A new concrete for the 21 century: Reactive Powder Concrete

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A recent topic of concrete researches is the so-called Reactive Powder Concrete (RPC) that has been developed in France in 1994 based on a new advanced technology. was used for the first time in the area of construction in 1997 in Canada. RPC is a new family of high-strength cement-based composites that achieves compressive strength on the order of 200 MPa and may reach 600 MPa under some circumstances. Based on extensive review of the literature, a state-of-the-art report on RPC is presented. It is aimed at defining the current status of RPC. The second phase of the work includes an experimental study to investigate the possibility of producing RPC using selective locally available materials. Optimization of RPC mix proportions, through detailed examination of different ingredient percentages, was studied in terms of compressive and flexural strengths. A total of 29 mixtures were considered. The compositions of RPC included Portland cement, silica fume, fine sand, crushed quartz, and polycarboxylate superplasticizer. Water-cement ratio (w/c) ranged from 0.15 to 0.21. Compressive strength up to 181 MPa and flexural strength up to 37.5 MPa (7 times greater than conventional normal-strength concrete and 3 times that for high-strength concrete) were achieved throughout the program. This concrete is designated herein as "RPC F30". Results show that silica fume and crushed quartz are essential ingredients of RPC. Optimum contents are recommended. The positive interaction between quartz and silica fume is also discussed. Optimization of the whole grain size distribution, densification of the matrix, utilizing aggregate with 600 μm maximum size, and the using very low w/c are the key-aspects of producing RPC. The research demonstrates that RPC can be locally produced.

يقدم هذا البحث نوعية جديدة من الخرسانة وهى خرسانة المواد الناعمة النشطة "أربى سي" التي تتميز بمقاومتها الفائقة التي تصل في الضغط إلى ٢٠٠ ميجابسكال أو أكثر وأحيانا قد تصل تحت ظروف خاصة إلى ٦٠٠ ميجابسكال. وقد تم معمليا ابتكار هذه النوعية الجديدة من الخرسانة في فرنسا عام ١٩٩٤ وتم استخدامها لأول مرة في مجال الإنشاء عام ١٩٩٧ في كندا. وقد قدم الجزء الأول من هذا البحث دراسة مكثفة عن تاريخ هذه الخرسانة الذي لم يتعدي بضع سنوات وما قد تم نشره عن تطور إنتاجها و مكوناتها وخواصها مع مقارنة بينها وبين الخرسانة العالية الأداء ومواد أخري مثل الحديد. أما الجزء الثاني من البحث فيقدم برنامج عملي إستهدف دراسة إمكانية إنتاج هذه النوعية من الخرسانة الجديدة في مصر باستخدام مواد البناء المحلية. وقد إشتمل البرنامج العملي علي خلطات تجريبية وعدد ٢٩ خلطة استخدم فيها أسمنت بورتلاندى محلي، رمل ناعم وكوارتز ومادة غبار السيليكا، بالاضافة إلى نوعية متقدمة من الملدنات الفائقة. وقد توصل البحث باستخدام المواد المتوافرة محليا إلى إنتاج خرسانة المواد الناعمة النشطة والتي أعطت مقاومات مميزة وصلت في الضغط إلي ١٨١ ميجابسكال وفى الانحناء إلى ٣٧,٥ ميجابسكال أي ما يقرب من سبع أضعاف مقاومة الخرسانة العادية التقليدية وحوالي ثلاث أضعاف مقاومة الخرسانة العالية المقاومة. وقد اعتمدت تكنولوجيا إنتاج هذه النوعية من الخرسانة علي تقليل الفراغان إلى أقل نسبة ممكنة عن طريق الاختيار الأمثل للمواد ومقاساتها ومحتوياتها في الخلطة، وكذلك علي التأثير المتداخل لكل من غبار السليكا مع الكوارتز وتمثل هذه الدراسة قاعدة من الممكن أن تؤدي إلى إمكانية إنتاج خرسانة المواد الناعمة النشطة في مصر.

Keywords: Reactive Powder Concrete, Microstructure, Quartz, Silica Fume, Strength

1. Introduction

Over the years, with the gradual development of new materials and concrete technology, concrete compressive strength has increased significantly. The ACI Committee 363, appeared in 1963, defined the 41 MPa-concrete as a borderline that distinguish between normal-strength concrete (NSC) and high-strength concrete (HSC). Since then, this limit has not changed and was retained in the 1999-edition [1]. In 1995; Dilger and Wang [2] considered a 50 MPa-compressive strength as the line that distinguish between NSC and HSC. However, within the paste two decades, there has been a phenomenal increase in the

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development of concrete with compressive strength in excess of 70 MPa and up to 90 MPa. This concrete has been consistently utilized in bridges and high-rise buildings, and it was referred to as ultra-high-strength concrete (UHSC) that is characterized by low water-cement ratio (typically 0.40 or even less), high cement content (500 kg/m^3), incorporation of silica fume and superplasticizer. With a proper selection of materials, UHSC could achieve high strength and high durability as well, and would be expected to perform well throughout the design life of structure. Such a quality concrete is referred to by most researchers as High-Performance Concrete (HPC) [3]

According to Vivekanandam and Patnaikuni, [4] HPC with small aggregates is similar to a strong rock. In the mid 1980's, HPC with compressive strength up to 110 MPa was considered for precast and prestressed structural members. The applications listed in Table 1 are good examples for the use of HPC with strength ranged from 69 MPa to 119 MPa (Aitcin and Neville) [5]. Chan et al. [6] also found from their experiments that 120 MPa-concrete may easily be produced by using crushed granite as a coarse aggregate providing that the w/c does not exceed 0.24. Similar strength levels have been achieved by Xie et al. [7] who reported that the 130 MPa-strength level is the upper limit for concrete with ordinary aggregates.

In a recent article by Sobolev [8] it has been again demonstrated that a compressive strength up to 145 MPa could be attained but by using the so-called "high-performance cement" and eliminating the coarse aggregate. The main idea of the HP-cement technology is based on optimizing the mixing and grinding process of cement to increase its dispersion and reaction ability, and also modifying the cement surface by complex admixtures.(8) Despite such high levels of strength, and with the speed of advancements in concrete technology, many attempts have been done to produce concrete with higher strength levels exceeding 150 MPa or even 200 MPa. The pre-described trend is outlined in fig 1.

In 1994, Roy and Silsbee [9] have summarized a new family of high-strength cement-based products. These include CBC and MDF and DSP. Chemically bonded ceramics (CBC) contain little or no coarse aggregate, very high cement content, and very low water-binder ratio without using superplasticizer. They are pressed under high pressure and then warm cured to exhibit high strength and other properties similar to those of fired ceramics, therefore they are defined as ceramic-like materials.

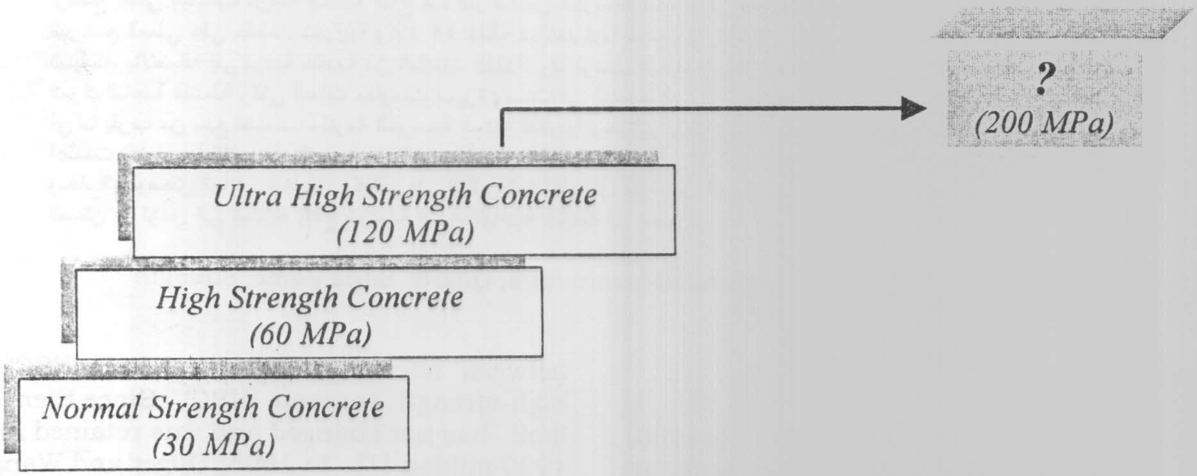


Fig. 1. Typical trend in advancements in the technology of concrete production.

