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Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength

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Synopsis : The use of ultra-high-strength concrete for the construction of some types of structural members can be considered if non-brittle behavior is achieved. This paper introduces Reactive Powder Concretes (RPC) which exhibit ultra-high-strength and high ductility at the same time. Compared to conventional concretes, the ductility estimated in terms of fracture energy is increased by one to two orders of magnitude, while the compressive strength values are in the range of 200 to 800 MPa.

Keywords: Cement pastes; compressive strength; concretes; density (mass/volume); ductility; flexural strength; high strength concretes; microstructure; silica fume; strength; structural members.

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INTRODUCTION

Concretes with compressive strengths of 100-120 MPa have recently been developed and are being used for the construction of structural members (1, 2). Concrete with compressive strength of 250-300 MPa can also be produced using different techniques (DSP-MDF) (3, 4, 5). Some of these concretes are used for non-structural applications such as flooring, safes and storage barrels for nuclear wastes (6). Strengths up to 650 MPa have been obtained on small samples of cement paste, hot-cured under pressure in hydrothermal conditions (compacts) (7).

For structural uses, high ductility is required together with ultra-high-strength. Reactive Powder Concrete (RPC) described in this paper has compressive strengths ranging from 200 MPa up to 800 MPa and fracture energies ranging from 1200 to 40 000 J/m^2.

BASIC PRINCIPLES UNDERLYING THE DEVELOPMENT OF RPC

Improvement of Homogeneity

Concrete is a heterogeneous material and performances obtained on hardened cement pastes are not fully retained when sand and aggregates are added.

Homogeneity is improved by using a powder concrete in which aggregates and traditional sand are replaced by ground quartz less than 300 microns in size. Compared with conventional concrete the distribution in the size of particles is therefore reduced by nearly two orders of magnitude. Another significant improvement is obtained by increasing by a factor of three the Young's modulus of the cement paste. For RPC, moduli ranging from 55 to 75 GPa are obtained, thus reducing the adverse effects of the modulus mismatch between the paste and the quartz powder.

Increase of Dry-compacted Density

The main factor governing the minimal amount of water required for fluidizing a concrete mix is the compacted density of the dry solids. With conventional concrete this compaction is improved by the use of a superplasticizer and particles smaller than cement grains such as silica fume, which is used at its optimal ratio of 25% of cement weight. This filler effect is further improved by the use of a smaller amount of precipitated silica. Another way to increase the density of concrete is to maintain the fresh concrete under pressure at the moulding stage and during setting. This has the following beneficial effects : removal of air bubbles, expulsion of excess water, and partial compensation of chemical shrinkage of concrete during setting.

The first effect is instantaneous, the second effect takes place within a few minutes and the third occurs after several hours. Altogether the application of a compacting pressure increases the density of the samples by 5 to 6 %.

Improvement of Microstructure

Pozzolanic reaction of silica fume is activated by temperature. A gain of 30 % in resistance is obtained by hot curing at 90°C during two days. At the same time, mercury porosimetry analysis shows that the average size of pores is decreased.

When ground quartz is added to the mix, a high curing temperature, from 250°C to 400°C, may be applied. At this temperature, amorphous cement hydration products are transformed into crystalline products. XRD analysis shows the presence of xonotlite. The formula of xonotlite C_6S_6H, corresponds to a H/C ratio of 1/6. Since this ratio is approximately 1 for cement hydration product formed at normal temperature, the formation of xonotlite results in a considerable loss of weight due to intense dehydration (Fig. 1). The water vapor from the dehydration process is entrapped within the sample thus creating the hydrothermal condition required for the formation of the crystalline product.

XRD analysis performed on fragments of concrete taken from the edge of the sample does not show any xonotlite since, local confinement of water vapor is not sufficient to maintain hydrothermal conditions.

High-temperature curing leads to extremely high compressive strengths, for instance 631 MPa at 250°C and 673 MPa at 400°C for pressurized samples, and 488 MPa at 250°C and 524 MPa at 400°C for soft-cast (without pressure) samples.

Figure 2 shows compressive stress as a function of residual water ratio. The latter is the ratio of the mass of water w_r remaining in the sample at the time of the test to the mass of water w_i initially introduced into the mix.

Achievement of Ductile Behavior

The cementitious matrix obtained with the application of the three abovementioned principles is nearly as brittle as an industrial ceramic. The hot-cured matrix has a flexural strength of 28 MPa and a fracture energy of 50 J/m^2.

The addition of steel micro-fibers results in flexural strengths ranging from 50 to 102 MPa and fracture energy from 10 000 J/m^2 up to 40 000 J/m^2 depending on the type of hot-curing applied and the amount of steel fibers used (from 2 % to 6 % by volume). These fracture energies indicate a very ductile behavior. They are obtained through three-point bending tests performed on notched samples. Similar values have been obtained on small samples (4 x 4 x 16 cm) and large samples (7 x 7 x 28 cm).

