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Effect of Quartz Content on Physical Parameters of Locally Developed Reactive Powder Concrete

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ABSTRACT

Reactive powder concrete (RPC) belongs to a new category of cement based composites bearing high compressive strength and negligible permeability. The introduction of RPC opened new applications for engineers and researchers specially to be used in nuclear installations. In this research, RPC has been developed first time in Pakistan using locally available ingredients. Present study focused on developing RPC with compressive strength up to 80 MPa because suitable background on RPC was not available in the country. RPC was developed using quartz powder, silica fume, sand, cement, super plasticizer and steel fibers. Different mixes were cast with varying content of quartz powder to check its effect on physical parameters of RPC like compressive strength, tensile strength, modulus of rupture, permeability and uniaxial stress-strain behaviour. The results demonstrated that RPC having compressive strength up to 80 MPa could be produced using materials available in local market. Values of physical parameters increased with the increase in quartz powder content up to a certain limit. After this optimum value, further increase in the quartz powder content caused a decline in the values of different physical parameters studied.

1. Introduction

Reactive powder concrete (RPC) is a concrete with ultra-high compressive strength and improved ductile properties. RPC is cast without using coarse aggregates, but it contains cement, sand, quartz powder, silica fumes and steel fibers (optional) with reduced water to binder ratio. Super plasticizer is also used to decrease water cement ratio and increase strength. The concept of RPC was first introduced by researchers of Bouygues Laboratory in France [1]. The basic concept on which RPC was developed lies in elimination of coarse aggregates, addition of supplementary materials, very low water to binder ratio, addition of steel fibers, heated curing and application of pressure before and during setting. Removal of coarse aggregates made it possible to increase the homogeneity between cement matrix and aggregates and is considered to be the key aspect for the microstructure and performance of RPC.

Collepardi et al. [2] conducted an investigation on the substitution of ground fine quartz sand (0.15-0.40 mm) by a part of the cementitious binder and all of the fine sand by graded natural aggregates with maximum size of 8 mm. The results of the study showed that there was no effect on the compressive strength of RPC at same water to binder ratio. It was also observed that increasing the water to binder ratio resulted in the reduction of cement content hence it decreased the compressive strength of RPC. Fully substituting the quartz sand with graded coarse aggregates resulted in reduced flexural strength. RPC has wide range of applications. It is suitable for pre-stressed concrete and for structures having light and thin components such as roofs of stadiums, space structures, long spanning bridges, blast resistant structures, high pressure thin pipes and the containment of nuclear wastes [3-5]. Fehling [6] studied the hardened properties of “Ultra High Performance Concrete” specially, the compressive and tensile strength. He noticed that range of compressive strength of Ultra High Performance Concrete (UHPC) was 150 to 220 MPa. Up to 70 to 80% of compressive strength UHPC with steel fibers showed a linear elastic behaviour and without steel fibers a brittle failure as there was no declining part in the stress-strain curve. In Hong Kong, Man et al. [7] investigated the production processes and physical properties of RPC with locally available materials.

Habel et al. [8] studied the possibilities for potential use of “Ultra High Performance Fiber Reinforced Concrete” (UHPFC) as rehabilitation material in combination with different structural members. Aim of his research was to evaluate the time dependent behaviour of elements combining ultra-high performance fiber reinforced concrete and reinforced concrete for the determination of durability and serviceability. Abdelalim et al. [9] suggested that reactive powder concrete could be produced using materials available in local Egyptian market. Reactive powder concrete thus produced had superior structural properties. A compressive strength up to 160 MPa and a flexural strength up to 46 MPa were achieved. The optimum value of water/cement ratio for reactive powder concrete mixes

