Mechanical properties of reactive powder concrete under distinct curing environment

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Abstract. Reactive Powder Concrete (RPC) is composed of fine powders (cement, sand, quartz powder and silica fume), steel fibres (optional) and superplasticizer. This gives good compaction and an impenetrable matrix is achieved, and this strong concentration gives RPC, an ultra-high strength and durability properties. In this research work, focus was aimed to produce reactive powder concrete (RPC) composite material with compression strength up to 100 N/mm². Components for RPC mixture are carefully selected to achieve optimal mixture. Detailed concrete mix proportions are given in this research paper. Preparation and testing of material were produced in laboratory belonging to the Department of Civil Engineering in SRM Institute of Science and Technology. Casting of concrete cubes and beams was done for both M60 and M100 grades of concrete. This paper investigates mechanical and fresh concrete properties of reactive powder concrete for both the design mix. Laboratory investigations like; Compressive test, split tensile test and flexural strength were conducted to evaluate strength characteristics of RPC, under different curing conditions like oven, steam, and hot water with respect to time factor of T1 (60 min), T2 (61-90 min) and T3 (91-120 min). In every aspect of testing, the steam curing at 100°C shows improved results of 15.71-17.40% in compressive strength, 24.66-25.93% in tensile strength and 20% in flexural strength for both grades of concrete.

1. Introduction
Concrete is an extensively used building material that governs the building engineering all over the world. In the last two decades, the development in the concrete industry resulted in numerous types of concrete with significant results for the reactive powder concrete. The application of reactive powder concrete (RPC) extensively used for military establishment and other tough applications like blast proofing, etc. In 1990s, RPC was formed by the addition of ancillary material, eradication of coarse aggregates, exceptionally low water/binder ratio, with calculated amount of superplasticizer, and if required, fine steel fibre reinforcement is also added for further reinforcement. Literature studies states that the ingredients may be set to experience heat curing and application of pressure before and during setting of concrete. RPC is an ultra-high-performance concrete (UHPC) capable of reaching compressive strength more than 200MPa and corresponding flexural strength more than 40MPa, as stated by its makers Richard and Cheyrezy [1-6]. There is an expanding use of RPC due to the remarkable mechanical properties and robustness.
Ultra-high performance is especially valuable attribute of RPC. The markets in which high-performance concrete products will be challenging are where resilience characteristic leads: any concrete composition discussed briefly.

The primary tests of materials such as cement, river sand, silica fume, quartz powder as well as chemical admixture (superplasticizer) are discussed in this section. Insights into research methodology were also released. The use of RPC allows not only improved mechanical performance of the structural elements, but it also guarantees a substantially prolonged service life due to its fundamental material properties.

Furthermore, in the creation of RPC, a partial replacement of cement by silica fume (which is a waste by-product of silicon alloy) results in less cement utilization and therefore less greenhouse gas gain. Moreover, in the creation of RPC, a partial replacement of cement by silica fume (which is a waste by-product of silicon alloy) results in less cement utilization and therefore less greenhouse gas gain. Additionally, the lower maintenance obligations effect in significant economic gain.

2. Materials and Methods

Ultra-high performance is especially valuable attribute of RPC. The markets in which high-performance concrete products will be challenging are where resilience characteristic leads: any concrete composition that will have to deal with harsh environmental situations will be made with a high-performance concrete to enhance its working life. In addition, the lower maintenance obligations effect in significant economic gain. Furthermore, in the creation of RPC, a partial replacement of cement by silica fume (which is a waste by-product of silicon alloy) results in less cement utilization and therefore less greenhouse gas release. The use of RPC allows not only improved mechanical performance of the structural elements, but it also guarantees a substantially prolonged service life due to its fundamental material properties. The primary tests of materials such as cement, river sand, silica fume, quartz powder as well as chemical admixture (superplasticizer) are discussed in this section. Insights into research methodology were also discussed briefly.

