Journal of Advanced Concrete Technology Vol. 2, No. 3, 409-417, October 2004 / Copyright © 2004 Japan Concrete Institute

Development of a Light Weight Reactive Powder Concrete

Abouzar Sadrekarimi[1]

Received 24 February 2004, accepted 23 June 2004

Abstract

Reactive Powder Concrete (RPC) is an ultra-high-strength, high ductility and low porosity cementitious material. RPC properties are improved by pressing fresh RPC samples, which can increase its specific weight as high as 3000 kg/m^3. However, high specific weight may be a shortcoming, where weight saving is important. Following to this review, a set of tests on RPC samples with high silica fume contents were carried out in a laboratory. The results show that although high silica fume content increases the compressive strength, however it decreases the density. It is concluded that by means of silica fume it is possible to produce high strength RPC with a specific weight as low as 1900 kg/m^3. This Light Weight Reactive Powder Concrete (LWRPC) could be used in areas where substantial weight savings can be realized and where some of the remarkable characteristics of the material can be fully utilized.

1. Introduction

Concrete is generally considered a proper construction material for many civil and military applications. It can be strong and produced to be durable, can be placed in many shapes and is economical. Since it is much stronger in compression than it is in tension, concrete is primarily used for its compressive strength (O'Neil et al. 2001). Therefore, intensive research efforts have been devoted to the improvement of the compressive strength of concretes. During the 1930s, Freyssinet (1936) demonstrated the advantages of applying pressure to fresh concrete during setting, in order to improve its strength. During the 1960s, strength values of 650MPa were obtained on compressed samples, heat-cured under elevated pressures (Roy and Gouda 1983).

Furthermore the mass of a concrete member can be increased or decreased by altering its component materials and geometry. For applications where mass is important, a large section of normal-density concrete or a smaller section of high-density concrete can be used. For applications where mass or size is detrimental yet strength is necessary, concrete structures are often designed to provide thin sections of higher-strength concrete. In other applications, the combination of high strength and high mass or high strength and low mass are important and often critical criteria. The strength and mass of a concrete section is important in applications where concrete is being considered as a material for use in protective structures (O'Neil et al. 2001). In this research an ultra high strength concrete named Reactive Powder Concrete (RPC) has been modified to be lightweight so producing an economical material with high strength to weight ratio.

2. High performance concretes (HPC)

Engineers are constantly looking for new materials to provide answers to complex problems. As construction and material costs escalate, demand has increased for stronger materials. One of the first breakthroughs was the development of High Performance Concrete (HPC) characterized by a compressive strength of 100-120 MPa and high level durability which lead to interesting realizations in civil engineering (Feylessoufi et al. 1996). The concrete that was known as high-strength concrete in the late 1970s is now referred to as high-performance concrete because it has been found to be much more than simply stronger (Aitcin 1997). O'Neil et al. (2001) discussed some significant differences between conventional and high-performance concrete as below:

1. size and composition of constituents
2. water to cementitious material ratio (w/cm)
3. the use of steel fibres (sometimes micro-fibres) to improve ductility and toughness
4. the amount of mixing energy employed
5. curing procedures.

Other improvements have been obtained by adding polymer components to macro-defect-free (MDF) concretes or by controlling the proportions and the mechanical behaviour of components in the case of densified with small particles (DSP) concretes.

3. Reactive powder concrete (RPC)

Reactive Powder Concrete is an ultra high-strength and high ductility composite material with advanced mechanical properties. Reactive Powder Concrete (RPC) is a fiber-reinforced, superplasticized, silica fume-cement mixture with very low water-cement ratio (w/c) characterized by the presence of very fine quartz sand (0.15-0.40 mm) instead of ordinary aggregate. In fact, it is not a concrete because there is no coarse aggregate in

---

[1] Department of Civil Engineering, University of Tehran, Iran.
E-mail: a_sadrekarimi@hotmail.com

the cement mixture. The absence of coarse aggregate was considered by the inventors to be a key-aspect for the microstructure and the performance of the RPC in order to reduce the heterogeneity between the cement matrix and the aggregate. However, due to the use of very fine sand instead of ordinary aggregate, the cement factor of the RPC is as high as 900-1000 kg/m^3 (Richard and Cheyrezy 1994, Cheyrezy et al. 1995).

The original concept of RPC was first developed, in early 1990s, by researchers at Bouygues laboratory in France. RPC is composed of more compact and arranged hydrates. The hydration process in RPC is brought to a more extensive and definite level. It consists of a special concrete where its microstructure is optimised by precise gradation of all particles in the mix to yield maximum density. It uses extensively the pozzolanic properties of highly refined silica fume and optimisation of the Portland cement chemistry to produce the highest strength hydrates (Dowd 2000). By introducing fine steel fibres, RPC can achieve remarkable flexural strength up to 50 MPa. The material exhibits high ductility with typical values for energy absorption approaching those reserved for metals (O'Neil and Dowd 1995). Cheyrezy et al. (1995) have stated that RPC properties are improved by two means: fresh samples may be pressed and heat treatment is applied to samples once moulded. In the case of pressed samples, pressure is applied before and during the setting period.