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ranged from 0.17 to 0.19 based on the matrix composition. The utilization of silica fume and quartz powder was indispensable for producing RPC. The optimum contents for silica fume and quartz powder were in the ranges of 15-25% and 30-40% of the cement weight, respectively. Premet al. [10] investigated the stress-strain curves of RPC and concluded that pre-peak curve was linearly ascending portion and strain at peak stress increased proportionally with increase in strength and reinforcement index. Flexural and split tensile strength at 28 days showed a linearly varying relationship between 28 days strength and reinforcement index. The flexural strength of the mixes was in the range of 16 to 44 MPa and split tensile strength in the range of 11.3 to 23.8 MPa. Khadiranaikar and Muranal [11] obtained 146 MPa as maximum compressive strength of RPC with accelerated curing at water to binder ratio of 0.2. For the production of reactive powder concrete, the optimum percentage of silica fume was 15% by weight of cement with available super plasticizer. The addition of quartz powder resulted in an increase of compressive strength of up to 20%. A simple analytical method for calculating the ultimate loads of RPC columns under large eccentric compression was set up by Shi et al [12] in 2017. Test results revealed that the equivalence coefficient of RPC column in tensile regions can be 0.6 (with steel fibers) or 0.4 (without steel fibers). In 2017, Parameshwar et al. [13] made an attempt to study the effect of mixing method, speed and duration on the fresh and hardened properties of RPC. Results indicate that improved mixing techniques prove beneficial in enhancing fresh and hardened properties of RPC. Mixing speed and duration also have significant effect on the fresh and hardened properties of RPC.

In Pakistan, no attempt to produce RPC has been reported yet. This is the first time; a successful attempt has been made. In this paper, quartz powder content has been varied to check its effect on different physical parameters of RPC.

2. Experimental Programme

2.1 Materials used

2.1.1 Cement

Type I Ordinary Portland Cement (OPC) was used. Its chemical and physical properties are given in Table 1.

2.1.2 Sand

Sand utilized in the research work was locally available Lawrencepur brand Pakistani sand. Sieve analysis of the sample was carried out according to ASTM C136-06 [14] in the concrete laboratory of Civil Engineering Department in UET Taxila. The value of fineness modulus was found to be 2.50 and it was calculated as the sum of cumulative percentages retained on different sieves divided by 100. The specific gravity of the sand was calculated as 2.71 (ASTM C128-79 [15]) and water absorption during 24 hours as 1.20% (ASTM C128-01 [16]).

Table 1: Chemical composition and physical properties of OPC

Chemical Composition		Physical Properties	
Compound	Quantity (%)	Parameter	Value
SiO_2	22.0	Specific surface	322 m^2/kg
Al_2O_3	5.50	Consistency	30 %
Fe_2O_3	3.50	Initial setting time	1hr, 42 min
CaO	64.25	Final setting time	3 hr, 55 min
MgO	2.50	Soundness	No soundness
SO_3	2.90	Specific Gravity	3.15
Na_2O	0.20	Compressive strength (28 days)	40.68 MPa

2.1.3 Water

The water utilized for mixing of mortar and concrete ingredients was ordinary tap water of concrete laboratory in UET Taxila. The characteristics of water utilized are given in Table 2.

Table 2: Characteristics of water

Sr No	Source Description	pH Value	Hardness ($CaCo_3$) Content (mg/l)	Chloride(Cl^-) Content (mg/l)	Sulfate (SO_4^{-2}) Content (ppm)
1.	Tap water	7	300	240	45
Maximum permissible limit as per WHO guidelines		6.5 to 8.5	500	250	400

2.1.4 Superplasticizer

Third generation superplasticizer based on modified polycarboxylic ether was used in the research programme. The superplasticizer meets the requirements of EN 934-2 T 3.1/3.2 [17] and ASTM C-494 Type F [18]. Typical properties of the superplasticizer are given as under:

Colour: Light brown

Relative density: 1.08 at 25°C

Chloride content: < 0.2%

Physical state: liquid

2.1.5 Silica fume

Silica fume used in the research programme conformed to ASTM C1240 – 97b [19]. Range of particle size was between 0.1 µm and 1 µm. Its physical properties and chemical composition are given in Table 3.

Table 3: Chemical and physical properties of silica fume

Parameter	Value
SiO_2 content (%)	85-97
Al_2O_3 content (%)	Nil
Fe_2O_3 content (%)	Nil
CaO content (%)	<1
Fineness as surface area (m^2/Kg)	15,000-30,000
Specific gravity	2.22
Colour	Grey

2.1.6 *Quartz powder*

The particle size of quartz powder was between 5–25 µm. Different physical properties and chemical composition of quartz powder is given in Table 4.

