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TECHNOLOGY | INNOVATION | INDUSTRY

International Journal of
Advanced Structures and Geotechnical Engineering
ISSN 2319-5347, Vol. 04, No. 02, April 2015

Optimizing mix proportions for Reactive Powder Concrete (RPC) and investigating the compressive strength.

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Abstract: In this paper a variety of mix proportions were prepared with varying different parameters. The specimens were tested for the compressive strength so as to get optimized mix design that would deliver the maximum performance in terms of compressive strength. A total of 54 cubes 3x3x3 inches were prepared. Specimens were treated with normal water as well as with hot water. The content of ingredients as well as the w-b ratio was also kept on changing, so as to get a better understanding. Results showed that the mix proportions with higher silica content and lower water-cement ratio delivered good results.

Keywords: *Reactive Powder Concrete, Mix Proportions, Compressive Strength*

Introduction:

Concrete, the most widely used construction material, has been a subject to key research and development over the past decade. Once thought to deliver magnificent structural and durable performance with little else, concrete has now grown into a material that is capable to be used in any environment it is subjected to. Exciting new advancements have been made since origination of concrete. Development of high strength concrete, high performance concrete and ultra-high strength or ultra-high performance concrete has tremendously increased its potential application. High Performance Concrete (HPC) may provide an ultimate compressive strength of 7250 to 14500 Psi (Washer et al.,2004). Despite the landmark achievements in improvement of concrete, higher self-weight, poor tensile strength and brittle nature have been a major concern among researchers. Lately, a new generation of ultra-high performance concrete known as Reactive Powder Concrete (RPC) has been innovated by Bouygues in France in 1990s (Richard et al., 1994, 1995; Aïtcin 2003;Yen Lei Voo at el, 2005). Reactive Powder Concretes (RPC) constitute particular type of cementitious materials including cement, precisely fine silica fume as secondary binding material, very finely grinded quartz powder, quartz sand with particle size almost equal to the natural sand (0.15-0.40mm) and steel fibers. Reactive Powder Concrete with tremendous high compressive strength has the capability of gaining a compressive strength as high as 29000 Psi (several times greater than conventional concrete). Investigations on the mechanical properties of RPC reveal that the material carries an increased amount of tensile strength and ductility, almost 250 times greater than the normal strength concrete, (Shaheen E, Shrive N (2006)). Some of the basic mechanical properties of RPC in comparison with ordinarily prepared high strength concrete (HPC) are presented in table 1.

The ultra-high mechanical performance of RPC can be explained by;

- Enhancement of homogeneity of RPC by the elimination of coarse aggregates, (maximum size of ingredients of RPC is usually less than 600 µm (Richard and Cheyrezy, 1995)
- Enhancement of compacted density by optimizing the granular mixture (Richard and Cheyrezy, 1995).
- Improved matrix properties by addition of pozzolanic admixtures, i.e. silica fume (Ma and Schneider, 2002).
- Improved matrix properties by reducing water to binder ratio. (Ma and Schneider, 2002).
- Enhancement of microstructure by heat treatment after hardening (Richard and Cheyrezy, 1995).

Table 1: Properties of RPC versus Conventional High Performance Concrete (NP Lee, 2005)

Property	HPC	RPC
Compressive Strength (Psi)	8700-14500	26100-29000
Flexure Strength (Psi)	870-1450	5800-7250
Fracture Energy (J/m^2)	140	1200-40,000

RPC is reported to be more appropriate in special pre-cast and pre-stress members owing to its high mechanical performance. Superior strengths of RPC usually reduce the self-weight of RPC members almost to one third of its corresponding Ng, Ka Man, (2009). The lightweight properties can also be exploited to the maximum advantage for seismically sensitive areas, giving greater durability and functional performance. Due to the high flexure strength and ductility, handsome reduction in re-bars is feasible; this may decreases the material cost as well as the labor cost. RPC members may also end up with reduced thickness, due to the high load carrying capabilities of RPC (Aïtcin PC (2003).

