



Article **Reactive Powder Concrete: Durability and Applications**

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Featured Application: In this current paper, Reactive Powder Concrete (RPC) durability is assessed. Thanks to the findings made here, optimization of the RPC mix design can be performed.

Abstract: Reactive powder concrete (RPC) is an ultra-high-performance concrete (UHPC) developed years ago by Bouygues, with the aim to build strong, durable, and sustainable structures. Some differences can be underlined between the RPC and high-performance concrete (HPC); that is to say, RPC exhibits higher compressive and flexural strength, higher toughness, lower porosity, and lower permeability compared to HPC. Microstructural observations confirm that silica fume enhances the fiber–matrix interfacial characteristics, particularly in fiber pullout energy. This paper reviews the reported literature on RPC, and it offers a comparison between RPC and HPC. Therefore, some RPC potential applications may be inferred. For instance, some examples of footbridges and structural repair applications are given. Experimental measurements on air permeability, porosity, water absorption, carbonation rate, corrosion rate, and resistivity are evidence of the better performance of RPC over HPC. When these ultra-high-performance concretes are reinforced with discontinuous, short fibers, they exhibit better tensile strain-hardening performance.

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). **Keywords:** reactive powder concrete; durability; silica fume; microstructure; composites; bond strength; interfacial transition zone

1. Introduction

Reactive powder concrete (RPC), otherwise known as ultra-high-performance concrete, was firstly developed by Pierre Richard, and later by Marcel Cheyrezy and Nicolas Roux, working for the French construction company Bouygues in 1993 [1,2]. RPC was originally named BPR, which stands for *Béton de Poudres Réactives*, i.e., reactive powder concrete in French. The first durability studies of these innovative concretes were performed by Carmen Andrade and Miguel Angel Sanjuán working for the "Eduardo Torroja" Institute for Construction Sciences, Madrid, Spain [3–9]. Corrosion assessment, mercury intrusion porosimetry and air permeability test results, among others, showed the high durability of this building material.

RPC was designed in two grades. The first one was called RPC200, with compressive strength between 170 and 230 MPa and tensile strength between 20 and 50 MPa. The second one named RPC800, which presents compressive strength and tensile strength of 500–800 MPa and 45–140 MPa, respectively [2].

1.1. Basic Design Principles

Reactive powder concrete is composed of very fine powders, i.e., Portland cement, sand, quartz powder, and silica fume. Sometimes (but not always) steel fibers are used, and superplasticizers are always employed to reduce the water to cement ratio (w/c) to less than 0.2, while improving the workability of the RPC. The optimization of the granular packing

of these materials was crucial from the beginning, in order to lead into an extremely dense cementitious matrix. This compact microstructure gives the reactive powder concrete its ultra-high strength and long-term durability [3–11].

The following basic principles were proposed for developing reactive powder concrete [2]:

- Removal of coarse aggregates for homogeneity improvement.
- Granular mix optimization to increase the compacted density.
- Application of pressure before and during setting) to enhance compaction.
- Post-set heat-treatment for the microstructural improvement.
- Incorporation of small-sized steel fibers to improve the ductility.
- Keeping the work procedures similar to that currently used.

In addition, an optimal amount of silica fume was used for its pozzolanic properties and filler capacity. Moreover, Portland cement chemistry and finesse optimization was necessary to produce hydrates with the highest strength [1,2]. A well-selected superplasticizer allowed the water/cement reduction with an enhancement of the workability.

Table 1 presents the different reactive powder concrete constituents and their selection parameters and functions, whereas Table 2 presents various typical mix proportions and main mechanical properties for RPC200 and RPC800 reactive powder concretes [1,2,11–13].

Components	Selection Parameters	Function	Particle Size	Types
Cement	$\begin{array}{c} C_{3}S > 60\%;\\ C_{2}S \cong 22\%;\\ C_{3}A < 5 \ (\cong 3.8\%);\\ C_{4}AF \cong 7.4\%. \end{array}$	Provides binding characteristics. Formation of primary hydrates.	1 μm to 100 μm	OPC (CEM I 42.5 R-SR 5–EN 197-1). Medium fineness.
Silica fume	High SiO ₂ content. Low amount of impurities.	Pozzolanic reaction. Formation of secondary hydrates. Filling the micropores. Improves rheology.	0.1 μm to 1 μm	Source: ferrosilicon industry (Highly refined). High fineness.
Quartz Powder	High fineness.	Maximum reactivity during heat-treating.	5 μm to 25 μm	Crystalline. Medium fineness.
Sand	Good hardness. Relatively available and low cost.	Provides strength. Skeleton of the concrete.	150 μm to 600 μm	Natural and Crushed.
Steel fibers	Optimized aspect ratio.	Enhances ductility.	Length: 13–25 mm. Ø: 0.15–0.2 mm	Straight shaped.
Superplasticizer	Low retarding characteristic.	Reduces the water/cement.	-	Polyacrylate-based additive.