Table 1
Typical HPC mixtures [5]

Application	Location	f_c' at 28 days, MPa
"Water tower place"	Chicago USA - 1975	65
"Joigny bridge"	France - 1989	80
"Scotia plaza"	Toronto Canada - 1987	83
"Laurentienne building"	Montreal Canada - 1984	93
"Two union square"	Seattle USA - 1988	119

The macro-defect-free cement products (MDF) initially developed by Birchall and Kendall [10] are made with a cement paste containing 4 to 7% of water-soluble polymers such as hydroxypropyl-methyl cellulose or hydrolyzed polyvinyl acetate [9]. High shear mixing process is adapted. Entrapped air is removed by applying 5 MPa-pressure to the fresh material to get a paste that is free of large defects, and finally heat cured at temperatures up to 80 C. Portland cement-based MDF exhibited 150 MPa compressive strength while 300 MPa is obtained for calcium aluminate cement-based MDF. Despite these high levels of strength, several studies have shown that moisture has an adverse effect on the mechanical properties of MDF. When the material is exposed to moisture, the polymer phase swells and softens, and strength may be reduced by up to 40%.

The so-called DSP (products densified with small particles), developed by Bache [11] contains 20 to 25% silica fume particles which are densely packed in a superplasticized Portland cement paste that has a water-binder ratio in the range of 0.12 to 0.22. Such a material achieved a compressive strength up to 270 MPa. It should be mentioned herein that due to the brittle behavior of CBC, MDF, and DSP limits their use to non-structural applications [3]. In addition, the required pressure needed for pressing CBC, DSP, and MDF can be obtained only under laboratory conditions or in special industries. Furthermore, the moisture problem in case of MDF is very critical [3].

The preceding argument emphasizes the need for other class of ultra high-performance concrete if strength on the order of 200 MPa or higher is the target for the design criteria. From that point, and through extensive work and effort of researchers, new principles have been considered in the development of advanced cement–based materials and led to the discovery of the so-called Reactive Powder Concrete (RPC).

2. Research significance

The compressive strength of conventional concrete in Egypt is mostly 25-30 MPa, frequently around 35-40 MPa, occasionally 50 MPa, and exceptionally 60-70 MPa. Even under laboratory conditions for research purposes it may not have exceeded 90-100 MPa in most cases, while much higher levels of strength have been attained all over the worlds. Whether or not local construction materials if optimized and carefully selected may produce 150-200 MPa is obviously questionable. The area of RPC is therefore directly addressed in this report. The study provides extensive information about RPC. Extensive review is presented that includes the concept of RPC, its potential, applications and future directions. May RPC be produced using locally selective materials? What are its optimum compositions? Up to what strength level can it reach? The current study was designed to answer such questions and it may serve as a basis for introducing RPC in Egypt.

3. State-of-the-art RPC

Reactive Powder Concrete (RPC) was first developed in the early 1990's by a team of researchers at the laboratory of HDR's, former parent company in Paris [12]. The first documented work about RPC was published in 1994 by Richard and Cheyrezy [13]. Since then, similar trends have been adopted worldwide, however a limited number of works have been documented.

3.1. What is RPC?

RPC is a cement-based composite material typically proportioned with fine sand, high content of cement, silica fume, pulverized or crushed quartz, and superplasticizer [3, 13]. Fine steel fibers may be added to enhance ductility [13-15]. The concept of RPC is based on the principle that a material with a minimum inside voids will be able to sustain a greater load-carrying capacity and give better performance. The absence of coarse aggregate is also considered to be a key-aspect for the microstructure and the performance of RPC in order to reduce the heterogeneity between the cement matrix and the aggregate and hence minimizing crack initiations [14, 15]. In another word, the least costly components of conventional concrete is basically eliminated or replaced in RPC mixtures by more expensive components; the fine sand in RPC becomes equivalent to the coarse aggregate, the Portland cement fills the role of fine aggregate, and the silica fume that of cement [16]. Following this trend, compressive strength in the range of 170-230 MPa, and flexural strength in the range of 30-60 MPa were recorded [13, 15]. Far more enhancement in the microstructure of RPC and strength exceeding 200 MPa can be achieved by applying post-set heat treatment and external pressure before or during setting that is considered as an optional principles relating to production [15].

The RPC is typically characterized by the followings [13, 15]:

1. The water-cement ratio (w/c) is limited at a value below that needed for complete cement hydration, typically 0.18 and down to 0.15. Therefore, a portion of cement content will remain unhydrated and act as filler in the matrix, and the final product will therefore contains anhydrous phases.
2. The maximum size of aggregate is 400-600 μm (the coarse aggregate is eliminated).
3. The content of Portland cement is in the range of 1000 kg/m^3.
4. The content of silica fume is typically 230 kg/m^3.
5. The average size of quartz is 4-10 μm.
6. The contents of fine sand and quartz are typically 900-1000 kg/m^3.
7. High dosage of efficient superplasticizer is utilized.

3.2. Extensive review

The basic formulation of RPC as reported in the original mixture proposed by Richard and Cheyrezy [15] is cement: 1; silica fume: 0.25; fine sand: 0.5 to 1.1, by cement weight. Some formulations contained crushed quartz with content up to 40% by weight of cement. The water-cement ratio for RPC ranged from 0.15 to 0.19, and the amount of dry superplasticizer varied from 1.25 to 1.75 by weight of cement.

Richard and Cheyrezy [13, 15] produced concrete possessing ultra high strength in the range of 200 to 800 MPa and high ductility as well. They defined RPC as a new family of advanced high-performance concrete. Based on their experiments, two grades of RPCs were defined; "RPC 200" and "RPC 800". The strength of "RPC 200" ranged from 170 to 230 MPa with heat curing at room temperature and up to 90 C. However, for "RPC 800", when a high curing temperature from 250-400 C was utilized with the application of 50 MPa-presetting pressure and using fine quartz in the mixes, the strength reached surprising levels up to 680 MPa. Replacing the silica aggregate with steel aggregate (< 800 μm) lead to strength up to 800 MPa. The following typical composition for a cubic meter of "RPC 800" has been reported [13]: 1000 kg Type V cement, 180 kg total water, 500 kg fine sand, 390 kg ground quartz, 230 kg silica fume, 18 kg superplasticizer (polyacrylate), and 630 kg steel fibers.

Since then, similar trends have been adopted worldwide, particularly in France, USA, Canada, and Italy, and RPC has become an interesting topic in the area of concrete advanced technology. In 1995 it have been pointed out that optimization of the whole grain size distribution of the matrix plays a significant role in maximizing compactness and obtaining a very dense cementitious matrix that exhibits ultra high performance (15). In a microstructural analysis of several

RPC compositions [17], Thermogravimetry and X-ray diffraction analysis highlight the beneficial effects of heat curing of RPC at temperature between 200 and 250 C on changing the microstructure and improving the pozzolanic activity as well as increasing the role of quartz in RPC. In 1996 O'Neil et al. [18], from USA, studied through a long project the technical and economic potential of using RPC commercially for producing culvert pipes, pressure pipes, piles, and prestressed beams. The encouraging uses of RPC have been reported [18].

Coppola et al. from Italy (1996)[16] studied the effect of the percentage of tricalcium aluminate (C_3A) on the compressive strength of RPC subjected to heat treatment at 160 C. Results indicated that the highest strength of the studied RPC was achieved (170 MPa) with the use of cement that had zero percent of C_3A. It should be noted herein that Type V cement with a low C_3A content was used throughout the first experimental study about RPC previously reported [13]. In a more recent article by Coppola et al. [19], it has been concluded that the strength of RPC specimens cured at room temperature is strongly dependent on the type of cement and superplasticizer [19]. The highest strength values obtained through the investigation (19) was 160-180 MPa that is lower than the reached values under similar conditions (170-230 MPa) obtained elsewhere [13, 15].

In 1997, Bonneau et al. [20], from Canada, have documented the production of two types of RPCs on an industrial scale at the University of Sherbrooke, and also in a precast plant [20]. Again it has been demonstrated that the development of an extremely dense and low porosity matrix is the key of producing RPC. Also Portland cement with C_3A = 0 was used in the work. It seems that avoiding the presence of C_3A is of primer concern in the production of RPC. This may be explained by the fact that higher values of C_3A may require higher amount of water and superplasticizer for the purpose of workability and hence adversely affect the strength. Based on the phenomena of self-autoclaving, it has been concluded that heat treatment can be applied by simply heating RPC in an oven without the need of using the usual expensive treatment in autoclaves [20]. Bonneau et al.[20] have also pointed out from their experiments that RPC when confined in a steel tube would attain much higher compressive strength, the slope of the descending part of the stress-strain curve of the materials is significantly reduced indicating improved ductility. The importance of producing RPC on a full scale anywhere using selective locally available materials and following uncomplicated process was also explored [20].