| MATERIALS | CEMENT | RIVER SAND | SILICA FUME | QUARTZ POWDER |
|-----------|--------|------------|-------------|---------------|
| Chemical composition [%] | | | | |
| Silica (SiO₂) | - | 20.79 | 51.00 | 99.5% | 99.886% |
| Alumina (Al₂O₃) | - | 4.71 | 6.83 | 0.08% | 0.043% |
| Titanium oxide (TiO₂) | - | 2.21 | 0.58 | 0.04% | 0.001% |
| Calcium oxide (CaO) | - | 60.20 | 0.48 | 0.01% | 0.001% |
| Magnesium oxide (MgO) | - | 2.74 | - | 0.01% | 0.000% |
| Sodium oxide (Na₂O) | - | 0.23 | - | 1.23 | 0.003% |
| SO₃ | - | 2.71 | - | 0.64 | - |
| Mineral composition [%] | | | | |
| C₃S | 55.4 | - | - | - |
| C₂S | 19.7 | - | - | - |
| C₃A | 6.6 | - | - | - |
| C₄AF | 9.3 | - | - | - |
| Physical and Mechanical properties | | | | |
| Specific gravity | 3.15 | 2.65 | 2.3 | 2.72 |
| Density g/cm³ | 3.13 | - | - | 2.63 |
| Initial setting time [min] | 140 | - | - | - |
| Final setting time [min] | 250 | - | - | - |
2.1. Materials and mix proportions
In this research study, the properties of various materials used to constitute RPC was tested and based on those outcomes, the experiments were conducted. Ordinary Portland Cement (OPC) of grade-53 is utilized throughout the work whose specific gravity was found to be 3.15. Fine aggregate was acquired from nearby obtainable river sand which passed through 4.75 mm sieve. In the reactive powder concrete sand plays the foremost role. Because of its high particle size its function is adds more strength to the concrete mix. Silica fume, which is a by-product of silicon metal or ferrosilicon alloys was also utilized in the production of RPC. Because of its finer particles, large surface area, and the high SiO₂ content, high strength and durability be able to be attained in concrete. Silica fume in concrete does not bleed and is more vulnerable in plastic shrinkage cracking. Segregation is also reduced since concrete mix is more cohesive. Another main element quartz powder is the very well used mineral admixture in high strength concrete. Combining it to the concrete mix will significantly boost the workability, strength & impermeability of concrete mixes whilst producing the concrete resilient to chemical strikes, abrasion & reinforcement oxidization, and increasing the comprehensive strength. Quartz powder is a very reflective and effective pozzolanic material due to its fine particle size and high purity of SiO₂ content. The main function of quartz powder is to give highest endurance to the concrete against heat. The properties of different materials employed in this research is tabulated in the table 1.

3. Testing and results
The RPC design mix is obtained from various trial mix based on previous literature studies and conducted experiments on M60 and M100 grade of concrete. Higher properties such as higher compressive and split tensile strength were achieved with the use of finer particle such as silica fume and quartz. Testing of hardened concrete is performed to ascertain the compressive strength for cube specimen, split tensile strength for cylindrical specimen and flexural strength test for beam specimen for 7 day, 14 days, 28 days of RPC grade M60 and M100. Their results are discussed in this paper with respect to time factor from the mixing minutes.

3.1. Compressive strength
Compression test is done to find the characteristic strength of concrete specimen and it depends on cement strength, water cement ratio, worth of concrete mix. The cube specimen of size 70.6 mm × 70.6 mm is casted and tested for 7 day, 14 days, 28 days under varied curing environments, such as normal water curing (room temperature), oven curing, steam curing and hot water curing. The cubes casted at time T1 are shown in figure 1. The graphical representations of compressive strength of M60 and M100 concrete are illustrated in figure 2 (a) and (b), correspondingly.
The cubes casted are varied by means of delayed time where T1 indicates casting time not greater than 60 minutes, T2 indicates 61-90 minutes, T3 indicates 91-120 minutes. This variation in time for casting cubes were indicated in figure 2 (a) and (b) for compressive strengths of M60 and M100 grades of RPC, respectively.

![RPC grade M60](image)

**Figure 2. (a) Compressive strength of M60 grade RPC**

![RPC grade M100](image)

**Figure 2. (b) Compressive strength of M100 grade RPC**
It is observed that the RPC grades irrespective of curing, at T1 timing has achieved higher strength than the delayed ones.

3.2. Split tensile strength
Split tensile potency analysis is performed for cylindrical specimen of size 100 mm × 50 mm are casted and tested for 7 days, 14 days, 28 days under varied curing environments, such as normal water curing (room temperature), oven curing, steam curing and hot water curing. The tested cylindrical specimen is displayed in figure 3. The graphical representations of tensile strength of M60 and M100 concrete are illustrated in figure 4 (a) and (b), respectively.