Table 4: Chemical and physical properties of quartz powder

Chemical properties		Physical properties	
Parameter	Value	Parameter	Value
Loss on ignition (%)	0.12	Appearance	White
SiO_2 content (%)	97.12	Odour	None
Fe_2O_3 content(%)	0.13	Melting Point	1710 ^{0}C
CaO content (%)	2.16	Boiling Point	2230 ^{0}C
Moisture (%)	0.07	Hardness (Moh's Scale)	7
Organic Matter	Negligible	Specific Gravity	2.65

2.1.7 *Steel fibers*

High strength steel fibers were used for obtaining better ductility. Table 5 shows the typical properties of steel fibers used.

Table 5: Typical properties of steel fibers used

Parameter	Value
Length (mm)	35
Diameter (mm)	0.55
Aspect ratio (L/d)	64
Tensile strength (MPa)	1345

2.2 *Mix Design*

Different trials were made to develop RPC. Ingredients from different sources were used in different ratios to develop it. The mix ratio which gave optimum values of physical properties was finally selected for research. Ratios of all ingredients were kept constant throughout the research except that of quartz powder.

Final mix design of RPC used in the casting of samples is given in Table 6. Quartz content was varied from 0.20 to 0.41% by weight of cement. Designation of samples with different quartz content is given in Table 7.

Table 6: Final mix design ratios

Ingredient	Mix ratio (By weight of cement)
Cement	1
Sand	1.1
Silica fume	0.15
Quartz powder	0.20-0.41 (To be varied)
Super plasticizer	2%
Steel fibers	1% by volume of concrete
water/cement ratio	0.23

Table 7: Designation of samples with respect to quartz content

Sample designation	Binder content (%)	
	Quartz powder	Cement
RT-1	20	80
RT-2	23	77
RT-3	26	74
RT-4	29	71
RT-5	32	68
RT-6	35	65
RT-7	38	62
RT-8	41	59

2.3 *Casting Schedule*

Eight different mixes were prepared for every test by varying quartz content to check its effect on mechanical parameters of RPC. For compressive and tensile strengths, a total no of 72 cubes and 72 cylinders were cast and tested at 7, 14 and 28 days. Standard cubes with dimensions, 100 x 100 x 100 mm , were used for compressive strength test while 150 x 300 mm cylinders were used for tensile strength test. Moreover, 24 cylinders with dimensions 150 mm (dia.) x 150 mm (length) were cast for permeability test and tested at 28 days age. Twenty four (24) beams with dimensions 100 x 100 x 500 mm were also cast to test flexural behaviour of RPC by modulus of rupture test and tested at the age of 28 days. Casting schedule and test specimen details are given in Table 8.

2.4 *Mixing and Curing*

Mixing was performed in a high speed mortar mixer to overcome high viscosity of RPC mix and ensure its homogeneity. The total mixing time was 7 minutes as per following sequence:

a. Dry mixing of cement, sand, and powders for 1.5 minute was carried out at slow speed.

b. A mixture of water and half superplasticizer was added and mixing continued for 2 minutes

c. After one minute rest time, remaining half of superplasticizer, diluted in an equal volume of water, was added followed by 1.5 minutes mixing at slow speed. Final mixing for one-minute at high speed was carried out.

Table 8: Test details and casting schedule of specimens

Test details	Specimen details	Sample designation	Age (days)			Total
			7	14	28	
Compressive Strength (ASTM C 109)	Cubes (100 × 100 × 100) (mm)	RT-1	3	3	3	72
		RT-2	3	3	3	
		RT-3	3	3	3	
		RT-4	3	3	3	
		RT-5	3	3	3	
		RT-6	3	3	3	
		RT-7	3	3	3	
		RT-8	3	3	3	
Split Tensile Strength (ASTM C496-71)	Cylinders (150 dia × 300 length) (mm)	RT-1	3	3	3	72
		RT-2	3	3	3	
		RT-3	3	3	3	
		RT-4	3	3	3	
		RT-5	3	3	3	
		RT-6	3	3	3	
		RT-7	3	3	3	
		RT-8	3	3	3	
Flexural Strength Test (ASTM C78-02)	Beams (100 × 100 × 500) mm)	RT-1	-	-	3	24
		RT-2	-	-	3	
		RT-3	-	-	3	
		RT-4	-	-	3	
		RT-5	-	-	3	
		RT-6	-	-	3	
		RT-7	-	-	3	
		RT-8	-	-	3	
Water Permeability (CRD-C 163-92)	Cylinders (150 mm dia × 150 mm length)	RT-1	-	-	3	24
		RT-2	-	-	3	
		RT-3	-	-	3	
		RT-4	-	-	3	
		RT-5	-	-	3	
		RT-6	-	-	3	
		RT-7	-	-	3	
		RT-8	-	-	3	

