Pergamon

Cement and Concrete Research 32 (2002) 173–177

CEMENT AND CONCRETE RESEARCH

Investigation on compounding and application of C80–C100 high-performance concrete

Jian Yin[a,*], Shiqiong Zhou[a], Youjun Xie[a], Yu Chen[b], Qinlian Yan[c]

[a]*Civil Architectural Engineering College, Central South University, 22 Shaoshan South Road, Changsha, Hunan 410075, China*
[b]*Changsha Communication College, Changsha, Hunan 410076, China*
[c]*Center of Quality Examination on Construction of Hunan, Changsha, Hunan 410007, China*

Received 26 September 2000; accepted 1 August 2001

Abstract

This paper presents the compounding technology and application of C80–C100 high-performance concrete (HPC) containing ultra-pulverized fly ash composite (PFAC) and superplasticizer. The properties of C80–C100 HPC are also studied systematically. The experimental results indicate that this concrete has excellent workability, high strength, lower drying shrinkage, outstanding volume stability, durability, etc.

Keywords: High-strength concrete; High-performance concrete; HPC; Application; PFAC

1. Introduction

As a concrete with high durability, high workability and high strength, high-performance concrete (HPC) deserves to be called the 21st century concrete [1–4]. Using composite superplasticizer and ultra-mineral powder is the most important and crucial technology in the development of HPC. Compared with ordinary concrete, HPC needs more ingredients, stricter construction technology and higher quality of administrative personnel and construction operating staff. The workability of fresh concrete, as well as the mechanical properties (especially durability) of HPC is greatly improved or raised.

Only about 390 kg/m^3 cement in concrete, 30–50% cement replaced by equal amount of pulverized fly ash composite (PFAC), and C80–C100 HPC with excellent workability (slump: 210 mm or so) are obtained in the study. Now this concrete has been satisfactorily applied to Hunan Book City engineering, and its pump height is 78 m. All these provide a reference basis for site application of this new technology to Hunan Province, then to the whole nation.

* Corresponding author. Tel.: +86-731-557-7290; fax: +86-731-557-1736.

E-mail address: yinjian1@public.cs.hn.cn (J. Yin).

2. Materials and methods

2.1. Materials

Cement: (1) Shaofeng 525 ordinary Portland cement, 28 days actual compressive strength, 53–57 MPa; and (2) Badao 625 ordinary Portland cement, 28 days actual compressive strength, 64 MPa.

Fine aggregate: Xiangjiang River sand, fineness modulus 2.88.

Coarse aggregate: Qualified 5–20 mm broken limestone and broken gravel, limestone broken index 7.6–8.6%; broken gravel is crushed from Xiangjiang River gravel, broken stone being 51–53%, broken index being 7.7–8.0%.

Superplasticizer: Naphthalene superplasticizer—TQN, FDN, FDN-W and Tanjian.

PFAC: PFAC is compounded by adding a small amount of inorganic mineral modifier into Grade I or II pulverized fly ash, is marked as PFAC I and PFAC II respectively, and the specific surface area of the former is 800 m^2/kg, and that of the latter is 600 m^2/kg. The chemical composition of original fly ash is given in Table 1.

2.2. Methods

The specimens (100 mm × 100 mm × 100 mm in size) for compressive strength testing were demoulded 24h after

PII: S0008-8846(01)00652-4

Table 1
Chemical composition of fly ash (%)

Composition	Ignition loss	Water content	SO_3	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O
Grade I	3.2	< 1	2.5	51.8	5.0	26.4	4.1	1.0	1.3	1.0
Grade II	1.1	< 1	0.4	48.2	5.6	30.5	5.3	1.1	1.3	0.5

casting and then cured in humid air with at 20 ± 3 °C and relative humidity not less than 90%. The quality of fly ash complies with the requirement of the Chinese National Standard GB1596-91. Referring to the test method of Aitcin et al. [5], cement paste flowability test (GB8077-87) and cement mortar strength test (GB177-92) are adopted to test the compatibility of cement, PFAC and superplasticizer.

3. Results and discussion

3.1. Optimum of mix proportions of C80–C100 HPC

3.1.1. Compatibility of cement, PFAC and superplasticizer

The results of the compatibility of cement, PFAC II and superplasticizer under the condition of low water–binder ratio are shown in Fig. 1 and Table 2.

From the above results, we could make the following conclusions.

