Mechanical Properties of Reactive Powder Concrete under Pre-Setting Pressure and Different Curing Regimes

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***Abstract*—Reactive Powder Concrete (RPC) is an ultra high performance concrete which has superior mechanical and physical properties. RPC is composed of cement and very fine powders such as crushed quartz (100–600 µm) and silica fume with very low water/ binder ratio (W/B) (less than 0.20) and Superplasticizer (SP). RPC has a very high compressive and tensile strength with better durability properties than current high performance concretes. Application of very low water/ binder ratio with high dosage of super plasticizer, different heat curing processes and pre-setting pressure improve mechanical and physical properties of RPC. In this study, RPC is composed of available materials in Iran. Two different mixing proportions were used in laboratory and samples were prepared in different water/ binder ratios and superplasticizer dosage under 0, 25, 50, 100 and 150 MPa pre-setting pressure, and then 7 different curing regimes were applied to the specimens. It was observed that higher temperature and pre-setting pressure increase the compressive strength of the compositions.**

***Index Terms*—reactive powder concrete, pre-setting pressure, heat curing, steam curing, compressive strength**

I. Introduction

Reactive Powder Concrete (RPC) is a general name for a class of cementitious composite materials developed by the technical division of Bouygues, S.A. in the early. It is characterized by extremely good physical properties, such as strength and ductility. The ultra-high performance of RPC in mechanical properties, particularly in compressive strength, makes it of tremendous interest to construction practitioners. RPC is a relatively new kind of ultra high performance concrete. Its main features include a high percentage of cement, very low water-to-binder (cement + silica fume) ratio, a high dosage of superplasticizer, and very fine crushed quartz and silica fume. Coarse aggregate is completely replaced by fine quartz sand.

The compressive strength of RPC is about 150–800 MPa, while its tensile strength changes between 25 and 150 MPa. Moreover, specific gravity of RPC is between 2.4–2.8 t/m^3 [1].

Fine powders such as crushed quartz (100–600 µm) are used instead of coarse aggregate in order to increase the homogeneity of RPC. Adding of silicafume to RPC reduces the total pore volume of the cement paste and the average diameter of the pores [2], [3]. Furthermore, researchers reported that application of different heat cure processes improve mechanical properties of RPC substantially after the application of 50 MPa pre-setting pressure to fresh mixture [4]-[7]. Application of pressure to fresh RPC during setting phase for 6–12 hours can eliminate some amount of pores caused by shrinkage. Micro cracks which are in fresh RPC are improved after discharging the applied pressure [4], [8].

Dugat *et al*. [9], applied 60 MPa pre-setting pressure to samples of fresh RPC with heat curing at 90 ℃ and 250 ℃. They reached compressive strength of about 500 MPa and static Young's modulus of 36,000–74,000 MPa for RPC. Bonneau *et al*. [10], studied confinement behavior of the RPC in a steel tube. They reported that compressive strength up to 200 MPa could be achieved in hot water curing at 90 ℃ and in low-pressure steam chambers at the precast plant. Teichman and Schmidt [11] studied structural properties of RPC and its effects on strength and durability. They used steam curing for 2 days at 90 ℃ and heat curing for 7 days at 250 ℃ after 2 days of de-moulding. In their study fresh RPC samples were exposed to pre-setting pressure of 50 MPa. The highest compressive strength as 487 MPa was reported.

Yazici [12] replaced Portland cement in RPC with fly ash and granulated blast furnace slag at percentages of 0, 20, 40, 60 and 80%, respectively. Three different curing methods (standard, autoclave and steam curing) were applied to the specimens. He achieved compressive strength up to 185 MPa when cement content of these mixtures were only 340 kg/m^3. Topçu and Karakurt [13] applied pre-setting pressure of 2.5 MPa to RPC mixture. These specimens were exposed to steam curing for 7 days at 250 ℃ and then were kept in water for 7 days at 90 ℃. Compressive strength up to 253.2 MPa and flexural strength up to 63.67 MPa were obtained.

Massidda *et al*. [14] studied the effects of autoclaving on the physical and mechanical properties of RPC reinforced with brass-coated steel fibers. Autoclaving improved flexural and compressive strength of RPC. High pressure steam curing for 3 hours yielded flexural strength of 30 MPa and compressive strength of 200 MPa.