All samples of RPC were cured in a temperature controlled water tank till the specified age of testing. Tap water of concrete lab was used in the tank for curing purpose.

2.5 Scanning Electron Microscopy (SEM) Test

Scanning electron microscopy (SEM) was utilized to study and photograph the microstructure of RPC Three samples of RPC were examined at 28 days age by SEM. Samples were obtained from the central parts of the test specimens to avoid any possible artifacts due to thermal effects at the outer surface. Samples were ground into very fine powder and thinly coated with gold prior to examination.

2.6 X-Ray Diffraction (XRD) Test

At 28 days age, samples of RPC were examined by XRD. These samples were similar to those tested on SEM. From the powder concrete samples different X-Ray Diffractograms were recorded over a 2ϕ angular range from 10º to 80º and different phases were identified.

3. Results and Discussion

3.1 Compressive Strength

According to ASTM C109 [20], compressive strength test was conducted on cubic samples of dimensions 100 x 100 x 100 mm. Compressive strength values were recorded at 7, 14 and 28 days respectively. The average reading of three cubes tested was recorded as the compressive strength at respective age. Tests were conducted in compression testing machine with a capacity of 3000 kN.

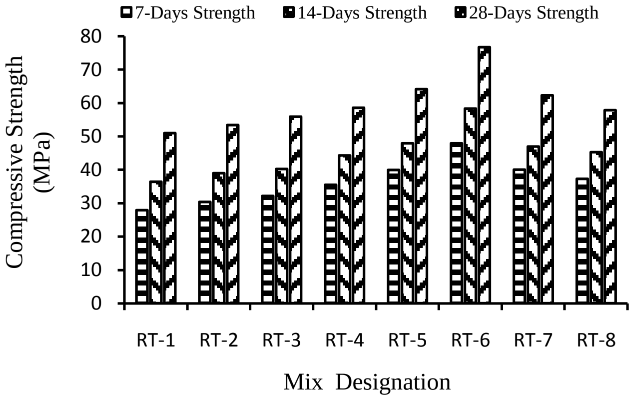

Fig. 1: Comparison of compressive strength at all ages

Fig. 1 shows the compressive strength of all mixes at 7, 14 & 28 days. It was observed that compressive strength gradually increased from RT-1 to RT-6 and then gradually decreased up to RT-8. RT-6 had maximum compressive strength at all ages as compared to other mixes. So, RPC samples showed maximum strength when quartz powder content was 35 percent by weight of cement. Maximum value of compressive strength of RPC was obtained as 76.73 MPa. As compared to RT-1, where quartz powder used was only 20 % by weight of cement, it is 71.88% more for 7-days strength, 37.59 % more in 14-days strength and 50.54% more in 28-days strength.

Rate of gain of compressive strength of all mixes is shown in Fig. 2. It can be seen that rate of gain of strength for all mixes is linear from 7 to 28 days. Maximum strength was achieved in first seven days of curing. After 7 days, rate of gain of strength was constant up to 28 days except some minor variation at higher quartz contents i.e. RT-7 and RT-8.