(1) The best compatible match is among FND, Shaofeng 525 ordinary Portland cement and PFAC II, not only because there is an obvious saturation point, at which FDN dosage is the lowest 1.0–1.2%, but also because the mixing of PFAC II dramatically improves both the paste flowability and its strength.

(2) The second compatible match is among TQN, Shaofeng 525 ordinary Portland cement and PFAC II. First, the loss with time of paste flowability is not evident though the saturation point is rather high (1.2–1.6%). Second, the mixing of PFAC II into cement does not affect the paste flowability and its loss with time obviously. Also, the former two effects give cement mortar higher strength.

(3) The third compatible match is among Tanjian, Shaofeng 525 ordinary Portland cement and PFAC II, which is just so–so. Its saturation point is not obvious, and there is segregation phenomenon. Moreover, when Tanjian dosage is small, the mixing of PFAC II exerts a side influence on the paste flowability.

(4) The compatibility of FDN-W, Shaofeng 525 ordinary Portland cement and PFAC II is the worst, owing to high saturation point (1.5%), much flowability loss with time, and the negative action of PFAC II, no higher mortar strength, lower paste flowability.

Concrete slump and strength tests are for verifying the above conclusions. Results show that the best compatible match is among FND, Shaofeng 525 ordinary Portland

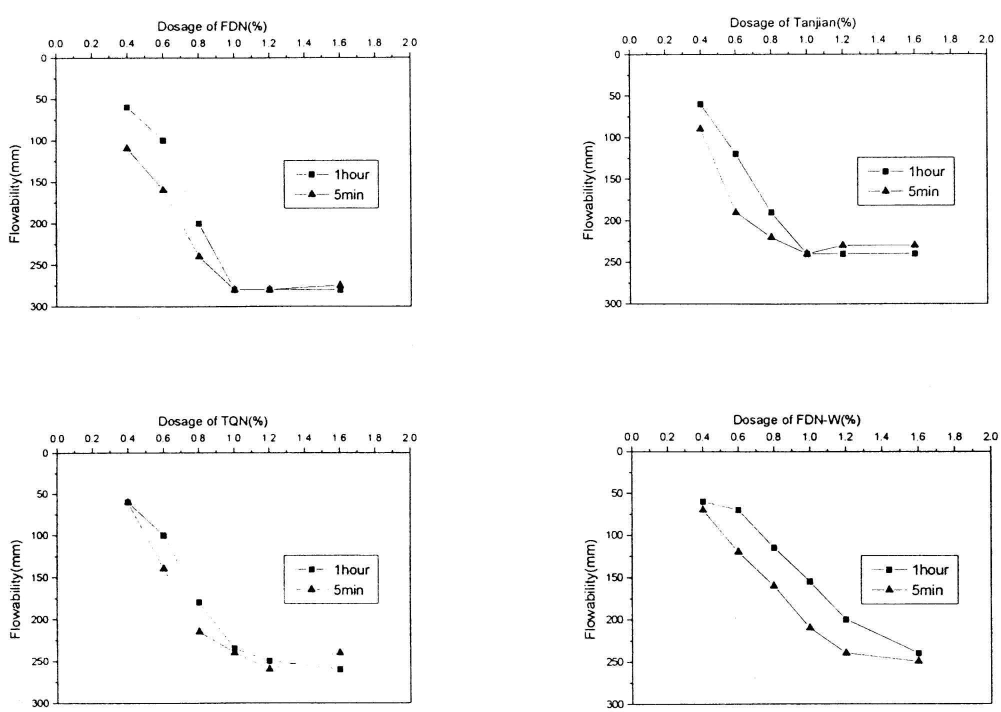

Fig. 1. Compatibility test of cement, PFAC II and superplasticizer. W/B = 0.3; temperature: 22 °C; cement: Shaofeng 525 ordinary Portland cement.

Table 2
Compatibility test of cement, PFAC II and superplasticizer — cement mortar strength test results

			Superplasticizer		Flexural strength (MPa)			Compressive strength (MPa)		
Number	Cement (g)	PFAC II (g)	Series	Dosage (%)	1 day	3 days	28 days	1 day	3 days	28 days
1	540	0	–	0.0	7.00	7.90	9.57	36.9	47.1	58.1
2	351	189	–	0.0	4.42	6.80	10.55	24.4	40.6	63.4
3	351	189	FDN	1.2	5.02	6.67	10.80	22.0	45.9	71.6
4	351	189	FDN-W	1.2	5.15	7.15	8.90	22.7	42.6	67.7
5	351	189	Tanjian	1.2	4.87	6.30	10.57	22.1	39.2	68.8
6	351	189	TQN	1.2	4.87	5.78	9.92	24.2	39.1	69.7

Shaofeng 525 ordinary Portland cement.

