The Influence of Curing Method on the Mechanical Properties of Reactive Powder Concrete: A Comparative Study

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ABSTRACT

Reactive Powder Concrete (RPC) is known for its high compressive strength and exceptional durability due to the fine and steel fiber combination. The objective of the current research is to examine the influence of different curing types and their effects on the mechanical properties of concrete. Using Jet Cure Gp - red coating along with heat cycle curing, which includes 1-day warm+27-day normal (C.A1N), 2-day warm+26-day normal (C.A2N), and 3-day warm+25-day normal (C.A3N), the results revealed a compressive strength improvement of up to 27.36%, 29.82%, and 30.05% at 7, 28, and 90 days, respectively, compared to normal curing. A flexural strength increase by 26.1%, 26.8%, and 27.5% at 7, 28, and 90 days and a tensile strength improvement of 24.8%, 25.2%, and 26.6% at 7, 28, and 90 days, respectively, were also demonstrated. Based on these findings, it is observed that the best curing technique is the heat cycle method (A3N) with 3 days of heat curing and 25 days of normal curing, which significantly enhances the mechanical properties of RPC.

Keywords-reactive powder concrete; coating curing; warm temperature cycle; normal curing

I. INTRODUCTION

Ultra-High-Performance Concrete (UHPC) with integrated fiber [1, 2] has very high durability and workability [3, 4] and is extensively used in bridge and building construction [5, 6]. RPC is an engineering component [7, 8], which uses very fine sand instead of traditional coarse aggregates, often reinforced with fiber, exhibiting high homogeneity [9, 10]. Various particles, such as Silica Fume (SF), quartz powder, sand, and Ordinary Portland Cement (OPC), are commonly utilized. However, fiber reinforcement is important because the cementitious composition of RPC leads to brittle failure in compression or tensile strength [11, 12]. The reactivity of concrete to both static and dynamic loading can be improved through fiber employment [13]. The bonding mechanism is triggered when reinforcement passes through the fractures, connecting the two fracture surfaces and distributing the stresses throughout the concrete [14]. Authors in [15] examined the compressive strength of fiber reinforced RPC showing that it had 33% higher compressive strength than the unreinforced RPC, rendering it useful for high compressive strength structural components. Curing is a critical step in the provision of concrete strength and durability, particularly in the first stages of mixing as it assists in the process of cement hydration [16]. The mechanical properties of Fiber-Reinforced Polymer (FRP) concrete can be enhanced by using curing methods, such as autoclaving, steam curing, or water curing, as shown in several studies [17, 18]. The type of curing process deployed depends on several factors, including weather, constituents in the mix, and the shape of the structure [19]. Authors in [20] studied the effect of using magnetized water in RPC, resulting in some improvements in their compressive, flexural, and splitting tensile strengths.

II. EXPERIMENTAL PROCESS

A. *Ingredients*

The ingredients utilized for the current study's experiment are:

- OPC: All tests conducted for this study used OPC of type CEM I-42.5 R. Tables I and II present the physical requirements and chemical composition of OPC, respectively [21].
- Fine Aggregate (sand): The research used Sikadur sand (fine broadcast aggregates) with 0.3 mm-0.7 mm grading, which can be applied in the control RPC production, as displayed in Table III [22].

- SF is defined by its physical and chemical characteristics, depicted in Tables IV and V.
- Micro Steel Fiber (MSF): The straight steel fiber product was used as the MSF for the present testing procedure and Table VI presents a comprehensive overview of its characteristics.
- Water: The utilized water must be suitable for its designated application and must comply with the quality criteria [23].

TABLE I. OPC PHYSICAL CHARACTERISTICS

Property	Test results	Limits of IQS No5-2019
Specific surface area (m^2/ kg)	397.8	≥ 280
Soundness by Autoclave (%)	0.7	≤0.80
Setting time (Vicat′s) initial (min)	146	≥45
Setting time (Vicat′s) final (min)	327	≤600
Compressive strength (2) days (MPa)	26	≥20
Compressive strength (28) days (MPa)	46	≥42.5

TABLE II. CEMENT PROPERTIES

Oxide compositions	Weight (%)	Limits of IQS No5-2019
Insoluble Residue (IR)	0.51	≤ 1.5 %
Magnesia (MgO)	3.26	≤ 5 %
Loss on Ignition (LOI)	2.53	≤ 4 %
Sulfate (SO_3)	2.42	SO_3≤ 2.8 if C_3A > 3.5
Bogue equation calculation according to ASTM C150		
(C_3A)	8.26	------