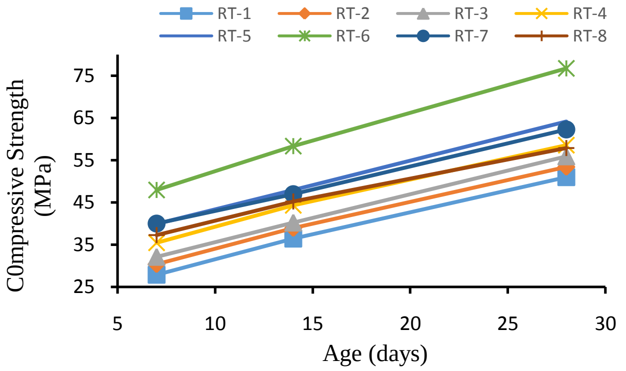

Fig. 2: Comparison of rate of gain of compressive strength for all mixes

3.2 *Tensile Strength*

According to ASTM C496-71 [21], split cylinder test was carried out on cylindrical specimens of 150 mm diameter and 300 mm height at the ages of 7, 14 and 28 days. The average values of split cylinder strength for tested three cylinders were recorded to obtain tensile strength at respective ages. Tensile strength of all mixes at all ages is shown in Fig. 3.

It can be observed that tensile strength gradually increased from RT-1 to RT-6 and then gradually decreased to RT-8. RT-6 had maximum tensile strength at all ages as compared to other mixes. So, RPC had maximum tensile strength when quartz powder content was 35 percent by weight of cement. Maximum tensile strength of RPC obtained was 9.04 MPa. Tensile strength of normal concrete ranges from 2 MPa to 5 MPa. So, tensile strength of RPC was almost 300% more than that of normal concrete.

Fig. 4 shows the rate of gain of tensile strength of all mixes. It can be seen that rate of gain of tensile strength for all mixes is almost linear. After 7 days of curing, maximum strength was gained. Rate of gain of strength is constant after 7 up to 28 days.

3.3 *Flexural Strength*

According to ASTM C78-02 [22], modulus of rupture test was carried on beams of size 100×100×500 mm. Three point loading was used to find modulus of rupture. Specimens were tested at the age of 28 days. The average reading of three beams was recorded to calculate modulus of rupture (MOR).

Fig. 5 shows the comparison of modulus of rupture of all mixes. It can be seen that RT-6 has maximum value of modulus of rupture. Modulus of rupture gradually increases from RT-1 to RT-6 and then decreases up to RT-8. Like compressive and tensile strengths, flexural strength is also maximum when quartz powder content is 35 percent by weight of cement. MOR of normal concrete ranges from 3 MPa to 5 MPa. Maximum value of MOR obtained for RPC is around 9 MPa at 28 days for RT-6.

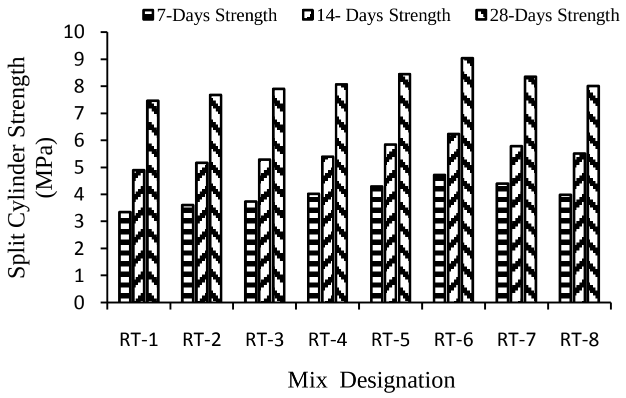

Fig. 3: Comparison of split cylinder strength at all ages

3.4 *Water Permeability*

Water permeability test was carried out as per CRD-C 163-92 [23] on standard samples in water permeability test apparatus. Constant pressure of 3000 KPa was applied on standard samples for more than seven hours and seepage was noted. No seepage took place for any sample. Hence, water permeability of all samples of RPC was found to be zero.