3.3. Benefits

The benefits of achieving the superior properties of RPC as compared to that of conventional concrete may be summarized in several points [12, 21]:

1. The ultra high-strength results in smaller sections and significant weight reductions that may reduce overall costs and provide more usable floor spaces in high-rise buildings.
2. Lightweight members reduce inertia load, and the small sections allow large deflection to occur within the elastic range. As a result, high energy can be absorbed or dissipated and the seismic performance of the system is significantly improved especially when fine steel fibers are added to enhance ductility.
3. The condensed composite matrix provides excellent protection for reinforcing steel against corrosion.
4. The remained amount of unhydrated cement particles provides the hardened concrete with a self-healing potential under cracking conditions.
5. The non-interconnected pores leads to provide almost impermeable environment that may stop the penetration of gas and liquid and protect the integrity of the system.

3.4. RPC as compared with HPC and steel

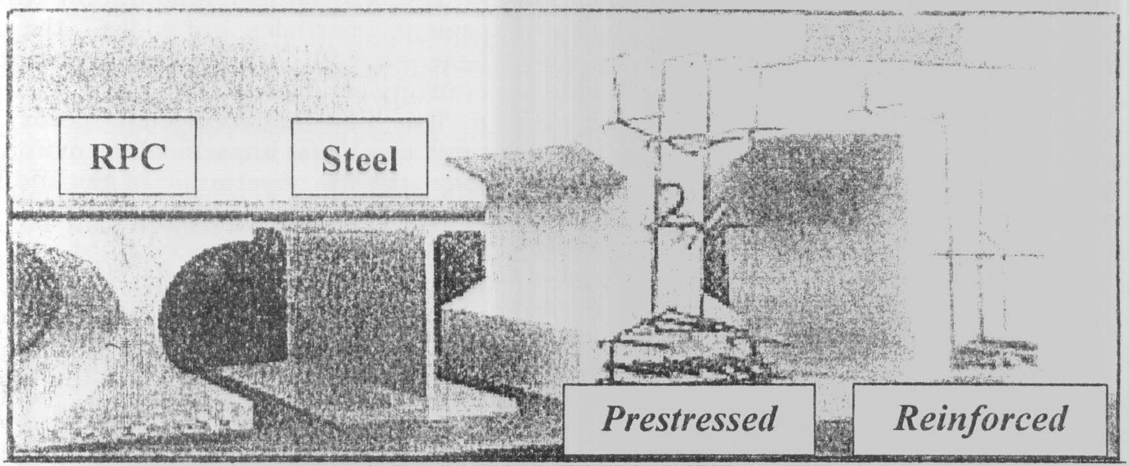
RPC may be considered as a new generation of HPC, or in another words it is an ultra-high performance cement-based composite material. Prestressed RPC flexural members possess a strength/weight ratio comparable to steel [12]. The enhanced physical characteristics of RPC when compared to HPC is presented in table 2. Similar findings have been reported by O'Neil et al. [18]. who have demonstrated that RPC is almost impermeable, and it is completely different than other types of concrete.

Dauriac [21] has reported that RPC may compete in some specific areas with steel. He stated that "RPC becomes truly competitive in areas where steel is predominant". A comparison of beams cross sections of equal moment capacity as taken from ref. [21] is given in fig 2. The comparison indicates a stiff competition in terms of weight and depth between the steel beam and the beam made with RPC having strength in the range of 200 MPa. The X-shaped beam shown in the figure is an RPC prestressed beam without any secondary reinforcing steel bars. The figure clearly demonstrates that for same section moment capacity the depth of the member is reduced by about 50% and its weight by about 75% compared to conventional prestressed concrete. In fact, the RPC section seems to be very comparable with the steel wide-flange section in terms of weight and depth:

3.5. Applications

Although RPC is are not intended to replace conventional concrete, RPC should be used in applications where substantial weight reduction is required and also where the performance criteria for design requires some remarkable characteristics to be achieved. It will have many benefits in precast concrete. Recommended special applications of RPC include high-pressure pipes, blast resistance structures, security enclosures, and the isolation and containment of nuclear waste [12]. In 1996, the actual uses of RPC in USA by that time, such as in concrete poles, railroad ties, and grade crossing planks, have been reported [18].

However, RPC was first introduced in the area of construction with the application of the Sherbrooke Pedestrian/Bikeway Bridge in Sherbrooke, Quebec, Canada [21-23]. This bridge, shown in fig 3 is the first structure to be built with RPC. According to Blais and Couture [23], the bridge is a post-tensioned open-web space truss containing no conventional steel reinforcement. It was made up of six prefabricated match-cast segments. In the top and bottom chord members, the RPC had a compressive strength of 200 MPa. For the web member diagonals, RPC was confined in stainless steel tubes, attaining improved ductility and a compressive strength of 350 MPa. Steel fibers were added to enhance ductility. The footbridge's effective thickness is 15.2 cm (6.0 in.). According to Dauriac [21], the same structure made of HPC would have required a thickness of 38.1 cm (15 in.), about 2.5 times greater than that using RPC.



Section parameters	RPC X-shaped	Steel wide-flange	Prestressed concrete	Reinforced concrete
Section depth	360 mm	360 mm	700 mm	700 mm
Weight	130 kg/m	110 kg/m	470 kg/m	530 kg/m

Fig. 2. Comparison of beam cross sections of equal moment capacity [21].

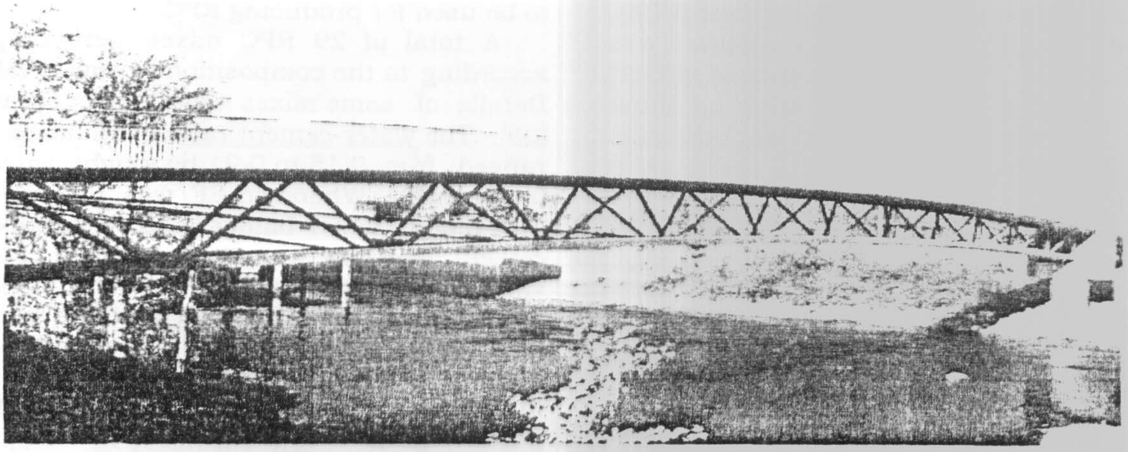


Fig. 3. The Sherbrooke pedestrian bridge, Quebec, Canada (1997).

Table 2
Enhanced physical characteristics of RPC when compared to HPC [12]

RPC compared to high-performance concrete	
Abrasive wear	2.5 times lower
Water absorption	7 times lower
Corrosion velocity	8 times lower
Chloride ions diffusion	25 times lower

3.6. Awards

Final but not least, the product of RPC was nominated for the 1999 Nova Awards from the construction innovation forum [24].

3.7. Closure

The use of RPC as a new category of concrete in structures is obviously questionable and requires further investigation. On the other hand, it would be appreciate to assess if RPC could be produced anywhere. Comprehensive test program should therefore be performed and different properties must be investigated

4. Current experimental study

The current study is the first part of a comprehensive program related to the area of advanced new materials that has been started in the year 2000 [25].

4.1. Materials and mix compositions

Portland cement produced by Alexandria Portland Cement Company was used in all mixes. The chemical compound compositions of cement were; 57.7% C_3S; 18.7% C_2S; 0.2% C_3A; and 15.3% C_4AF. Blain fineness of cement was 3200 cm^2/gm. Natural siliceous sand with grain size ranging from 0.15 to 0.6 mm and specific gravity of 2.67 was used in all mixes. This fine sand was obtained by screening the natural sand on sieves. It should be pointed out herein that since optimization of the grain size distribution of the ingredients of RPC is of great concern as mentioned earlier, the very fine sand (less than 0.15 mm) was thrown away to avoid the interference with the coarse cement particles (80-100 μm). A locally produced silica fume (SF) was used as a high active pozzolan in most of the mixes. Its SiO_2 content is about 96 %. Chemical composition of silica fume (SF) is given in table 3.