Table 3
Compounding test results of C80–C100 HPC

					Compressive strength (MPa)			Note		
Number	C (kg/m^3)	PFAC (kg/m^3)	W (kg/m^3)	Slump (mm)	3 days	28 days	56 days	Cement series	PFAC	Coarse aggregate
1	273	307	133	180	37.2	95.2	99.2	Ordinary 525	I	broken gravel
2	350	187	130	200	65.3	105.7	–	Ordinary 625	II	broken gravel
3	347	213	134	185	60.1	94.7	103.6	Ordinary 525	I	broken gravel
4	308	232	124	170	61.8	96.7	104.5	Ordinary 525	I	broken gravel
5	364	196	125	195	61.8	107.5	132.0	Ordinary 525	I	broken gravel
6	348	232	122	195	50.3	108.8	–	Ordinary 525	I	broken gravel
7	374	226	122	235	70.8	114.9	–	Ordinary 525	I	broken limestone
8	390	220	122	200	81.2	126.1	–	Ordinary 625	I	broken limestone
9	390	220	124	225	73.3	122.1	–	Ordinary 625	I	broken limestone
10	400	225	125	200	82.8	128.8	–	Ordinary 625	I	broken limestone

cement and PFAC II. Fresh concrete slump is more than 240 mm and slump loss after 3h is only 60 mm. Twenty-eight days of compressive strength reach 93.6 MPa.

The test conclusions of Shaofeng 525 Portland cement or Badao 625 Portland cement, superplasticizer and PFAC I are the same as the aforementioned table.

According to these results, we have chosen Shaofeng 525 Portland cement or Badao 625 Portland cement, FDN and PFAC II or PFAC to produce HPC.

3.1.2. C80–C100 HPC compounding

In order to ensure the target slump of 200 ± 20 mm, HPC mix parameters are optimized as: superplasticizer dosage 1.2–1.6%, binder material 540–610 kg/m^3, specific surface area of PFAC 600–800 m^2/kg and content 30–50% [6,7]. Compounding results of HPC are partly seen in Table 3.

3.2. Mechanical properties of C80–C100 HPC

3.2.1. Compressive strength

(1) Adopted 525 ordinary Portland cement within the dosage between 273 and 392 kg/m^3, river sand, broken gravel, PFAC I or FPAC II, high-strength HPC with excellent workability (slump: 200 mm or so) and high strength (compressive strength 28 days of 95.2–114.9 MPa) could be attained. Using 625 ordinary Portland cement 390–400 kg/m^3, super-high-strength HPC can also be achieved, and its slump surpasses 200 mm and compressive strength 28 days of reaches 128.8 MPa.

(2) In contrast with basic concrete, 1- or 3-day strength of HPC containing PFAC grows and the later strength increases notably too. Its 3- and 28-day strength rises to 8.3–26.9% and 18.3–48.9% respectively, under the prerequisite of almost equal workability.

(3) In order to improve the green degree of concrete, we have produced over 100MPa high-strength HPC, which opens another way to apply fly ash to engineering, which has been proved feasible.

3.2.2. Tensile properties

A large number of tests indicate that in pace with the increase of compressive strength f_{cu} of concrete, its split tensile strength f_{ts} and axis tensile strength f_t are raised, f_{ts}/f_{cu} being 1/11–1/19 (average value 1/15.5) and f_t/f_{cu} being

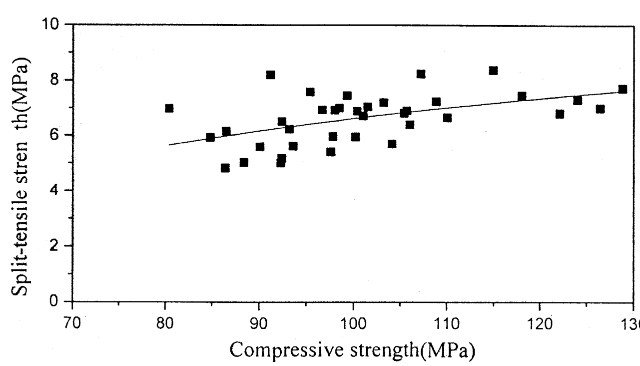

Fig. 2. Optimum regression curve of split tensile strength and compressive strength of C80–C100 HPC.