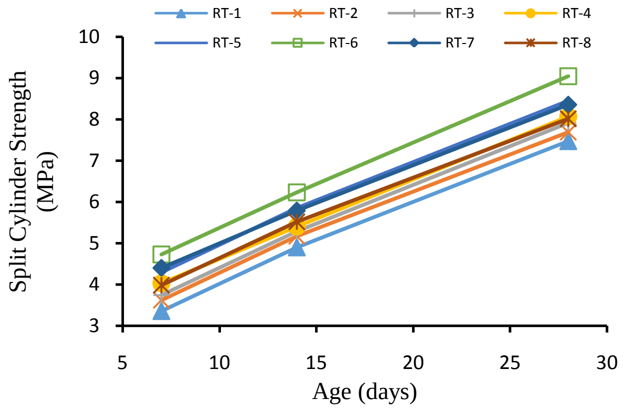

Fig. 4: Comparison of rate of gain of split cylinder strength for all mixes

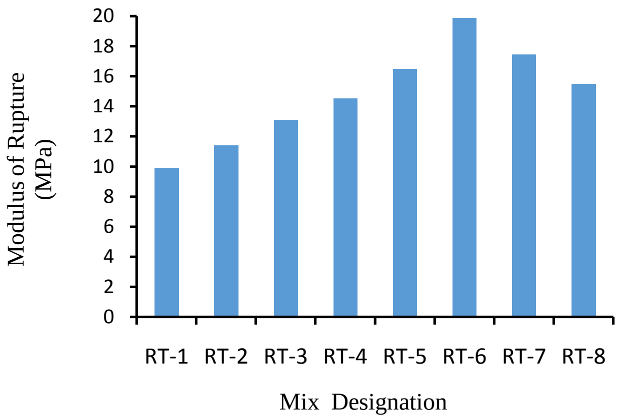

Fig. 5: Modulus of rupture Vs Mix Designation

3.5 Stress-strain Behaviour under Uniaxial Compression

Strain gauges were attached to the cubes in the direction of compressive load. Cubes of size 100x100x100 mm were used for this purpose. Compressive load was applied using universal testing machine. P3 box was used to obtain strain readings. After regular interval of load, strain values were recorded from P3 box.

Stress strain behaviour of all mix types is shown in Fig. 6. Stress and corresponding strain values were used to draw these curves. These curves were used to calculate the modulus of elasticity. A stress value of 23 MPa along with corresponding strain values obtained from the trend line equations of each mix were used to evaluate the modulus of elasticity. The failure strain for all mix types was found to lie in the range of 0.0027-0.0033.

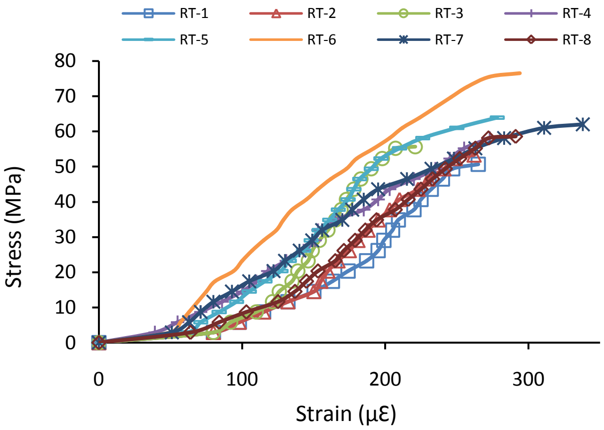

Fig. 6: Stress-Strain behaviour of all mixes

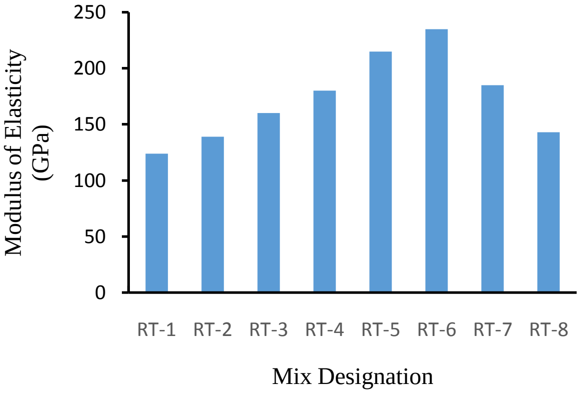

Fig. 7: Modulus of elasticity Vs mix designation

Fig. 7 shows the comparison of modulus of elasticity for all mixes. Modulus of elasticity gradually increases from RT-1 to RT-6 and then decreases to RT-8. RT-6 has maximum value of modulus of elasticity i.e 235 GPa.