Crushed quartz in a powder form with Blain fineness of 3000 cm^2/gm, and a specific gravity of 2.85 was incorporated. The quartz used in this investigation was a commercial product obtained from a local producer. Chemical composition of quartz (Q) is also given in table 3. The quartz was composed mainly of quartz mineral as proved by X-ray diffraction spectra (XRD), shown in fig 4. After several trials, a relatively new superplaticizer based on Poly-Carboxlic Ester polymer (PCE), currently available in the local market, was selected which contains carboxylic (COO^-) instead of sulfonic (SO_3^-) groups as those present in the melamine or naphthalene-based superplasticizers. It has a solid content of 35% and 1.18 specific gravity.

Table 3
Chemical compositions of silica fume and crushed quartz

Oxides	Silica fume	Crushed quartz
CaO	---	1.02
SiO_2	96.02	97.0
Al_2O_3	1.01	0.83
Fe_2O_3	0.52	0.35
MgO	0.18	0.21
SO_3	0.26	0.33
K_2O	0.35	0.22
Na_2O	0.14	0.05
Cl_2	0.16	0.05

According to Collepardi [26], the PCE polymer acts as dispersant without changing the electrostatic charge on the cement particles as usually occurs in the presence of sulfonated polymers. Contradictory finding has been reported by Corradi, M., and Khurana [27] who stated that both steric and electrostatic effects of PCE play major roles. As seen in fig 5 taken from ref [27], the negative electrostatic charge is indicated as "A", while the long graft side chains, indicated as "B", guarantee a steric type of repulsion which keeps the cement particles separated even after the molecule of the PCE polymer is covered by initial hydration products. As hydration progresses, the alkalinity of the concrete matrix increases and hence causes other molecules of to open and get adsorbed onto the cement particles keeping them dispersed long. These two effects cause a very high water reduction and long slump retention. In a recent article by Xu and Beaudoin [28], they have pointed out that the dispersion mechanism of PCE depends mainly on the steric effect while the electrostatic repulsion plays a minor role. In spite of the disagreements mentioned above between researchers regarding the mechanism by which the PCE polymer improves the workability, its superior performance has been previously documented [26-28]. Therefore, the authors strongly recommend the PCE polymer to be used for producing RPC.

A total of 29 RPC mixes were prepared according to the compositions given in table 4. Details of some mixes may be seen elsewhere [25]. The water-cement ratio in all mixes (w/c) ranged from 0.15 to 0.21 by weight, with 0.02 increment. Wherever SF was incorporated, the highest water-binder ratio (with respect to cement and SF) was 0.18. Cement contents varied from 800-1090 kg/m^3. The amount of PCE polymer based on solid contents was kept at 1.4% by cement weight in all mixes. The amount of fine sand was kept constant in all mixes at 110% of cement weight. Different percentages of SF (0.0, 0.15, and 0.25 of cement weight), and of crushed quartz (0.0, 0.2, and 0.4 of cement weight) were examined. Silica fume and crushed quartz were added as replacement from all ingredients. Some mixes (not included in table 4 with low water-cement ratio of 0.15 were excluded in some cases due to their inappropriate mixing and placing. It should be mentioned herein that trial mixes showed a delayed effect on the setting time of RPC when higher dosage of PCE polymers was used.

4.2. Mixing, casting, and curing procedures

RPC was mixed in batches of five liters. Mixing was performed in a high speed-mixer to overcome the high viscosity and cohesiveness of the mixtures associated with the extremely low w/c, and to facilitate the dispersion of water and superplasticizer.

Cement, sand, and dry powders were pre-mixed for one minute, after which mixing water containing half of the total amount of superplasticizer were added, and mixing continued for two minutes. This was followed by one-minute rest. Second half of superplasticizer, diluted in an equal volume of water, was added followed by two minutes mixing, and one minute rest. Final mixing was applied for two minutes. The total mixing time was about 9 to 10 minutes. Small size specimens were used to meet the requirement of the compression-testing machine. The prepared specimens were 5.1x5.1x5.1 cm cubes for compression tests and 4x4x16 cm prisms for flexure tests. After casting, RPC

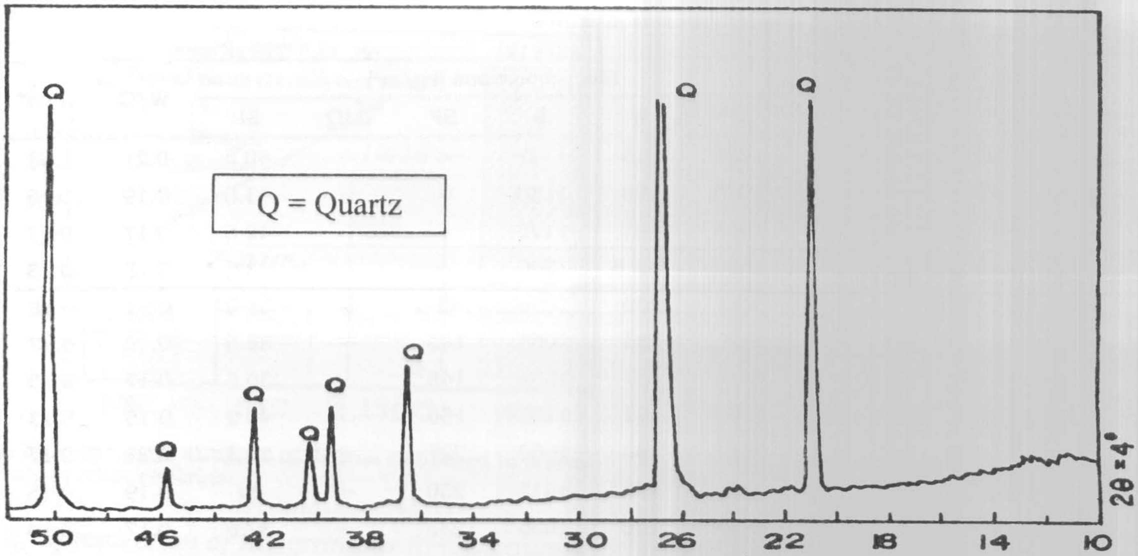


Fig. 4. X-ray diffraction pattern of crushed quartz used in this study

were compacted manually with the help of a vibrating table. Specimens were demolded after 24 hrs and cured in water bath at 25±2°C. Compressive strength and flexural strength tests were performed at the ages of 28, and 56 days according to ASTM C-109, and C-348, respectively. The end portions of the flexure specimens for Mixes No. 17, 21, 23, and 29 were prepared and tested also for compression in accordance with ASTM C 349.

5. Results and discussion

Test results including compressive and flexural strength of RPC at different ages are listed in tables 5 and 6, and presented graphically in figs from 6 to 13.

5.1. Strength levels for RPC

As seen in table 6, the compressive strength (f_c) of RPC Mix No. 29 is 181 MPa at the age of 6 months when the tests were performed on the end blocks of flexure beams. It may also be seen in table 5 that the results of testing the 5.1 cm-cubes made from the same mix but tested at earlier age (56 days) possessed 37% lower compressive strength (132 MPa). This difference may be attributed to the age of testing, and also to a large extent to the difficulty of the compaction of the small cube as compared to the relatively larger beam (4x4x16 cm). As evident from table 6, similar trend is noticeable for other three mixes (No. 17, 21, and 23). Similarly, superior values for flexural strengths of RPC were attained. Very high flexural strength (f_b) of 35 MPa was recorded for RPC Mix No. 28 at the age of 28 days increased to 37.5 MPa at the age of 56 days. This RPC is designated here as "RPC F30". It is similar to "RPC 200" previously produced elsewhere [13]. It should be noted that the f_c results of the RPC mixes reported herein are generally not in good agreement with the 160-230 MPa-values previously reported [15], however the flexural strength exhibited comparable ranges.

In fact, more than half the total number of flexural specimens exhibited f_b higher than 25 MPa. Figs 6 and 7 demonstrate an interesting comparison between the highest obtained f_c and f_b throughout the program with the typical strengths for NSC, HSC, and UHSC. The figure clearly indicates that RPC made by using local materials exhibited strengths six to seven times greater than conventional NSC, and 3-4 times that for HSC. The authors strongly believe that, in addition to its superior strength, RPC should posses other valuable properties such as low permeability and increased corrosion resistance, however this is beyond the scope of this part of the program.