Table 1. Parameters selection for reactive powder concrete constituents.

Some industrial by-products, such as fly ash, silica fume, and ground granulated blast-furnace slag, used in high-performance concrete, provide good resistance to chloride penetration and sulfate attack [14]. In addition, different binary and ternary-based concrete mixtures offer a low chloride diffusion coefficient [15].

For instance, Ting et al. studied the effects of adding 10% and 15% ultra-fine slag or silica fume on the compressive strength and durability of high-strength concrete. Cement paste with ultra-fine slag showed better fluidity and dispersibility than that containing silica fume, whereas chloride ion penetration resistance of ultra-fine slag and silica fume concretes is quite similar [16].

Table 3 describes the reactive powder concrete properties, recommended values, and types of failure improved. The main objective of this mix design is the setting up of a compact granular system. Packing models and particle size distribution software are tools in this "contest" [12].

Material	Characteristics	RPC200	RPC800
Cement	Portland cement—type V (ASTM C150)	955	1000
Sand	Fine sand (150–400 μm)	1050	5000
Silica fume	Silica fume $(18 \text{ m}^2/\text{g})$	229	390
Precipitated silica	Precipitated silica $(35 \text{ m}^2/\text{g})$	10	230
Super plasticizer	Super plasticizer (polyacrylate)	13	18
Steel fibers	Steel fibers (length 3 mm and diameter 180 μm)	191	630
water	Total water	153	180
	Typical Mechanical Properties of Rea	active Powder Concrete (M	Pa)
Compressive strength	Compressive strength (cylinder)	170–230	490–680
Flexural strength	Flexural strength	25–30	45-102
Young's modulus	Ŭ	54-60	

Table 2. Typical composition, kg/m³, and main mechanical properties, MPa, of reactive powder concretes RPC200 and RPC 800.

1 A cement type V according to the ASTM C150 is a sulfate resistant cement. In Europe, this cement is designated as CEM I 52.5 R-SR 5 according to the EN 197-1.

RPC Property	Description	Recommended Values	Types of Failure Improved
Reduction in aggregate size	Coarse aggregates are replaced by fine sand, with a reduction in the size of the coarsest aggregate by a factor of about 50	Maximum size of fine sand is 600 μm	Mechanical, Chemical and Thermo-mechanical
Enhanced mechanical properties	Improved mechanical properties of the paste by the addition of silica fume	Young's modulus values in 50–75 GPa range	Disturbance of the mechanical stress field
Reduction in aggregate to matrix ratio	Limitation of sand content	Volume of the paste is at least 20% greater than the voids index of non-compacted sand	By any external source (e.g., formwork)

Table 3. Main properties of reactive powder concrete and recommended values [1,2].

1.2. Main Properties of Reactive Powder Concrete

High strength concrete (HPC) provides a high compressive strength with its typical microstructure. Nevertheless, the weakest point in this kind of concrete is the coarse aggregate. Reactive powder concrete removes such coarse aggregates and optimizes the microstructure by packing with particle gradation of all the concrete constituents to reach the highest density [17].

The lack of coarse aggregate minimizes the concrete's internal defects, i.e., microcracks and pore spaces. The resulting main mechanical property is the achievement of higher compressive strengths than the high strength concrete (HPC) [1,2]. This compact microstructure is also the responsible of the low permeability and, thereafter, high durability [4–9]. A weak point of the first generation of the reactive powder concrete is the relatively low tensile strength of about 8 MPa in some cases. Thus, it can only be used in reinforced or prestressed concrete structural elements, substituting partially transverse reinforcement. New RPC derivatives achieve tensile strength of 25–150 MPa and their fracture energy ranges over 1200–40,000 J/m².

Currently, ultra-high-performance concretes (UHPC) have a high bond strength in addition to an ultra-high compressive strength. When UHPC is reinforced with discontinuous, short fibers, it exhibits a tensile strain-hardening performance of short distance cracks [18]. Non-linear models are used to predict the response and highlight the beneficial

effect of the added fibers in this type of concrete, namely the load-bearing capacity, energy dissipation, deformation, enhanced cyclic behavior in respect of residual stiffness, and cracking performance [19].