![Figure 3. Testing of cylinder specimen](image)

The cylinders casted are also varied by means of delayed time where T1 indicates casting time not greater than 60 minutes, T2 indicates 60-90 minutes, T3 indicates 90-120 minutes. This variation in time for casting were indicated in figure 4 (a) and (b) for tensile strengths of M60 and M100 grades of RPC, respectively.

![Figure 4. (a) Split tensile strength of M60 grade RPC](image)
Figure 4. (b) Split tensile strength of M100 grade RPC

3.3. Flexural strength
The flexure strength of beam specimen of size whose width and depth are 40 mm and length 160 mm are tested for 14 days in addition to 28 days under varied curing environments, such as normal water curing (room temperature), oven curing, steam curing and hot water curing. Figure 5 shows the flexural testing of beams at SRMIST Strength of Materials laboratory. The graphical description of flexural strength of M60 as well as M100 concrete are shown in figure 6.

Figure 5. Flexural strength of M60 and M100 grade RPC
4. Inference
The mechanical properties for instance, compression, tension and flexure of the cube, cylinder and beam specimen are mainly concentrated. The specimens were cured at varied curing environments for 7, 14 and 28 days, with respect to time of casting from the mixing of ingredients to produce RPC compound. A sample of mixing method involved in preparation of RPC is indicated in figure 7.

**Figure 6.** Flexural strength of M60 and M100 grade RPC

**Figure 7.** Formulation of RPC
The specimens casted within 60 minutes (T1) of mixing all the necessary ingredients of RPC yields good results in all the curing methods.

4.1 M60 grade RPC results
With respect to normal curing, considering the time T1, the RPC of grade M60 has attained a compressive strength of 50 MPa, 59 MPa and 70 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 46 MPa, 55 MPa and 67 MPa in 7, 14 and 28 days, correspondingly. For time T3, it has attained a compressive strength of 44 MPa, 51 MPa and 65 MPa in 7, 14 and 28 days, correspondingly.

With respect to oven curing at 90°C, considering the time T1, the RPC of grade M60 has attained a compressive strength of 62 MPa, 67 MPa and 78 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 59 MPa, 63 MPa and 73 MPa in 7, 14 and 28 days, correspondingly. For time T3, it has attained a compressive strength of 56 MPa, 61 MPa and 70 MPa in 7, 14 and 28 days, correspondingly.

With respect to steam curing at 100°C, considering the time T1, the RPC of grade M60 has attained a compressive strength of 62 MPa, 78 MPa and 81 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 59 MPa, 71 MPa and 74 MPa in 7, 14 and 28 days, correspondingly. For time T3, it has attained a compressive strength of 56 MPa, 69 MPa and 71 MPa in 7, 14 and 28 days, correspondingly.

The tensile strength of specimens of RPC grade M60, under normal curing has attained 7.3 MPa, 7 MPa and 6.8 MPa in 28 days for the period T1, T2, T3, correspondingly. Under oven curing at 90°C it has attained 8.2 MPa, 7.6 MPa and 7.45 MPa in 28 days for the period T1, T2, T3, correspondingly. Under steam curing at 100°C it has attained 9.1 MPa, 8.6 MPa and 8.3 MPa in 28 days for the period T1, T2, T3, correspondingly. Under hot water curing at 100°C it has attained 8.9 MPa, 8.5 MPa and 8 MPa in 28 days for the period T1, T2, T3, correspondingly.

4.2 M100 grade RPC results
With respect to normal curing, considering the time T1, the RPC of grade M100 has attained a compressive strength of 75 MPa, 87 MPa and 115 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 73 MPa, 85 MPa and 112 MPa in 7, 14 and 28 days, correspondingly. For time T3, it has attained a compressive strength of 72 MPa, 82 MPa and 108 MPa in 7, 14 and 28 days, correspondingly.

With respect to oven curing at 90°C, considering the time T1, the RPC of grade M100 has attained a compressive strength of 85 MPa, 91 MPa and 125 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 81.5 MPa, 88 MPa and 120 MPa in 7, 14 and 28 days, correspondingly. For time T3, it has attained a compressive strength of 81 MPa, 88 MPa and 115 MPa in 7, 14 and 28 days, correspondingly.

