Pergamon

Cement and Concrete Research 32 (2002) 477–480

CEMENT AND CONCRETE RESEARCH

# Optimum mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash

Youjun Xie*, Baoju Liu, Jian Yin, Shiqiong Zhou

*Civil Engineering and Architecture College, Central South University, 410075 Changsha, Hunan, China*

Received 18 October 2000; accepted 16 October 2001

**Abstract**

This paper presents the preparation technology of high-strength self-compacting concrete (SCC) containing ultrapulverized fly ash (UPFA) and superplasticizer (SP). After selecting the parameters of mix proportions, a SCC with good workability, high mechanical properties, and high durability is developed. The experimental results indicate that the fresh mixture has low slump loss. The compressive strength of concrete reaches 80 MPa, and the concrete presents low permeability, good freeze–thaw resistance, and low drying shrinkage.


*Keywords:* Self-compacting concrete; Ultrapulverized fly ash; Mix design; High-performance concrete; Properties

## 1. Introduction

The development of self-compacting concrete (SCC) has made casting of dense reinforcement and mass concrete convenient, has minimized noise, and has improved the quality of concrete in situ. The use of SCC in civil engineering has gradually increased over the last few years, as reported in Refs. [1–5].

In China, the strength grade of concrete used in precast concrete members adopted by railway department is C50–C60. Combined with the characteristics of concrete used in Chinese railway, high-strength SCC (Grade C60–C80) has been studied since 1995.

In this paper, high-strength SCC containing ultrapulverized fly ash (UPFA) was studied, and the assessment of workability, main mix parameters, and properties of this concrete are presented.

## 2. Experimental procedure

The cement used is 525 ordinary Portland cement made in Xiangxiang and complies with the Chinese National Standard GB175-92. The fine aggregate comes from the Xiangjiang River, and its fineness modulus is 2.83. The coarse aggregates are crushed stone or broken gravel with nominal maximum size of 20 mm. A superplasticizer (SP) based on sulfonated naphthalene formaldehyde is used in the mix, which complies with the Chinese National Standard GB8077-87. The UPFA is pulverized by a vibrating ball mill from the original fly ash produced by Xiangtan coal-fired power plant. Its Blaine surface area is in the range of 330–1100 $m^2/kg$. The chemical compositions of cement and original fly ash are given in Table 1. The physical properties of cement, fly ash, and UPFA are given in Table 2. In order to decrease the drying shrinkage of SCC resulting from so many cementitious materials, an expansion agent manufactured in Jianxi special type cement plant was used, whose commercial name is UEA (united expansive agent), its main mineral component is $C_4A_3\bar{S}$.

A normal concrete placed under vibration (OC) and the SCC presented the same mixture proportions. The cubes

Table 1
Chemical composition and properties of cement and original fly ash

| Specimen | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $K_2O$ | $Na_2O$ | $SO_3$ | LOI |
|---|---|---|---|---|---|---|---|---|---|
| Cement | 24.3 | 4.8 | 3.8 | 55.3 | 4.2 | | | 2.2 | 2.4 |
| Fly ash | 54.0 | 27.7 | 6.1 | 2.6 | 1.2 | 1.6 | 0.7 | 0.1 | 1.2 |

* Corresponding author. Tel.: +86-731-5640060; fax: +86-731-5571736.

*E-mail address*: xieyj@csru.edu.cn (Y. Xie ).

0008-8846/02/$ – see front matter 
PII: S0008-8846(01)00708-6

Table 2
Physical properties of cement, fly ash, and UPFA

| Specimen | Blaine finenesses ($m^2$/kg) | Density (g/$cm^3$) | Mean diameter (μm) |
|---|---|---|---|
| Cement | 330 | 3.15 | 29.6 |
| Fly ash | 260 | 2.03 | |
| | 330 | 2.15 | |
| UPFA | 550 | 2.46 | 13.8 |
| | 800 | 2.49 | 5.5 |
| | 1100 | 2.58 | 2.5 |

Mean particle diameter by volume.

used to assess the compressive strength had the following dimensions (100 × 100 × 100 mm), and those for unrestrained drying shrinkage: 100 × 100 × 515 mm.