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Due to the novelty of Reactive Powder Concrete (RPC), proper guidelines for mix design have not been developed so far. Therefore a study was desired to be conducted to get an idea for an optimized mix design. The experimental program proceeded as follows;

1. Experimental Program:

Experimentation was performed in Structural Laboratory at University of Engineering and Technology, Peshawar. In this regard, 54 cube samples were casted and tested in compliance with ASTM standards to investigate the compressive strength of RPC.

2.1 Constituent Materials:

The constituent materials incorporated in the production of RPC mixes were different from those used in conventional concrete mixes as shown in figure 1. Unlike the normal river sand, quartz sand with particle size in the range of general sand size, accompanied with the ultra-fine particles of quartz were used as inert aggregates. Highly reactive silica fume was used to enhance the cementitious behavior. For achieving the desired workability, at a reduced w-c ratio, high quality super plasticizers were also used.

2.11 Ordinary Portland Cement:

Locally available Portland Cement manufactured by Kohat Cement Company, Pakistan was procured. Standard of Cement was verified in compliance with ASTM C150. In order to investigate the efficiency of cement used in the current study, the fineness was calculated conforming to ASTM C184. Tests results showed that the fineness modulus was 7% which is in the range of allowable limits (0-10%). The summary is shown in table 2.

Table 2: Properties of OPC used in RPC

S. No.	Property	ASTM C150 limits	Kohat Cement
1	Fineness	<10	7
2	Soundness (mm)	<10	2
3	Loss on ignition (LOI) %	3 (Max)	2.0
4	Sulphuric Anhydride (SO_3)	3.5 (Max)	2.8
5	Insoluble residue (I.R) %	0.75 (Max)	0.3
6	Magnesium Oxide (MgO) %	6 (Max)	1.4

2.12 Silica Fume:

During the course of the experimental program two types of silica fume were used.

Sikament: Sikament was the densified, dark color silica fume with a fineness modulus of 2.07. This silica fume was provided by Sika Pakistan Private Limited.

Expan silica: Expan Silica was the undensified silica fume, light grey in color provided by FosPak Private Limited Pakistan. The silica fume with smaller particle size and low density was used to provide higher reactivity.

2.13 Quartz Sand:

The quartz sand acquired from Jihangira, Nowshehra Pakistan was white high purity silica sand crystalline in nature. The particle size distribution was checked according to ASTM C 136 and found in the range of 450-600 microns.

2.14 Quartz Powder:

The aforementioned quartz sand was crushed down to a size of 41 microns in the "Mineral Testing Laboratory, Industrial State Peshawar". The fine powder was used as fine aggregates in the mix.

2.15 Super-plasticizer:

The very low water-binder ratio obtained in RPC can only be made possible through the use of superplasticizers to achieve the required workability. In this research, two types of super plasticizers, Expanplast SP333 and Glenium51 provided by FOSPAK Private Limited and BASF Pakistan respectively were used.

Figure:1(a)Ordinary Portland Cement (b) and (c) Typical Silica Fume materials.

(d)Typical quartz sand (e)Quartz Powder (f) Expanplast SP333 (g) Glenium 51

1.2 Mixing Sequence:

An important factor for studying new cementitious materials is the mixing procedure (Geiker et al., 2007). This influence is often neglected and might be a source of error when analyzing experimental results. Since RPC is composed of very fine materials, the conventional mixing method is not appropriate and mixing method cannot be the same. The following sequence in mixing RPC is based on some previous studies (Bonneau et al., 1997; Feylessoufi et al., 2001; Morin et al., 2002; Chan and Chu, 2004; Lee and Chisholm, 2005; Shaheen and Shrive, 2006), as well as trial-and-error approaches:

1. Dry mixing powders (including cement, quartz sand, crushed quartz and silicafume) for about 3 minutes with a low speed of about 140 rpm (1 minute at a constant speed of 1800 rpm if the high speed mixer is used).
2. Addition of half volume of water containing half amount of superplasticizers.
3. Mixing for about 3 minutes with a high speed of about 285 rpm (applicable to both types of mixers).
4. Addition of the remaining water and superplasticizers.
5. Mixing for about 10 minutes with a high speed of about 285 rpm (8 minutes at a constant speed of 1800 rpm if the high speed mixer is used).
6. The whole mixing process takes about 12 to 16 minutes.

