The effects of using magnetized water in reactive powder concrete with different curing methods

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Abstract. The effects of using magnetized water in reactive powder concrete (RPC) under various curing procedures was investigated. The RPC samples were separated into four groups, cured with three different curing methods compared to normal curing (lab conditions) as a reference procedure, these methods were; autogenous curing, submersion in warm water (35 °C) and curing by applying high temperature (70 °C) cycles. A magnetic water device was used to produce magnetic water for use in the RPC mix. Where, the intended water was moving with flow rate equal to 0.1 m³/hr. passing through a magnetic field with an intensity of 0.9 Tesla. This circulation process was used for 60 minutes to produce the magnetized water utilised in this study. Test results showed some improvements in the compressive, flexural and splitting tensile strength for RPCs cured with different curing methods. The percentage increases for compressive strength for RPC mixes containing magnetic water. Where, the enhancing percentage reached 7.66, 8.43, 8.86, and 9.15% for normal curing, autogenous curing, warm-water, and high temperature curing respectively at 28 days. The high temperature curing method showed the maximum improvement in compressive strength, with up to 34.4, 30.6, and 28.52% increases at 7, 28, and 90 days, respectively.

Keywords: reactive powder concrete, magnetic water, magnetised water, RPC improvement, curing technics.

1. Introduction

Reactive powder concrete (RPC) is a new type of concrete which offers high strength and good durability. The application of magnetized water (MW) is one of the newest methods for improving concrete properties, and a 20% increase in compressive strength can be achieved by using this technology. In order to increase the mechanical properties of RPC further, the effect of different curing procedures was considered in this study, with comparisons made to traditional water immersion curing. When normal water (NW) passes through a magnetic field, its ions are affected and its physicochemical properties changed, and it becomes magnetic field treated water (MFTW) or magnetized water (MW). The device that induces MW is called a magnetic treatment device (MTD). The resulting improvement in water properties can be traced as far back as 1803, when numerous successful experiments were conducted in this area.

According to Cai et al., when water is treated with an MTD, it displays

- A decrease in surface tension,
- An increase in water viscosity as the treatment time increases,
- Increasing water stability,
- Decreasing molecule energy, and
- Increasing activity energy.
As water is a polar substance, its molecules are connected with hydrogen bonds, as shown in Figure 1 [7]. The magnetic field thus separates clusters of water into single molecules, as shown in Figure 2. accordingly water activity is improved and potentially enhancing in concrete mixtures properties could be achieved [8].

Figure 1. Hydrogen bonding between water molecules [7].

The curing methods should be selected based on the required structural geometry, the mixture, the prevailing weather, and similar factors [9]. Many previous researchers have indicated that heat curing improves RPC mechanical properties [10], and this study thus adopted numerous forms of curing procedure in addition to normal curing (water submerges), i.e. Three technics have been carried out; autogenous curing, warm water curing, and high temperature water curing.

Several previous researchers studied RPC enhancing either by using magnetized water or different curing procedures. Raouf et al. [11] studied the effectiveness of using magnetized water within RPC mixtures that containing nano silica (NS) with different ratios (1, 1.5, 2, 2.5, and 3% by weight of cement). The tests result at 28 days showed a remarkable improvement in RPC strength when the MW was used, with compressive strength, modulus of rupture, and splitting increased by 22.37%, 17.96% and 19.44% respectively. Malathy et al. [12] investigated the influence of adding magnetic water to concrete mixes and how this affects the compressive strength and workability of concrete, concluding
that, in addition to improving the compressive strength, the cement content could be reduced down to 10.25% when MW was used without affecting the resulting concrete strength. Ngene et al. [13] also studied MW’s influence on the properties of concrete containing recycled waste glass aggregate; in their work, the magnetic intensity used to produce the MW added to the mixture in a ratio of 1:1.5:3 (cement: sand: granite) was 0.012 Tesla, for a water to cement ratio of 0.48. The results showed an increase of 25 to 30% in concrete properties. Ahmad [14] worked on concrete improvement by using MW with an intensity of 1.2 Tesla circulated at 4.5 sec./litre, reporting enhancements of 10 to 20%.