Table 4
Mix proportions for different reactive powder concrete mixtures

Mix. No.	Mix proportions (ratios by weight) C : W : S : SF : MQ	Mix proportions (kg/m³)						W/C	W/B*
		C	W	S	SF	MQ	SP		
1	1 : 0.21 : 1.1 : 0 : 0	1020	215	1125	--	--	40.8	0.21	0.21
2	1 : 0.19 : 1.1 : 0 : 0	1040	198	1150	--	--	41.6	0.19	0.19
3	1 : 0.17 : 1.1 : 0 : 0	1065	181	1175	--	--	42.6	0.17	0.17
4	1 : 0.15 : 1.1 : 0 : 0	1090	163.5	1200	--	--	43.6	0.15	0.15
5	1 : 0.21 : 1.1 : 0.15 : 0	950	200	1040	142.5	--	38.0	0.21	0.18
6	1 : 0.19 : 1.1 : 0.15 : 0	965	183	1065	145	--	38.6	0.19	0.17
7	1 : 0.17 : 1.1 : 0.15 : 0	985	167	1085	148	--	39.4	0.17	0.15
8	1 : 0.15 : 1.1 : 0.15 : 0	1005	151	1105	150	--	40.2	0.15	0.13
9	1 : 0.21 : 1.1 : 0.25 : 0	905	190	1000	227	--	36.3	0.21	0.17
10	1 : 0.19 : 1.1 : 0.25 : 0	925	176	1015	230	--	37	0.19	0.15
11	1 : 0.17 : 1.1 : 0.25 : 0	940	160	1035	235	--	37.6	0.17	0.14
12	1 : 0.15 : 1.1 : 0.25 : 0	960	144	1055	240	--	38.4	0.15	0.12
13	1 : 0.21 : 1.1 : 0 : 0.2	950	200	1045	--	190	38	0.21	0.21
14	1 : 0.19 : 1.1 : 0 : 0.2	965	184	1065	--	193	38.6	0.19	0.19
15	1 : 0.17 : 1.1 : 0 : 0.2	985	167.5	1085	--	197	39.4	0.17	0.17
16	1 : 0.21 : 1.1 : 0.15 : 0.2	890	187	980	133.5	178	35.6	0.21	0.18
17	1 : 0.19 : 1.1 : 0.15 : 0.2	905	172	995	136	181	36.2	0.19	0.17
18	1 : 0.17 : 1.1 : 0.15 : 0.2	920	156.5	1015	138	185	36.8	0.17	0.15
19	1 : 0.21 : 1.1 : 0.25 : 0.2	850	178.5	935	212	170	34	0.21	0.17
20	1 : 0.19 : 1.1 : 0.25 : 0.2	865	165	950	216	173	34.6	0.19	0.15
21	1 : 0.17 : 1.1 : 0.25 : 0.2	880	150	970	220	176	35.2	0.17	0.14
22	1 : 0.21 : 1.1 : 0 : 0.4	890	187	980	--	356	35.6	0.21	0.21
23	1 : 0.19 : 1.1 : 0 : 0.4	905	172	995	--	362	36.2	0.19	0.19
24	1 : 0.21 : 1.1 : 0.15 : 0.4	835	175	920	125	335	33.4	0.21	0.18
25	1 : 0.19 : 1.1 : 0.15 : 0.4	850	161.5	935	127.5	340	34	0.19	0.16
26	1 : 0.17 : 1.1 : 0.15 : 0.4	865	147	950	130	346	34.6	0.17	0.15
27	1 : 0.21 : 1.1 : 0.25 : 0.4	800	168	880	200	320	32	0.21	0.17
28	1 : 0.19 : 1.1 : 0.25 : 0.4	815	155	900	205	325	32.6	0.19	0.15
29	1 : 0.17 : 1.1 : 0.25 : 04	830	141	915	208	332	33.2	0.17	0.14

C: cement, W: water, S: fine sand, SF: silica fume, MQ: Milled quartz, SP: Superplasticizer
* W/B = water to binder ratio

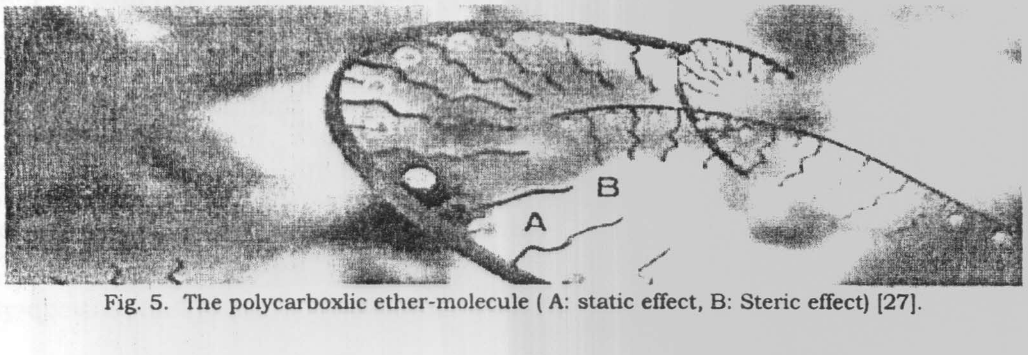


Fig. 5. The polycarboxlic ether-molecule (A: static effect, B: Steric effect) [27].

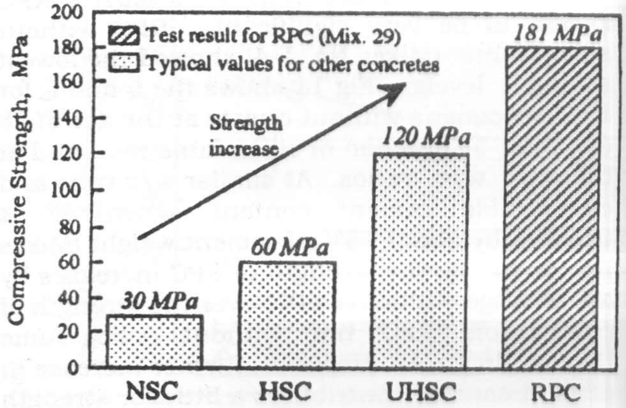


Fig. 6 Compressive strength of RPC as compared to typical values of other concrete.

5.2. Optimization of the granular RPC mixtures

Optimization of the whole grain size distribution of the matrix can be achieved by utilizing the optimum content for each ingredient in the mixture and the optimum w/c ratio as well. The effect of w/c on the strengths of RPC specimens may be seen in figs 8-10. Fig 8 indicates that the optimum w/c that produces the highest strengths is 0.17, however, when crushed quartz is introduced by the ratio 0.2 or 0.4 of cement weight, the optimum w/c goes up to 0.19 regardless the content of SF as seen in figs 9 and 10. Generally speaking, the strength increases up to a certain value with the decrease in w/c, then remains quite unchangeable or even reduces in some cases with reducing w/c.

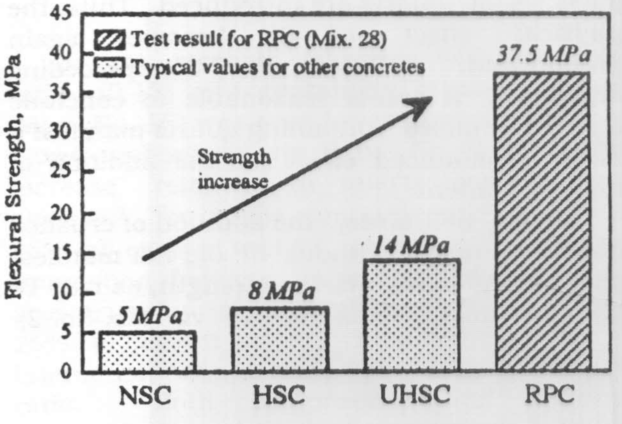


Fig.7. Flexural strength of RPC as compared to typical values of other concrete.