DEFINITION OF RPC 200 AND RPC 800

From our research it appears that two products, RPC 200 and RPC 800, with different fabrication processes, properties and uses, can be developed for practical applications. They are described below.

RPC 200

A typical composition of the RPC 200 mixture is given in Table 1. The cement used is Type V ordinary Portland Cement. The aggregate is fine quartz sand (150 to 300 microns). Micro-silica is mostly undensified silica fume and partly synthesized precipitated silica. The steel fibers are 12.5 mm in length and 180 microns in diameter. They are straight and smooth.

Even though the water-cement ratio is low this concrete can be mixed, cast and vibrated in the same way as conventional concrete. Mechanical properties are given in Table 2. The lower value of compressive strength (170 MPa) corresponds to 28 days of curing at ambient temperature, while the upper value (230 MPa) corresponds to hot-curing at 80-90°C after two days of precuring at ambient temperature.

Variation in flexural strengths and fracture energies are governed by the percentage of fibers added. Figure 3 shows the behavior of a conventional mortar and RPC 200 during a three-point bending test performed on notched samples. It can be seen that RPC 200 exhibits a great strain-hardening stage followed by gradual strain-softening. The maximum flexural stress reached is twice as high as the stress at first cracking (50 MPa and 25 MPa respectively). The displacement at maximal stress is approximately ten times greater than the displacement at the opening of the first crack.

The fracture energy, proportional to the area underneath the behavior curves, is 30 000 J/m^2 for RPC 200 and 110 J/m^2 for conventional mortar (Fig. 4). RPC is characterized by a high flexural strain combined with a very ductile behavior. This material can be used in prestressed members without passive reinforcement. In compressive members such as columns, RPC 200 can be used without prestressing. Prestressed, non-reinforced RPC 200 ten-meter-span beams have been constructed and successfully tested.

RPC 800

A typical composition of RPC 800 is given in Table 3. This material is to be used only for small or medium size prefabricated elements.

The components used are the same as those used for RPC 200 with the exception of the steel fiber which is replaced by a stainless steel microfiber less than 3 mm in length.

A dry-curing temperature of 250°C or more is applied after demoulding. Improved properties are obtained through pressure applied in the moulds before and during setting.

Compressive strengths are measured on cylindrical samples of 7 cm in diameter and 14 cm in height. Mechanical properties for pressurized samples cured at 400°C are given in Table 4. Fracture energies are in the range of 1200 to 2000 J/m^2. These values are more than ten times those obtained on conventional concrete. When steel powder is used instead of quartz sand, compressive stress can reach 800 MPa. For instance, one sample sustained without failure a compressive stress of 776 MPa corresponding to the full capacity of the press.

A typical sequence for hot-curing is given in Figure 5. The ratio of residual water to initial water is plotted on the vertical axis. It can be seen that it takes a long time to reach constant weight at a given temperature. In practice, the curing sequence can be accelerated when higher temperatures are used.

Figure 6 shows a scanning electron micrograph of the microstructure of a fractured sample of RPC. It can be seen that failure occured in the paste at some distance from the paste-aggregate interface. This illustrates the high bond strength at the interface.

RPC 800 is a strong material that can be used as a substitute for steel. For instance prototypes of multistrand prestressing anchorage heads have already been fabricated. Protective panels made of RPC 800 have shown excellent performance against impacts from projectiles.

CONCLUSION

Main advances in the concrete industry during the last decade include the development of high-performance concrete using silica fume and superplasticizers. Additional progress can be made through a rational use of ultra-high-strength cementitious matrices. In the development of RPC (Reactive Powder Concrete), ductility and strength were both considered as important. This approach resulted in two products :

- RPC 200 with a compressive strength of 170-230 MPa, a flexural strength of 25-60 MPa and a fracture energy of 30 000 J/m^2,

- RPC 800 with a compressive strength of 500 to 800 MPa, a flexural strength of 45-102 MPa, and a fracture energy of 1500 J/m^2.