Abdulrahman et al. [15] investigated the effect of curing techniques on RPC strength, performing experimental tests that showed that the best method for achieving the highest strength was immersion of samples in high temperature water at to 90 °C, with the compressive strength, modulus of rupture and splitting tensile strength increased by up to 41.9%, 36.9%, and 38.4% respectively. Additionally, Chen and Zheng [16] examined RPC components’ optimal dosage when cured using different methods including standard curing, steam curing, and autoclave curing. Zhang et al. [17] also investigated RPC strength after curing with different curing programmes, with results suggesting that hot water curing has the best effect on the RPC mechanical properties, with compressive and splitting tensile strength increased by 19.2% and 15.2%, respectively for a steel fibre dosage of 4%.

The aim and objectives of this study were thus developed as follows:

- To study the effects of adding MW instead of NW within a reactive powder concrete mixture;
- To study the influence of different curing procedures on RPC mechanical properties.

2. Experimental Work

2.1. Programme

In this study, 72 specimens were prepared. The mix components were similar for all specimens, with cement, fine aggregate, silica fume, steel fibres, and superplasticizer. The main difference was in the water types used. In the first mix, normal water was used (control mix), while in the second group magnetized water was added. After casting, the specimens from both groups were categorised by intended curing procedure. Four curing techniques were adopted: ordinary curing (control samples), autogenous curing, warm water curing, and high temperature cycle curing. All concrete samples were tested after curing, and the percentage differences from the control samples noted in both groups.

2.2. Materials

- Ordinary Portland cement (OPC)

The physical attributes and chemical composition of the OPC (Karasta) are presented in Table 1 and Table 2 respectively; these results indicate that the cement met both IQS No.5/1984 [18] and ASTM C150-12 [19] requirements.

| Table 1. OPC Physical properties |
|---------------------------------|
| **Physical properties**         | **Test results** | **Limits of Iraqi Specification No. 5/1984** | **ASTM Specification C150-12** |
| Specific surface area (Blaine method) (m²/kg) | 300 | ≥ 230 | ≥ 280 |
| Soundness percentage (Autoclave Method) | 0.02 | ≤ 0.8 | - |
| Setting time (Vicat’s method) | | | |
| Initial setting (minute) | 100 | ≥ 45 min | ≥ 45 min |
| Final setting (minute) | 280 | ≤ 600 min. | ≤ 375 min. |
| Compressive strength (MPa) | | | |
| In three days | 21 | ≥ 15 | ≥ 12 |
| In seven days | 27 | ≥ 23 | ≥ 19 |
Table 2. Chemical Composition and Main Compounds of OPC

| Oxide Composition | Abbreviation | Percentage by weight | Iraqi Specification No. 5/1984 | ASTM Specification C150-12 |
|-------------------|--------------|----------------------|-------------------------------|----------------------------|
| Lime              | CaO          | 61                   | -                            | -                          |
| Iron Oxide        | Fe₂O₃        | 4.8                  | -                            | -                          |
| Alumina           | Al₂O₃        | 5.08                 | -                            | -                          |
| Silica            | SiO₂         | 19.84                | -                            | -                          |
| Sulphate          | SO₃          | 2.49                 | ≤ 2.8% if C₃A ≤ 5%           | ≤ 3.0% if C₃A ≤ 8%         |
|                   |              |                      |                              | ≤ 3.5% if C₃A > 8%         |
| Equivalent Na₂O+  | Na₂O+0.658K₂O| 0.34                 | ≤ 0.6%                       | -                          |
| Magnesia          | MgO          | 2.46                 | ≤ 5.0 %                      | ≤ 6.0 %                    |
| Insoluble residue | I.R.         | 0.40                 | ≤ 1.5 %                      | ≤ 0.75%                    |
| Loss on ignition  | LOI          | 3.76                 | ≤ 4.0 %                      | ≤ 3.0 %                    |

Main Compounds

- Tri calcium Silicate: C₃S 49.45%
- Tetra calcium Aluminate –Ferrite: C₄AF 14.61%
- Di calcium Silicate: C₂S 19.57%
- Tri calcium Aluminate: C₃A 5.34%

- Fine aggregate

The physical and sulphite content tests for the sand used are presented in Table 3, which confirms compliance with IQS 45 1984 [20] for zone 4.

