Comparability Study on the Effects of Curing Approaches on the Mechanical Behaviours of Reactive Powder Concrete

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Abstract. Reactive Powder Concrete (RPC) is the most commonly used type, known as Ultra High-Performance Concrete (UHPC). This type of concrete requires very low water/binder ratios to ensure that the microstructure is very dense and impermeable. Thus, it also needs special types of curing to ensure its high strength, high durability, and dimensional stability. The main target of this study is thus a comparison of different curing regimes to investigate their impacts on the mechanical performance of RPC. Three different curing regimes, Normal Curing (NC), Steam Curing (SC), and Boiling Curing (BC) were thus adopted in this study. To assess the mechanical behaviour of RPC, compressive strength, direct tensile strength, and density measures were implemented for the different curing regimes and SC and BC were compared with normal curing at various curing ages. The investigation results revealed that, among the three different curing approaches, the steam curing method most significantly enhanced the mechanical behaviour of the RPC, particularly compressive strength.

1. Introduction

The introduction of very fine materials such as fine powders and silica fume into concrete matrices to develop pozzolanic reactions and particle condensation, combined with the use of super plasticizers to reduce the water to binder (cementitious materials) ratio has driven the development of an innovative range of cement based materials known as reactive powder concrete (RPC) [1]. The fundamentals of reactive powder concrete were introduced in a study by Richard and Cheyeryzi [2]. However, simply put, compared with traditional cement based materials, RPC has multiple advantages [2] [3] [4] [5] [6] [7], including improved homogeneity in particle size and condensation of the microstructure due to the removal of coarse aggregate and use of very fine sand (100 - 600 µm) and a decreased water to binder ratio of less than 0.2, due to the application of superplasticizers, which improves the mechanical behaviours of RPC. Unusually, reducing the cement paste pore volume and improved reactivity because of the insertion of silica fume at high percentage accelerates pozzolanic reaction to create extra calcium silicate hydrate. Properly distributed steel fibres in the cementitious matrix act as rigid constituents to develop improved RPC mechanical performance, principally tensile strength, modulus of elasticity, and ductility. Enhanced microstructure attributable to the acceleration of the hydration of cement is a further
consequence of RPC being subjected pressure to at the fresh stage and different curing regimes (normal, steam curing, and autoclave curing) being employed.

It has become possible to develop RPC by relying on the basic principles of concrete components, their mixing and curing types [2], and tuning curing approach plays a big role in determining the level of quality within the process, which usually requires the concrete to be protected from loss of moisture and kept within a reasonable temperature range [8]. Usually, RPC requires heat curing regimes of 80 °C to 90 °C, with the high temperatures supporting the pozzolanic influence of silica fume; consequently, the mechanical properties become greater and the microstructures denser than in normally cured RPC. A number of investigations have thus been undertaken on the influences of curing regimes on RPC performance.

Tam et al. [9] Studied the mechanical behaviour of reactive powder concrete to determine the optimum conditions for fabricating reactive powder concrete based on the effect of curing regimes on the microstructure and mechanical properties of RPC. The adopted methods of curing were normal water curing at 27 °C, water curing at 60 °C for the first 7 days, and moist chamber curing at 60 °C for the first 7 days. In addition, some heat cured specimens were retained before testing in an oven at 100 and 250 °C for 16 and 48 h. According to the results, RPC cured at 27 °C in water conditions offered the best outcomes in terms of mechanical and microstructure properties, though heat-curing of RPC resulted in a substantial increase in the development rate of compressive strength. Al-Jubory [10] accomplished an investigation assessing the mechanical properties of RPC on application of local materials cured normally at 20 °C and in steam at 80°C. The results showed that heat curing at 80 °C increased the rate of development of mechanical properties when compare with the equivalent normal cured specimens, though the normal curing mixes had higher ensuing properties. Halit et al. [5] Applying the curing regimes involved one day at room temperature in a 95% moisture chamber followed by two days of steam curing at 90°C or autoclave curing. Both steam curing and autoclave curing enhanced the compressive strength of RPC samples compared with normal curing. The percentage increase for steam curing methods were between 25 and 63%, and the percentage increase for autoclaving ranged from 9% to 61%. Likewise, Loukili et al. [11] utilized collective curing systems to improve RPC properties. Two curing systems were adopted, normal curing and hot water curing at 90 °C, for periods of 5 days and 3 days, respectively. The outcomes showed that the combined curing was effective in improving the mechanical properties of RCP. Mujamil et al. [12] investigated the mechanical strength properties of RPC cured with accelerated boiled water curing and normal curing. The composition of the RPC included cement, quartz sand, and quartz powder with different proportions of silica fume varying from 0% up to 50% as a partial replacement for cement. The accelerated programme involved boiling the specimens at 100°C for 3.5 hours and then immersing them in water for 28 days. The results showed that the accelerated boiled water curing developed less compressive strength but greater flexural strength as compared with normal curing, due to accelerated hydration process and non-uniform structure.