To summarize, reactive powder concrete is a type of ultra-high-performance concrete with high mechanical strength and high toughness due to the very low porosity. In addition, increasing the fineness and chemical activity of the components a long durability is achieved.

1.3. Early Works

Reactive powder concrete was successfully applied in several civil engineering projects due to its excellent mechanical and durable properties. For instance, in Sherbrooke, Canada, the first footbridge made of RPC200 was built in the world [20]. The lower chord was formed with prefabricated twin beams made with RPC200 ($10 \text{ m} \times 3 \text{ m}$). The use of RPC200 reduced the size and then the weight, increased the mechanical strength, and improved the durability. Consequently, it can resist the deicing salt effect in cold environments.

The background of producing very high-performance concrete goes back to the availability of silica fume that was pioneered by Elkem (Norway) and Norwegian researchers. This availability moved [21] H. Bache from Aalborg Cement, in 1986, to develop a very dense material named compact reinforced composite, CRC, which was a very high-performance steel fiber-reinforced concrete. The fiber content was in the range of 2–6% by volume with a strength ranging between 120 and 160 MPa. This material was developed further [22] and its durability was studied by researchers from the Institute of Construction Sciences of Spain [23].

The original reactive powder concrete was developed a bit further under the use of silica fume as a novel mineral addition, first without fibers, and after adding them due to a Bouygues and Aalborg cement collaboration [1]. This set of BPR concretes provided a basis for the development of several derivative ultra-high-performance fiber reinforced concretes (UHPFRC), e.g., Ductal[®]. This is a range of materials developed by BOUYGUES, Lafarge (currently LafargeHolcim) and Rhodia, with new properties [24], and furthered by other companies. The following is worth noting:

- New, hard, and very fine fillers were used to enhance the compactness. This fact improved both the mechanical strength and durability.
- Fibers were treated chemically to enhance the matrix-fiber bonding.
- Replacement of part of the sand, by mineral microfibers (e.g., wollastonite) to increase the homogeneity.

More than 200 engineering projects were carried out with this type of concrete. A selection of such projects can be found in reference [25]. One good example is the Mars Hill Bridge, which was built in Iowa, USA, by Lafarge Corporation. This project won the Bridge Competition Award held by the Portland Cement Association (PCA) in 2006. Another example of this ultra-high-performance concrete (UHPC) is the rehabilitation of The Pulaski Skyway, which is a steel bridge, built in 1930s between Newark and Jersey City, USA [26]. The Federal Highway Administration (FHWA) used this bridge to assess the technical benefits offered by this concrete. It should not be forgotten that infrastructure rehabilitation in the USA is a major political issue, since it is currently estimated that more than 70,000 bridges are structurally obsolete. The new Nipigon River Bridge in Ontario is a cable-stayed structure that commenced in 2013 (full completion was in 2019). This type of concrete was used for the junction of the longitudinal and transverse joints to the steel girders and beams, and the junction of the precast tower segments [27]. Finally, the Saint-Pierre-la-Cour was the first bridge in France made with this type of concrete. It was built with 10 precast girders, and they were pre-stressed with pre-tensioned strands. All of these elements proved to be very durable with low maintenance requirements [28]. In addition, Liu et al. reported several applications of reactive powder concrete in the bridge engineering [29], and they suggested that it could replace reinforcement steel bars [30]. Xialouzi Bridge is a bridge totally built of reactive powder concrete; the reinforcement steel bars were replaced by RPC [30].

Regarding the use of this ultra-high-performance concrete (UHPC) in architectural applications, a selection of roofing and facades examples built with this type of concrete can be found in reference [31]. The Great Mosque of Algeria, in Djamaa el Djazaïr, has more than 23,000 m² of facades made of this type of concrete [32]. Particularly, the Mashrabiya, i.e., a type of projecting oriel window enclosed with carved wood latticework, which is characteristic of the Arabic architecture, could weigh no more than 65 kg/m². The lightness of the material is well suited for this application.

2. Experimental

Mercury intrusion porosimetry (MIP) was utilized to analyze the total accessible porosity. This technique relies on employing high pressure to force mercury into capillary pore spaces to measure its porosity. Air permeability testing was performed by the method described in [33]. The experimental device used to measure air is composed of two metallic cells placed at each side of the specimen. In the first one, inlet air was held at 287,658 N × m⁻² by means of a compressor and a precision pressure regulator. In the second one, the passing air was measured at atmospheric pressure in a cylinder with a piston in which the outflow was collected. Finally, the airflow rate was measured, and the air permeability coefficient was calculated according to the Hagen–Poiseuille equation, for laminar flow under steady state conditions of a compressible fluid, through a porous material composed of a network of small capillary pores.