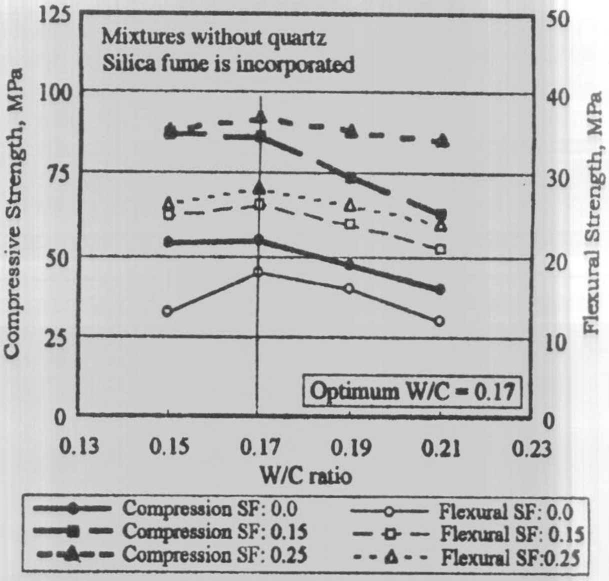


Fig. 8. Effect of water /cement ratio on RPC strength at 28 days.

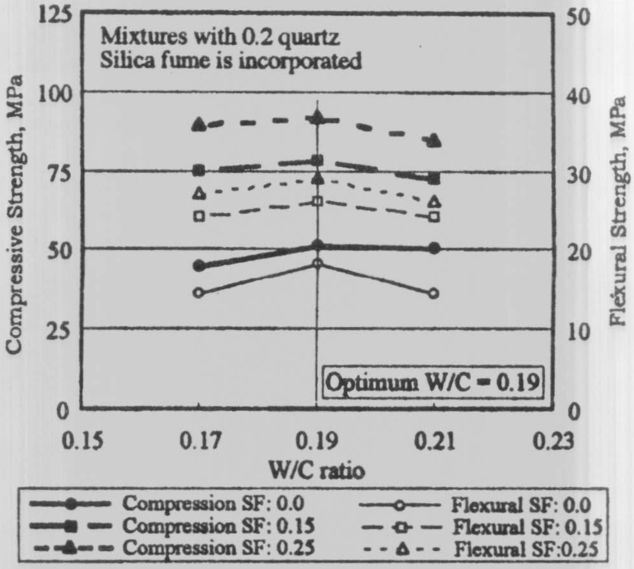


Fig. 9. Effect of water/cement ration on RPC strength at 28 days.

It can therefore be concluded that the optimum w/c that provides RPC with the highest strength is not a constant value but it depends on the mix composition. This agrees with Richard and Cheyrezy [15] who reported that the w/c in typical RPC varied from 0.15 to 0.19. In other words, the well-established traditional relation between the w/c and the concrete strength is not applicable in case of RPC. In addition, the principle of mix design adopted in this study that expresses silica fume and quartz in terms of cement percentage is based on their incorporation as a partial replacement of the ingredients.

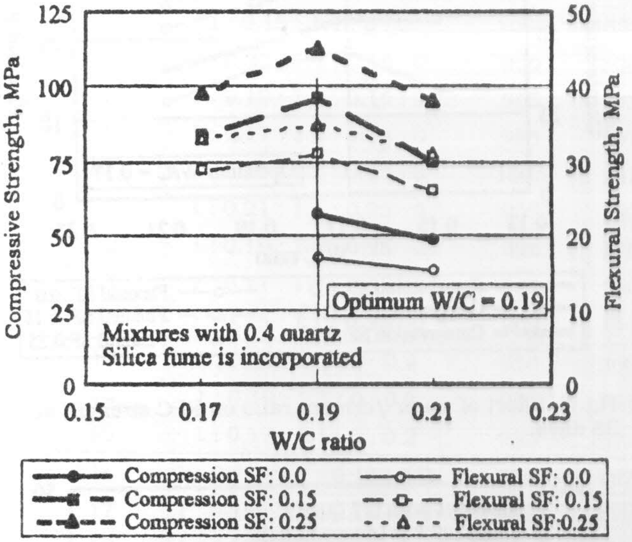


Fig. 10. Effect of water/cement ratio on RPC strengths at 28 days.

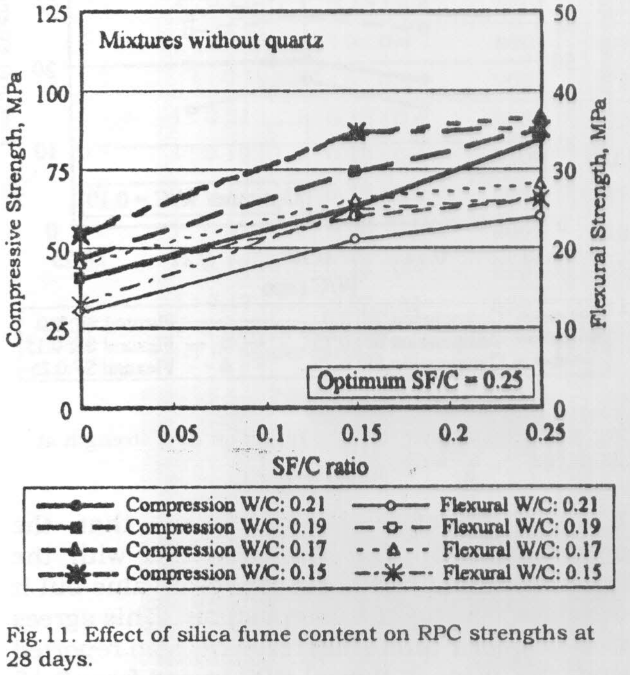


Fig. 11. Effect of silica fume content on RPC strengths at 28 days.

The role of silica fume in producing RPC seems to be very significant. RPC without silica fume (Mixes No. 1-4) showed the lowest strength levels. Fig 11 shows the f_c and f_b for RPC specimens without quartz at the age of 28 days as a function of silica fume ratio and at different w/c ratios. At similar w/c ratio and comparable cement content, when SF is utilized by about 15% of cement weight (Mixes No. 5 to 8), the strength of RPC increases by an average values of 60% over the strength of comparable RPC but without silica fume (Mixes No. 1-4). However, further increase in cement content contributes a little for strength improvement when the ratio w/c is 0.15 or 0.17 (Mix No. 7 vs. No. 11, and Mix No. 8 vs. No. 12). It seems that with such small ratios of w/c (0.15 and 0.17), extra dosage of SF may be useless since another filler already do exist in the matrix which is the unhydrated cement particles. Also the amount of calcium hydroxide developed through the cement hydration process may not be sufficient to complete the pozzolanic reaction of SF.

Introduction of quartz at this point raises a critical issue, and a somewhat different trend appears. As seen in table 5, the strength gain associated with increasing SF from about 15% to 25% of cement weight becomes relatively appreciated. Up to 20 to 30% gain may be seen between f_c of RPC Mix No. 18 and Mix No. 21 where the ratio w/c is 0.17 in both mixes. Similar finding may also be observed by comparing Mix No. 26 with Mix No. 29. This could be attributed to the need of extra ultra fine particles of SF to optimize the grain size distribution after the 10-15 μm-particles of quartz are introduced. Thus, the physical effect of SF becomes again pronounced. Based on the preceding argument, it seems reasonable to conclude that RPC mixes containing quartz manifest a more pronounced effect for the addition of high SF content.

Unlike SF mixes, the addition of crushed quartz to mixes without SF did not manifest positive influence on the strength, as may be seen in table 6 (Mix No. 14 vs. Mix No. 2).

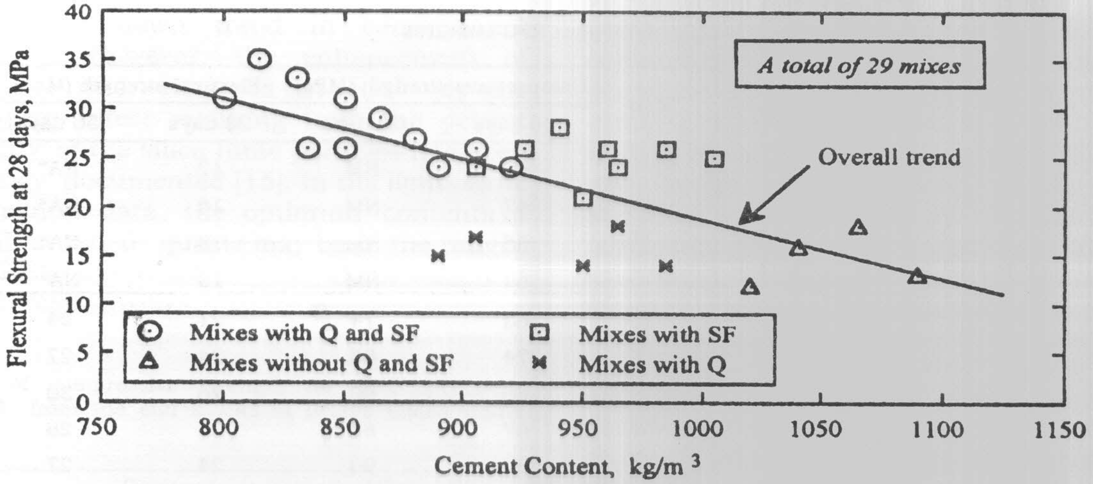


Fig. 12. Flexural strength of RPC as affected by cement content at 28 days.