TABLE III. PHYSICAL AND CHEMICAL PROPERTIES OF SAND

Physical and chemical characteristics	Result	Limit of IQS No.45/1984
Sulfate content (SO_3) (%)	0.00	≤ 0.50
Specific gravity	2.5	-------
Absorption (%)	1.3	--------

TABLE IV. CHEMICAL REQUIREMENTS OF SF

Oxide (%)	Result (%)	ASTM C1240
Silicon Oxide (SiO_2)	93.2	≥ 85
Magnesium Oxide (MgO)	0.61	-------
Aluminum Oxide (AL_2O_3)	1.4	------
Iron Oxide (Fe_2O_3)	1.5	------
Calcium Oxide (CaO)	0.53	-------
LOI	2.13	≤ 6

TABLE V. SF PHYSICAL REQUIREMENTS

Physical characteristics (%)	Test Result	ASTM C1240
Percentage retained on 45µm (No.325) sieve	1.4	≤ 10
Accelerated pozzolanic strength activity index	111	≥ 105 at7days

TABLE VI. MSF CHARACTERISTICS

Description	Specification
Tensile strength (MPa)	2600
Density (kg/m^3)	7860
Type	Straight
Diameter (mm)	0.20 mm ± 0.05
Average length (mm)	13
Aspect ratio (L/D)	65

III. RPC DESIGN AND MIXING PROCEDURE

A. Mixing

The Control-RPC (C-RPC) mixture was produced in accordance with [28], as portrayed in Table VII.

TABLE VII. DESIGN OF C-RPC MIXTURES (kg/m^3)

Mix	CM
OPC	900
Fine aggregate	1200
SF	200
Water	250
W/Cm	0.227
SP Lit/100kg cementitious materials	13.05
Fiber (MSF) by2% of RPC	156

B. Sample Preparation

To meet the objectives of the present study, three different molds were made: cubic molds measuring 100 mm × 100 mm × 100 mm, cylindrical molds with a diameter of 100 mm and a height of 200 mm, and prism molds with dimensions of 250 mm × 50 mm × 50 mm.

C. Curing

This study examined the impact of three distinct curing methodologies on RPC strength. The specimens were methodically grouped for the purpose of curing subsequent to casting. The curing process for each specimen is presented in Figure 1:

- Normal Curing: The preparation of concrete specimens followed ASTM C192 [24] for standard curing procedures. Prior to testing at 7, 28, or 90 days, the specimens were submerged in water at room temperature (i.e., laboratory conditions).
- Coated curing: Following a drying period of two hours, the samples were coated with Jet cure Gp - red. Subsequent to a 24-hour period, the concrete models were removed from the molds. A uniform layer of Jet cure Gp - red was applied to the entire surface using a hand brush, as specified in [25].
- Warm temperature cycles: After 24 hours, the concrete specimens were removed from the molds and placed in a 20 ^{o}C water bath. The water's temperature was then gradually increased until it reached 35°C. This technique involved three different cycles: 1-day warm+27-day normal (C.A1N), 2-day warm+26-day normal (C.A2N), and 3-day warm+25-day normal (C.A3N). After maintaining this temperature for five hours, it was gradually lowered until it reached 20 ^{o}C. Subsequently, the sample temperature was raised for 17 hours before the next curing cycle began. After three days of repeating this temperature rise and fall cycles, the specimens were immersed in water tanks in a manner similar to normal curing, as shown in Figure 2.
- Specimen Testing: In accordance with the specifications of BS EN 12390-3, the compressive strength of RPC cubes was tested [26]. A series of concrete cylinders was subjected to a splitting tensile test according to [27]. Additionally, following ASTMC293M-16 [28], the specimens were subjected to a single point flexural test.

IV. RESULTS AND DISCUSSION

A. Compressive Strength

The compressive strength of the specimens cured for 28 days was 92.5 MPa, 102.9 MPa, 112.6 MPa, 115.7 MPa, and 120.1 MPa for C.S, C.C, C.A1N, C.A2N, and C.A3N, respectively, as shown in Table VIII. Each curing mode has an independent effect on the strength development of RPC, with the hot water curing exhibiting the highest compressive strength.