3.1 Properties

(1) Mechanical properties

RPC has compressive strength between 200 ~ 800 MPa, modulus of rupture between 25 ~ 150 MPa, fracture energies (proportional to the area underneath the behaviour curves of equivalent bending stress and deflection) of about 30,000 J/m^2 and volume weights of 2500 ~ 3000 kg/m^3 (Richard and Cheyrezy 1994). RPCs invariably have Young's modulus values exceeding 50 GPa, which can go as high as 75 GPa. In the latter case we observe that the global modulus for the paste and aggregate is slightly higher than that for the silica aggregate. Thus the effect of mechanical heterogeneity has been totally removed, and even reversed (Richard and Cheyrezy 1995).

(2) Homogeneity

The homogeneity of the concrete material can be improved by eliminating all coarse aggregates and making as much of the dry component materials the same particle size as possible. All the dry components for use in RPC are less than 600 μm (Richard and Cheyrezy 1994).

(3) Compactness

The compactness can be enhanced by optimisation of the granular mixture and the application of pressure before and during the concrete setting period (Richard and Cheyrezy 1994).

(4) Microstructure

The microstructure of the cement hydrate can be changed by applying heat treatment during the curing of concrete (Richard and Cheyrezy 1994).

(5) Material ductility

RPC matrix can reach very high compressive strength by application of heat treatment and pressure, but its material ductility isn't better than that of a conventional matrix. The material ductility can be improved through the addition of short steel fibres (Richard and Cheyrezy 1994).

3.2 Composition

Conventional concrete is a heterogeneous material with components from fine cement to coarse aggregates each exhibiting different strengths and modulii of elasticity. Under a system of forces, all these components deform at different rates. The differential movement of these components produces strains between the component materials which initiate the process of tensile fracture when the strains exceed the tensile strain capacity of concrete. RPC is composed of particles of similar modulii and size which helps increasing the homogeneity of the composite material thereby reducing the differential tensile strain in the concrete and consequently increasing the ultimate load-carrying capacity of the material. High density is the second principle employed to increase strength and decrease permeability. In choosing the volumes of component materials, particle-packing techniques can be used to maximize the amount of solids per unit volume of concrete. As with conventional concrete, the material having the largest particle size in RPC is the aggregate, which is the sand. The material having the next largest particle size is the cement, which is on the order of 10 to 100 μm. The smallest particles are silica fume, which are on the order of 0.1 μm in diameter. The volumes of all these particles are selected to achieve the greatest particle packing and hence the greatest density of the paste. The higher the density the greater the strength of the paste and lower the permeability because there are fewer and smaller voids (O'Neil et al. 2001).

In RPCs calcium silicate hydrates (C-S-H) result from two reactions: cement hydration reaction and the so-called pozzolanic reaction between silicate ions, produced by the dissolution of silica fume in water and the calcium ions coming mainly from calcium hydroxide, present in the medium (Philippot et al. 1996). Strength of RPC is further improved by increasing the volume of pozzolanic components that can react to form hydration products. In RPC, materials with high silica content are necessary for optimum performance. Cements high in silica content produce higher strengths. Large volumes of low-carbon silica fume (Neeley and Walley 1995) also enhance the production of strength. These materials provide chemically active silica which helps to produce larger volumes of calcium silicate hydrate (C-S-H). High amounts of C-S-H increase the strength of the binder and improve the bond between cement and aggregate. To optimise performance, w/cm in RPC must be held to a minimum. Excess water in the mixture is detrimental to the strength of concrete. The quantity of water required to hydrate all of a given amount of Portland cement is about that present at a w/c of 0.4 (O'Neil et al. 2001). Water that is not chemically or physically combined in the hydration or pozzolanic reaction products, weakens the paste and thus the compressive and tensile strength of the concrete. The volume of water used in RPC is kept low to insure that there is no excess. The w/c ratio used in RPC ranges from 0.15 to approximately 0.25 (US Army Engineer Waterways Experiment Station 1998). This range of w/c ratio not only produces the highest range of strengths, but also ensures that all the water in the mixture will be combined in producing calcium silicate hydrate (C-S-H) and will form voids. This volume is less than that needed to hydrate all the cement so as to insure that all water is consumed in the hydration/pozzolanic reaction process. However, this small quantity of water usually does not provide sufficient workability to the mixture. High-range-water-reducing admixtures (HRWRA) are used to make the otherwise very stiff concrete flowable (O'Neil et al. 2001). Bonneau et al. (2000) discussed that the dispersing effect of a superplasticizer (SP) used at its optimal value decreases the w/c ratio while improving the rheology of the paste. In order to increase concrete ductility and flexural strength, metallic fibres can be added (Cheyrezy et al. 1995). A review of recently published literature (Richard and Cheyrezy 1994 , 1995; Richard et al. 1995; Bonneau et al. 1996; Dugat et al. 1996; Feylessoufi et al. 1996; Roux et al. 1996; Collepardi et al. 1997; Aitcin et al. 1998; US Army Engineer Waterways Experiment Station 1998; Cheyrezy 1999; Matte and Moranville 1999) reveals that RPCs are essentially made of ordinary Portland cements specially type V Portland cement or similar with a high silica and low tri-calcium aluminate (C_3A) content, undensified silica fume, fine sand, crushed (or ground) aggregate, water, surperplasticiser, and steel fibres (optional). The composition of RPC differs somewhat from that of normal strength concrete: the amount of cement is markedly increased, the amount of mixing water is significantly less, the amount of superplasticiser is significantly higher and the maximum size of the coarse aggregate is usually smaller (Richard and Cheyrezy 1994).

