Research on the cracking control and pumpability of HPC in S-C segment of Sutong Bridge

H. Zhang, S.K. Li & J.F. Tao
The Second Bureau of Harbor Engineering, CCCG, Wuhan, Hubei, China

ABSTRACT: The height of the main tower of Sutong Bridge is 306 meters and the strength grade of concrete casting cover the steel anchor box is C50. The Elastic Modulus between steel and concrete is different obviously, so the concrete is prone to cracking, thus the pumpability and cracking-resisting of the concrete cause much attention. In this paper, fly ash, hybrid fibers (steel fibers and polypropylene fibers), water content, and polycarboxylic water-reducing agent were used to optimize the mix proportion of concrete. The elementary mechanical properties of concrete including compressive strength, flexural strength, split tensile strength and elastic modulus were investigated and the cracking-resisting property of different concrete mix proportions was tested. The results indicated that the mechanical properties of concrete satisfied the construction requirement, the cracking-resisting property of concrete mixed with hybrid fibers was the best and the optimized concrete was pumped to the height of site.

1 INTRODUCTION

Sutong Bridge is the largest span cable-stayed bridge of the world with main span of 1088 meters, and the height of the main Tower is 306 meters. The main tower uses the steel anchor boxes outsourcing concrete composite structure, and the strength grade of concrete is C50. The composite zone of tower is the key segments that endures and transfers cable force, so the concrete shouldn’t have cracks; however, the composite segments need so much cementing material that the hydration heat of concrete is high. And the elastic modulus between steel and cement concrete is different obviously, so temperature and dry shrinkage crack is easy to occur. At the same time, the concrete requests excellent fluidity due to the pumping height.

Various references have showed that using fibers could improve the anti-cracking performance and durability of concrete. In this paper, fly ash, steel fibers, polypropylene fibers, hybrid fibers and polycarboxylic water-reducing agent were used to optimize the mix proportion. Comparative experiments on workability, elementary mechanical properties and anti-cracking performance were carried out to study the cracking control and pumpability property of concrete. It could make sure that concrete in steel-concrete composite segment of the cable tower could meet the requests of construction and durability.

2 MATERIALS AND TEST METHODS

2.1 Materials
Normal Portland (P · O) 42.5 cement of NanTong Huaxin cement factory was used, whose specific surface area was 340 m²/kg. Fine aggregate was from Jiangxi Ganjiang sand, the fineness modulus was about 2.8 and the apparent density was 2.63 g/cm³. Coarse aggregate was crushed rock whose size grade was 5~25 mm. The other materials including, fly ash, high performance water reducing agent, steel fibers and polypropylene fibers were also commercially available. Grade I fly ash was used, from Jianbi Power plant in Zhenjiang, The retardation type water reducing agent was HP400 from Shanghai Huadeng Co., and fibers used were polypropylene fibers and dumbbell-shaped steel fibers, whose length were 19 mm and 20 mm respectively.

2.2 Test methods
(1) Properties of fresh concrete were tested respectively according to GB/T50080, including the slump, gas content, density and workability etc.
(2) Mechanical properties of hardened concrete were tested according to GB/T50081.
(3) Concrete Shrinkage was tested according to GBJ82 “Testing methods for long-term and long-lasting performance of ordinary concrete”.

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(4) Slab test of early-age plastic cracking referred to CECS38.
(5) Temperature stress testing machine was used to evaluate concrete property of crack-resisting. The size of the specimen was 150 mm × 150 mm × 150 mm. During the test, make sure the length was constant all the time, measure the value of stress and temperature per 10 seconds, when the temperature of concrete fell to room temperature, began to cool until the specimen cracking. It is generally thought that the lower temperature of cracking, the better property of crack-resisting.

3 CONCRETE MIX-PROPORTIONING DESIGN

The main goal of proportioning design is to improve the properties of workability, crack-resisting and durability:

(1) To make the concrete good fluidity, workability and no segregation, mineral admixtures and high range water reducing were needed.
(2) The content of the water and cement should been controlled, using fly-ash to reduce the risk of cracking.
(3) To improve the property of crack-resisting, polypropylene and steel fibers was used.
(4) Controlling the sand ratio to optimize the proportioning design, to improve the volume stability of concrete, the sand ratio should be as little as possible.