In addition, to assess the chloride penetration resistance, the apparent chloride diffusion coefficient was determined by a migration method consisting of applying a potential difference of 12 V between the two faces of a concrete disc of 5 mm [4]. Natural carbonation testing was performed in samples exposed to lab conditions, sheltered from rain at 20 ± 2 °C and 50% RH for two years. Electrochemical impedance spectroscopy (EIS) measurements were carried out to assess the corrosion kinetic of the electrolyte (concrete), which addresses the rate of electrode reactions, by using potential control and measuring the corresponding current response. The equipment used was a Solartron type 1250 digital frequency response analyzer and Solartron type 1286 electrochemical interface with a three-electrode arrangement. A Faraday cage and a frequency analog filter KEMO type VBF 8 were utilized to keep the concrete specimens free from noise [5].

Tests were performed on the reactive powder concrete RPC200 provided by Bouygues and defined in Table 3. For comparison purposes, a conventional concrete, C30, and a high strength concrete, C80, were tested.

3. Results and Discussion

Figure 1 compares the mercury intrusion porosimetry (MIP) results of a normal concrete, C30, a high strength concrete, C80, with the reactive powder concrete [4–8]. These results confirm and emphasize the extremely low porosity of RPC200 with absence of capillary pores. The mercury intrusion porosimetry (MIP) results are in agreement with the microstructural study performed by Cheyrezy et al. [13]. They found that the microstructure depends on the heat treatment and applied pressure, which was applied before and during the setting time. The pozzolanic reaction was enhanced by the temperature.

Determination and evaluation of the air permeability coefficient was performed by using the permeability method described in [33]. Concretes were conditioned by heating for 5 days at 50 °C or 30 days at 80 °C. Table 4 shows that RPC200 presents an air permeability coefficient 48 times lower than that of C80 when the treatment was curing at 80 °C for 30 days. However, the air did not flow through the RPC200 when the curing was at 50 °C for 5 days.



Figure 1. MIP cumulative porosity curves showing the curve corresponding to the reactive powder concrete in comparison with two curves for the C30 and C80 concretes.

Table 4. Durability of the reactive powder concrete compared with normal and high strength concrete [3–9].

Property —	Concrete Type			
горену —	$\begin{tabular}{ c c c c c } \hline Concrete Type \\ \hline C30 & C80 \\ \hline (\times 10^{-18} \mbox{ m}^2): & & & & \\ 0 \ ^{\circ}C & 30 & 0.3 & & \\ 0 \ ^{\circ}C & - & 120 & & \\ 0 \ ^{\circ}C & - & 120 & & \\ 0 \ ^{\circ}C & - & 0.3 & & \\ 0 \ ^{\circ}C & - & 0.3 & & \\ 0 \ ^{\circ}C & 1.7 & 0.4 & & \\ ent \ (\times 10^8 \mbox{ m}^2/s) & 1.26 & 0.09 & \\ results: & & & & \\ \hline \end{array}$	RPC200		
Air permeability coefficient ($\times 10^{-18}$ m ²):				
5 days curing at 50 °C	30	0.3	-	
30 days curing at 80 °C	-	120	2.5	
Porosity (%vol)	15	10	1	
Water absorption (kg/m^2)	2.7	0.3	<0.2	
Carbonation rate $(mm/y^{0.5})$	1.7	0.4	<0.1	
Carbonation diffusion coefficient ($\times 10^8 \text{ m}^2/\text{s}$)	1.26	0.09	< 0.007	
Electrical impedance results:				
Corrosion potential (E _{corr} , mV <sce>)</sce>	-0.82	+0.28	+0.90	
Ohmic resistance (kOhm·cm ²)	0.37	12	3022	
Capacity (C_{HF} , pF/cm ²)	10,793	145	14	
Corrosion rate (μ m/year)	1.2	0.25	< 0.01	
Resistivity (kOhm·cm)	16	96	1133	

In addition to these tests, resistance to chloride ingress was studied. In Figure 2, the chloride profiles from a natural diffusion test using a NaCl solution of 0.5% in chloride ion (around 30 g/L NaCl) are given. The values of the apparent diffusion coefficient (D_{ap}) calculated from them, are given in Table 5.