Table 3. Fine aggregate physical tests and sulphate content

| Sieve size (mm) | % passing by weight | Iraqi specifications No. 45/1984 (Zone 4) |
|-----------------|---------------------|------------------------------------------|
| 10              | 100                 | 100                                      |
| 4.75            | 100                 | 95-100                                   |
| 2.36            | 100                 | 95-100                                   |
| 1.18            | 100                 | 90-100                                   |
| 0.6             | 85.62               | 80-100                                   |
| 0.3             | 38.3                | 15-50                                    |
| 0.15            | 9.62                | 0-15                                     |
| Fineness modulus| 1.9                 | -                                        |
| Percentage Sulphate content | 0.13 | Max. 0.5 |
| Specific gravity | 2.65                | -                                        |
| Absorption percentage | 1.02 | - |
| Moisture content percentage | 6.2 | - |
Steel fibres, silica fume, and superplasticizer

The steel fibres used in this work was straight, with lengths equal to 13mm and diameters of 0.2mm; these were covered with a brass coating. The average splitting tensile strength, as indicated by the manufacturer, was 2600MPa.

Micro-silica 920D silica fume was used within the concrete mixture in this study; its chemical and physical property test results are reported in Table 4, confirming adherence to ASTM 1240 [21] specifications. A superplasticizer was also added to the mixture to ensure the water content performed effectively [22].

### Table 4. Chemical and physical properties of silica fume

| Oxide Composition                  | Test results | ASTM C 1240 Specification |
|------------------------------------|--------------|----------------------------|
| SiO₂, min. Percent                 | 92.84        | > 85.0                     |
| Moisture content                   | 0.33         | < 3.0                      |
| Loss on ignition                   | 1.59         | < 6.0                      |

**Physical Properties**

| Percentage of retaining on 45-μm (Sieve No.325). | 8.2 | ≤ 10 |
|--------------------------------------------------|-----|------|
| Accelerated pozzolanic Strength activity index with Portland cement at 7 days. | 112.8 | ≥105 |
| Specific surface, Min, m²/g                    | 17  | ≥15  |

#### 2.3. Water treatment

Based on Al-Safy [23], the magnetizing water process was conducted. Water taken from a 20-litre container was moved by water pump toward a WTD of intensity 0.9 Tesla with a low flow rate of 0.1 m³/hr.; the treated (magnetized) water then accumulated in another container, as shown in Figure 3. The adopted circulation time was 60 mins, as recommended by Al-Safy [23]. At all times, the containers were kept separate, ensuring that the NW and the produced MW did not mix.

![Figure 3. Magnetic treatment station.](image)
2.4. Mixture
Based on Al-Hassani et al. [24], and after several trial mixes were attempted, the material dosage was determined as follows:

- Sand to cement (S/C) ratio of 1:1
- Water to cement ratio (W/C) of 0.19
- Silica fume (SF) dosage of 10% replacement by mass of cement.
- Steel fibres at 2% of concrete wight.
- Superplasticizer, Hyperplastic PC 600, dosed at 2.1% by weight of cement.

The ACI 234R-96 [25] specification was adopted for adding silica fume in this study, with a small mixer with 0.03 m³ used.

The mixing procedure was conducted as recommended by Al-Hassani et al.:

- The cement and silica fume were blended for 3 minutes initially;
- The sand was then added and mixing continued for 5 minutes;
- After that, water and superplasticizer were added within the next 3 minutes and mixing continued for a further 5 minutes;
- Finally, the steel fibres were added within 3 minutes and the mixing continued for not less than 2 further minutes to ensure uniform distribution of the mixing materials.

2.5. Sample preparation
To achieve the objectives of this study, three kinds of molds were prepared:

- Cubic molds with dimensions 100 × 100 × 100 mm,
- Cylindrical molds with 100 mm diameter and a height equal to 200 mm and,
- Prism of dimensions 100 × 100 × 400 mm.

2.6. Curing
The effects of four curing techniques on RPC strength were investigated in this study. Consequently, after casting, all specimens were subdivided into groups to be cured using a unique curing procedure:

1- **Ordinary curing (OC):** the RPC samples were cured according to ASTM C192 [26], being immersed in room temperature (lab conditions) water until testing at 7, 28, or 90 days.

2- **Autogenous curing (AC):** as ASTM C684-99 [27] specifications, the RPC specimens were covered by burlap and polythene after casting immediately, and after 2-days it was forwarded to the water tank as first curing technique.