While meeting the crack-resisting requirements in the steel concrete combined sections, C50 HPC should be prepared in the way above. Selecting the content of Cementing material 480 kg/m³, the proportion of fly ash 20%, the composition of concrete was showed in table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>(%</th>
<th>Fly ash</th>
<th>Proportion and kind of fiber</th>
<th>Mix proportion (Cementing material: sand: coarse aggregate: water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-1</td>
<td>80</td>
<td>20 /</td>
<td></td>
<td>1:1.560:2.248:0.344</td>
</tr>
<tr>
<td>M-2</td>
<td>80</td>
<td>20 0.9(PPF)</td>
<td></td>
<td>1:1.560:2.248:0.348</td>
</tr>
<tr>
<td>M-3</td>
<td>80</td>
<td>20 64(SF)</td>
<td></td>
<td>1:1.610:2.048:0.342</td>
</tr>
<tr>
<td>M-4</td>
<td>80</td>
<td>20 0.9 + 64(PPF + SF)</td>
<td></td>
<td>1:1.610:2.048:0.342</td>
</tr>
</tbody>
</table>

*Cementing material was 480 kg/m³, PPF was polypropylene fiber, SF was steel fiber, and the proportion of water reducing agent was 0.88%.

4 RESULTS AND DISCUSSION

4.1 The properties of the fresh concrete

Concrete in the steel concrete combined sections was prepared according to table 1; the results of properties of the fresh concrete test were showed in table 2.

The results in Table 2 showed that the workability of the concrete mixed with fly ash was better. The dispersion of fiber in concrete was good, but the addition of steel fiber and polypropylene fiber would affect the slump of fresh concrete. In this experiment, the slump reduced about 10%; the slump of concrete with steel fiber was lower than that of the concrete with polypropylene fiber. Except the concrete mix sample with hybrid fiber, the workability of all the concrete mix samples were good, slump loss after 1 hour was less and there was no bleeding and segregation, which was beneficial to pump highly and far.

4.2 The mechabucal properties of concrete

The results in Table 3 indicated that:

(1) The 28 days compressive strength and elastic modulus of concrete mixed with polypropylene fiber were 73.3 MPa and 4.40 × 10⁴ MPa respectively, which was a little lower than that of the control concrete; however, the 28 days flexural strength and spilt tensile strength were 6.22 MPa and 5.20 MPa respectively, which was higher than that of the control concrete.

<table>
<thead>
<tr>
<th>No.</th>
<th>Slump/ (mm)</th>
<th>Slump (kg/m³)</th>
<th>Air Content (%)</th>
<th>Slump (after 1 h)</th>
<th>Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-1</td>
<td>210/520</td>
<td>2480</td>
<td>1.8</td>
<td>200</td>
<td>good</td>
</tr>
<tr>
<td>M-2</td>
<td>200/500</td>
<td>2460</td>
<td>2.3</td>
<td>180</td>
<td>good</td>
</tr>
<tr>
<td>M-3</td>
<td>190/470</td>
<td>2490</td>
<td>2.4</td>
<td>180</td>
<td>good</td>
</tr>
<tr>
<td>M-4</td>
<td>180/480</td>
<td>2470</td>
<td>2.7</td>
<td>160</td>
<td>normal</td>
</tr>
</tbody>
</table>

Table 2. The results for the properties of the fresh concrete.

Table 3-1. The results for the mechanical properties of concrete.