2.3 Mix design:

A number of mixing proportions from the current literature were taken under consideration and playing around with these mix proportions and curing regimes, numerous mix proportions were established. With this in view, the aim was to verify and if promising, optimize the previous mix designs grounded on locally available ingredients. Table 3 presents the detail of mix proportions investigated in this study.

These Mix Proportion quantities i.e. cement, silica fume, quartz powder and quartz sand were taken from the previous literature and the super plasticizer was added as according to its dosage (1.5 to 3.0 L/kg). These Mix Proportions were made by hand mixing in UET Peshawar concrete lab.

* Liters added per 100 kg of the cementitious materials.

SP: Super Plasticizer

CC1: Curing condition 1, Immersed in water at 25oC for 28 days.

CC2: Curing condition 2 Immerse in water at 90oC for 3days and then Immersed in water at 25oC for rest of the 28 days

Table 3: Various Mix designs and curing regimes of RPC

Sample Name	Cement (lb/ft^3)	Silica Fume (lb/ft^3)	Quartz Sand (lb/ft^3)	Quartz Powder (lb/ft^3)	Super Plasticizer (L/100kg*)	w/c	w/c+s	Curing Regime
A1	44	14	63	13	2.5	0.	0.	CC
A2	44	14	63	13	2.5	0.	0.	CC
A3	44	14	63	13	3	0.	0.	CC
A4	44	14	63	13	3	0.	0.	CC
A5	54	12	58	13	3	0.	0.	CC
A6	54	12	58	13	3	0.	0.	CC
A7	54	12	58	…	3	0.	0.	CC
A8	54	12	58	…	3	0.	0.	CC
A9	45	11.	55	16	1.6	0.	0.	CC
A1	45	11.	55	16	1.6	0.	0.	CC
A1	45	11.	55	16	2	0.	0.	CC
A1	45	11.	55	16	2	0.	0.	CC
A1	45	11.	55	16	3	0.	0.	CC
A1	45	11.	55	16	3	0.	0.	CC
A1	45	11.	55	16	2.5	0.	0.	CC
A1	45	11.	55	16	2.5	0.	0.	CC
A1	45	11.	55	16	2.5	0.	0.	CC
A1	45	11.	55	16	2.5	0.	0.	CC

2.4 Preparation of the specimens:

When RPC mixes were ready, it was poured into the required molds which were sprayed with mold oil to reduce the friction at the interface between the molds and RPC mix. The molds were 3x3x3in cubes as shown in figure 2, six cubes for each mix proportion. To ensure adequate compaction all samples were compacted with hand tamping using a tamping rod. The specimens were demolded at least for 24 hours after casting because of the high SP dosage which required longer setting time.

After finalizing the Mix Proportion, various specimens were casted according to standard procedures. For each mix, there were six types of specimen casted, three of them were to be cured at normal temperature and the rest at elevated temperature.

Figure 2: Wooden Molds prepared for casting RPC cubes specimens

2.5 Curing of the specimens:

After casting the concrete in cubes, the specimens were left in molds. After 24 hours the cubes specimens were removed from molds and placed for curing in a container containing clean water as shown in figure 3. Water in the container was replaced after regular intervals in order to provide fresh and clean water for curing.

Figure 3: (a) normal water curing

Due to the unavilabilty of the proper hot water curing faciliy, small trays of sizes 7×4×12 inches, were locally made each was able to carry 6 cubes only (figure 3 (b)). As presented in the figure 4 the laboratory oven was used for exposing the given specimen to hot water curing. The temperature of the oven was kept at 90°C. Two curing methods, listed below, were adopted throughout the pilot mixing program.