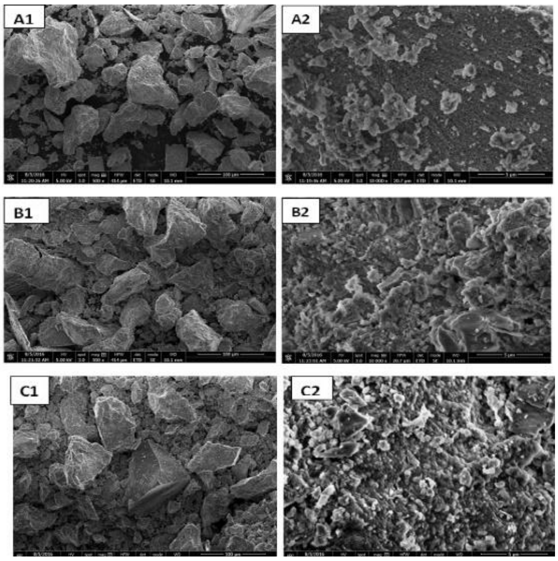

Fig. 8: SEM micrographs of RT-1, RT-6 and RT-8 (A, B and C respectively)

3.6 SEM Analysis

Three samples were selected for SEM test. These samples were RT-1 with minimum quartz content, Rt-8 with maximum quartz powder content and Rt-6 with maximum strength. The internal morphology of selected samples was visualized from Scanning Electron Micrograph (SEM) shown in Fig. 8 by letters A, B and C respectively.

These photographs clearly show 1-5 µm needle shaped densely packed cubical and hexagonal hydrates. Several typical points on the surface of each sample were selected for Electronic Data System (EDS) analysis to determine the elemental contents of Si, Al, Ca, Mg and K. Results of EDS are shown in Table 9. The percentage of silicon in RT-1, RT-6 and RT-8 is 42.66%, 48.91% and 45.68% respectively. Percentage of AlK in RT-6 and RT-8 is 2.19% and 1.1% respectively while calcium content in RT-1, RT-6 and RT-8 is 0.66%, 30.39% and 15.54% respectively.

The quantitative "Energy Dispersive Spectrum (EDS)" analysis given in Table 9 revealed that the relative atomic ratio of Si and Al is more in RT-6 which is possibly the reason for high strength of RT-6. Pure quartz sample contains hexagonal silica fume particles. On the other hand, the micrographs of the mixtures containing small amounts of CaK and AlK which reveal that there is compact formation of hydration products and a reduced content of $Ca(OH)_2$ crystals. SEM microstructure of silica fume in all images is in the form of typical round dark grains which can be clearly seen with magnification up to 1-5 µm in all micrographs. It is suggested that hexagonal particles on some of cubic crystals represent the presence of Mg, Ca and other atoms. This is due to the absence of coarse aggregates and the presence of sand, silica and alumina particles. Formation of ettringite as small needles was also observed in samples which may be due to $Ca(OH)_2$. Percentage of Ca, Si and Al present in all samples especially in RT-6 is believed to be the reason for textural strength and physical properties of RPC samples. Calcium-silicate-hydrate (C-S-H) gel is identified by its short needle-like shape and fine bundles as seen in Fig. 8 (B2) and (C2). C-S-H gel is expanded like a bundle in Figs. 8 (A1), (B1) and (C1). Colour of some particles in selected areas reveal the presence of water content in anhydrous cement. It also identifies the presence of silica fume and calcium hydroxide in circular and plate shape.

Table 9: EDS analysis of specific points at surface of materials

Component		Sample		
		RT-2	RT-6	RT-8
SiK	Weight (%)	42.66	48.91	45.68
	Atomic weight (%)	29.91	6.56	14.16
AlK	Weight (%)	---	2.19	1.1
	Atomic weight (%)	---	1.68	0.79
SK	Weight (%)	---	0.97	---
	Atomic weight (%)	---	0.62	---
CaK	Weight (%)	0.66	30.39	15.54
	Atomic weight (%)	0.32	15.67	7.46
OK	Weight (%)	56.67	17.81	52.23
	Atomic weight (%)	69.76	68.23	62.8
MgK	Weight (%)	---	1.03	0.81
	Atomic weight (%)	---	0.88	0.64

SEM photographs clearly show that there is no quartz agglomerates present in any sample which is responsible for high strength of RPC samples especially of RT-6. Silica fume is present in the form of separate particles attached with C-S-H.