Table 4
Elastic modulus test results of HPC

Number	W/B (%)	PFAC (%)	f_{cu} (MPa)	f_{ep} (MPa)	$E \times 10^1$(MPa)
1	25.9	35.0	91.2	80.7	4.24
2	20.8	32.0	107.4	95.9	4.71
3	24.1	37.5	90.1	79.2	4.91
4	20.1	37.5	105.7	85.0	5.38
5	28.2	35.0	84.8	66.8	4.14
6	20.3	37.6	114.9	99.9	4.81
7	20.0	36.7	122.1	109.7	5.75

f_{ep}: prism compressive strength.

1/15–1/20. Relevant data show that f_{ts}/f_{cu} of high-strength concrete is about 1/20–1/24, and f_{ts}/f_{cu} of C20–C60 ordinary concrete is 1/10–1/20. So we conclude that f_{ts}/f_{cu} of HPC is higher than that of high-strength concrete, and is closer to ordinary concrete. All of these illustrate how the tensile property of HPC rises and its brittleness drops.

The axis tensile strength test result of C80–C100 HPC indicates that the ultimate tensile strain reaches 222 $\mu\varepsilon$ and average value is 212 $\mu\varepsilon$ [8]. Test value is approximately 30% higher than 150 $\mu\varepsilon$, as suggested by CER-FIP standard draft (1990).

On the basis of the split tensile strength and compressive strength test data of 37 sets of C80–C100 HPC, we made a regression analysis according to the principle of the least squares method. The best is the powder series, shown in Fig. 2.

The experience formula is: $f_{ts} = 0.18 f_{cu}^{0.79}$ (relation coefficient: R=.85; standard deviation: S.D. = 0.54).

3.2.3. Elastic modulus

The elastic modulus test results of HPC containing PFAC are seen in Table 4. It shows that the elastic modulus of high-strength HPC increases markedly in comparison with that of ordinary concrete, which indicates that it is very efficient to mix PFAC into concrete to improve the stiffness and volume stability of concrete.

3.3. Durability and long-term performance of C80–C100 HPC

3.3.1. Freeze–thaw resistance and permeation resistance

Table 5 is the result of fast permeation resistance test of HPC. The following conclusions can be made. HPC has quite an excellent permeation resistance and freeze–thaw resistance, with the evaluate sign being over S40 and over D150 separately.

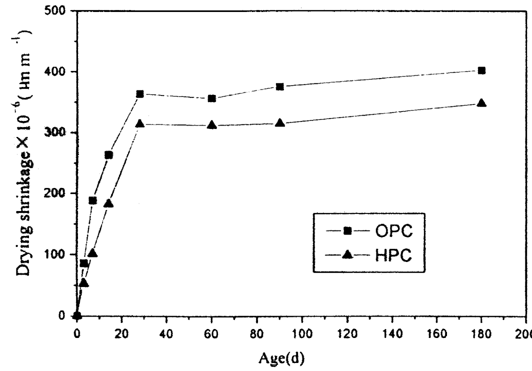

Fig. 3. Drying shrinkage change curves.

3.3.2. Protection-reinforcing bar and carbonization resistance

The special concrete specimen (slump 210 mm, 28-day compressive strength, 101 MPa), preplaced steels, containing 30% PFAC and 378 kg/m^3 525 ordinary cement, were prepared on May 1994 and were pounded on July 6, 2000, in order to examine corrosion of steel and carbonization depth in concrete. Results show no corrosion of steel and 0 mm carbonization depth, which proved that PFAC HPC has outstanding protection-reinforcing bar and carbonization resistance.

3.3.3. Drying shrinkage

Drying shrinkage is an important performance of concrete, especially of HPC, because concrete drying shrinkage causes structure cracking if there is restrain, which would do harm to the durability and volume stability of concrete. So we have done many HPC drying shrinkage tests, and the typical deformation curves are shown in Fig. 3. According to the results, the following conclusions are made. While PFAC is no more than 40%, the drying shrinkage of HPC is less than the basic concrete at any time in spite of similar slump. When PFAC reaches 50%, though the water content is only 137 kg/m^3, the early-stage drying shrinkage values (before 14 days) surpasses those of the basic concrete. Therefore, we must pay more attention to the early-stage curing of HPC before 14 days if PFAC is above 50%.

