steel Fibres (L/d = 72)	192	192
Water	240	240
Treatment	**RPC 200-a**	**RPC 200-b**
Curing Temperature, °C	20	160
Mechanical Performance	**RPC 200-a**	**RPC 200-b**
Compressive Strength [MPa]	150	170
Flexural Strength [MPa]	33	34
Tensile Strength [MPa]	14	15
Fracture Energy [J/m^2]	44000	45000
Secant Elastic Modulus [GPa]	36	40
Tangent Elastic Modulus [GPa]	63	77
Poisson Modulus	0.19	0.17
Bond Strength with Steel [MPa]	32	34

Table 3: Characteristics and performance data of different construction materials.

	R.C.	**Glulam**	**Steel**	**RPC 200**	**RPC 800**
Elastic Modulus [GPa]	25	12	210	60	75
Compressive strength [MPa]	30	32	360	200	800
Tensile Strength [MPa]	3	15	360	45	100
Flexural Strength [MPa]	5	32	360	60	130
Unit weight [kN/m^3]	25	5	78.5	23	28
Specific Elasticity [10^6 m]	1.0	2.4	2.7	2.6	2.7
Specific Strength [10^3 m]	1.2	6.4	4.6	8.7	28.6
Elastic Strain [%]	0.15	0.25	0.18	0.33	0.80
Ultimate Strain [%]	0.30	0.25	14	2	2
Ductility [%]	2.0	1.0	77	6.1	2.5
Fracture Energy [J/m^2]	300-400	-	-	20000-40000	20000

3 Comparison of structural characteristics of different construction materials

In Table 3 a comparison is made, in terms of characteristics and performance, between five different structural materials usable for structural elements.

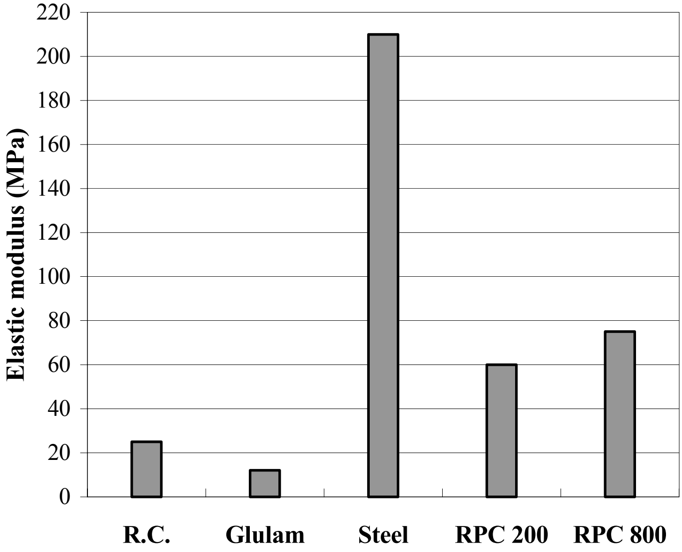

Figure 2: Comparison of elastic modulus of different construction materials.

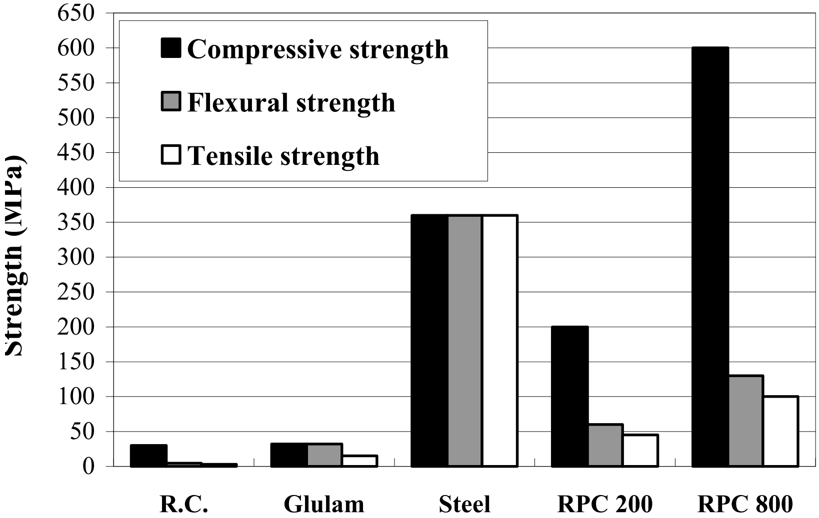

Figure 3: Comparison of mechanical strength of different construction materials under compression, bending and tension.