The combination of these principles leads to produce a concrete with an ultimate compressive strength up to approximately 175 MPa when mixed and cured at ambient temperatures. Strength greater than 200 MPa can be achieved when the concrete is cured at 90ºC for a few days. The processes of applying sufficient pressure during initial hardening to expel any excess water and air from the fresh mixture, and providing a curing environment of up to 400ºC can produce concrete with compressive strengths greater than 800 MPa (O'Neil et al. 2001).

3.3 Benefits

O'Neil and Dowd (1995) summarized some of the most profitable benefits of RPC as below:

- RPC is a better alternative to high performance concrete and has the potential to structurally compete with steel.
- Its superior strength combined with higher shear capacity results in significant dead load reduction and less limited shapes of structural members.
- With its ductile tension failure mechanism, RPC can be used to resist all but direct primary tensile stresses. This eliminates the need for supplemental shear and other auxiliary reinforcing steel.
- RPC provides improved seismic performance by reducing inertia loads with lighter members, allowing larger elastic deflections by reducing cross sections, providing higher energy absorption and improved confinement.
- Its low and non-interconnected porosity diminishes mass transfer making penetration of liquid/gas or radioactive elements nearly non-existent. Caesium diffusion is non-existent and Tritium diffusion is 45 times lower than conventional containment materials.

3.4 Utilization

RPC is a natural extension of existing high performance concrete and has the potential to structurally compete with steel. RPC is significantly more expensive than normal strength concrete or even high performance concrete, but less expensive than steel on a volumetric basis, since steel has a compressive strength similar to RPC. Based on the properties and cost of RPC, RPC will have potential in the construction industry in a number of markets where it may compete with steel. At present RPCs are still under study in several countries (Richard and Cheyrezy 1994). For instance, the test of a 10m RPC pretensioned beam without conventional reinforcing has been successful to show the potentialities of RPC in civil engineering (Richard et al. 1995). The development of these materials could lead to drastic modifications in design and structural analysis of future construction projects. Potential applications of RPC include prestressed structures without passive reinforcement (Richard 1996; Adeline and Behloul 1996), pressure precast pipes (Dowd and O'Neil 1996), impermeable containers for hazardous fluids or nuclear wastes (Torrenti et al. 1996).

(1) Sherbrooke pedestrian bridge

An example of application of a structure made with RPC is the pedestrian bridge in the city of Sherbrooke in Quebec, Canada (Dowd 2000). To demonstrate the unique characteristics of RPC and minimize weight, a design concept was chosen which differs significantly from those used for traditional concrete structures. The superstructure of the bridge is a three-dimensional prestressed space truss spanning 60 meters. The walkway deck, which also serves as the top chord of the truss, is only 25 mm thick. The web members are a composite design using RPC confined in thin-wall stainless steel tubing. No conventional reinforcing steel is used for the entire superstructure. The footbridge's effective thickness is 150 mm. A comparative study showed that the same structure made of HPC would have required a thickness of 375 mm. RPC technology allows the footbridge builders to optimize material usage, realize economic benefits and build a structure that is environmentally friendly (Dauriac 1997).

(2) X-shaped prestressed beams

The current structural precast shapes used for prestressed beams in bridges and buildings have been proportioned for concrete with much lower strength properties. These proportions would not take maximum advantages of the capabilities of RPC. There is now an opportunity to introduce new shapes into prestressed beam design. An RPC prestressed beam, with an hourglass cross section (referred to as X-shaped) and without any kind of secondary steel bar reinforcement, was configured and tested to carry equal moment capacity when compared to its steel wide-flange counterpart and to have the same depth and very close weight (**Fig. 1**). By using RPC, the depth of the member can be reduced by 50 percent and its weight by 75 percent compared to conventional prestressed concrete (Adeline et al. 1996). The elimination of passive reinforcing steel in RPC structures allows for nearly limitless freedom in structural member shape and form.