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Shaheen and Shrive [15] investigated freeze–thaw resistance of RPC. Test results showed that RPC has excellent freeze–thaw resistance even up to 600 cycles (according to ASTM C 666). Rougeau and Borys [16] showed that RPC can be produced with fly ash, limestone microfiller or metakaolin.

In this study, RPC samples were made using local available materials in Iran. Computer software and basic principles were used to determine the mixture ratios. Compressive strength tests were applied to the samples prepared according to this mixing ratio and the sample with the highest compressive strength value was selected. Some moulds and a compression machine were specially designed for application of pre-setting pressure process. The effects of different W/B ratio, SP dosage, curing regimes (water, hot water, steam) and pre-setting pressures (25, 50, 100 and 150 MPa), during setting phase to RPC in order to improve its physical and mechanical behaviors were investigated.

II. Experimental Procedure

A. Materials

The choice of cement is an important factor because the cement type has a very high effect on the performance of RPC. The ideal cement must have a high C3S and C2S (di- & tri-calcium silicate) and low C_3A (tri-calcium aluminate) content. This is understandable because C3A has little intrinsic value as a binding agent and is primarily included in cement due to its role as a flux during the calcination process [17]. The RPC considered here, is prepared by ASTM Type 2 Portland cement from Abadah Company in Iran which is formulated specifically for low C3A content.

Silica Fume (SF), which is an industrial product of the manufacturing and purification of silicon, zirconia and ferro-silicon alloys in submerged-arc electric furnaces has been used for RPC. It fills micro voids and produces secondary hydrates by puzzolanic reaction. SF was provided from Azna Company in Iran.

Quartz sands (with maximum particle size of 0.6 mm and 0.3 mm) and quartz powder (with maximum particle size of 0.1 mm) with a density of 2.75 t/m3 were used for preparing RPC mixtures. The very low water/binder ratios used in RPC would be possible by using high amount of high-quality superplasticizer (about 4% of cement amount). A polycarboxylate based superplasticizer Glenium-55p was used for this purpose. This superplasticizer had fluidity within time of fresh concrete and high strength in a short time.

B. Sample Preparation

Mooney suspension model and Fuller method were used for RPC mixture design [18]-[22]. Two mixtures having the highest compressive strength were selected and used to prepare the samples.

One mixture was applied to prepare non pre-setting pressurized specimens and the other used for pre-setting pressurized specimens. The mix proportions of RPC are shown in Table I.

TABLE I. Mix Proportions of RPC (kg/m^3)

Material	Mix.1 (non pressurized)	Mix.2 (pressurized)
Cement	936	1037
SF	280	300
0-1 mm Quartz	374	410
1-3 mm Quartz	268	290
3-6 mm Quartz	268	290
Water	234	165
SP	28	42

High shear mixing can enhance flow properties. To increase the shear mixing, one method is to use a mixer with a higher speed. Mixer with speed as high as 2000 revolutions per minute (rpm) should be used in order to effectively breaks down the agglomerated particles of very fine materials of RPC.

For each type of the proposed RPC mixtures, dry ingredients (i.e. cement, quartz powders, quartz sand and silica fume) were first mixed for about 3 minutes at low and high speed. Water and superplasticizer were added and re-mixed for about 5 minutes at high speed.

C. Test Method

High compression strength of RPC limits the dimensions of specimens. Some special moulds and a compression mechanical jack were designed to apply the pre-setting pressure.

Fresh RPC, was compacted into 50 mm cube moulds by hand tamping in two layers. The pre-setting pressure (25, 50, 100, 150 MPa) were applied to fresh RPC using the special machine. The specimens were allowed to harden in their moulds for 24 hours at 21 ℃ and 95% relative humidity, before being stripped and subjected to one of the different curing regimes.

Different curing regimes which were applied to the samples are presented in Table II. Maximum and minimum temperatures were reached with increment or decrement of 10 ℃ per hour.