The water demand of mortar was estimated according to GB/T2419-94, the compressive strength according to GBJ81-85, the drying shrinkage, freezing resistance, and permeability according to GBJ82-85.

## 3. Assessment of workability

Several methods exist to evaluate workability of fresh SCC [2,3,5–10], such as standard slump and slump flow, L-box test, Orimet method, segregation resistance (stability), and passing ability (resistance to blocking). The results obtained by comparative testing indicate that the method combining slump flow and L-box test can adequately evaluate the workability of fresh SCC with UPFA [7], and the assessment index is the following: slump, 240–270 mm; slump flow, 600–750 mm; flow velocity of L-box test ($V_L$), 35–80 mm/s.

The slump lies on the yield shear stress of the mixture, and the slump flow and $V_L$ are correlative with the viscosity. The $V_L$ is a simple index to evaluate resisting segregation of the mixture. The results indicate that the viscosity of fresh concrete is too low to resist segregation when $V_L$ is more than 80 mm/s, coarse aggregate reveals and bleeding appears; but when $V_L$ is less than 35 mm/s, the viscosity is too high to attain self-compacting.

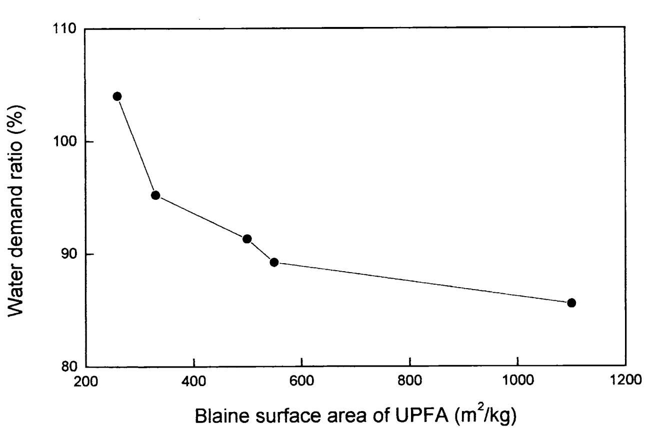


Fig. 1. Influence of UPFA fineness on the water demand of mortar.

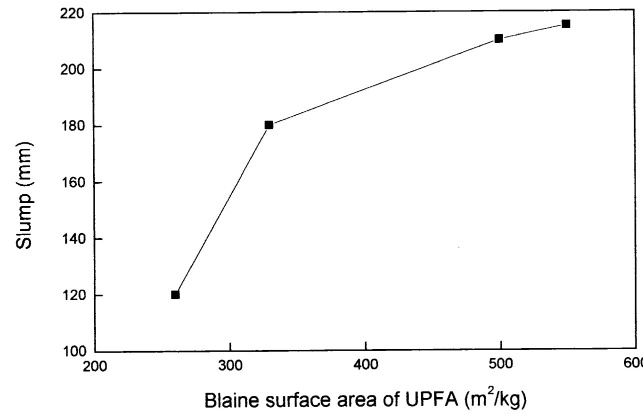


Fig. 2. Influence of UPFA fineness on the slump of SCC.

## 4. Optimum of main mix parameters of high-strength SCC

### 4.1. Selection of the fineness and content of UPFA

The influence of the fineness and content of UPFA on water demand ratio of mortar, slump, slump loss, and compressive strength of SCC is shown in Figs. 1 and 2, Tables 3 and 4, respectively. The mortar contains 210 g cement, 90 g UPFA, and 750 g standard sand. The experimental results indicate that when the Blaine surface area of UPFA reaches 500 $m^2$/kg, fresh concrete has an excellent fluidity, and when the content of UPFA is no more than 40% of all cementitious materials, the compressive strength of concrete does not significantly decrease. Therefore, a Blaine surface area of UPFA of 500–600 $m^2$/kg and a content of 30–40% were selected. The results shown in Table 3 indicate that UPFA reduces slump loss.