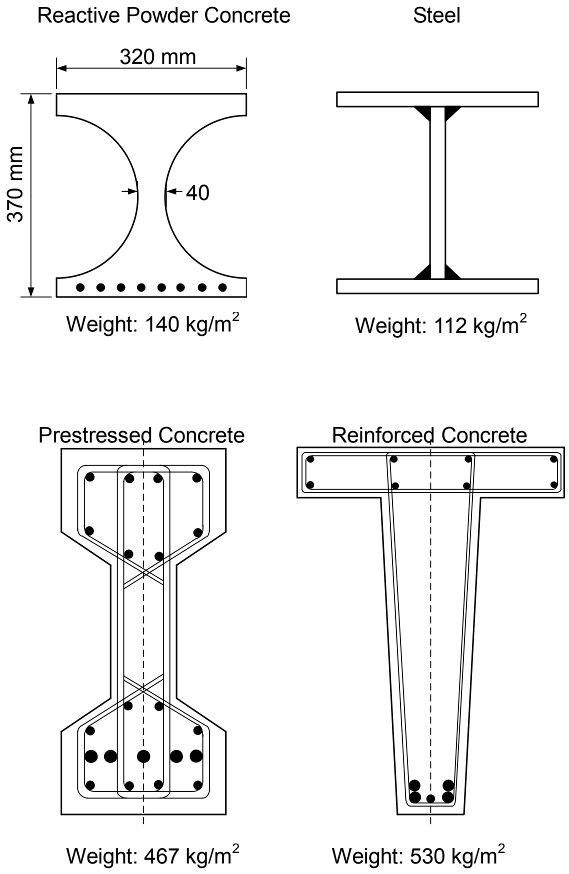

Fig. 1 Comparison of beam cross sections of equal moment capacity.

(3) Containment of nuclear waste

RPC has also been used for isolation and containment of nuclear wastes on several projects in Europe. Clients include federal agencies and public utilities. This application of RPC has been used for blocking and stabilization of contaminated waste and is studied to be used as a container for radioactive high-level waste storage (Torrenti et al. 1996).

Historically, concrete and cement-based composite materials have been incorporated into structures as compression-only systems. RPC transcends this traditional limitation and brings a new approach to prestressed concrete design because it can be used to resist all but direct primary tensile stresses. This eliminates the need for shear and other auxiliary reinforcing steel in precast members, which results in cost reduction for the items themselves, but more important for the labour they usually generate. High-strength liners for tunnels and mining shafts as well as architectural and technical floor panels are also being developed (Dauriac 1997).

4. Light weight RPC (LWRPC)

Reactive powder concrete can have high densities because of its high quality and high density aggregates and its low water content; moreover the physical compression applied during early hardening may raise its density further. Richard and Cheyrezy (1995) have stated that the application of pressure can have three effects: reduction of entrapped air, excess water removal and chemical shrinkage compensation.

As seen in **Table 1**, among other solid ingredients in RPC silica fume has the lowest particle density. It is worth notable that the values in **Table 1** are the particles intrinsic densities, and because of the presence of voids in the produced concrete, the materials contribute with a lesser specific weight. The ultra-fine silica fume particles have a surface area of approximately 20000 m^2/kg compared to 300 ~ 400 m^2/kg for normal Portland cement, so that silica fume is 50 ~ 60 times finer than that of Portland cement. Richard and Cheyrezy (1995) have discussed that silica fume in RPC has three main functions:

- Filling the voids between the next larger class particles(cement);

Table 1 Particle density of ingredients.

Ingredient	Particle density
Cement	3.11 ~ 3.15
Quartz aggregate	2.6 ~ 2.8
Silica fume	2.1 ~ 2.2

- Enhancement of rheological characteristics by the lubrication effect resulting from the perfect sphericity of the basic particles;
- Production of secondary hydrates by pozzolanic reaction with the lime resulting from primary hydration.

The main quality of a silica fume is the absence of aggregates. This leads to the use of non-compacted silica fumes. Slurry cannot be used, as the quantity of water contained in the slurry exceeds the total quantity of water required for the mixture. Nagataki (1994) has stated that silica fume generally contains more than 90% SiO_2 and De Larrard (1989) has purposed that the most injurious impurities of silica fume are carbon and alkalis. In general, the colour of silica fume is grey, but it can range from whitish to blackish depending on the content of carbon. The different colours of silica fume have an effect on RPC in terms of w/c ratio and strength and the best results, in terms of w/c ratio and compressive strength in the absence of superplasticiser, have been provided by C_3A-free Portland cement with low specific surface area (340 m^2/kg), white silica fume with no unburnt carbon at all and mean particle size of about 0.7 µm (Coppola et al. 1996). Typically the fume/cement ratio used for RPC is 0.25. This ratio corresponds to optimum filling performance (Seki et al. 1985) and it is close to the dosage required for complete consumption of the lime resulting from total hydration of the cement. However, cement hydration is incomplete in a reactive powder concrete, and the available quantity of silica fume is more than required by the pozzolanic reaction (Richard and Cheyrezy 1995).