Figure 2. Chloride penetration profile in C30, C80, and RPC200 concrete.

The results for the RPC were not conclusive (or were misleading) due to the small chloride entrance (concentration between 0.1% and 0.03% by sample weight, which are in the range of the chloride concentration in the raw materials).

Consequently, accelerated tests were used by the application of an electrical field, and were made in order to have results in a reasonable short time. Table 5 shows the effective chloride diffusion coefficient (Def) (not considering binding) obtained by applying

a potential difference of 12 V between the two parallel faces of a concrete disc of 5 mm [4] in thickness. In both cases, the diffusion velocity is two orders of magnitude smaller in the case of BPR concretes.

Table 5. Chloride diffusion coefficients, effective and apparent, of the reactive powder concrete, C30, and C80.

Bromerty	Concrete Type		
rioperty	C30	C80	RPC200
Effective chloride diffusion coefficient ($\times 10^{-12} \text{ m}^2/\text{s}$) Apparent chloride diffusion coefficient ($\times 10^{-12} \text{ m}^2/\text{s}$)	1.1 12.4	0.6 1.11	0.02 0.8

For the calculation, the measured effective chloride diffusion coefficient was taken into account, which was higher than the apparent chloride diffusion coefficient. This is a conservative way of estimating the service life. Consequently, a reinforcement cover of 10 mm of RPC200 is enough to ensure a service life longer than 80 years in comparison to the five years for C80 with the same cover [4–8].

The carbonation rate of RPC was also calculated from accelerated tests. It was more than four times less in the RCP than in the C80 concrete (Figure 3). Therefore, a natural carbonation lower than 2 mm after 500 years in reactive powder concrete is expected.



Figure 3. Two years natural carbonation depth results of concretes: (a) C30 and C80; (b) RPC200.

Four high strength concretes named A, B, C, and D, with 28-day compressive strengths of 192 MPa, 138 MPa, 127 MPa, and 123 MPa, and made with the same constituents (CEM I 52.5 R, siliceous aggregates, and a high range water reducer) were tested for natural carbonation.

Figure 4 shows the carbonation rate results of these four high strength concretes, which were cured at four different conditions as follows:

- 1. Twenty-eight days of curing under water;
- 2. Air-curing (50% RH, 20 °C);
- 3. Air-curing (50% RH, 50 °C);
- 4. Carbon dioxide pre-curing $(5\% \text{ CO}_2, 60\% \text{ RH}, 20 \degree \text{C})$.



Figure 4. Carbonation rate of four high strength concretes cured at four different conditions: (**a**) carbonation rate; (**b**) Carbonation rate versus compressive strength relationship.

Then, they were submitted to indoor natural carbonation conditions (50% RH and 20 ± 2 °C) for 10 years. Carbonation rate, V_{co2}, is calculated from Equation (1).

$$x = V_{co2}\sqrt{t},$$
(1)

where: x = average carbonation front, mm. t = time, years.

The main findings are: (i) concrete A is the most resistant against carbonation, with expected carbonation depths at 50 years around 25 mm; (ii) concrete D is the least resistant, of the four mixes tested, with expected carbonation depths at 50 years of between 50–70 mm; (iii) concretes B and C behave similar, in regards to their carbonation resistance; then, carbonation depths lesser than 50 mm are expected at 50 years; (iv) 28-day wet curing does not contribute significantly to the carbonation resistance of high strength concretes.

In regards to the risk of reinforcement corrosion—its resistivity is so high (Table 4) that corrosion is excluded as there is no capillary porosity. This is confirmed by means of electrochemical impedance spectroscopy (EIS). The response of the system (concrete cured at 100% RH and 25 °C for 230 days) is displayed in Nyquist format in Figure 5, as this system is inherently capacitive.



Figure 5. Nyquist diagram of the reactive powder concrete (RPC200).

With respect to the metallic fibers, when they were added, only corrosion was detected in the zones of the fibers not covered by the paste in the concrete surface.