<table>
<thead>
<tr>
<th>No.</th>
<th>Compressive Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3d</td>
<td>7d</td>
</tr>
<tr>
<td>M-1</td>
<td>48.5</td>
<td>54.0</td>
</tr>
<tr>
<td>M-2</td>
<td>45.7</td>
<td>54.1</td>
</tr>
<tr>
<td>M-3</td>
<td>47.5</td>
<td>54.5</td>
</tr>
<tr>
<td>M-4</td>
<td>45.2</td>
<td>53.7</td>
</tr>
</tbody>
</table>

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(2) The 28 days compressive strength of concrete mixed with steel fiber was 75.9 MPa, which was a little higher than that of the control concrete; the elastic modulus was $4.60 \times 10^4$ MPa which was almost equal to that of the control concrete; however, the flexural strength and spilt tensile strength were 6.79 MPa and 5.89 MPa respectively, which was higher than that of the control concrete obviously.

(3) The 28 days of compressive strength of concrete mixed with steel fiber and polypropylene fiber was 74.5 MPa, which was almost equal to that of the control concrete; the elastic modulus was $4.50 \times 10^4$ MPa which was little lower than that of the control concrete; however, the flexural strength and spilt tensile strength were 6.85 MPa and 6.06 MPa respectively, which was maximal in the four concrete mix samples.

4.3 Dry shrinkage of concrete

The mix proportion in table 1 was used and the specimens dimension was $100 \times 100 \times 515$ mm. The cured days of specimens were 1d, 3d, 7d, 14d, 28d, 60d and 90d. The results were showed in Figure 1.

The results indicated that the addition of steel fiber or polypropylene fiber could reduce dry shrinkage of concrete. The dry shrinkage rate of the control concrete Table 3-2. The results for the mechanical properties of concrete.

<table>
<thead>
<tr>
<th>No.</th>
<th>3d (MPa)</th>
<th>7d (MPa)</th>
<th>28d (MPa)</th>
<th>28d ($\times 10^4$ MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-1</td>
<td>3.99</td>
<td>4.23</td>
<td>5.10</td>
<td>4.67</td>
</tr>
<tr>
<td>M-2</td>
<td>4.07</td>
<td>4.95</td>
<td>5.20</td>
<td>4.40</td>
</tr>
<tr>
<td>M-3</td>
<td>4.35</td>
<td>5.51</td>
<td>5.89</td>
<td>4.60</td>
</tr>
<tr>
<td>M-4</td>
<td>4.39</td>
<td>5.60</td>
<td>6.06</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Figure 1. Dry shrinkage rate development of concrete.

was $3.816 \times 10^{-4}$ at 90d, but the dry shrinkage rate of steel fiber concrete and polypropylene fiber concrete was $3.436 \times 10^{-4}$ and $2.903 \times 10^{-4}$ respectively at 90d. Compared with the concrete with polypropylene fiber, the addition of steel fiber could reduce the dry shrinkage rate more effectively; the dry shrinkage rate of concrete with hybrid fiber or steel fiber was almost equivalent.

4.4 Crack-resisting of concrete

The mix proportion in table 1 was used, and the Temperature Stress Test Machine and slab cracking test were used to evaluate the property of crack-resisting respectively.

4.4.1 Slab cracking test

The results in the table 4 showed that the total crack area per unit area of control concrete was $636.0 \text{mm}^2/\text{m}^2$; Compared with the control concrete, the crack-resisting grade of concrete mixed with polypropylene fiber, steel fiber or hybrid fibers was grade I, and the total crack area per unit area was $76.4 \text{mm}^2/\text{m}^2$, $82.0 \text{mm}^2/\text{m}^2$ and $52.8 \text{mm}^2/\text{m}^2$ respectively.

4.4.2 Temperature stress testing machine test

Temperature Stress Testing Machine was used to evaluate the crack-resisting property of concrete in the steel-concrete composite segment. The second zero stress temperature, cracking sensitivity index and cracking temperature could exhibit the mechanical and thermal properties of concrete.

According to the experiments of different mix proportion samples and the actual project experience, the concrete has excellent property of crack-resisting[4] when the second zero temperature is less than 40$^\circ$C, the stress reserve is more than 0.35, and the cracking temperature is less than 14$^\circ$C.

The results in Figure 2 showed that:

(1) The second zero stress temperature was the temperature at which the compressive stress changed into tensile stress. It was correlated with the heat of hydration and the development of the stress. The second zero stress temperature of control concrete

Table 4. The results for slab cracking test.