Considering the above aspects several mix design were prepared with varying silica fume contents in order to investigate the effects of silica fume content on strength and density of RPC. These designs are noted in **Table 2**; in this table B represents the binder materials which are cement and silica fume, W/B is the water/binder ratio, SF/C is the silica fume/cement ratio and finally SP/B describes the super plasticizer/binder ratio. Specimens R1, R2 and R3 were made by applying 40 MPa pressure in a 24 hours period to compact them; the rest were not compacted. Elaborated specimens were all $50^{mm}x50^{mm}x50^{mm}$ cubes. Portland cement type I (Blaine fineness 340 m^2/kg), and white-coloured undensified silica fume with a bulk density of 0.12, were used as cementitious binder. An aqueous solution of modified polycarboxylate was used as superplasticizer which complied with the ASTM C494 specifications. In LWRPC, fibers are not used because their presence increases the density, so reducing the benefits arising from its low density. However the behavior of LWRPC without fibers is purely linear and elastic, with its material ductility being no better than that of a conventional concrete; so fibers must be added to enhance LWRPC ductility. Fine ground quartz sand (0.125-0.500 mm) with a density of 2.75 was used for manufacturing the RPC mixture. The amount of the superplasticizer (3%) was selected after preliminary tests in order to find the best performance in terms of water reduction at a given workability level. In other words, no significant further reduction in the mixing water was recorded when an amount of superplasticizer higher than 3% was used. The amount of water coming from the aqueous solution of the superplasticizer is included in the water/binder ratio. The mixing of the ingredients was done with an electric mixer equipped with an ohm-meter, which was an indication of the mixes workability. So constant workability was achieved in all mixes by adding water to the mix and obtaining the same resistance value shown by the ohm-meter. As seen in **Table 2** mixes with high silica fume content needed more water to gain the same workability.

Thermal curing is a classical method of improving the mechanical properties of cement based materials. The most important effects are better crystallization of the hydrates and activation of the pozzolanic reaction of the silica fillers. How this leads to improvement of the mechanical properties is still unclear, but the effect is undoubtedly beneficial in most cases. Djuric et al. (1994) and Taylor (1990) have stated that in hydrothermal conditions, the reaction of lime with silica leads to the formation of tobermorite at temperatures below 200˚C and to truscottite, gyrolite, xonotlite, and hillebrandite at higher temperatures, depending on the CaO/SiO_2 ratio. Xonotlite (C_6S_6H) is a crystalline product. It forms

Table 2 Mix designs.

No.	B (kg/m^3)	W/B (%)	SF/C (%)	SP/B (%)	Sand Content (kg/m^3)	Max Curing Temperature(˚C)	Compaction
R1	1400	11.8	35	3.0	1000	240	YES
R2	1400	13.0	60	3.0	1000	240	YES
R3	1400	14.0	80	3.0	1000	240	YES
R4	1400	12.0	30	3.0	1000	240	NO
R5	1400	12.8	35	3.0	1000	240	NO
R6	1400	13.0	50	3.0	1000	240	NO
R7	1400	13.5	60	3.0	1000	240	NO
R8	1400	15.9	80	3.0	1000	240	NO
R9	1400	12.0	30	3.0	1000	90	NO
R10	1400	13.6	52	3.0	1000	90	NO
R11	1400	16.2	75	3.0	1000	90	NO
R12	1400	16.2	100	3.0	1000	90	NO

readily under normal autoclaving conditions from mixtures in which the SiO_2 is supplied partly as quartz. Also average C-S-H chain length increases with increasing heat treatment temperature (Yang 2000). In the current study all of the samples are kept in the moulds for at least 24 hours; it was found that early demoulding would lower the compressive strength. After demoulding they were kept in water for a week following by 18 days in 90˚C water; during this period the pozzolanic reactions are substantially accelerated and the micro-structure of the formed hydrates are modified, however these hydrates remain amorphous (Richard and Cheyrezy 1995). High temperature heat-curing which leads to the formation of crystalline hydrates (xonotlite) accompanied by major dehydration of the hardened paste (Richard and Cheyrezy 1995), is applied to specimens number R1 to R8 in order to investigate the effects of high temperature heat-curing in micro-structural enhancement. These specimens were cured in a dry 240˚C oven for 24 hours; after cooling in a 24 hours period, they were weighed and tested at an age of 28 days. In order to prevent high water vapour pressure generation inside the samples, a temperature gradient of 10˚C/h was selected to lower the dehydration rate and allow sufficient diffusion. The remaining samples (R9-R12) were kept in a dry 90˚C oven for 24 hours, then weighed and tested at the age of 28 days. **Table 3** shows the results. It is worth notable that by pressing specimens R1, R2 & R3 some of the mix water was expelled out, by measuring this expelled water, the water/binder ratio is estimated to be reduced by 4%.

Table 3 The densities and compressive strengths of samples.

No.	Density	Compressive Strength(MPa)
R1	2.45	280
R2	2.35	353
R3	2.28	370
R4	2.27	193
R5	2.24	230
R6	2.19	238
R7	2.05	277
R8	1.93	280
R9	2.28	142
R10	2.26	202
R11	2.22	211
R12	2.16	217

Figures 2 and **3** show the variation of density and compressive strength by increasing the silica fume content. Dividing the dry weight of the cubic samples to their exact volume, the densities are obtained.

