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Mechanical properties of reactive powder concrete containing mineral admixtures under different curing regimes

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ABSTRACT

Mechanical properties (compressive strength, flexural strength, and toughness) of reactive powder concrete (RPC) produced with class-C fly ash (FA) and ground granulated blast furnace slag (GGBFS) were investigated under different curing conditions (standard, autoclave and steam curing) in this study. Test results indicate that, compressive strength of RPC increased considerably after steam and autoclaving compared to the standard curing. On the other hand, it was observed that steam and autoclave curing decreased the flexural strength and toughness. Increasing the GGBFS and/or FA content improved the toughness of RPC under all curing regimes considerably. Furthermore, SEM micrographs revealed dense microstructure of RPC.

1. Introduction

Reactive powder concrete (RPC) is a new generation concrete and it was developed through microstructure enhancement techniques for cementitious materials. As compared to ordinary cement-based materials, the primary improvements of RPC include the particle size homogeneity, porosity, and microstructures. The mechanical properties that can be achieved include the compressive strength of the range between 200 and 800 MPa, fracture energy of the range between 1200 and 40,000 J/m^2, and ultimate tensile strain at the order of 1% [1,2]. This is generally achieved by micro-structural engineering approach, including elimination of the coarse aggregates, reducing the water-to-cementitious material ratio, lowering the CaO to SiO_2 ratio by introducing the silica components, and incorporation of steel micro-fibers [3]. It was reported that RPC has a remarkable flexural strength and very high ductility. Its ductility is about 250 times higher than that of conventional concrete [1,2]. Low permeability, dense micro-structure and superior mechanical properties (very high compressive strength, flexural strength, fracture energy and toughness) define the RPC as an ultra-high performance concrete [4]. Nowadays, RPC seems to be a promising material for special pre-stressed and precast concrete members. This material can therefore be used for industrial and nuclear waste storage facilities [1–4]. Although production costs of RPC are generally high, some economical advantages also exist in RPC applications. It is possible to reduce or eliminate passive reinforcement using with steel fibers. And, due to ultra-high mechanical performance of RPC, the thickness of concrete elements can be reduced, which results in materials and cost savings.

Chan and Chu [3] reported that incorporation of silica fume in RPC matrix remarkably enhances the steel fiber–matrix bond characteristics due to the interfacial-toughening effect upon fiber slip. Massidda et al. [5] studied the effects of autoclaving under saturated vapor at 180 °C on the physical and mechanical properties of reactive-powder mortars reinforced with brass-coated steel fibers. Autoclaving generally has beneficial effects on the mechanical properties both in terms of flexural and compressive strength. High pressure steam curing for 3 h of specimens pre-cured at ambient temperature for 3 days, yielded flexural strength of 30 MPa and compressive strength of 200 MPa. Shaheen and Shrive [6] investigated freeze–thaw resistance of RPC. Test results showed that RPC has excellent freeze–thaw resistance with no sign of damage up to 600 cycles according to ASTM C 666 test procedure. Rougeau and Borys [7] showed that ultra-high performance concrete can be produced with ultra-fine particles other than SF such as fly ash, limestone microfiller or metakaolin. Furthermore, Kejin and Zhi [8] showed that the maximum heat of cement hydration in binary/ternary cement (fly ash and/or GGBFS) concrete decreased with supplementary cementitious material (SCM) replacements. As a result, SCM concrete generally has a lower risk of thermal cracking than Portland cement (PC) concrete.

Cement dosage of RPC is generally as high as 800–1000 kg/m^3 to achieve ultra-high strength under very low water/cement ratios. A high amount of cement not only affects the production

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costs, but also has negative effects on the heat of hydration and may cause shrinkage problems. Mineral admixtures can be a feasible solution to overcome these problems in RPC. The main objective of this research is to determine the effect of mineral admixtures on the mechanical properties of the RPC. Furthermore, this research aimed to reduce consumption of cement and silica fume in order to lower the material costs and to decrease the negative impacts (heat of hydration, shrinkage and environmental problems). Portland cement and silica fume was replaced with GGBFS and/or FA at different proportions and mechanical performance determined after different curing regimes. Test results indicate that low cement RPC has satisfactory performance compared to the conventional RPC the matrix phase of which consist of cement and silica fume. In other words, it seems that greening the RPC is also possible using with high amount of mineral admixtures.

2. Experimental

The RPC considered here is prepared by the following ingredients: Ordinary Portland cement (CEM-I 42.5-R); quartz powder (0–0.4 mm) and quartz sand (0.5–1.0 and 1.0–3.0 mm, with a specific gravity of 2.65), silica fume (SF), a polycarboxylate-based superplasticizer (SP) in conformity with ASTM C 494-81 type F and brass-coated steel micro-fibers (6 mm long with the diameter of 0.15 mm, the aspect ratio and tensile strength of the fibers is 40 and 2250 MPa, respectively). The physical, chemical and mechanical properties of cement, silica fume, fly ash and slag are presented in Table 1.