3- **Warm water curing (WC):** the samples were cured after 24 hours, according to ASTM C684-99 [27] procedures, being immersed in water at a temperature of 35 °C until testing at 7, 28, or 90 days.

4- **High temperature cycles (HC):** based on ACI 517.2R-92 [28], 24 hours after casting, the specimens were forwarded to the water bath. During this procedure, the water temperature was varied such that, in the first few hours, the temperature was increased by 20 °C per hour until reaching 70 °C, with that temperature fixed for 5 hours. A temperature decrease was then applied at 20 °C per hour until the bath reached 20 °C. This technique was repeated continuously for days, after which the specimens were immersed in lab temperature water as used in the OC procedure until testing.

2.7. Specimen testing
The strength of all RPC specimens was tested as follows:

- The compressive strength of RPC cubes was tested according to BS EN 12390-3 [29] specifications,
• The splitting tensile strength was reported for the RPC cylinders according to the ASTM C496 / C496M-17 guidelines [30], and
• The flexural strength was tested in conformance with the ASTM C1018-97 [31] test for fibre-reinforced concrete.

3. Results and Discussion

Based on the experimental tests in this work, including MW within RPC mixture has a remarkable influence on the resulting mechanical properties, including increases in the compressive, flexure and splitting tensile strength. However, different curing procedures also significantly affect RPC mechanical properties.

3.1. Compressive strength.

The enhancement in compressive strength when magnetized water is used instead of normal water and the improvements when different curing techniques are applied instead of ordinary curing are presented in Table 5. All of the results are also offered in column-chart form in Figure 4 and Figure 5.

As presented in Figure 4, the compressive strength was improved by 9.15% on testing after 28 days as a result of adding magnetized water within the RPC mixture, suggesting that water activity is increased due to the magnetization effect, thus improving the concrete properties. Based on the experimental results, it can also be concluded that the enhancing percentage per day decreases after 7 days, however, as in the first 7 days the average improvement is 1.21% per day, while after that, up to 28 days the improvement is just 0.03% per day, while after the latter, up to 90 days, the improvement decreases further to 0.0024% per day. That can be explained by the fact that the effect of MW is reduced with time as the water molecules return to their original condition over time with respect to their hydrogen bonds. Thus, the activity also decreases over time. These results are in agreement with previous researchers’ conclusions with regard to strength increments over aging [12] when magnetised water is used within concrete mixtures.

However, the curing procedure also affects the compressive strength of RPC, with curing using a high temperature cycle procedure and a mixture with magnetized water presenting the most efficient RPC enhancement, with the compressive strength increased by 34.4%, 30.57% and 28.53% when tested at 7, 28 and 90 days, respectively, as shown in Figure 5. This can be explained by the special nature of silica fume, as this curing technique makes the silica fume mature earlier, causing its effect to present more clearly in the first days of curing.

Table 5 below presents all compressive strength tests results at 7, 28, and 90 days of curing.

| Mixture description | Curing procedure | Compressive strength (MPa) |
|---------------------|-----------------|---------------------------|
|                     | Description     | Abbreviation | 7-days | 28-days | 90-days |
| RPC mixed with Normal water (NW) | Ordinary curing | OC | 84.81 | 99.21 | 102.92 |
|                     | Autogenous curing | AC | 95.22 | 110.34 | 113.25 |
|                     | Warm water curing | WC | 110.44 | 124.11 | 127.41 |
|                     | High temp cycle | HC | 112.24 | 127.81 | 130.32 |
| RPC mixed with Magnetize water (MW) | Ordinary curing | OC | 90.62 | 106.85 | 110.92 |
|                     | Autogenous curing | AC | 102.61 | 119.63 | 123.01 |
|                     | Warm water curing | WC | 119.42 | 135.08 | 138.78 |
|                     | High temp cycle | HC | 121.79 | 139.51 | 142.44 |
Figure 4. RPC compressive strength improvement with different curing procedures when magnetized water is used within the mixture.

Figure 5. RPC compressive strength improvements with different curing procedures when normal water is used within the mixture.
3.2. Flexure strength.