The main effect of UPFA is to improve the grade of the cementitious material: it acts as a filling material and densifies the matrix. UPFA makes concrete with enough viscosity to resist segregation, but the flowability is not decreased; this effect is the same as that of a viscous agent [11–13], and is necessary for SCC.

Table 3
Influence of UPFA on the slump loss of SCC

| Mix proportions (kg/$m^3$) | | | Slump (mm) | | | | Slump flow (mm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C | UPFA | UEA | 0 | 1 h | 2 h | 3 h | 0 | 1 h | 2 h | 3 h |
| 540 | – | – | 235 | 210 | 190 | 150 | 530 | 430 | 360 | 280 |
| 270 | 216 | 54 | 250 | 240 | 225 | 200 | 640 | 610 | 560 | 440 |

W = 153 kg/$m^3$, S = 600 kg/$m^3$, broken gravel = 1100 kg/$m^3$, SP = 8.1 kg/$m^3$ (1.5%C).

Table 4
Influence of UPFA on the compressive strength of concrete

| Cementitious materials (kg/m$^3$) | W (kg/m$^3$) | UPFA (%) | SP (%) | Slump (mm) | $f_{cu,3}$ (MPa) | $f_{cu,28}$ (MPa) | $f_{cu,56}$ (MPa) |
|---|---|---|---|---|---|---|---|
| 540 | 158 | 30 | 2 | 205 | 38.7 | 71.1 | 82.2 |
| 540 | 147 | 40 | 2 | 235 | 32.9 | 67.7 | 79.1 |
| 540 | 147 | 50 | 2 | 240 | 26.8 | 58.2 | 77.9 |

S = 600 kg/m$^3$, broken gravel = 1100 kg/m$^3$.

### 4.2. Selection of total cementitious material

When the content of SP is 1.3% of the total cementitious material, and the total cementitious material is shifted from 400 to 700 kg/m$^3$, the properties of concrete are different. The mix proportions and experimental results are listed in Table 5.

The results indicate that the slump, slump flow, and $V_L$ increase when the total cementitious material increases. The compressive strength ratio between SCC and ordinary concrete increases, too. In order to prepare high-strength SCC, the total cementitious material ought to exceed 500 kg/m$^3$, and the content of UPFA can be increased to reduce the cement content.

### 4.3. Selection of sand ratio

The sand ratio is the percentage of sand in total aggregate by weight, it means S/(S + G). The sand ratio increased from 36% to 48%, but other parameters were kept constant. The total cementitious material was 693 kg/m$^3$ and UPFA replaces 30% cement. The mix proportions and experimental results are listed in Table 6.

The results indicate that the higher the sand ratio, the better the workability of fresh SCC, and the smaller the compressive strength difference between SCC and OC. Thus, the sand ratio cannot be less than 40%.

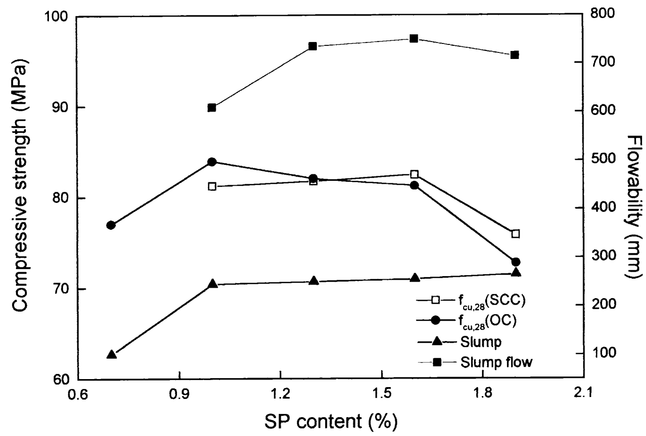


Fig. 3. Influence of SP content on the properties of SCC.