These materials are: reinforced concrete (RC), glued laminated timber (Glulam), steel, RPC 200 (made by soft casting) and RPC 800 (made by pressure moulding and high temperature curing). In Fig.2 and 3 also a comparison is made, in terms of elastic modulus and strength respectively, between these materials.

4 RPC structure design trial

In the absence of a precise frame of reference standards, calculations of RPC elements have been carried out by way of reference to Eurocode 2 (Parts 1-1, 1-3, 1-5), Document UNI/CIS/SC4-SFRC n°29 (Design of structural elements made of fibre reinforced concrete), AFGC (Association Française du Génie Civil) Recommendations on “Ultra High Performance Fibre-Reinforced Concretes”.

Preliminary dimensioning of structural elements

Firstly, dimensioning of structural members made of the different construction materials reported in Table 3 was carried out. Seven beams were designed according to EC2, EC3, EC5 in order to bear the same bending stress with the same deflection. The seven beams were made of:

- C 30/35 concrete reinforced with FeB44k steel;
- C 40/45 concrete reinforced with pre-stressed tendons (2 ducts containing 6 strands each);
- a truss-girder with members made of steel Fe 360;
- glued laminated timber (glulam) BS16 according to EC5;
- steel Fe 360 (full cross section beam);
- RPC 200 reinforced with FeB44k steel only at the lower flange in tension;
- RPC 800 reinforced with FeB44k steel only at the lower flange in tension.

The dimensions for each beam resulting from calculations are compared in Fig. 4.

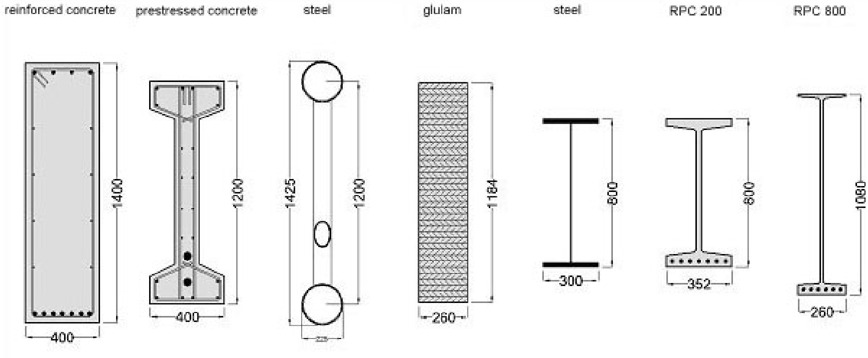

Figure 4: Comparison of equivalent strength beam cross sections obtained from calculations with seven different structural materials (all dimensions are in mm).

An unusual problem for concrete beams

Due to RPC high strength and consequently to high slenderness attainable for RPC elements, a new problem can arise, unusual for concrete: local instability of thin parts making up the RPC beam, analogously to steel beams. This issue compels to verify the equilibrium stability of compressed parts in the element section, as for instance the web of a H-shaped beam subjected to normal and/or shear stress, or its compressed flange (Fig. 5).

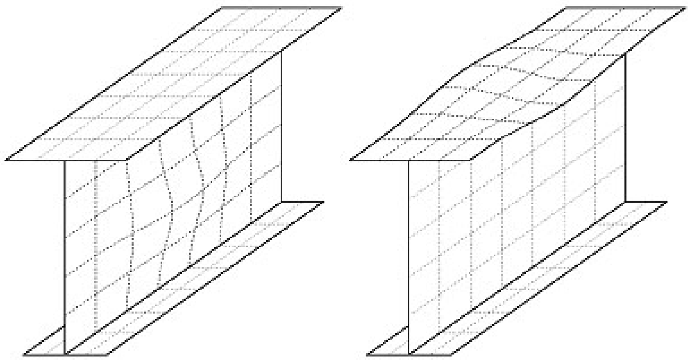

Figure 5: Schematic representation of local instability phenomena of slender parts in structural elements, like the web (left) and the flanges (right) of a beam.