The tests results for RPC flexural strength when NW and MW are used and cured using different curing techniques are presented in Table 6, with the enhancements presented in Figure 6 and Figure 7 in column-chart manner for mixtures using MW and NW, respectively. MW increases the flexural strength by 9.01% at 28 days, while choosing a high temperature cycle curing procedure for mixtures using magnetized water could increase the flexural strength by 31.85%, 28.8%, and 28.08% at 7 days, 28 days, and 90 days, respectively.

| Mixture description          | Curing procedure | Flexure strength (MPa) |
|------------------------------|------------------|------------------------|
|                              | Description      | Abbreviation | 7-days | 28-days | 90-days |
| RPC mixed with Normal water  | Ordinary curing  | OC           | 17.78   | 19.93   | 21.09   |
| (NW)                         | Autogenous curing| AC           | 19.87   | 22.05   | 23.16   |
|                              | Warm water curing| WC           | 22.64   | 24.68   | 25.67   |
|                              | High temp cycle  | HC           | 23.02   | 25.19   | 26.58   |
| RPC mixed with Magnetize     | Ordinary curing  | OC           | 18.93   | 21.32   | 22.65   |
| water (MW)                   | Autogenous curing| AC           | 21.3    | 23.78   | 24.99   |
|                              | Warm water curing| WC           | 24.29   | 26.67   | 27.75   |
|                              | High temp cycle  | HC           | 24.96   | 27.46   | 29.01   |

**Figure 6.** RPC flexure strength improvement when the magnetized water is used with different curing procedures.
3.3. Splitting tensile strength.

The improvements in the splitting tensile strength when magnetized water is used instead of normal water and different curing techniques applied are presented in Figure 7. Additionally, the enhancement effects for all tests are shown in Figure 8 and Figure 9 for MW and NW, respectively.

A similar conclusion that seen for the compressive strength improvement appeared, with MW increasing the splitting tensile strength by 7.6% at 28 days. Choosing the right curing technique with magnetized water mixtures could further increases the splitting tensile strength by 28.95%, 25.42%, and 24% at 7, 28, and 90 days, respectively.

Table 7 presents all splitting tensile strength test results in 7, 28, and 90 days of curing.

Table 7. Splitting tensile tests results

| Mixture description | Curing procedure         | Splitting tensile strength (MPa) |
|---------------------|--------------------------|---------------------------------|
|                     | Description              | Abbreviation | 7-days | 28-days | 90-days |
| RPC mixed with Normal water (NW) | Ordinary curing          | OC           | 10.41   | 11.25    | 11.98    |
|                     | Autogenous curing        | AC           | 11.57   | 12.38    | 13.05    |
|                     | Warm water curing        | WC           | 13.03   | 13.76    | 14.54    |
|                     | High temp cycle          | HC           | 13.27   | 13.94    | 14.64    |
| RPC mixed with Magnetize water (MW) | Ordinary curing          | OC           | 11.02   | 11.96    | 12.75    |
|                     | Autogenous curing        | AC           | 12.33   | 13.27    | 13.91    |
|                     | Warm water curing        | WC           | 13.94   | 14.76    | 15.70    |
|                     | High temp cycle          | HC           | 14.21   | 15.00    | 15.81    |
Figure 8. RPC Splitting tensile strength when MW is used with different curing procedures.

Figure 9. RPC Splitting tensile strength when NW is used with different curing procedures.
4. Conclusions

Based on the experimental work in this study, the following conclusions can be drawn:

- Using magnetized water instead of normal water within RPC mixtures could improve the compressive strength, flexural strength, and splitting tensile strength by 9.15%, 9.01%, and 7.6% respectively where such samples are cured with high temperature water technique and tested at 28 days.
- The improvements gained by using MW in terms of compressive strength, flexural strength, and splitting tensile strength are 7.7%, 6.97%, and 6.31% respectively when samples are cured with ordinary water submersion and tested at 28 days.
- Choosing a high temperature cycle curing procedure can improve the compressive, flexural, and splitting tensile strength of the RPC by 30.57%, 28.8%, and 25.42% respectively when using magnetized water within the RPC mixture, where specimens are tested at 28 days.
- At the 28-day mark, the high temperature curing procedure can improve the compressive, flexural, and splitting tensile strength of RPC by 28.83%, 26.39%, and 23.91% respectively even when ordinary water is used within RPC mixtures.
- The effectiveness of MW in terms of the improvement of RPC mechanical properties in the week is relatively high, with its influence decreasing over time.
- The effect of choosing curing procedures other than traditional water submersion is also higher in the first 7-days than at later ages.

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