From **Fig. 2** it can been observed that in all cases increasing the silica fume content decreases the density. In other words the space occupied by cement is partly replaced by a relatively lighter powder which is silica fume. However, by pressing the samples the density is increased. High-temperature heat curing (240˚C) lowers the density more than 90˚C curing and the density decrease rate for samples cured at 240˚C is substantially higher than the samples cured at 90˚C. This can be due

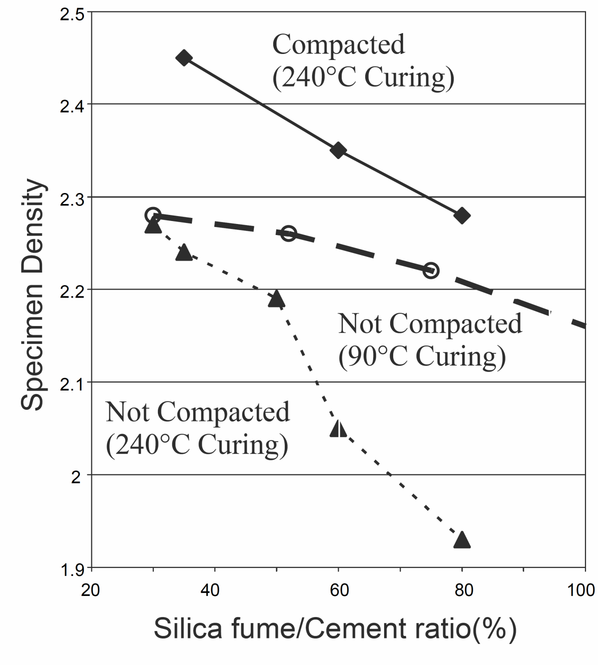

Fig. 2 Variation of density with silica fume content.

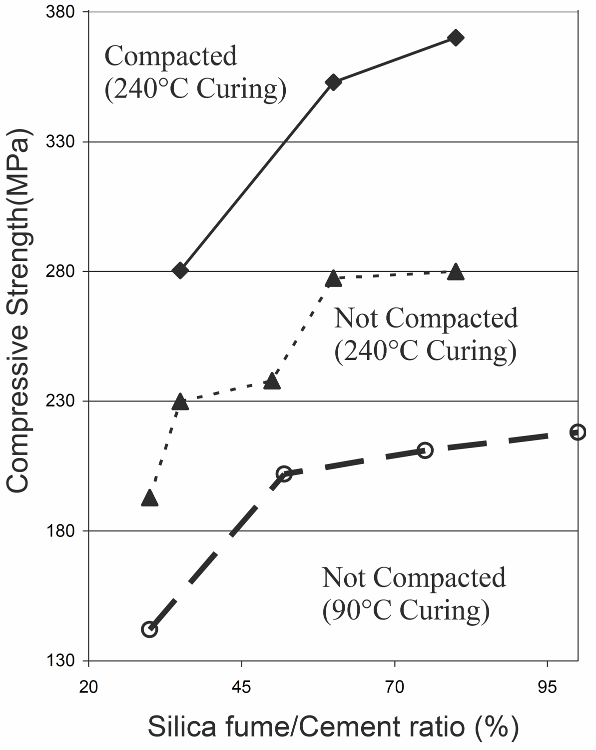

Fig. 3 Variation of compressive strength with silica fume content.

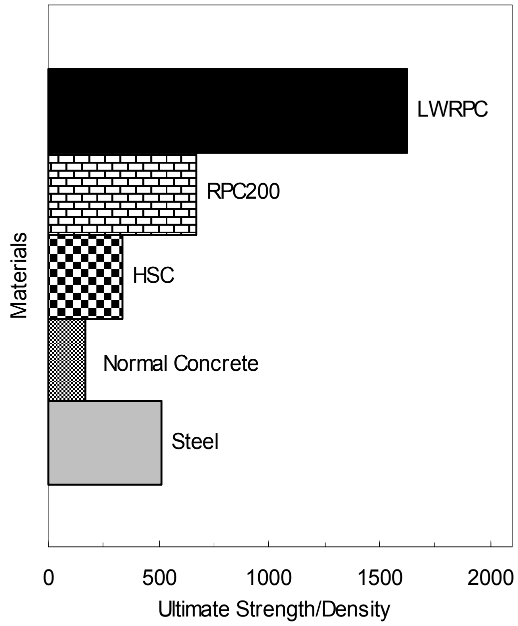

Fig. 4 Ultimate Strength to Density ratio for some materials

to more dehydration of samples and the formation of xonotlite (C_6S_6H) which is lighter than its seminal elements (C-S-H). Also by increasing the silica fume content, xonotlite formation also increases; resulting in higher density difference between the samples cured at 240°C and 90°C.

From **Fig. 3** it can be observed that in all cases increasing the silica fume content increases the compressive strength. Also by applying high temperature heat curing (240°C) accompanied by pressing the samples, very high compressive strengths can be achieved. The ultimate strength to density ratio for a material can be a good indication of its economical characterization. These ratios are computed for some materials in **Fig. 4** proving the economical efficiency of LWRPC.

