Construction and Building Materials 154 (2017) 72–87

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of different curing regimes and durations on early strength development of reactive powder concrete

Parameshwar N. Hiremath, Subhash C. Yaragal *

Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, India

HIGHLIGHTS

- Efficiency of various curing regimes have been compared.
- Curing temperature has significant effect on strength development.
- Ultra high strength is achieved under combined curing regime.
- Formation of strength enhancing compounds is discerned with SEM and XRD.

ARTICLE INFO

Article history:
Received 18 April 2017
Received in revised form 12 July 2017
Accepted 25 July 2017
Available online 2 August 2017

Keywords:
Reactive powder concrete
Hot air curing
Hot water bath curing
Accelerated curing
Microstructure

ABSTRACT

The early strength development of Reactive Powder Concrete (RPC) has been investigated under different curing regimes and compared with standard water curing condition. Four different curing regimes have been considered: ambient air curing, hot air curing, hot water bath curing and accelerated curing. The effect of hot air curing on strength development of RPC at different temperatures and durations are studied in detail. The present study is focused on the effect of combined curing regimes on the early strength development of RPC. Test results indicate that, among the four different curing regimes, hot water bath curing gives higher strength. The combined curing regime has considerably enhanced the compressive strength of RPC by about 63% as is evident by the rise in compressive strength from 110 MPa (standard curing) to 180 MPa (combined curing). Microstructure studies were also conducted to understand the arrangements of hydrated particles and development of other secondary hydrated products under different curing conditions using scanning electron microscope and X-ray diffraction spectroscopy respectively.

1. Introduction

Concrete is the highest utilized construction material only next to water. Based on strength and durability considerations concrete is termed as normal strength concrete, high strength concrete, high performance concrete and ultra-high-performance concrete. High strength concrete is typically utilized in the erection of high rise buildings and it is also necessary for prestressed concrete as the material offers high résistance in tension, shear bond and bearing. The utilization of high strength and high-performance concrete has been increasing throughout the world due to their better engineering properties. The necessity of high performance concrete comes in to picture, due to premature deterioration of concrete structures in aggressive environment. The penetration of harmful substances such as chloride and sulphate ions, carbon dioxide, water and oxygen are responsible for deterioration of concrete strength. To address this problem, the use of high surface area mineral admixtures, such as silica fume and fly ash are proved to be essential in the production of high performance concrete with reduced porosity of concrete. The improved pore structure of high performance concrete checks the ingress of harmful substances into the body of concrete.

The ultra-high performance concrete, is designed for enhancement of performance oriented infrastructures, that reduce thickness of concrete structural members with added advantages of using optimized mix design, leading to large saving in both costs and materials. RPC is a type of ultra-high performance concrete, which is considered as a new revolutionary material, that can provide both ultra-high strength and high ductility through the inclusion of short fiber reinforcement.

---

* Corresponding author.
E-mail address: subhashyaragal@yahoo.com (S.C. Yaragal).

http://dx.doi.org/10.1016/j.conbuildmat.2017.07.181
0950-0618/

RPC is a cementitious based composite. It was developed through microstructure enhancement technique. This includes elimination of coarse aggregate, reducing water to binder ratio, addition of micro-cementitious materials, such as silica fume with high ratio of surface area to volume and introduction of silica sand and crushed quartz with particle size ranging from 45 to 600 μm instead of coarse aggregate.

In the early 1990s RPC was developed by P. Richard and M. Cheyrezy for the first time in Bouygues laboratory France [1]. RPC is more durable because of the low water to binder ratio that results in very low porosity [2]. The enhanced properties such as high strength, improved durability and ductility with the use of ultra-high strength concrete has encouraged many researchers, engineers and practitioners throughout the world, to use RPC in many practical applications such as precast structures, bridge deck overlays, dam repair, coupling beams in high rise buildings, nuclear waste containment structures, tall structures, long span bridges and walk ways. Many structures are being built currently adopting RPC. The first major RPC structure built is the Sherbrook pedestrian/bike way bridge in Canada (1997). Other bridges like foot bridge with a single span of 120 m in Seoul, Korea, Sakata-mirai foot bridge with no reinforcement in sakata, Japan, Shepherds creek road bridge with a thin permanent precast RPC formwork panels in Australia and Wapello country bridge with no reinforcement in USA (2006).

RPC was developed to produce high order compressive and flexural strengths in the range of 120–180 MPa and 40–60 MPa respectively. The production process of RPC includes two important parameters such as (i) selection of proper ingredients (ii) type of curing [3–5]. Curing phase has a vital role on strength development of RPC. There is no standard curing condition for RPC as of now. Generally, RPC is cured in two types of curing regimes (i) autoclave curing and (ii) thermal curing. The thermal/heat curing includes steam curing, hot water bath curing and hot air curing. Autoclave curing is done by applying heat and pressure simultaneously on fresh samples.