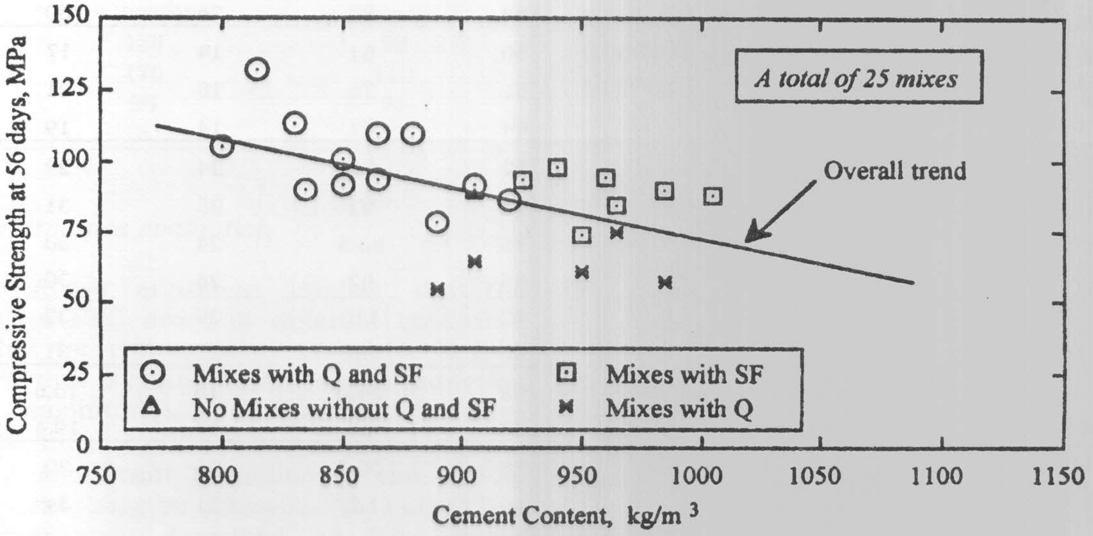


Fig. 13. Compressive strength of RPC as affected by cement content at 56 days.

In fact, strength of mixes with low w/c ratio (0.17) and containing crushed quartz (Mix. No. 15) was even lower than comparable mixes without quartz (Mix. No. 3). Strength increase relative to quartz content was observed for mixes containing SF of about 15% of cement weight revealing the positive interaction between quartz and SF. This was also true for mixes containing SF of about 25% of cement weight, where higher degree of interaction was found, irrespectively of w/c ratio. Both compressive and flexural strengths showed the highest strength level for mixes containing 0.4 quartz. The highest strength at the later ages was achieved by Mix No. 29 and with compressive and flexural strengths of 181 and 35 MPa, respectively. Mix No. 28 revealed similar behavior where the compressive and flexural strengths at the age of 56 days were 132, and 37.5 MPa, respectively.

Based on the above findings, it seems reasonable to conclude that at room temperature, crushed quartz is an essential ingredient for producing RPC that is

Table 5
Compressive strength and flexural strength of different RPC mixtures

Mix. No.	SF	MQ	W/C	W/B	Compressive strength (MPa)		Flexural strength (MPa)	
					28 days	56 days	28 days	56 days
1	--	--	0.21	0.21	40	NM	12	NA*
2	--	--	0.19	0.19	47	NM	16	NA*
3	--	--	0.17	0.17	55	NM	18	NA*
4	--	--	0.15	0.15	54	NM	13	NA*
5	0.15	--	0.21	0.18	63	74	21	24
6	0.15	--	0.19	0.17	74	85	24	27
7	0.15	--	0.17	0.15	86	90	26	30
8	0.15	--	0.15	0.13	87	88	25	28
9	0.25	--	0.21	0.17	85	90	24	27
10	0.25	--	0.19	0.15	88	94	26	29
11	0.25	--	0.17	0.14	92	98	28	31
12	0.25	--	0.15	0.12	88	95	26	30
13	--	0.2	0.21	0.21	50	61	14	17
14	--	0.2	0.19	0.19	51	75	18	21
15	--	0.2	0.17	0.17	44	57	14	19
16	0.15	0.2	0.21	0.18	72	79	24	29
17	0.15	0.2	0.19	0.17	78	92	26	31
18	0.15	0.2	0.17	0.15	75	86.5	24	30
19	0.25	0.2	0.21	0.17	85	92	26	30
20	0.25	0.2	0.19	0.15	92	110	29	32
21	0.25	0.2	0.17	0.14	90	110	27	31
22	--	0.4	0.21	0.21	48	54.6	15	16.6
23	--	0.4	0.19	0.19	57	64	17	19.4
24	0.15	0.4	0.21	0.18	75	90.3	26	30
25	0.15	0.4	0.19	0.16	96	101	31	34
26	0.15	0.4	0.17	0.15	84	94	29	32
27	0.25	0.4	0.21	0.17	95	105	31	34
28	0.25	0.4	0.19	0.15	113	132	35	37.5
29	0.25	0.4	0.17	0.14	98	113	33	35

* NA= Not available data

characterized by the presence of SF. It is of interest to note that the role of quartz may become more significant in RPC under heat treatment conditions. Thermogravimetric and XRD studies previously published showed that heat-treatment in the range of 200-250 °C substantially accelerates the pozzolanic reaction, in which crushed quartz may become a supplementary source for silica and leads to the formation of crystalline hydrates [17]. The beneficial effect of heating RPC in an oven has also been reported elsewhere [20].

On the other hand, it was observed during mixing that the presence of SF improves the workability of RPC mixtures. Despite their relatively low water/binder ratio (w/b), Mixes No. 9-12 (with SF) showed a relatively higher workability and easier casting ability when compared to Mixes No. 1-4 (without SF).

This result is in sharp contrast with the general well-known trend in conventional concrete. However, the enhancement of rheological characteristics of RPC by the lubricating effect resulting from the perfect sphericity of the silica fume particles has been previously documented [15]. In the light of the experimental data, the optimum contents of SF and crushed quartz may be in the ranges of 15-25% and almost 40% of the weight of cement, respectively.

Table 6
Results of compressive strength for RPC specimens prepared from the end blocks of beams tested under flexure

Mix. No.	Compressive strength (MPa) End portions of 4x4x16 cm-beams at 6 months	Compressive strength (MPa) 5.1 cm-cubes at 56 days
17	158	92
21	170	110
23	98	64
29	181	132

5.3. Performance evaluation

The above argument implies that the criteria of RPC are quit different compared with that for conventional concrete. In fact, for RPC that is characterized with a reduction in the maximum size of aggregate by more than 40 times (600 μm as compared with 25 mm), a significant reduction in the size of microcracks may be achieved. This effect has been previously described as "the meso-effects", in addition, the reduction of sand content may represent a more global "macro-effect" [15]. As evident from table 5, mixes containing cement and sand without SF and quartz showed the lowest strength level in spite of their highest cement content (Mixes No. 1-4). Besides, these mixes also showed the worst workability although they contain the highest dosage of superplasticizer. In fact, the performance of these RPC mixes is directly related to the granular components of the mixtures. Since the size of sand particles ranges from 150-600 μm, and the mean size of cement particles ranges from 10-20 μm, these mixes may be regarded as coarse granular mixtures, when compared with other mixes containing SF and quartz. Obviously, matrix densification in these mixes, which is the utmost target for RPC, was not accomplished leading to relatively low strengths. This aspect was eliminated by the inclusion of other ingredients, particularly SF. In addition to its pozzolanic reaction, the physical effect of SF associated with the presence of quartz plays a major role as mentioned earlier.

The flexural strengths of all mixes at the age of 28 days are plotted against cement contents in fig 12. The figure clearly demonstrates a general interesting trend. The strength of RPC may adversely be affected by the randomly increase in the cement content, within a certain range, without giving attention to other principles. Again, optimization of the ingredient contents is of highly importance. Fig 13 confirms this finding.