CC1: Curing condition 1, Immersed in water at 20oC for 28 days

CC2: Curing condition 2, Immerse in water at 90oC for 6 days and then immersed in water at 20oC for rest of the 28 days.

Figure 3: (a) normal water curing (b) steel containers for hot water curing in the oven

Figure 4: hot water curing

2. Scheme of Testing of Specimens:

Compressive strength determination is the most common factor to predict the performance of concrete as it performs stronger under compression as compared to tension. Due to this importance of compressive strength of concrete, certain other parameters are also related to the compressive strength. For this reason the main objective in the first place was to examine variations in the characteristic compressive strength results, and to get a better understanding of the processes involved in manufacturing and production of non-fibered Reactive Powder Concrete.

3.1 Compressive Strength:

Cubes were removed from respective curing environments two hours before testing. The 28-day compressive strength of each mix design was determined in accordance with ASTM C109. The tests were performed using the universal testing machine of the UET structure lab (Peshawar) as shown in figure 5. Average of the trial results of three samples belonging to a mix were accepted as the 28-day compressive strength of that mix.

Figure 5: Compressive strength testing using UTM

Compressive strength fc' is determined as the maximum load (failure load) of the specimen that can withstand over the contact load area. It is expressed in Eqn. 1 and is illustrated in Figure 6.

$f_{c'}$ = Failure Load/Area (tons/in^2) Eqn. 1

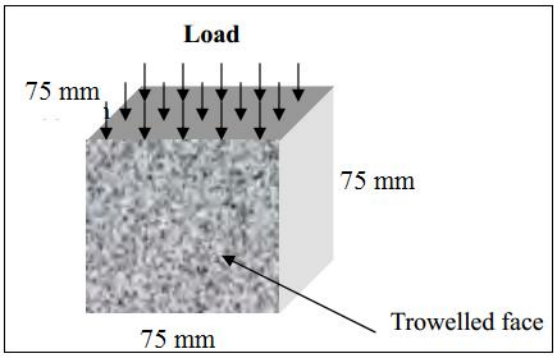

Figure 6: Force applied on the 75 mm (3in) cube

3. Results

Table 4 presents the compressive strength results, came out from testing 54 cube samples, cured at two different curing regimes and tested after 28 days curing. The details of curing regimes and results are listed.

Figure 7 shows the effect of different curing regimes. Mix proportions are presented in pairs, with one mix proportion cured with normal water and the other with hot water. Hot water had a temperature of 90 degree Celsius.

Table 4: Compressive strength results at various mix designs of RPC

Sample Na	Cement (lb/	Silica Fume	Quartz Sa	Quartz Powd	Super Plasticize	w/c	Curing Regi	fc' (psi)
A1	44	14	63	13	2.5	0.	CC	12
A2	44	14	63	13	2.5	0.	CC	14
A3	44	14	63	13	3	0.	CC	11
A4	44	14	63	13	3	0.	CC	13
A5	54	12	58	13	3	0.	CC	11
A6	54	12	58	13	3	0.	CC	14
A7	54	12	58	…	3	0.	CC	12
A8	54	12	58	…	3	0.	CC	14
A9	45	11.	55	16	1.6	0.	CC	12
A1	45	11.	55	16	1.6	0.	CC	14
A1	45	11.	55	16	2	0.	CC	11
A1	45	11.	55	16	2	0.	CC	13
A1	45	11.	55	16	3	0.	CC	12
A1	45	11.	55	16	3	0.	CC	13
A1	45	11.	55	16	2.5	0.	CC	11
A1	45	11.	55	16	2.5	0.	CC	12
A1	45	11.	55	16	2.5	0.	CC	11
A1	45	11.	55	16	2.5	0.	CC	13

* Liters added per 100 kg of the cementitious materials.