TABLE II. Sample Codes and Curing Regimes

Sample Code	Cure Type			
	1 day	2-4 days	5-7 days	8-28 days
W20	in mould	20˚C W	20˚C W	20˚C W
3W60	in mould	60˚C W	20˚C W	20˚C W
6W60	in mould	60˚C W	60˚C W	20˚C W
3W90	in mould	90˚C W	20˚C W	20˚C W
6W90	in mould	90˚C W	90˚C W	20˚C W
3S90	in mould	90˚C S	20˚C S	20˚C W
6S90	in mould	90˚C S	90˚C S	20˚C W

W=water curing S= steam curing

Compressive strength test was made on the sample. The compressive strength of the specimens was determined with an ELE 2000 KN capacity testing machine.

TABLE III. COMPRESSIVE STRENGTH OF SPECIMENS AT 28 DAYS (MPA)

Sample Code	P=0 MPa	P=25 MPa	P=50 MPa	P=100 MPa	P=150 MPa
W20	156	249.6	255.8	279.2	270.4
3W60	184	267	272	301.2	291
6W60	186.4	275	280.3	308.3	293
3W90	196	278	280.5	318.5	295.8
6W90	205	278.5	287.4	322	298.4
3S90	198	280	278.5	320	296.5
6S90	206	286	285.6	328.1	301.5

III. DISCUSSION

A. Effect of Temperature on Compressive Strength

Table III and Fig. 1 show the effect of temperature and heat-treatment duration on compressive strength of RPC.

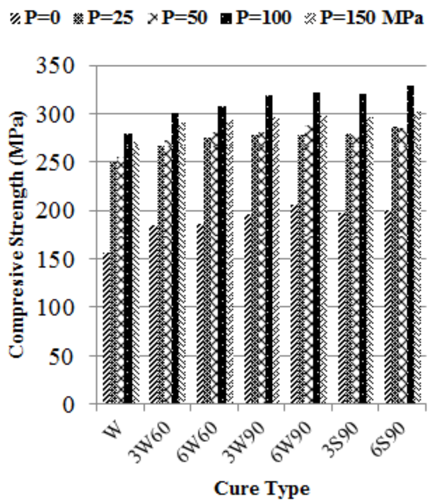

Figure 1. Effect of cure type on compressive strength

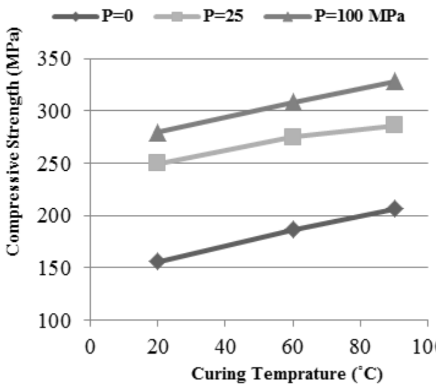

Figure 2. Effect of curing temperature on compressive strength

Fig. 2 shows the effect of curing temperature on compressive strength of RPC under pre-setting pressure (without pressure, 25 MPa and 100 MPa). The increases in compressive strength of W20 samples for 25 MPa and 100 MPa pre-setting pressures are 14.5% and 17.5% respectively. It is observed that, the increase in compressive strength of the samples due to heat curing in without any pre-setting pressure specimens are more considerable than others.

In heat and steam curing, hydration process activated and continued for a long time. The reactions of pozzolans were also accelerated by the higher curing temperatures and it directly affected on the compressive strength. Compressive strength of heat and steam cured specimens was higher than that of water cured specimens. In addition, C-H-S compositions change with temperature.

In addition, pores of the microstructures of hot water and steam cure at 90℃ are less than the standard cures that can explain the compressive strength changes.

The rate of changes in compressive strength at different ages is presented in Fig. 3.

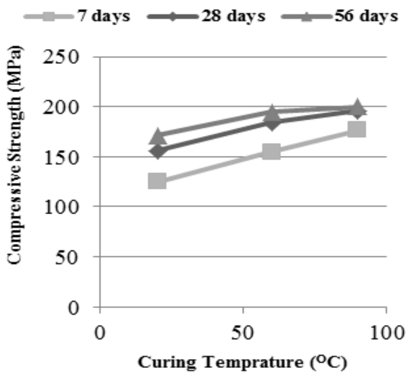

Figure 3. Rate of changes in compressive strength at different ages.