The main aim of the current experimental research was to assess the effect of different curing approaches on RPC, as well as the effects of different time periods of boiling curing. This objective was attained by testing the mechanical strength and density of specimens attained by applying three different curing regimes, Normal Curing (NC), Steam Curing (SC), and Boiling Curing (BC).

2. Experimental Program

In this study, three methods were adopted for inspection for curing results as a basis for upgrading the quality of RPC. The relevant components and experimental procedures are discussed in this section.

2.1 Materials

2.1.1 Cementitious materials

In this research the cement used was Type V sulphate resisting Portland cement, commercially known as Al-Jisr, from the Karbala cement factory. This cement conformed to ASTM C-150 [13] in terms of physical and chemical properties. A silica fume as a supplementary cementitious mix used to fabricate high-performance concrete [14] was used under the trade name of CONMIX-Mega-Add MS, which has
an accelerated activity index at 7 days of about 135 %. The chemical composition and physical requirements of the silica fume conformed to ASTM C-1240 specifications [15].

Fine Sand
Al-Ukhaider natural zone (4) sand from Karbala, with maximum particle size 600 µm was used, in “saturated surface dry” (SSD) condition. The particles size distribution for fine aggregate met the requirements of ASTM C-33 [16].

2.1.2 Chemical Admixture
In this investigation, a commercially existing high range water-reducing admixture with the trademark BASF Glenium 51 was utilised to maintain the preferred workability. The admixture conformed to the requirements of type F in ASTM C-494 [17].

2.1.3 Steel Fibres
In this research, corrugated steel fibres were used in the experimental work at 2%. The aspect ratio of these was about 22 and the steel fibre diameter was 0.79 mm, with density being 7,825 kg/m$^3$ and tensile strength 1,150 MPa; these appears as shown in figure 1.

![Corrugated steel fibres](image)

**Figure 1** Corrugated steel fibres

2.1.4 Mix proportions
Essentially, RPC is composed of cementitious material (cement and silica fume), with the addition of natural sand finer than 600 µm particle size, and a low water to binder ratio. Usually, RPC is comprised of Portland cement ranging from 700 to 1000 kg/m$^3$. The silica fume is added by cement weight in proportions from 15 to 35%, and the water/binder ratio is held lower than 0.2 [14]. The proportions for all mixes in this research were based on the trial mix, which was itself based on previous local research [18][19][20][21], to attain the required properties. Table (1) illustrates the mixture proportions of the RPC experimental mix.

2.2 Experimental work
The procedure of mixing was carried out in such a manner as to ensure that the reactive powder concrete’s ingredients affected both its fresh properties and hardened properties. The mixing procedure was thus adapted from a previous study [22]. According to ASTM C-109 [23] and ASTM C-138 [24], compressive strength and density tests of RPC were applied. A 50 x50 x50 mm mould was adopted for casting the samples, with three samples for each test age (7 days, 14 days, and 28 days). Three samples (brquettes) for the direct tensile strength testing of RPC were also cast, and tested in agreement with ASTM C-190 [25] for each test age (7 days, 14 days, and 28 days), as seen in Figure 2. After that, all samples were left at room temperature with 90% humidity for 24 hours and then de-moulded for the specified curing regimes to be applied. There is often a significant effect of curing noted on the properties of RPC; thus, three curing procedures were adopted. Normal curing (NC): the specimens were cured in water at about 20 to 25 °C for 7, 14 and 28 days; Boiling curing (BC): the specimens were cured at about 100 °C for 2 hours. Afterward, they were cooled at room temperature and then placed in water and left for 7 days, 14 days, and 28 days;
Steam curing (SC): the specimens were steam cured at about 90°C at 95% relative humidity for 48 hours in a water bath, after that, they were cooled at room temperature then placed in water and left for 7 days, 14 days, and 28 days.

Table 1: Mixture Proportions, kg/m³

|                | Cement (kg/m³) | Silica fume (kg/m³) | Fine Sand (kg/m³) | W/C | Super Plasticizer % | Steel fibre (%) |
|----------------|----------------|---------------------|-------------------|-----|---------------------|-----------------|
| 900            | 290            | 977                 | 0.22              | 2.5 | 2                   |

Figure 2. Tensile strength measurement device.

3. Results and discussion

Table 2 demonstrates the outcomes of the influence of different curing regimes on the behaviours of RPC at different ages.