3.7 *XRD Analysis*

Fig. 9 shows the XRD results comparison of RT-1, RT-6 and RT-8. Different symbols are drawn to show the intensity of different components. The main observation from the XRD analysis was that the strongest portlandite (CH) peaks were absent on diffractograms of the RPC mixtures examined. This confirms the conclusion that CH was largely consumed by the pozzolanic reaction and converted to strong C-S-H gel.

Major peaks in XRD spectra are related to silicon hydroxide and calcium silicate hydrates. The phenomenon can be attributed to the transformation of hydrates. It is observed that major diffraction peaks of all three samples confirm that prepared samples belong to Ca_xSiO_x, brinrobertite, portlandite and wallastonite.

Table 10: Compounds and their symbols

Compound		Symbol
SiO_2		o
Brinrobetite		☆
Portlandite $Ca(OH)_2$		✦
Calcium Silicate Hydrate	$Ca_5SiO_{16}(OH)_2 4H_2O$	⇩
	Ca_3SiO_5	⬢
	Ca_2SiO_4	♡
Wallastonite $CaSiO_3$		⬢

Table 10 shows the chemical ingredients found in the microstructure of RPC and their symbols as shown in Fig. 9.

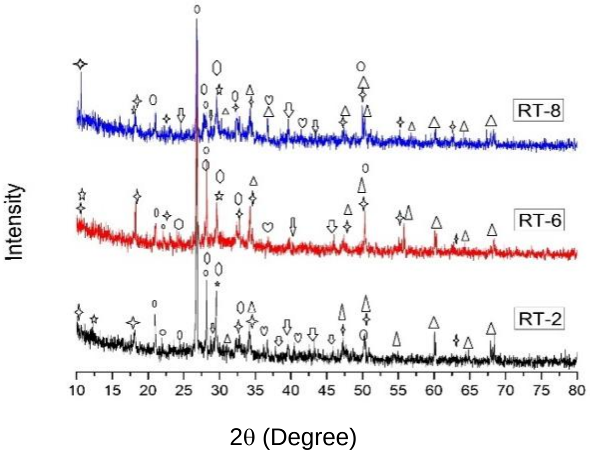

Fig. 9: Comparison of XRD results of RPC samples

Sharp peaks found at 20.99◦, 21.03◦, 26.82◦, 27.96◦ and 28.01 belongs to SiO_2. $Ca_5SiO_{16}(OH)_2$ showed broad and sharp signalsat 26.79◦, 28.01◦, 29.01◦, 30.10◦, 39.62◦, 47.49◦ and 49.98◦. Peaks between 18.19◦ and 64◦ belong to $Ca(OH)_2$. The samples showed sharp diffraction peaks at 20.99◦, 21.03◦, 26.82◦ and 27.96◦ for SiO_2 intensity. These peaks are associated with strength changes in samples. The sample having high amount of quartz powderi. e., RT-8 showed intensive diffraction patterns which is connected with strength of samples. Intensity of XRD peaks increases with increase of quartz powder content upto a specific valuei. e., RT-6. After this value, increase of quartz powder content decreases the strength which is due to the fact that bonds start dissolving at this stage.

4. Conclusions

Following conclusions are drawn from the current research:

- RPC can be produced successfully using materials available in the local market of Pakistan.
- RPC has superior structural properties; compressive strength up to 80 MPa, tensile strength up to 10 MPa

and flexural strength up to 20 MPa can be achieved with confidence.

- Mechanical parameters like compressive strength, tensile strength, flexural strengths and modulus of elasticity have maximum values when quartz content is 35 percent by weight of cement. Thus, values of Mechanical parameters can be enhanced by optimizing quartz content in RPC.
- RPC with negligible permeability of water and produced using local ingredients.
- Tensile strength up to 300 percent and flexural strength up to 500 percent as compared to those of normal strength PCC can be produced using local ingredients, e.g., cement, sand, silica fume, steel fibers, etc..

5. Recommendations

RPC cast using local materials can be confidently used in sensitive locations like nuclear installations where concrete of high strength with zero water absorption is required.

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