It can be found that the compressive strength of the samples slightly increased with increasing age. These Increases from 7 days to 28 days are more than 28 days to 56 days. But, the compressive strength increased a small amount in the applied samples hot steam curing after 7 days. It shows the accelerating effect of temperature on the hydration process of cement and Pozzolanic reaction of Silica fume in the early ages of specimens. So, at the following content only compressive strength Results at 28 days are presented.

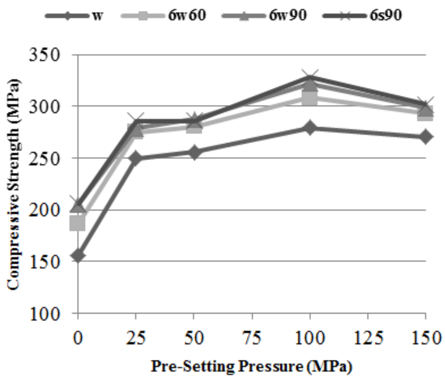

Figure 4. Compressive strength in comparison to pre-setting pressure.

B. Effect of Pre-Setting Pressure on Compressive Strength

Application of pre-setting pressure is applied for minimizing adverse effects of autogenous shrinkage and for removing water and air in the RPC. The compressive strength of specimens at 28 days of specimens under different pre-setting pressure is presented in Fig. 4.

As it is illustrated in Fig. 4, compressive strength highly affected by increasing pre-setting pressure until 100 MPa. Table III shows that the samples were pre-setting pressurized at 25 MPa their compressive strength reached to 285.6 MPa while samples without any pre-setting pressure had the compressive strength of 206 MPa.

It can be observed in Fig. 4, the samples which were pre-setting pressurized at 100 MPa had the maximum compressive strength of 322 MPa.

Pre-setting pressure up to 100 MPa was sufficient for going out of large air spaces and free water in the - samples, but in more pre-setting pressure cases micro cracks were created due to expansion of the aggregate after pressure was released. In addition, water which was needed for hydration could be gone out and that materials experience more deformations.

IV. Conclusions

Two mix proportions with the highest compressive strength value were selected. One mixture was used for non pre-setting pressurized samples and the other used for pre-setting pressurized samples. Special moulds and a compression machine were designed for application of pre-setting pressure process. Specimens were exposed to pre-setting pressure during setting phase in the moulds for 24 hours at room temperature of 20 ℃ and then samples were exposed to cure regimes given in experimental procedures.

The strength development of RPC is strongly temperature dependent. Curing temperature had a significant effect on the early strength development of RPC. The increased early strength is due to the rapid hydration of cement at higher curing temperatures of 60 ℃ compared to that of 20 ℃. There was not much significant difference in the rate of strength development between RPC cured under hot water and hot mist because they were kept at the same temperature.

The other observation is that the rate of strength development is greater for RPC cured under 20 ℃ water than that cured under 60 ℃ water. The 7-day/28-day strength ratio is 0.8 for mix W20; whereas the value for mix 6W60 and 6W90 are 0.84 and 0.92, respectively. The 28-day/90-day strength for mix W20 is 0.91; whereas the value for mix 6W60 and 6W90 are 0.94 and 0.95, respectively.

It was observed that when curing temperature increased from 20 ℃ to 90 ℃, compressive strength of RPC samples without pressure shows an increment ratio of 32%.

In addition, it can be seen that pre-setting pressure was sufficient for going out of large air spaces and free water from samples. In terms of applicability, pre-setting pressure of 25 MPa was more suitable although, the highest compressive strength reached to 328.1 MPa by choosing pre-setting pressure at 100 MPa.

When the W20 samples were pre-setting pressurized at 25 MPa their compressive strength reached to 249.6 MPa while samples which were not pre-setting pressurized had the compressive strength of 156 MPa. It shows an increment ratio of 60%. Other pre-setting pressures had low increment rates.

The 6S90 samples which were pre-setting pressurized at 100 MPa had the maximum compressive strength of 328.1 MPa. Compressive strength for 150 MPa pre-setting pressure decreased, because microcracks were created due to expansion of the aggregate when pressure was released. In addition, water needed for hydration could be gone out under pressure of 150 MPa.

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