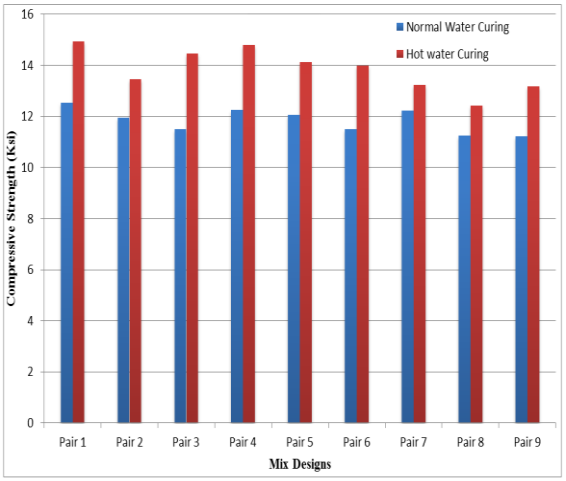

Figure 7 : Effect of curing temperature on the compressive strength of RPC

5. Discussion:

The compressive strengths of several RPCs made with different matrices, different constituents and curing regimes were measured and given in table 3. As clear from the table, it was observed that the matrix A1 and A2 exhibited the highest compressive strength among these matrices. The highest values of upto 15000 Psi for A2 was recorded. Samples A1 and A2 both had exactly the same mix design following Olivier Bonneau et al (2000), except for the curing regimes, as visible in the table. However keeping temperature effect a side this instance, the discussion

is under the general comparison of the compressive strength of RPC.

The highest value of A1 is primarily due to the increased amount of silica fume which enhances the secondary reaction of silca fume with excessive calcium hydroxide that arrived previously after silica gel interacted with water. This is explained by (Wildet al., 1995) as the range of the strength development is governed by the chemical composition of the pozzolan; the larger the composition of alumina and silica, the better is the pozzolanic reaction and strength development. Hence, it can be explained that the high content of silica fume is responsible for the continuous strength development of these RPCs and as quartz sand and quartz powder are used in the manufacturing, so these products being the main form of pure silica in nature thus leading to a continuous pozzolanic reaction at the later stage. Similar results on ordinary concrete having silica fume were set up by Wild et al. (1995). They stated that for concrete containing high silica fume content, the inhibiting layer of reaction product around the fume particles was not completely developed and thus continued reaction of silicates and lime to form extra C-S-H gel will result in further strength improvement. In addition, silica fume particles fill micro- and sub micro level pores in paste and limit the particle size of hydrates that is known as a space filling effect**.**

The enhancement of uniformity of Reactive Powder Concrete by the elimination of coarse aggregates also plays a key role (Richard and Cheyrezy, 1995). This also assures the high packing density of solid particles of the mix as the packing density of the binder particles significantly improves the performance of a concrete mix mentioned by Wong and Kwan's study (2005). Since there are no coarse aggregate in RPC, therefore the bulk of the particles of the paste has a reduced content of the voids in it, hence low amount of water is required for filling up the voids among these particles, as a result the ultimate strength of Reactive Powder Concrete is always high.

6. Conclusions:

During the course of this study, a number of mix proportions were followed and were cured at different curing conditions. With low quality super plasticizer it was difficult to achieve the required workability at low water-binder ratio. The maximum strength achieved was about 15000psi. The relative high strength is attributed to the high content of silica fume. The lowest compressive strength achieved was about 11000 Psi. The compressive strength values lied far below those claimed by many of the researchers i.e 50MPa to 200 MPa (7000-29000 Psi). The reason may be the higher water-binder ratio. Hot water treatment played its role in each mix proportion. For exactly the same mix proportion, the specimens cured with hot water showed a considerable increase in the compressive strengths. The compressive strength can further be improved by choosing advanced generation superplasticizers and thus reducing the water-binder ratio.

Acknowledgement:

A profound gratitude to Mr. Aman for a relentless support in providing the required material through FOSPAK and for practical suggestions in using the chemicals efficiently. I also want to pay thanks to the UET structure lab staff for providing full cooperation and expertise beyond their duties during conducting the lab tests. Thanks to the project review and evaluation committee at Civil Engineering Department UET Peshawar, for their valuable contribution towards the achievement of the research goals.

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