<table>
<thead>
<tr>
<th>No.</th>
<th>Average crack area (mm$^2$/piece)</th>
<th>Crack No. per area (piece/m$^2$)</th>
<th>The total crack area per unit area (mm$^2$/m$^2$)</th>
<th>The crack width (mm)</th>
<th>Crack-resisting grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-1</td>
<td>17.2</td>
<td>37</td>
<td>636.0</td>
<td>0.75</td>
<td>V</td>
</tr>
<tr>
<td>M-2</td>
<td>8.49</td>
<td>9</td>
<td>76.4</td>
<td>0.16</td>
<td>I</td>
</tr>
<tr>
<td>M-3</td>
<td>9.11</td>
<td>9</td>
<td>82.0</td>
<td>0.18</td>
<td>I</td>
</tr>
<tr>
<td>M-4</td>
<td>7.54</td>
<td>7</td>
<td>52.8</td>
<td>0.13</td>
<td>I</td>
</tr>
</tbody>
</table>
(sample M-1) was 40.6°C, but the second zero
stress temperature of sample M-3 mixed with steel
fiber was minimum (33.9°C).

(2) Cracking stress of concrete could reflect the
mechanical property of concrete; and the higher
the crack stress of concrete was, the better the
crack-resisting property was. The crack stress
of the four concrete mix samples was among
2.659~3.636 MPa, stress reserve was 31.8%,
40.1%, 43.3% and 51.1% respectively. The tensile
strength of control concrete (sample M-1) was
low, and its cracking stress was minimum; how-
ever, the cracking stress of concrete mixed with
fiber was higher.

(3) Cracking temperature was the comprehensive
index which was used to evaluate the crack-
resisting property of concrete. The cracking tem-
perature of control concrete (sample M-1) was
high (14.2°C), and its crack-resisting property
was bad; The cracking temperature of concrete
mixed with fiber was lower, whose crack-resisting
property was better.

5 EXPERIMENTS IN SITE

According to the results in laboratory, the steel fiber
was used to prepare concrete which jointed the steel
anchor in the tower. Consequently, the mix proportion
in site was m(cement):m(fly ash):m(fine aggregate):
(coarse aggregate):m(water-reducing agent):m(steel
fiber):m(water) = 388.8:97.2:806:946:5.10:62.4:164.
The tested results in site showed that this steel fiber
cracked concrete could be pumped to the top of the tower by
SANY HBT90C. And the quality of the fresh concrete
was good, which could meet the requirements of construc-
tion; there was no bleeding and segregation.
Moreover, there was no cracks in the harden concrete.

6 CONCLUSIONS

(1) Hybrid fibers (steel fibers and polypropylene
fibers), fly ash, water content, and polycarboxylic
water-reducing agent were used to optimize the
mix proportion of high performance concrete
in steel-concrete composite segment. And the
pumpability and crack-resisting property of con-
crete were good.

(2) The workability of concrete with fiber was good.
The slump and its loss, air content, bleeding rate
and the density of fresh concrete satisfied the
design index.

(3) The compressive strength and elastic modulus of
concrete were similar to that of control concrete,
but the flexural strength and split tensile strength
were higher than that of the control concrete.

(4) The dry shrinkage could be reduced by mixing
fiber. The results of slab cracking test indicated
that the crack-resisting grade of concrete with
fiber was grade I. The results of temperature stress
test machine showed that the cracking temperature
of fiber concrete was low and its crack-resisting
property was good.

(5) The experiments in site showed that the high
performance concrete with steel fiber could be
pumped to the height of 306 m, and the properties
of them were excellent, and no cracks occured in
harden concrete.

REFERENCES

HSC. Beijing: The Science press.

Lee, MK. & Barr, BIG. 2004. An Overview of the
Fatigue Behavior of Plain and Fiber Reinforced Concrete.

Civil and Water Engineering Department of China, Project
Team of the Study on Security and Durability of Engi-
and Construction of Concrete Structures. Beijing: China

Zhang, G.Z. & Tu, L.Q. 2005. Study on evaluation index of