For elements carrying bending (beams and slabs) or tension (truss elements), dissymmetry in RPC and LWRPC behaviour in tensile and compressive strength can be compensated by the utilization of prestressing techniques. In structures of this type, the main tensile forces are taken up by the prestressing, whereas secondary tensile stresses and all compressive loads are taken up directly by the concrete itself (Richard et al. 1995). Structures configured in this way can be about three times lighter than equivalent structures fabricated with conventional concrete.

The combined effects of the elimination of reinforcement, reduction of permanent loads by lightening the structure and reduction of the quantities of concrete used, generate major cost savings (Richard and Cheyrezy 1995). Apart from these mechanical properties, the high silica fume content of LWRPC results in advantageous waterproofing and durability characteristics allowing it to be used for industrial and nuclear waste storage facilities. In addition, LWRPC can provide sought properties with less material, providing its more ecological nature.

5. Conclusions

It can be concluded that by increasing the silica fume content although the density decreases, the compressive strength is raised. This can be explained by the low density of silica fume among other ingredients of the mix and the role of being a dense filler which increases the strength. Also both high-temperature heat curing and pressing the samples will increase the compressive strength of concrete. However they have contrary effects on the density; whereas high-temperature heat curing decreases the density but compression increases density.

So by using high silica fume contents and applying high-temperature heat curing without compression, it is possible to produce light weight reactive powder concretes (LWRPC) with a density as low as 1.9, without losing strength. LWRPC should be used in areas where substantial weight savings can be realized and where some of the remarkable characteristics of the material can be fully utilized. However in order to utilize this product for structural purposes further investigations and improvements are necessary to be carried out.

References

Abo-El-Enein, S. A., Hanafi, S., Salem, T. M. and Hekal, E. E. (1992). “Thermal and physico chemical studies on ettringite: IV - modes of interaction with water and associated energetics.” *Il Cemento*, 1, 31-42.

Adeline, R. and Behloul, M. (1996). “High ductile beams without passive reinforcement.” in: F. de Larrard and R. Lacroix, Eds. *4th International Symposium on Utilization of High-Strength/High Performance Concrete*, Paris, France 29-31 May 1996. Paris, France: Presses de l'ENPC, 1383-1390.

Adeline, R., Behloul, M. and Bernier, G. (1996). “Reactive powder concrete pretensioned beams.” *FIP Symposium on Post-Tensioned Concrete Structures*, Concrete Society Publication CS112/113, 592-606.

Aitcin, P. C. (1997). “The art and science of high-performance concrete.” in: P.K. Mehta, Ed. Proceedings of Mario Collepardi Symposium on Advances in Concrete Science and Technology, 8 October 1997, Rome, 107-126.

Aitcin, P. C., Lachemi, M., Adeline, R. and Richard, P. (1998). “The sherbrooke reactive powder concrete footbridge.” *Structural Engineering International*, 8 (2), 140-144.

Bonneau, O., Poulin, C., Dugat, J., Richard, P. and Aitcin, P.C. (1996). “Reactive powder concretes: from theory to practice.” *Concrete International*, 18 (4), 47-49.

Bonneau, O., Vernetb, C., Moranvillea, M. and Aitcin, P. (2000). “Characterization of the granular packing and percolation threshold of reactive powder concrete.”

Cement and Concrete Research, 30, 1861-1867.

Cheyrezy, M. (1999). "Structural applications of RPC." *Concrete*, 33 (1), 20-23.

Cheyrezy, M., Maret, V. and Frouin, L. (1995). "Micro structural analysis of RPC (Reactive Powder Concrete)." *Cement and Concrete Research*, 25 (7), 1491-1500.

Collepardi, S., Coppola, L., Troli, R. and Collepardi, M. (1997). "Mechanical properties of modified reactive powder concrete." In: V. M. Malhotra Ed. *Proceedings Fifth CANMET/ACI International Conference on Superplasticizers and Other Chemical Admixtures in Concrete*, Rome, Italy, 1997. Farmington Hills, MI: ACI Publication SP-173, 1-21.

Coppola, L., Troli, R., Collepardi, S., Borsoi, A., Cerulli, T. and Collepardi, M. (1996). "Innovative cementitious materials. from HPC to RPC. part II. The effect of cement and silica fume type on the compressive strength of reactive powder concrete." L'Industria Italiana del Cemento, 707, 112-125.

Dauriac, C. (1997). "Special concrete may give steel stiff competition." *The Seattle Daily Journal of Commerce* [online], May 9. Available from :<http://www.djc.com/special/concrete97/10024304.htm> [Accessed 28 May 2001].

De Larrard, F. (1989). "Ultrafine particles for the making of very high strength concretes." *Cement and Concrete Research*, 19 (1), 161-172.

Djuric, M., Komljenovic, M., Petrasinovic-Stojkanovic, L., Ziavanovic, B. (1994). "Thermodynamic analysis of the C-S-H- System." *Advanced Cement Research*, 6, 19-61.

Dowd, W. (2000). "Reactive powder concrete[online]." Purdue University. Available from: <http://www.new-technologies.org/ECT/Civil/reactive>[Accessed 11 September 2001].