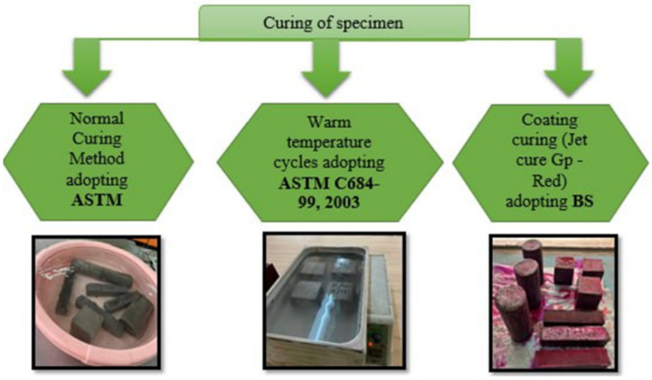

Fig. 1. Curing of specimen.

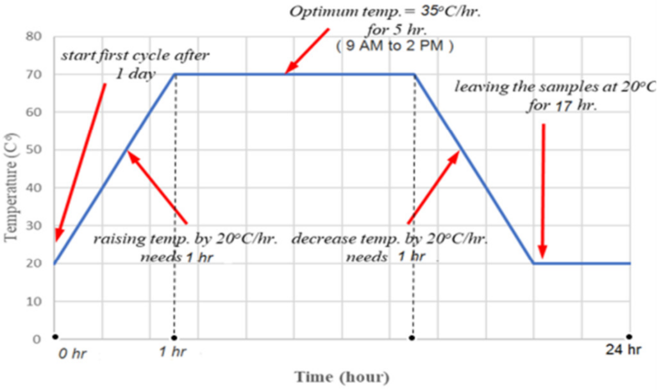

Fig. 2. Curing cycle of warm water curing for C.A1N.

TABLE VIII. THE RESULTS OF COMPRESSIVE-STRENGTH TEST WITH DIFFERENT CURING TECHNIQUES

Type of curing	7 Days	28 Days	90 Days
Standard Curing (C.S)	74.2	92.5	100.6
Coating Curing (C.C)	82	102.9	113.2
Accelerated + Normal (C.A1N)	88.8	112.6	122.5
Accelerated + Normal (C.A2N)	92.5	115.7	125.8
Accelerated + Normal (C.A3N)	94.5	120.1	130.6

The continuous development of the calcium silicate hydrate (C-S-H) chain during the heat cycles is due to the accelerated hydration reactions that occur at elevated temperatures. Heater conditions gain the order of chemic reactions between sweat and cementum particles, up to quicker and further comprehensive formation of the C-S-H mousse, which is responsible for the strength of the concrete. The elevated temperature reduces the setting time, enabling C-S-H chains to form and bond more rapidly within the matrix, resulting in a denser microstructure. This increased hydration and perpetual evolution of C-S-H low-tender temperature cycles lead to higher compressive, flexural, and malleable strengths. Authors in [29] demonstrated that the C-S-H net clay actively casts and secures passim the curing work. As shown in Figure 3, the C.A3N condition exhibited the highest compressive strength, with values of 27.36, 29.82, and 30.05 at 7, 28, and 90 days, respectively. Furthermore, Figure 4 illustrates that the compressive strength was improved by using heat cycles compared to normal curing. The enhancement was 19.68%, 21.77%, and 22.2% for C.A1N at 7, 28, and 90 days, respectively, and for C.A2N, it was 24.66%, 25.05%, and 25.08% at 7, 28, and 90 days, respectively. The highest overall performance was observed with heat cycles, which can be attributed to the high cementitious content of RPC, resulting in a large percentage of hydrated products. Moreover, by using an appropriate curing technique, the pozzolanic activity increases rapidly and the hydrated products fill the internal voids and pores [30]. The minor enhancements observed in coating curing are presumably due to the limited interaction between the coating and the underlying material. Coatings typically cast amp tender layer so that they do not lead to significant hydration work or general force evolution compared to standard curing methods, which enable further comprehensive hydration and chemical reactions, resulting in relatively small effectiveness.

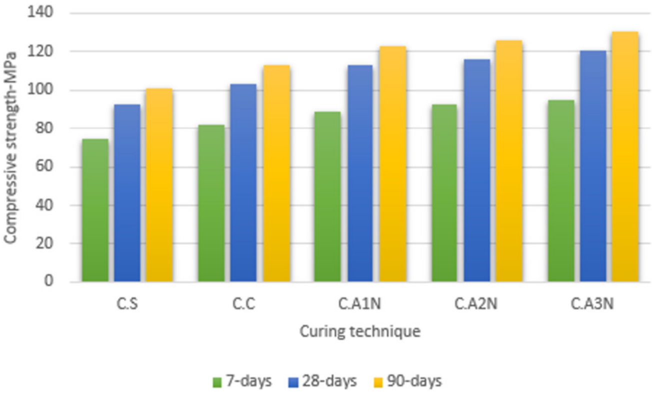

Fig. 3. Impact of curing techniques on compressive strength results.