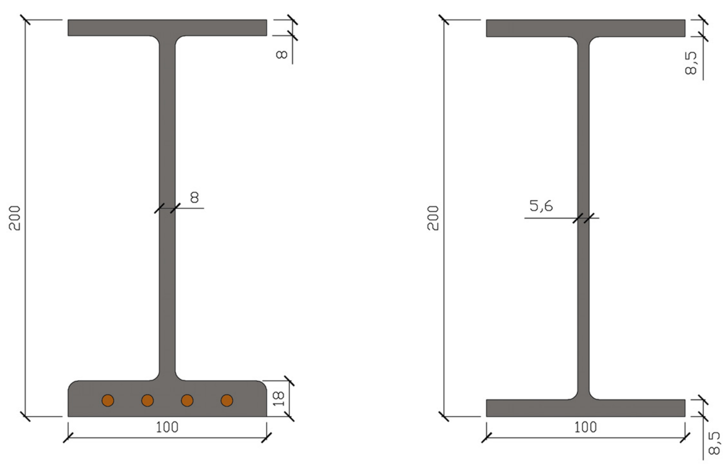

Figure 6: Comparison between RPC 200 (left) and steel (right) equivalent strength I-shaped beam cross section (sizes in mm). The lower flange is reinforced with 4×ø6 mm steel bars.

Preliminary testing of a real scale RPC 200 beam under flexure

Firstly, an I-shaped RPC 200 beam 2 meters in length with steel reinforcement embedded in the lower flange, has been manufactured according to the dimensions reported in Fig. 6 in comparison with the equivalent strength steel beam cross section.

Then, the 2 meter long RPC 200 beam underwent the bending test (Fig. 7) according to the European Norm UNI EN 12390-5:2002, and, in spite of the cementitious nature, it quite surprisingly twisted like steel (Fig. 8).

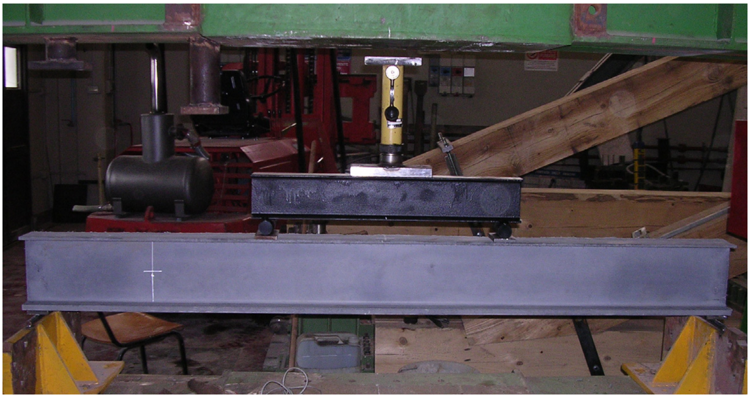

Figure 7: Four-points bending test on the RPC 200 beam.

Figure 8: The RPC 200 beam after the bending test. No crack can be observed in the shear-stressed area (left) of the twisted section (right).

This behaviour opens new scenarios for revolutionary structures, since RPC proves to be an innovative material able to outrun traditional limits of cementitious materials, as well as to compete with structural steel in challenging structures.

5 Conclusions

RPC material shows very high compressive and tensile strength as well as high toughness according to its high fracture energy.

This excellent behaviour, which takes RPC further from a common concrete, is due to accurate mixture proportioning and processing with selected raw materials. However, even using more easily available ingredients in order to make RPC more affordable, this work shows that very high mechanical performance can be usefully achieved, allowing one to avoid steel reinforcement for compression and shear and use it only for tension. This approach makes the girder cross section much more slender, which gives rise to unusual structural issues for cementitious elements, as high strain and equilibrium stability of the beam web. These problems can be in any case overcome by externally pre-stressing the RPC beams. In this way, external pre-stressing, which permits one to completely avoid traditional steel reinforcement, suits extremely well calendered or extruded RPC beams. Further, external pre-stressing can disallow any cracking under the service conditions, and significantly increases the durability of the structural member.

In conclusion, RPC proves to be a usefully innovative material able to outrun the traditional limits of cementitious materials, as well as to compete with structural steel in challenging structures.

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