Dowd, W. M. and O'Neil, E. F. (1996). "Development of reactive powder concrete (RPC). Precast products for the USA market." in: F. de Larrard and R. Lacroix, Eds. *4th International Symposium on Utilization of High-Strength/High Performance Concrete*, Paris, France 29-31 May 1996. Paris, France: Presses de l'ENPC, 1383-1390.

Dugat, J., Roux, N. and Bernier G. (1996). "Mechanical properties of reactive powder concretes." *Materials and Structures*, 29 (188), 233-240.

Feylessoufi, A., Villiéras, F., Michot, L. J., De Donato, P., Cases, J.M. and Richard, P. (1996). "Water environment and nanostructural network in a reactive powder concrete." *Cement and Concrete Composites* 18, 23-29.

Freyssinet, E. (1936). "High-early-strength concrete with Portland cement." *Cement and Concrete Manufacture*, 9, 71-77.

Matte, V. and Moranville, M. (1999). "Durability of reactive powder composite: influence of silica fume on the leaching properties of very low water / binder pastes." *Cement Concrete Composite*, 21 (1), 1-9.

Nagataki, S. (1994). "Mineral admixtures in concrete: state of the art and trends." in: V. Wieczorek Ed. *Concrete Technology: Past, Present, and Future, Proceedings of the V. Mohan Malhotra Symposium ACI SP-144*, March 1994 San Francisco. Detroit, MI: American Concrete Institute, 447-482.

Neeley, B. D. and Walley, D. M. (1995). "VHS concrete." *The Military Engineer*, 87 (572), 36-37.

O'Neil, E. F. and Dowd, W. M. (1995). "Reactive powder concrete: A new material for the construction industry." In: S. K. Ghosh, Ed. *Third National Concrete and Masonry Engineering Conference*, 15-17 June 1995. San Francisco, CA., 43-50.

O'Neil, E. F., Neeley, B. D. and Cargile, J. D. (2001) "*Tensile Properties of Very-High-Strength Concrete for Penetration-Resistant Structures*[online]." US Army Engineers Research and Development Centre. Available from: <http://www.hdrinc.com/engineering/Topics/TensilePropertiesForPenetration-Resistant%20Structures.htm> [Accessed 28 May 2001].

Philippot, S., Masse, S., Zanni, H., Nieto, P., Maret, V. and Cheyrezy, M. (1996). "Si NMR study of hydration and pozzolanic reactions in reactive powder concrete (RPC)." *Magnetic Resonance Imaging*, 14 (7,8) 891-893.

Richard, P. (1996). "Reactive powder concrete: a new Ultra-High-Strength cementitious material." in: F. de Larrard and R. Lacroix, Eds. *4th International Symposium on Utilization of High-Strength/High Performance Concrete*, Paris , France 29-31 May 1996. Paris, France: Presses de l'ENPC, 1343-1349.

Richard, P. and Cheyrezy, M. H. (1994). "Reactive powder concretes with high ductility and 200-800 MPa compressive strength." in: P. K. Mehta Ed. *Concrete Technology: Past, Present, and Future, Proceedings of the V. Mohan Malhotra Symposium ACI SP-144*, 21-23 March 1994, San Francisco, CA. Detroit, MI: American Concrete Institute, 507-518.

Richard, P. and Cheyrezy, M. H. (1995). "Composition of reactive powder concretes." *Cement and Concrete Research*, 25 (7), 1501-1511.

Richard, P., Cheyrezy, M. and Dugat, L. (1995). "Pretensioned beam without conventional reinforcing." *FIP Notes*, (1), 2-3.

Roux, N., Andrade, C. and Sanjuan, M. A. (1996). "Experimental study of durability of reactive powder concretes." *Journal of Materials in Civil Engineering*, 8 (1), 1-6.

Roy, D. M. and Gouda, G. R. (1973). "High strength generation in cement pastes." *Cement and Concrete Research*, 3 (6), 807-820.

Seki, S., Morimoto, M. and Yamane, N. (1985). "Experimental research on amelioration of concrete by partly incorporation of industrial by products." *Annals of l'ITBTPN*, 436, 16-26. (in French)

Taylor, H. F. W. (1990). "*Cement Chemistry.*" New York: Academic Press.

Torrenti, J. M., Matte, V., Maret, V. and Richet, C. (1996). “High integrity containers for interim storage of nuclear wastes using reactive powder concrete.” in: F. de Larrard and R. Lacroix, Eds. *4th International Symposium on Utilization of High-Strength/High Performance Concrete*, Paris , France 29-31 May 1996. Paris, France: Presses de l'ENPC, 1407-1413.

US Army Engineer Waterways Experiment Station (1998). “Reactive powder concrete for producing sewer, culvert, and pressure pipes.” Technical Report CPAR-SL-98-3.

Yang, Y. (2000). “*Manufacturing Reactive Powder Concrete Using Common New Zealand Materials.*” Thesis (Master of Engineering). University of Auckland.