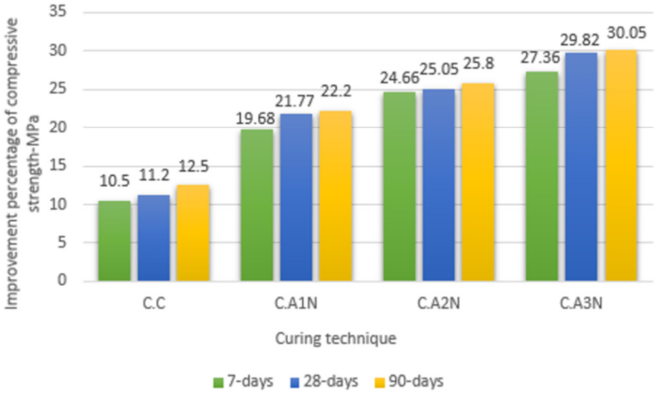

Fig. 4. The improvement percentage of compressive test compared with normal curing.

B. Flexural Strength

The flexural strength for samples cured for 28 days ranged from 9.552 MPa to 12.112 MPa, depending on the type of cement (C.S., C.C., C.A1N, C.A2N, or C.A3N). The highest strength was observed in C.A3N, followed by C.A2N, C.A1N, C.C, and C.S, as depicted in Table IX. The heat cycle resulted in the highest strength, presumably due to the continuous expansion of the C-S-H chain in a warm environment [27]. As displayed in Figures 5 and 6, the flexural strength exhibited an increase in the heat cycle compared to normal curing. The results were 18.5%, 20.2%, and 20.8% for C.A1N at 7, 28, and 90 days, respectively; 23.2%, 23.5%, and 24.1% for C.A2N and 26.1%, 26.8%, and 27.5% for (3-day warm+25-day normal), respectively. C.A3N exhibited the highest overall performance, resulting in more efficient hydration, while C.C exhibited small gains due to its limited effect on hydration. The effectiveness of standard curing remained relatively unchanged.

TABLE IX. FLEXURAL STRENGTH TEST RESULTS WITH DIFFERENT CURING TECHNIQUES

Type of curing	7 Days	28 Days	90 Days
C.S	7.645	9.552	10.508
C.C	8.272	10.459	11.580
C.A1N	9.059	11.482	12.694
C.A2N	9.419	11.797	13.04
C.A3N	9.64	12.112	13.398

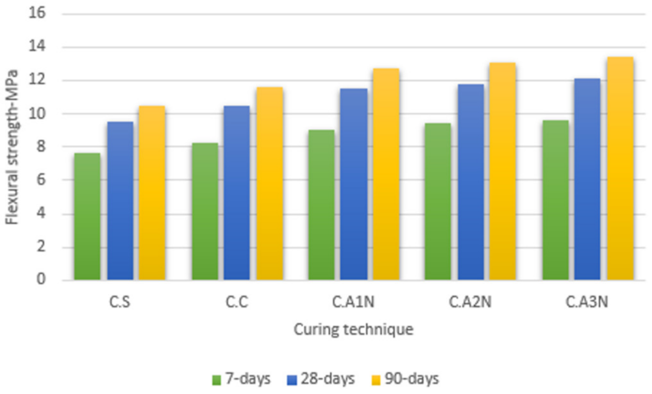

Fig. 5. Impact of curing techniques on flexural strength results.

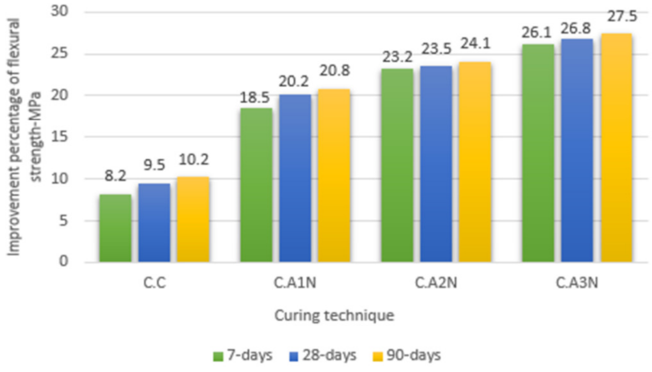

Fig. 6. The improvement percentage of flexural test compared with normal curing.