Table 2 summarizes the mixture designs of RPC produced in this study. As can be seen from Table 2, abbreviations were used for mixtures according to GGBFS and/or FA content. FA and GGBFS were denoted by F and G. FA or GGBFS ratios by cement weight were also given in the abbreviations. For instance, G10F20 means cement was replaced with 10% GGBFS and 20% FA. Moreover CTRL shows Portland cement RPC that contain only cement and SF as a binder without FA or GGBFS. Replacement ratios presented here were chosen according to results of previous study [9].

Table 1
Physical, chemical and mechanical properties of cement, silica fume, fly ash and slag

	Chemical composition (%)			
	Cement	Silica fume (SF)	Fly ash (FA)	Slag (GGBFS)
SiO_2	20.10	92.26	42.10	39.66
Al_2O_3	5.62	0.89	19.40	12.94
Fe_2O_3	2.17	1.97	4.60	1.58
CaO	62.92	0.49	27.00	34.20
MgO	1.14	0.96	1.80	6.94
Na_2O	0.30	0.42	–	0.20
K_2O	0.85	1.31	1.10	1.44
SO_3	2.92	0.33	2.40	0.72
Cl^-	0.001	0.09	–	–
L.O.I.	3.84	–	1.30	1.20
I.R.	0.63	–	–	–
F.CaO (%)	0.52	–	4.30	–
Physical properties of cement				
Specific gravity				3.13
Initial setting time (min)				130
Final setting time (min)				210
Volume expansion (mm)				1.00
Specific surface(m^2/kg)				
Cement (Blaine)				380
SF (nitrogen Ab.)				20,000
FA (Blaine)				290
GGBFS (Blaine)				396
Compressive strength of cement (MPa)				
2 days				29.9
7 days				43.2
28 days				51.9

Table 2
Mixture proportions of RPC

Material	CTRL	G10F10	G10F20	G10F30	F20	G40
Cement (kg/m^3)	830	664	581	498	664	498
SF (kg/m^3)	291	205	157	141	195	173
GGBFS (kg/m^3)	–	83	83	83	–	332
FA (kg/m^3)	–	83	166	249	166	–
1–3 mm Quartz (kg/m^3)	489	521	534	530	516	541
0.5–1 mm Quartz (kg/m^3)	244	260	266	264	257	269
0–0.4 mm Quartz (kg/m^3)	244	260	266	264	257	269
Water (kg/m^3)	151	151	151	151	151	151
SP (L/ m^3)	55	35	34	33	38	35
Water from SP	33	21	20	20	23	21
Water/cement	0.18	0.23	0.26	0.30	0.23	0.30
Water/powder	0.13	0.15	0.15	0.16	0.15	0.15
Water/powder[a]	0.16	0.17	0.17	0.18	0.17	0.17
CaO (Mol)	9.40	8.38	7.82	7.27	8.29	7.55
SiO_2 (Mol)	7.22	6.43	6.00	6.06	6.36	6.29
Steel fiber (kg/m^3)	234	234	234	234	234	234
Flow table (mm)	115	115	113	113	114	117
Molar CaO/SiO_2	1.30	1.30	1.30	1.20	1.30	1.20

[a] Calculated with total water (water + water from SP).

For each type of the proposed mixture proportions of RPC, dry ingredients (i.e. cement, SF, FA and GGBFS, quartz powders, quartz sand and silica fume) were first mixed for about 3 min at low and high speed in Hobart mixer. Water and superplasticizer were added and re-mixed for about 5 min at high speed. Subsequently, fibers were added and additional mixing was applied for about 2 min. The specimens were kept in the moulds for 16 h at room temperature of about 20° C. After that RPC specimens were removed from the steel molds. One-third of the RPC specimens were cured in water at 20° C. The other one-third of specimens were autoclaved under 2.0 MPa pressure for 8 h (210° C). Temperature and pressure reached to their maximum values in 2.5 h. Remaining specimens were exposed to steam curing at 100° C for 3 days. Heating rate of steam cure treatment was 11° C/h. This extended (3 days) high temperature (100° C) steam curing which is different from conventional curing process were preferred due to the high amount of reactive cementitious materials in RPC. Studies showed that high mechanical properties can be achieved under these conditions at early ages [1–3]. Cwirzen et al. [10] also indicated that heat treatment densified the microstructure of the RPC matrix. The specimens, which were subjected to heat treatment, were kept in laboratory conditions for cooling before testing in this study.

Prismatic specimens (40 × 40 × 160 mm) were used to determine the flexural strength and toughness. Flexural specimens were tested at the loading rate of 0.1 mm/min up to mid-span deflection of 2.5 mm under closed loop control test procedure. The specimens were loaded from their mid span and the clear distance between simple supports was 130 mm. Toughness was regarded as the area under the load–deflection curve up to 2.5 mm mid-span deflection. The compressive strength test was performed following to the flexural tests. The two broken pieces left from flexural test were subjected to compressive strength test. The loaded area under compressive strength test is 40 × 40 mm and the height of the specimens is also 40 mm. The moduli of elasticity values were determined on 100 × 200 mm cylinders. Each data presented here are the average test results of three specimens. On the other hand, flexural load–deflection curves were drawn using with one specimen graph that represents closest to the average mechanical performance.