With respect to steam curing at 100°C, considering the time T1, the RPC of grade M100 has attained a compressive strength of 92 MPa, 99.5 MPa and 135 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 89 MPa, 97 MPa and 131 MPa in 7, 14 and 28 days,
correspondingly. For time T3, it has attained a compressive strength of 85 MPa, 95 MPa and 126 MPa in 7, 14 and 28 days, correspondingly.

With respect to hot water curing at 100°C, considering the time T1, the RPC of grade M60 has attained a compressive strength of 88 MPa, 96.5 MPa and 132 MPa in 7, 14 and 28 days, correspondingly. For time T2, it has attained a compressive strength of 85 MPa, 95 MPa and 127 MPa in 7, 14 and 28 days, correspondingly. For time T3, it has attained a compressive strength of 84 MPa, 91 MPa and 122 MPa in 7, 14 and 28 days, correspondingly.

The tensile strength of specimens of RPC grade M100, under normal curing has attained 8.1 MPa, 7.6 MPa and 7.4 MPa in 28 days for the period T1, T2, T3, correspondingly. Under oven curing at 90°C it has attained 9.0 MPa, 8.4 MPa and 8.1 MPa in 28 days for the period T1, T2, T3, correspondingly. Under steam curing at 100°C it has attained 10 MPa, 9.2 MPa and 8.7 MPa in 28 days for the period T1, T2, T3, correspondingly. Under hot water curing at 100°C it has attained 9.5 MPa, 8.8 MPa and 8 MPa in 28 days for the period T1, T2, T3, correspondingly.

The flexural strength of specimens of RPC grade M100, under normal curing has attained 25 MPa, 23.5 MPa and 22 MPa in 28 days for the period T1, T2, T3, correspondingly. Under oven curing at 90°C it has attained 28 MPa, 26.2 MPa and 24 MPa in 28 days for the period T1, T2, T3, correspondingly. Under steam curing at 100°C it has attained 30 MPa, 27.5 MPa and 25.5 MPa in 28 days for the period T1, T2, T3, correspondingly. Under hot water curing at 100°C it has attained 28.5 MPa, 26.6 MPa and 25 MPa in 28 days for the period T1, T2, T3, correspondingly.

5. Conclusions
The mechanical properties of RPC grades of M60 and M100 are experimentally verified for different curing conditions with specimens casted under set of batches where T1 refers to casting time not greater than 60 minutes, T2 refers to 60-90 minutes and T3 refers to 90-120 minutes.

- The results of both the grades of concrete in any curing conditions shows higher strength under curing period T1, which is not greater than 60 minutes.
- Considering three time periods, the compressive strength of M60 grade of RPC with oven curing at 90°C gains strength in the range of 7.70 – 11.43%, the range increases to 7.70 – 12.86% under hot water curing at 100°C and the range further increases to 9.23 – 15.71% for steam curing at 100°C.
- Considering three time periods, the compressive strength of M100 grade of RPC with oven curing at 90°C gains strength in the range of 8.04 – 11.30%, the range increases to 12.96 – 14.78% under hot water curing at 100°C and the range further increases to 16.67 – 17.40% for steam curing at 100°C.
- Considering three time periods, the tensile strength of M60 grade of RPC with oven curing at 90°C gains strength in the range of 8.57 – 12.33%, the range increases to 17.65 – 21.92% under hot water curing at 100°C and the range further increases to 22.06 – 24.66% for steam curing at 100°C.
- Considering three time periods, the tensile strength of M100 grade of RPC with oven curing at 90°C gains strength in the range of 10.81 – 13.58%, the range increases to 15.80 – 18.52% under hot water curing at 100°C and the range further increases to 19.0 – 25.93% for steam curing at 100°C.
- Considering three time periods, the flexural strength of M60 grade of RPC with oven curing at 90°C gains strength in the range of 10.81 – 12.50%, the range increases to 13.51 – 17.50% under hot water curing at 100°C and the range further increases to 13.51 – 20.00% for steam curing at 100°C.
- Considering three time periods, the flexural strength of M100 grade of RPC with oven curing at 90°C gains strength in the range of 9.09 – 12.80%, the range increases to 13.64 – 15.20% under hot water curing at 100°C and the range further increases to 15.91 – 20.00% for steam curing at 100°C.
The scope of research on reactive powder concrete is vast and the key lies in the right mix proportion of ingredients with right amount of time. The micro elementary level analysis on tested specimen of different curing methods are under progress of this study.

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