Table 2. The behaviours of RPC.

| Curing regime | Compressive strength (MPa) | Direct tension (MPa) | Density (Kg/m³) |
|---------------|----------------------------|---------------------|-----------------|
|               | 7 days  | 14 days | 28 days | 7 days  | 14 days | 28 days | 7 days  | 14 days | 28 days |
| NC            | 54      | 69      | 90      | 7.2     | 8.4     | 9.1     | 2329    | 2378    | 2425    |
| BC            | 69      | 81      | 105     | 8.1     | 9.2     | 10.7    | 2367    | 2435    | 2490    |
| SC            | 89      | 110     | 128     | 9.6     | 11.3    | 12.6    | 2464    | 2487    | 2531    |
3.1 Compressive strength

The test results are shown in Table 2. The results clearly demonstrate that there is a significant increase in compressive strength for curing regimes BC and SC as compared to NC for each age. The percentage increases at 7 days for BC and SC compared to NC were 27.8%, and 64.8%, respectively. The percentage increases at 14 days for BC and SC compared to NC were 17.3% and 59.4%, respectively. The percentage increases at 28 days for BC and SC compared to NC were 16.6% and 42.2% respectively. After 7 days of BC and SC, the compressive strengths were 69 MPa and 89 MPa, almost 76.6% and 98.9% of the 28 day NC results, respectively. This strength enhancement is due to prompt cement hydration and Pozzolanic reactions at high temperatures over 90°C. The boiling curing and steam curing play vital roles in terms of invigorating the silica fume as a cementitious material, preventing it from only acting as a filler instead of as a binder [26]. When these curing regimes were used, the compressive strength increased over time, but at a rate lower than that seen in normal curing. The compressive strength outcomes, as displayed in Figure 3, show that the SC is the superlative curing regime, with 48 hours of steam curing being sufficient to obtain a 7-day compressive strength approximately equal to the 28-day compressive strength of normal curing. On other hand, this dramatically rise of compressive strength is associated with a decrease in strength gain over longer durations.

The binder's chemical reactions also develop in a co-dependent way, leading to the formation of solid structures and re-arrangement of hydration products, which affect strength development. The curing regime is strongly affected by the hydration progress and strength gain can be attributed to kinetic and thermodynamic effects. Kinetic effects, that is, high temperatures associated with curing regimes leading to hydration activation and strength evolution, and vice versa are in opposition to thermodynamic effects, such as hydrate re-arrangement and strength decreases in the long-term under higher curing temperatures [27]. Normal curing offers sufficient time to produce uniformly distributed hydration products throughout the cementitious matrix, while high temperatures curing leads to build ups of high concentrations of hydration products around the hydrating grains that retard subsequent hydration and cause non-uniform distribution of hydration products within the microstructure of cementitious matrices [28].

![Figure 3. Effects of curing regimes on compressive strength with age.](image_url)
3.2 Direct tensile strength

In design terms, the tensile strength properties of concrete are often ignored due to the material’s inherently brittle nature. The stress–strain characteristics of plain RPC are nearly linearly elastic to failure, so that steel fibre additions improve the first-crack load. These small fibres crossing potential cracks offer good bonds with matrices to provide high fibre pull-out resistance, greatly increasing the toughness of the concrete [29]. Table 2 indicate the type and period of curing applied. Note that each set of results listed is the average for three test briquettes. Table 2 and Figure 4 indicate that hot curing regimes (boiling or steam curing) offer substantial increases over normal curing in terms of direct tensile strength for all test ages (7 days, 14 days, and 28 days). The percentage increases were 12.5% and 33.3% at 7 days with boiling curing and steam curing respectively, 9.5% and 34.5% at 14 days with boiling curing and steam curing respectively, and at age of 28 days, 17.6% and 38.4% for boiling curing and steam curing respectively. The results showed that the steam curing system permits significant development of direct tension strength, far more than boiling and normal curing, in agreement with [8], [9] and [30].

Figure 4. Direct tensile strength for all curing regimes.

3.3 Hardened Density

The hardened densities of RPC as obtained from the measurement of three cubes of 50 mm side per result are presented in Table 2. The range is from 2,329 to 2,531 kg/m³, consistent with previous studies [2] [31] and [32]. These results elucidated that the different curing regimes for 7 days, 14 days, and 28 days have a minor intensifying effects on the microstructure of RPC. The percentage increases for BC and SC at 7 days compared with NC were 1.6% and 5.8%, respectively. The percentage increases for BC and SC at 14 days compared with NC were 2.4% and 4.6%, respectively. The percentage increases for BC and SC at 28 days compared with NC were 2.7% and 4.4% respectively. These figures suggest, as seen in Figure 5, that the density increased under the effect of both curing regimes, but that steam curing is the most effective method of curing at all ages. It was observed that the rate of increase of density at early ages was greater than that at later ages, due to accelerated reaction of hydration which gives rise to more rapid products in the microstructure of the RPC matrix, intensifying density [7] [9] and [14].
4. Conclusion

Based on the outcomes of this experimental investigation, several conclusions emerged, as shown below:

1- Using steam curing has a more significant effect than using the other curing systems on mechanical properties
2- When steam curing regimes are used, the compressive strength increases with time; however, the increase rate is lower than in normal curing.
3- The rate of increase of direct tension strength was higher at the earlier age (7 days) than the latter ages.
4- The results show an increase in density of RPC at early ages over later ages; in addition, using steam curing methods offers higher values than other curing regimes.

5. References

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