### 4.4. Selection of SP content

Based on a constant content of raw materials, the SP content varied to study the properties of SCC. The total cementitious material was more than 550 kg/m$^3$, UPFA replaced 35% cement, the water content was 175 kg/m$^3$, and the sand ratio 44%. The mix proportions and experimental results are shown in Fig. 3.

The slump and slump flow of SCC increased when the SP content increased to 1.6%. When the SP content is 1.0%, the slump of fresh concrete is 245 mm, and its slump flow is 610 mm, but when the SP content is 1.3%, the slump of fresh concrete varies less and its slump flow attains 735 mm. If the SP content increases sequentially, the slump flow has less increment, which indicated that the SP content was near saturation dosage [14]. When the SP content is higher than 1.9%, the compressive strength decreases because of bleeding. So the optimum SP content is 1.0–1.6% of the total cementitious material for a water content of 175 l/m$^3$.

Table 5
Mix proportions and experimental results — influence of the total cementitious material

| C | UPFA | W (kg/m$^3$) | S | G | Slump (mm) | Slump flow (mm) | $V_L$ (mm/s) | $f_{cu,28}$ (SCC) (MPa) | $f_{cu,28}$ (OC) (MPa) |
|---|---|---|---|---|---|---|---|---|---|
| 485 | 208 | 200 | 620 | 945 | 265 | 745 | 56 | 79.6 | 84.2 |
| 392 | 168 | 180 | 630 | 1002 | 240 | 680 | 35 | 72.4 | 79.2 |
| 333 | 143 | 180 | 693 | 1053 | 235 | 650 | 32 | 38.0 | 50.1 |
| 286 | 123 | 180 | 756 | 1100 | 195 | 510 | 14 | 27.1 | 42.1 |

Table 6
Influence of the sand ratio on the properties of SCC (crushed stone)

| W (kg/m$^3$) | Sand ratio (%) | Slump (mm) | Slump flow (mm) | $V_L$ (mm/s) | $f_{cu,28}$ (SCC) (MPa) | $f_{cu,28}$ (OC) (MPa) |
|---|---|---|---|---|---|---|
| 200 | 36 | 240 | 675 | 31 | 77.8 | 85.4 |
| 200 | 40 | 265 | 745 | 56 | 79.6 | 84.2 |
| 200 | 44 | 265 | 775 | 61 | 86.3 | 81.6 |
| 200 | 48 | 260 | 765 | 68 | 81.3 | 85.9 |

Table 7
Influence of the water content on the properties of SCC

| C + UPFA + UEA (kg/m$^3$) | W (kg/m$^3$) | Slump (mm) | Slump flow (mm) | $V_L$ (mm/s) | $f_{cu,28}$ (SCC) (MPa) | $f_{cu,28}$ (OC) (MPa) |
|---|---|---|---|---|---|---|
| 390 + 180 + 30 | 175 | 265 | 680 | 32 | 81.2 | 81.6 |
| 373 + 172 + 29 | 178 | 265 | 700 | 40 | 70.7 | 70.5 |
| 364 + 168 + 28 | 185 | 260 | 745 | 62 | 57.2 | 59.5 |
| 362 + 167 + 28 | 195 | 230 | 720 | 167 | 52.5 | – |

### *4.5. Selection of water content*

The flowability is determined by unit water content in ordinary concrete mix design. When water content is low, the workability can be improved by SP and ultrafine powders. Changing the SP content leads to a decrease in yield shear stress of fresh concrete, and it also leads to bleeding.

SCC needs a low yield shear stress of fresh concrete and a suitable viscosity. Thus, the water content has suitable range, and is affected by SP and ultrafine powder contents. When the content of SP and ultrafine powders is constant, the workability of fresh concrete depends on the water content. The influence of water content on the workability is listed in Table 7.

The experimental results indicate that when the mixture has no obvious segregation, the slump remains quite constant with the increment of water content, but the index of slump flow and $V_L$ increase. When the water content is 195 kg/m$^3$, the mixture presents segregation and bleeding, the slump flow decreases, and $V_L$ increases remarkably. The increment of $V_L$ indicates that the viscosity decreases, and segregation occurs and this concrete is no more self-compacting. So when SCC is prepared with broken gravel, the water content must not exceed 185 kg/m$^3$, and when prepared with crushed stone, the water content can reach 200 kg/m$^3$.