Furthermore, the highest packing density of the matrix is also greatly dependant on the water content not only the w/c or w/b ratios. In reality, the void of the granular mixture corresponds to the sum of water demand and entrapped air [15]. Therefore, achieving the lowest w/c ratio may not be the target where the entrapped air will be still high in this case. By increasing the water content to a certain extent, the additional quantity of water will replace the entrapped air and consequently will be integrated in the solid phase during hydration. Based on the foregoing argument, strength should be regarded as a synonymous of achieving optimum granular mixture with the corresponding water content. This also may explain the increase in strength for mixes with relatively low cement content and relatively higher w/c ratio. As seen in tables 4 and 5, mixtures composed of cement and sand achieved their highest strengths at w/c of 0.17, while mixtures containing SF revealed their optimum strengths at w/c of 0.17 and 0.19. With the addition of quartz, the highest strength was achieved at 0.19 w/c.

It is too early to predict the future of RPC. Further work is strongly recommended to achieve better understanding of RPC and its constituents in order to achieve higher strength level.

5. Conclusions

Based on the study reported here, the following conclusions may be drawn:

1. Reactive Powder Concrete "RPC" is a new family of high-strength cement-based composites that may achieve compressive strength on the order of 200 MPa and flexural strength exceeding 30 MPa.
2. It is possible to make RPC from locally available materials in Egypt if they are carefully selected, and the mix composition is optimized in terms of grain size distribution.
3. Optimization of the whole grain size distribution, matrix densification, utilizing aggregate with 600 µm maximum size, and the extremely low w/c are the key-aspects of producing RPC.
4. A compressive strength up to 181 MPa and a flexural strength up to 37.5 MPa were achieved throughout this study using local materials including fine sand, high content of Portland cement, silica fume, crushed quartz, and Poly-carboxlic superplasticizer (PCE).
5. More than half the total number of flexural specimens exhibited flexural strength higher than 25 MPa. This obtained levels of strength (up to 37.5 MPa) for RPC may eliminate the need for secondary reinforcing steel in beams, and may permit the use of thinner sections and a wider variety of acceptable shapes.
6. Results imply that silica fume and crushed quartz play an important role in the strength and rheological properties of RPC, and therefore they are essential ingredients for producing RPC.
7. In the light of the experimental data, and within the studied range of variables, the recommended optimum contents of SF and crushed quartz are in the ranges of 15-25% and almost 40%, respectively, of the weight of cement.
8. The highest packing density of the matrix is greatly dependent on the water content.
9. The strength of RPC may adversely be affected by the randomly increase in the cement content, within a certain range, without giving attention to other principles. Optimization of the ingredient contents is of highly importance.
10. RPC seems to have much potential in modern technology.

References

[1] ACI Committee 363R-92, "High-Strength Concrete," ACI Manual of Concrete Practice Part 1: Materials and General Properties of Concrete," Farmington Hills, Michigan (1999).

[2] W. H. Dilger, and C. Wang, "Effects of W/C, Superplasticizers and Silica Fume on the Development of Heat of Hydration and Strength in HPC", 4th Weimar Workshop on High Performance Concrete, Weimar, Germany, Oct., pp. 3-22, (1995).

[3] P. Mehta "Advancements in Concrete Technology", Concrete International, Publication of the American Concrete Institute, Vol. 21(6), pp. 69-76 (1999).

[4] K. Vivekanandam, I. and Patnaikuni, "Transition Zone in High Performance Concrete During Hydration," Cement and Concrete Research, Vol. 27 (6), pp. 817-823 (1997).

[5] P. C. Aitcin, and A. Neville, "High-Performance Concrete Demystified," Concrete International, Vol. 15 (1), pp. 21-26 (1993).

[6] S. Chan, N. Feng, Dallaire, and Tsang, M., "Mechanical Properties of High-Strength Concrete Incorporating Carrier Fluidifying Agent", ACI Material Journal, V. 97 (2), pp. 108-114 (2000).

[7] J. Xie, A. Elwi, and J. MacGregor, "Mechanical Properties of Three High-Strength Concretes Containing Silica Fume", ACI Material Journal, Vol. 92 (2), pp. 135-145 (1995).

[8] K. Sobolev, "High Performance Cement", Downloaded from the web at http: //www.geocitie.com, Dec. (2000).

[9] D. Roy, M. Silsbee: 'Novel Cements and Concrete Products for Application in the 21st Century", Proceedings of V. M. Malhotra Symposium on "Concrete Technology; Past, Present, and Future", SP-144, ACI, Farmington Hills, Mich., pp. 349-382 (1994).

[10] A. Birchall, K. and Kendall, "Strong Hydraulic Cements", Proceedings of British Ceramic Society, Ottawa, Vol. 32, pp. 256-258 (1982).

[11] H. Bache, "Densified Cement/Ultra-Fine Particle-Based Materials", The Second International Conference on Superplasticizers in Concrete, pp. 33-35 (1981).

[12] HDR Engineering web site, "Reactive Powder Concrete: Ultra-High Performance Cement-Based Composite Material", Downloaded from the web site at http: //www.hdrinc.com, updated Nov. (1999).

[13] P. Richard, M. Cheyrezy, "Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength", Proceedings of V. M. Malhotra Symposium on "Concrete Technology; Past, Present, and Future", SP-144, ACI, Mich., pp. 507-518 (1994).

[14] S. Collepardi, L., Coppola, R., Troli, and M. Collepardi, "Mechanical Properties of modified Reactive Powder Concrete", Proceedings of the 5th CANMET/ACI International Conference on Superplasticizers and other Admixtures in Concrete, SP-173, ACI, Farmington Hills, Mich., pp. 1-21 (1997).

[15] P. Richard, M. Cheyrezy, 'Composition of Reactive Powder Concrete", Cement and Concrete Research, Vol. 25 (7), pp. 1501-1511 (1995).

[16] L. Coppola, R. Troli, S. Collepardi, A. Borsoi, and M. Collepardi, "Inovative Cementitious Materials: from HPC to RPC", L'Industria Italiana del Cemento, Vol. 707, pp. 112-125 (1996).

[17] M. Cheyrezy, V. Maret, and L. Frouin, "Microstructural Analysis of RPC (Reactive Powder Concrete)", Cement and Concrete Research, Vol. 25 (7), pp. 1491-1500 (1995).

[18] E.F. O'Neil, C. E. Dauriac, S. K. and Gilliland, "Development of Reactive Powder Concrete Products in the United States Construction Market," American Concrete Institute, Mich., SP 167, "High-Strength Concrete: An International Perspective", pp. 249-261 (1996).

[19] L. Coppola, R. Troli, A. Borsoi, P. Zaffaroni, M. Collepardi, "Influence of Superplasticizer Type on Compressive Strength of RPM", Proceedings of Fifth CANMET/ACI International Conference on Superplasticizers and other Chemical Admixtures in Concrete, SP-173, ACI, Mich., pp. 512-536 (1997).

[20] O. Bonneau, M. Lachemi, E. Dallaire, J., Dugat, P. and Aïtcin, "Mechanical and Durability of Two Industrial Reactive Powder Concretes", ACI Material Journal, Vol. 94 (4), pp. 286-290 (1997).

[21] C. Dauriac, "Special Concrete may Give Steel Stiff Competition", Downloaded from the web site of "The Seattle Daily Journal of Commerce" (DJC) at http://www.djc.com, special issue, May (1997).

[22] W. Dowd, C., Dauriac, R., and Adeline, "RPC for Bridge Construction", Downloaded from the web site of 'HDR Eng.' at http: //www.hdrinc.com, updated Jan. (2001)

[23] Y.Blais, and M. Couture, "Precast, Prestressed Pedestrian Bridge - World's First Reactive Powder Concrete Structure", PCI Journal, Vol. 44(5), pp. 60-71 (1999).

[24] 1999 Nova Award Nominations, The Nova Award, Construction Innovation Forum, Inc., Oct. (1998).

[25] M. Salah-Eldin, "New Generation of High-Performance Concrete", Diploma Project, Materials Science Dept., Institute of Graduate Studies and Research, Alexandria University, Alexandria (2001).

[26] M. Collepardi, "Superplasticizers and Air Entraining Agents: State of the Art and Future Needs", Proceedings of V. M. Malhotra Symposium on "Concrete Technology; Past, Present, and Future", SP-144, ACI, Mich., pp. 399-416 (1994).

[27] M. Corradi, R. and Khurana, "New Generation of Superplasticizers", Proceedings of RILEM – WTA, Seminar on High Pwerformance of Cement Based-Materialds, pp. 119-129, Sept (1997).

[28] G. Xu, and J. Beaudoin, "Effect of Polycarboxylate Superplasticizer on Contribution of Interfacial Transition Zone to Electrical Conductivity of Portland Cement", ACI Material Journal, Vol. 97 (4), pp. 418-424 (2000).

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