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TABLE 1 — TYPICAL COMPOSITION OF REACTIVE POWDER CONCRETE 200

Portland cement - Type V	955 kg/m^3
Fine sand (150-400 microns)	1051 kg/m^3
Silica fume (18 m^2/g)	229 kg/m^3
Precipitated silica (35 m^2/g)	10 kg/m^3
Superplasticizer (polyacrylate)	13 kg/m^3
Steel fibers	191 kg/m^3
Total water	153 l/m^3

TABLE 2 — MECHANICAL PROPERTIES OF REACTIVE POWDER CONCRETE 200

Compressive strength f_{ck} of cylinders	170 MPa to 230 MPa
Flexural strength	25 MPa to 60 MPa
Fracture energy	15 000 J/m^2 to 40 000 J/m^2
Young's modulus	54 GPa to 60 GPa

TABLE 3 — TYPICAL COMPOSITION OF REACTIVE POWDER CONCRETE 800

Portland cement - Type V	1000 kg/m^3
Fine sand (150-400 microns)	500 kg/m^3
Ground quartz (4 microns)	390 kg/m^3
Silica fume (18 m^2/g)	230 kg/m^3
Superplasticizer (polyacrylate)	18 kg/m^3
Steel fibers	630 kg/m^3
Total water	180 l/m^3

TABLE 4 — MECHANICAL PROPERTIES OF REACTIVE POWDER CONCRETE 800

Compressive strength f_{ck} of cylinders	490 MPa to 680 MPa
Flexural strength	45 MPa to 102 MPa
Fracture energy	1 200 J/m^2 to 2000 J/m^2
Young's modulus	65 GPa to 75 GPa