## 5. Durability

The SCC has higher mechanical properties and has excellent impermeability and freezing resistance. The compressive strength loss after 100 times freeze–thaw cycle is 11.0%, and the mass loss is 0. Under 2.5 MPa, the specimens do not permeate water, and the average permeability height is 15.1 mm. The drying shrinkage is lower and the value after 90 days is $383 \times 10^{-6}$ mm/mm [15].

## 6. Conclusion

(1) The workability of high-strength SCC with UPFA can be evaluated by the method combining slump flow and L-box test.

(2) The effect of UPFA on fresh concrete is to improve the viscosity of fresh concrete, and its effect is the same as that of a viscosity agent. It does not decrease the flowability of fresh concrete.

(3) The main mix parameters of 60–80 MPa SCC with UPFA are the following: the fineness of UPFA is about 500–600 m$^2$/kg, and its content 30–40%, the total cementitious material is not less than 500 kg/m$^3$, the sand ratio cannot be less than 40%, and the unit water and SP content can be determined by the workability of SCC. The limit value of water content can be selected based on the optimum SP content.

(4) This SCC with UPFA has higher mechanical properties, excellent impermeability and freezing resistance, and lower drying shrinkage.

## References


[1] K. Ozawa, K. Mackawa, H. Okamura, High performance concrete based on the durability design of concrete structures, Proceedings of the 2nd East Asia Pacific Conference on Structural Engineering and Constructure, Chiang-Mai, 1989, pp. 445–450.

[2] H. Okamura, K. Mackawa, K. Ozawa, High Performance Concrete, Gihodo Publishing, Tokyo, 1993 (in Japanese).

[3] H. Okamura, Self-compacting high-performance concrete, Concr. Int. 19 (7) (1997) 50–54.

[4] K.H. Khayat, K. Manai, A. Trudel, In situ mechanical properties of wall elements cast using self-consolidating concrete, ACI Mater. J. 94 (6) (1997) 491–500.

[5] P.J.M. Bartos, M. Grauers, Self-compacting concrete, Concrete, (4) (1999) 9–13.

[6] K.H. Kyayat, Workability, testing, and performance of self-consolidating concrete, ACI Mater. J. 96 (3) (1999) 346–353.

[7] Y. Xie, S. Zhou, J. Yin, Test and assessment of workability of fresh self-compacting concrete, Concrete, (3) (1997) 10–14 (in Chinese).

[8] P. Domone, The slump flow test for high-workability concrete, Cem. Concr. Res. 28 (2) (1998) 177–182.

[9] J. Yang, W. Qin, J. Lu, A new method to evaluate workability of high-performance concrete, Ind. Constr. 28 (4) (1998) 5–9 (in Chinese).

[10] H. Chong, F. De Larrard, The rheology of high performance concrete, Cem. Concr. Res. 26 (2) (1996) 283–294.

[11] Y. Xie, S. Zhou, J. Yin, B. Liu, Study on the effect of ultra-pulverized fly ash, J. Shandong Inst. Build. Mater. ('98 East Asia Seminar on High Performance Concrete) 12 (S1) (1998) 119–122 (in Chinese).

[12] M. Sari, E. Prat, J.F. Labastire, High strength self-compacting concrete original solutions associating organic and inorganic admixtures, Cem. Concr. Res. 29 (6) (1999) 813–818.

[13] S. Rols, J. Ambroise, J. Pera, Effect of different viscosity agents on the properties of self-leveling concrete, Cem. Concr. Res. 29 (2) (1999) 261–266.

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

[15] Y. Xie, S. Zhou, J. Yin, B. Liu, Study on mechanical properties and durability of self-compacting high performance concrete, J. Build. Mater. 3 (2) (2000) 118–123 (in Chinese).