4. Discussion

Ultra-high-performance material reactive powder concrete origins, durable performance, and the main applications are presented and analyzed in this paper. Incorporation of very fine materials, such as silica fume or quartz powder into the concrete matrix to achieve a high level of compactness, combined with the utilization of additives to reduce the water/binder ratio, led to the development of a new generation of high strength/performance concretes. However, not all show the same durability. Pore volume measured by means of mercury intrusion porosimetry (MIP) was much lower in reactive powder concrete (RPC200) than in high-performance concrete, C80, and normal concrete, C30. The porosity of RPC200 was concentrated around 0.01 µm, which is four times lower than the concentration of the pores in the high-performance concrete, C80. A similar trend was also observed in normal concrete, C30. In this case, porosity around $0.01 \ \mu m$ was seven times higher than that of RPC200. These findings show the great compactness of RPC200. Because mercury intrusion porosimetry (MIP) measures the connection from the concrete surface to the pore, this technique fails to measure the internal pore size. Accordingly, the air permeability coefficient was about 50 times lower in RPC200 than in C80, and the effective chloride coefficient was about 30 times lower. In addition, the carbonation depth in RPC200 after two years of natural exposure was almost nil. Regarding the corrosion parameters, similar results were found, i.e., the corrosion rate was much lower (25 times) in RPC200 than in C80. Furthermore, its resistivity was about half of the value found in C80.

The excellent mechanical and durable properties of this material makes it a good option for special civil works and buildings because it prolongs their service life in aggressive environments. In addition, it was shown that by optimizing the procedure to reinforce the matrix with fibers, it is possible to achieve an adequate tensile performance to manufacture structural members without reinforcement. Consequently, in some cases, the use of RPC could replace steel reinforcement, leading to a simpler construction procedure. Furthermore, the steel reinforcement corrosion is avoided. Therefore, reactive powder concrete derivative concretes are promising cement-based materials for high durability concrete structures, such as ultra-high-performance fiber reinforced concretes (UHPFRC). In addition, the peculiar properties of reactive powder concrete makes it a suitable material for use in pre-stressed and precast concrete elements. To summarize, experimental measurements of air permeability, porosity, water absorption, carbonation rate, corrosion rate, and resistivity are evidence of the better performance of UHPFRC over HPC.

The main barrier for UHPC is its cost—a life cycle cost analysis is seldom made for the selection of the structural material and, consequently, the initial cost. On the other hand, although these materials are now being included in codes for structural calculations, some of the highest strengths are still not well known by numerous designers, meaning these "high strengths" are not used in all structural possibilities. However, the durability of these materials is a strong reason for the designer to consider them, particularly when taking into account the whole life cycle.

For UHPCs of the future, new mixes are being developed that will improve their characteristics. Different mix designs were reported in the literature [34–37]. For instance, Wang et al. [38] mixed Portland cement with silica fume, ground granulated blast-furnace slag, and limestone, with a water/binder ratio of 0.16, and steam curing. They reached a compressive strength of 176 MPa. Similar results were also found by using coal fly ash instead of limestone [39,40]. Yunsheng et al. [41] mixed Portland cement with silica fume, ground granulated blast-furnace slag and fly ash. Their concrete with microfibers achieved a compressive strength of over 200 MPa. Mostofinejad et al. [42] found an enhancement of 174% by applying an optimized mix design and curing treatment from 85 to 233 MPa. The effect of the heat and pressure conditions to achieve a microstructural refinement and mechanical property improvement was reported in several papers [43–45]. Some researchers proposed decreasing the Portland cement or silica fume content via the use of other mineral admixtures in order to reduce the hydration heat, such as ground phosphorous slag [46], glass powder [47], etc. To summarize, the superior performance, and durable and mechanical properties of these concretes provide several advantages over high strength concretes.

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5. Conclusions

After studying several types of UHPCs, the following conclusions can be made:

- 1. UHPC can be considered a material, usually with several types of small size fibers in the mix. All of the components are densely packed, and contain relatively large amounts of anhydrous cement particles due to the low water/binder ratios, which are below 0.35.
- 2. UHPCs have porosities lower than 5% by volume, in the range of 0.01 μ m.
- 3. Not all UHPCs possess the same durability. Those tested here presented an air permeability coefficient about 50 times lower in RPC200 than in C80, and the effective chloride coefficient was about 30 times lower. In addition, the carbonation depth in RPC200 after two years of natural exposure was almost nil. Regarding the corrosion parameters, similar results were found, i.e., the corrosion rate was much lower (25 times) in RPC200 than in C80. Furthermore, its resistivity was about half of the value found in C80.
- 4. It was shown that by optimizing the procedure to reinforce the matrix with fibers, it is possible to achieve an adequate tensile performance to manufacture structural members without reinforcement. This leads to UHPFRC.
- 5. This material has high potential of application, in terms of sustainability, but also when considering the lifecycle cost analysis. Although the initial price is higher than other concretes, its greater durability makes its application cost-effective for special structures.

One drawback with the reactive powder concrete is the absence of a robust standardization system and regulatory framework.

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