Autoclave curing has shown highest compressive strength up to 500 MPa by applying 60 MPa pre-setting pressure and 250 °C heat treatment [2]. Bonneau et al. [6] have investigated confined behavior of RPC in a steel tube. In this study, compressive strength of 285 MPa was achieved with hot water curing at 90 °C and at low-pressure steam curing. Teichman and Schmidt [7] have studied strength and durability properties of RPC. The cement content used in this study was very high (1900 kg/m^3). RPC samples were prepared with presetting pressure of 50 MPa. The compressive strength of RPC reached was 487 MPa.

Topcu and Karakurt [8] have investigated combined effect of autoclave curing, steam curing and hot water bath on the strength development of RPC. Samples were prepared with presetting pressure of 2.5 MPa and then exposed to steam curing for 7 days at 250 °C, later curing is continued in water for 7 days at 90 °C. The highest compressive strength of 253.2 MPa and flexural strength of 63.67 MPa were achieved. Shaheen [9] have produced RPC using autoclave curing regime with 50 kN load for 24 h at 150 °C. The highest compressive strength achieved was in the range of 243–288 MPa. Yazici et al. [10] have developed RPC using mineral admixture under different curing regimes (standard, steam and autoclave curing). Autoclave curing was done with 2 MPa pressure for 8 h at 210 °C and steam curing was done for 3 days at 100 °C. The maximum strength of 273 MPa and 255 MPa were achieved using autoclave and steam curing respectively. Helmi et al. [11] have developed RPC with compressive strength of 120 MPa using autoclave pressure of 8 MPa for 48 h at 240 °C. Yazici et al. [12] have investigated the effect of autoclave pressure, temperature and duration on the mechanical properties of RPC. Different autoclave pressures were selected such as 1, 2 and 3 MPa with temperatures of 180 °C, 210 °C and 235 °C respectively. The duration of autoclave was varied like 4 h, 6 h, 10 h, 12 h and 24 h. The maximum strength was achieved with 2 MPa pressure at 210 °C for 10 h.

A systematic study was carried out by Ipek et al. [13] on the effect of pre-setting pressure on mechanical behavior of RPC. Presetting pressure of 25, 50, 75, 100 and 125 MPa were considered for the study. From the results, it was confirmed that, RPC with high strength can be achieved by presetting pressure of 25 MPa. The highest compressive strength of 475 MPa was achieved with presetting pressure of 100 MPa. The study also has shown the adverse effect of high pre-setting pressure at 125 MPa. The reduced strength was due to huge expansion of microcracks around aggregates, after release of pressure at 125 MPa. Other studies have also reported, the fact that micro cracks consequently improved due to expansion of aggregate after discharging the applied pressure [14]. Autoclave curing has some limitation, such as absence of silica fume in the mix that restrict the rapid formation of different hydrated products. This leads to formation of porous and weak microstructure. Further, there are few more disadvantages of autoclave curing such as size of the specimen, limited to smaller scale. It requires special moulds to prepare sample. The high capital cost of autoclave instrument and need for steam curing chamber increases, the cost of the plant. The major disadvantage of autoclave is that, the bond strength between concrete and reinforcement is lower by about 50% and the material tends to be more brittle when compared to normally cured samples.

Thermal curing has strong influence on strength development of RPC. Development of dense microstructure with formation of calcium silicate hydrate phases that result in higher mechanical properties. Under heat treatment silica fume dissolves rapidly and it reacts with portlandites and forms new hydrates which are also C-S-H. Presence of crushed quartz in RPC mixture, has three main functions, (i) filling voids between the next larger class particles (sand) (ii) increment of rheological characteristics by the lubrication effect resulting from the perfect sphericity of the particles (iii) production of secondary hydrates by pozzolanic reaction when RPC samples, are cured under hot environment. It is established fact that crushed quartz acts as pozzolanic material at high temperature (greater than 90 °C) [15]. Thermo-activation nature of crushed quartz enhances the amount of secondary hydrated products. The properties of RPC vary with different curing regimes, temperature and durations. Earlier studies have shown that, strength development of RPC is mainly dependent on composition of mix, type of curing, temperature of curing and duration of curing. Richard and Cheyrezy [1] have studied the composition of RPC. In this study, compressive strength up to 170 MPa was achieved with combined curing regimes such as one day Ambient Temperature Curing (ATC) followed by two days of Hot Water Curing (HWC) at 90 °C. Zanni et al. [16] have quantified the hydration process and pozzolanic reaction in RPC, under different curing regimes with different temperature ranges (90 °C, 200 °C and 250 °C) and durations (8, 24 and 48 h).

Halit et al. [17] implemented one day ATC followed by two days of Steam Curing (SC) at 90 °C for UHPC with high volume mineral admixtures. The maximum strength achieved was in the range of 153–209 MPa. Loukili et al. [18] used combined curing regimes to develop ultra-high strength concrete. Two curing regimes such as ATC and HWC at 90 °C were utilized with combined curing condition, for a duration of 5 days and 3 days. Highest compressive strength achieved in this study was in the range of 160–200 MPa. Collepardi et al. [19] have investigated the effect of different curing regimes on modified reactive powder concrete. In this study the effect of ATC with SC at 90 °C and one day of ATC with autoclave curing at 160 °C were used as curing regime. The maximum strength obtained was 200 MPa. To know the effect of temperature