C. Tensile strength

As shown in Table X, the tensile strength for the samples cured for 28 days ranged from 8.228 MPa to 10.301 MPa, depending on the specimen (C.S., C.C., C.A1N, C.A2N, or C.A3N). The results indicate a clear correlation between the tensile strength and the curing temperature of the specimens. As presented in Figures 7 and 8, tensile strength increased with warm water curing compared to normal curing at a rate of 176%, 181%, and 188% for C.A1N; 225%, 235%, and 238% for C.A2N; and 248%, 252%, and 268% for C.A3N. C.A3N exhibited the highest overall tensile strength, due to better hydration, while C.C led to minor gains. The increased tensile strength was attributed to the hydration, which accelerated the tender temperature round and fast curing methods.

TABLE X. TENSILE STRENGTH TEST RESULTS WITH DIFFERENT CURING TECHNIQUES

Type of curing	7 Days	28 Days	90 Days
C.S	6.625	8.228	9.015
C.C	7.122	8.952	9.871
C.A1N	7.791	9.717	10.710
C.A2N	8.116	10.162	11.161
C.A3N	8.268	10.301	11.431

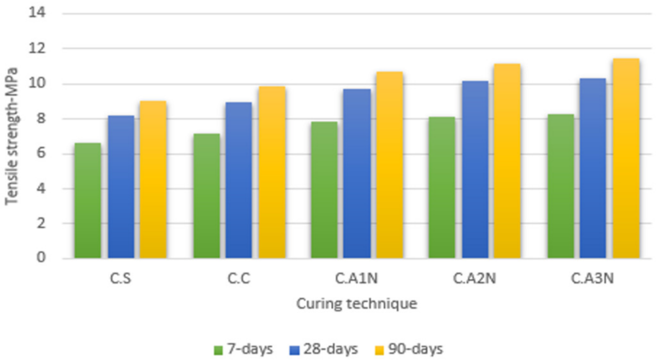

Fig. 7. Impact of curing techniques on tensile strength results.

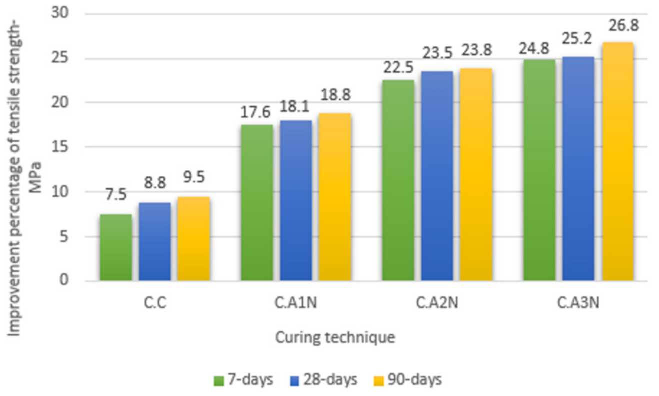

Fig. 8. The improvement percentage of tensile test compared with normal curing.

V. CONCLUSIONS

The objective of the present study was to determine the effect of curing techniques on the strength of Reactive Powder Concrete (RPC). The RPC used in this study was composed of

1:0.2:1.3 cement:Silica Fume (SF):sand, with a water to cement (w/c) ratio of 0.227 and an MSF content of 2% by volume of concrete. The increase observed on compressive, tensile, and flexural strengths was 92.5 MPa, 8.228 MPa, and 9.552 MPa, respectively, after 28 days of normal curing. The application of Coating Curing (C.C) led to an enhancement of these strengths by 11.2%, 8.8%, and 9.5%, respectively, in comparison with standard curing methods. The application of heat cycle, specifically the 1-day warm + 27-day normal curing (C.A1N), resulted in increases in compressive, tensile, and flexural strengths of 21.77%, 18.1%, and 20.2%, respectively, at 28 days compared to normal curing. A further enhancement was observed with the 2-day warm + 26-day normal curing cycle (C.A2N), which demonstrated gains of 25.05%, 23.5%, and 23.5%, respectively, for compressive, tensile, and flexural strengths at 28 days. The most significant improvement values were achieved with the 3-day hot + 25-day normal cycle (C.A3N), where the compressive, tensile, and flexural strengths increased by 29.82%, 25.2%, and 26.8%, respectively, at 28 days. These rates remained consistent at 90 days across the diverse curing modes.

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