4. Application

In the center of Changsha lies Hunan Book City, a structure that stands 20 stories above ground, two stories under ground, and attains a building height of 92.4 m,

Table 5
Results of fast permeation resistance test

Sample	Mixture proportions (kg/m^3)	Slump (mm)	f_{cu}, 3 (MPa)	f_{cu}, 28 (MPa)	Average height permeated of six specimens (cm)
HPC	C:W:PFAC II:S:G:SP = 390:122:220:600:1100:10.8	200	80.3	97.9	2.24
OPC	C:W:S:G:SP = 610:140:600:1100:13.7	200	64.0	84.7	8.92

(1) Water pressure is exerted to 4 MPa at once, and then kept for 8 hours. (2) Two specimens permeated by water in OPC and none in HPC.

cast-on-spot frame shear stress wall structure. Four columns (800mm diameter × 800mm height) on the 20th floor were cast on C80 pump HPC with PFAC, pump height 78m. The whole process of mixing, pumping, vibrating and curing complies with the construction plans. Having few air bubbles, the surfaces of the reinforced concrete columns are rather smooth and have not cracked until now.

The spot C80 fly ash pump HPC mix is C:PFAC I:S:G:SP = 350:190:600:1100:140:7.56 (kg/m^3). Without bleeding, the fresh concrete (slump 195–235 mm) has very excellent viscosity and pump ability. The concrete cubic specimens (100 mm × 100 mm × 100 mm) were shaped by hand, then moved to concrete standard curing room after its final setting, and then measured its 28-day compressive strength, split tensile strength, elastic modulus and flexural strength. The test results indicate that the compressive strength even value of eight series of concrete is 88.3 MPa (standard deviation 3.5 MPa, variation coefficient 4%). By the way, the even values of split tensile strength, flexural strength and elastic modulus were 8.2 MPa, 10.1 MPa and 42.6 GPa respectively. We conclude that the split tensile strength and compressive strength ratio of HPC at 28 days is 1/11, lower than that of ordinary high-strength concrete, and the high flexural strength reaches 10.1 MPa; HPC with PFAC is proved to be tougher and less brittle.

According to the above tests on the mechanical properties of in situ concrete, the applied pump HPC with PFAC reaches the requirement of C80 and is successfully applied to concrete engineering.

5. Conclusions

The results and conclusions are summarized as follows.

(1) Adopting 525 ordinary Portland cement (minimum content 273 kg/m^3, maximum content 392 kg/m^3), river sand, broken gravel, PFAC I or PFAC II, HPC with excellent workability (slump: 200 mm) and high strength (28-day compressive strength: 95.2–114.9 MPa) can be achieved. If using 390–400 kg/m^3 625 ordinary Portland cement, we could obtain slump above 200 mm and 28-day compressive strength 128.8 MPa HPC.

(2) It is the successful application of C80 HPC containing PFAC to Hunan Book City engineering that provides a theoretical basis and in site construction model for further application.

(3) There is only 350 kg/m^3 cement in C80 HPC — the first time this is observed is nearly as domestically and as seldom overseas.

(4) The double effects of PFAC and superplasticizer give concrete a series of excellent performances, such as excellent workability, lower drying shrinkage, better durability, higher mechanical properties, etc.

(5) The experience formula with a higher, new precision expresses the relationship between split tensile strength (f_{ts}) and compressive strength (f_{cu}) of C80–C100 HPC: $f_{ts} = 0.18 f_{cu}^{0.79}$.

References

[1] F. Neiqian, High-Performance Concrete, China Construction Industry Publishing House, Beijing, 1996.

[2] W. Zhongwei, Green high-performance concrete — the trend of concrete development, China Concr. Cem. Prod. 99 (1) (1998) 3–6.

[3] P.-C. Aitcin, A.M. Neville, High-performance concrete demystified, Concr. Int. 15 (1) (1993) 21–26.

[4] W. Forster Stephen, High-performance concrete stretching the paradigm, Concr. Int. 16 (10) (1994) 33–34.

[5] P.-C. Aitcin, C. Jolicoeur, J. MacGregor, Superplasticizers: how they work and why they occasionally don't, Concr. Int. 16 (5) (1994) 45–52.

[6] Y. Jian, Z. Shiqiong, An experimental study of high-performance concrete, J. Changsha Railw. Univ. 15 (4) (1997) 18–24.

[7] Y. Jian, Z. Shiqiong, X. Youjun, Study and application of high-performance composite pulverized fly ash concrete, New Build. Mater. 228 (3) (2000) 4–7.

[8] Y. Jian, Z. Shiqiong, X. Youjun, Study of ultimate tensile strain of high-strength and high-performance concrete, Ind. Constr. 30 (7) (2000) 47–49.