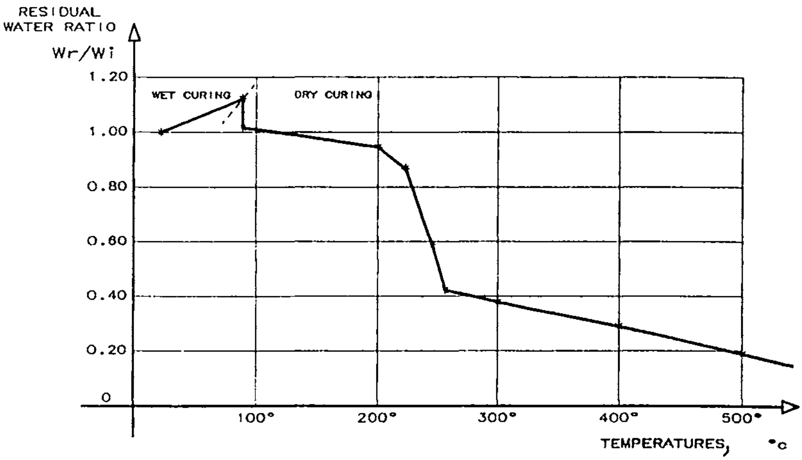

Fig. 1—Loss of water as a function of curing temperature

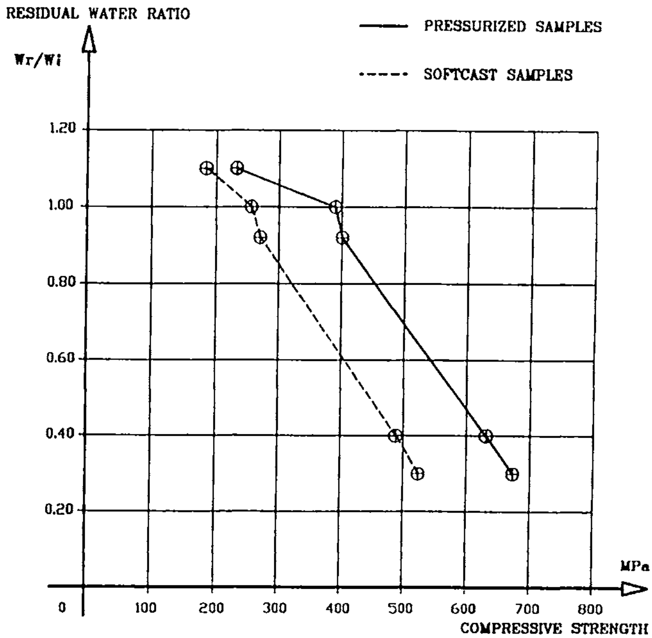

Fig. 2—Compressive strength as a function of residual water ratio

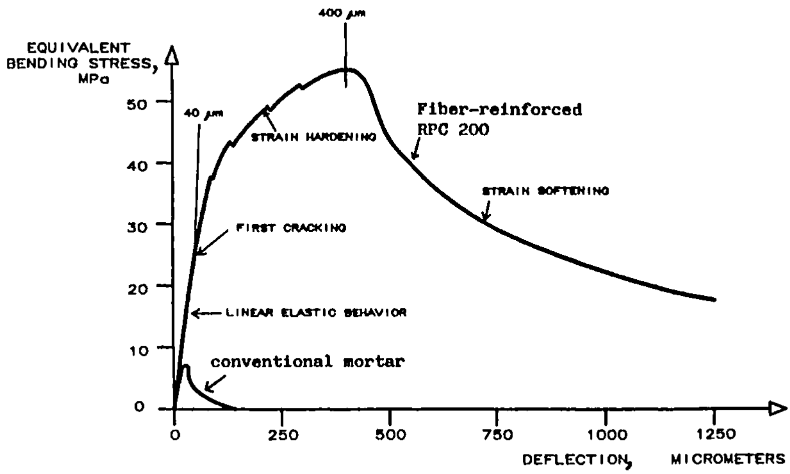

Fig. 3—Flexural strength of conventional mortar and reactive powder concrete 200

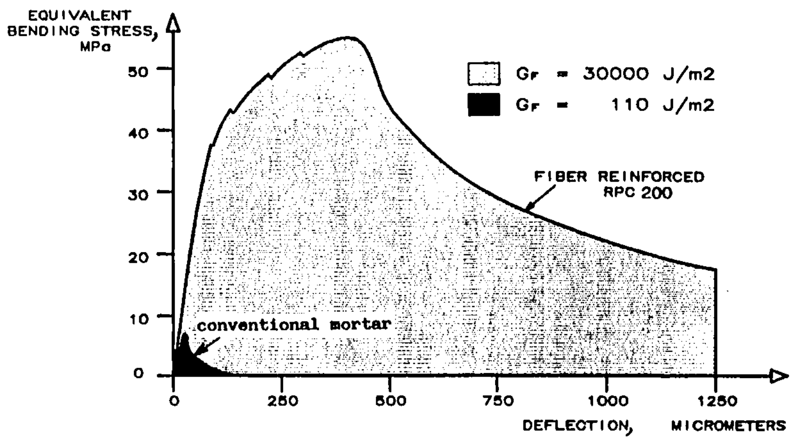

Fig. 4—Fracture energies of conventional mortar and reactive powder concrete 200

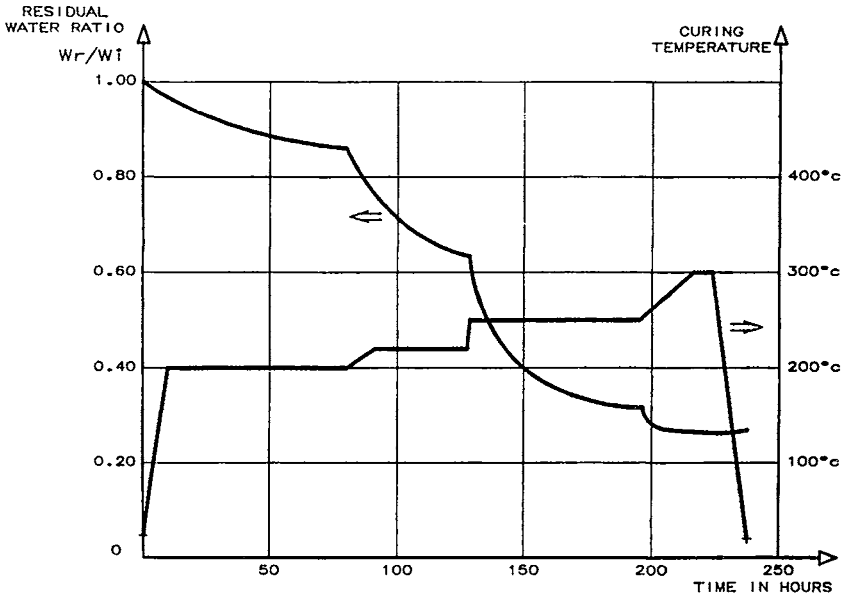

Fig. 5—Typical curing sequence

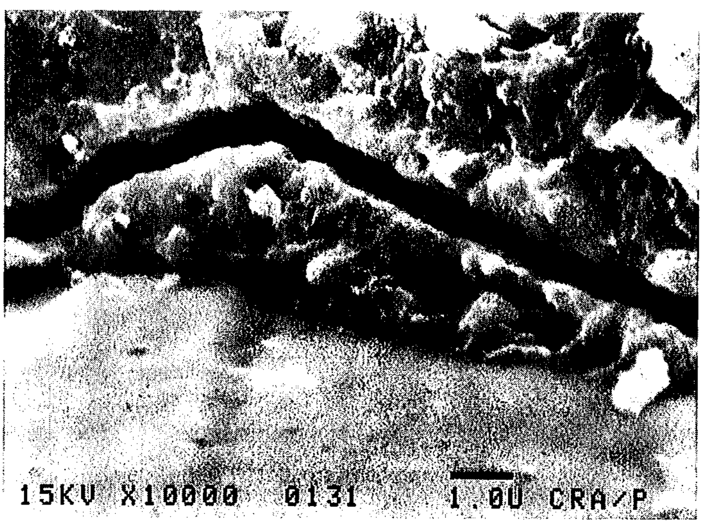

Fig. 6—Scanning electron micrograph of the microstructure of reactive powder concrete 800