Manufacturing technology and cost analysis of SFRC segment

Wang Bin\textsuperscript{1}, Deng Yisan\textsuperscript{2}, Cheng Xiaopeng\textsuperscript{1}, Li Deming\textsuperscript{2} and Zhang Shijie\textsuperscript{2}  
\textsuperscript{1} Qingdao Metro Group Co., Ltd., Qingdao, Shandong, China  
\textsuperscript{2} Railway Academy CO., Ltd., Chengdu, Sichuan, China  
\textsuperscript{*}Corresponding author’s e-mail: ztkyywz@cragc.com.cn

Abstract. The manufacturing technology of SFRC segment is introduced. The main differences between SFRC segment and ordinary reinforced concrete segment are clarified. The cost norm of SFRC segment is established. By studying material and mechanical consumption in the production process of SFRC segment, the entire-cost of SFRC segment is obtained. Based on the production and application process of SFRC segment in the test section of Qingdao Metro Line 1, the engineering cost of SFRC segment and ordinary reinforced concrete segment were compared and analyzed.

1. Introduction

Ordinary reinforced concrete segments are mostly used in domestic shield tunnel lining. Reinforced concrete segment has the advantages of reliable mechanical strength, good corrosion resistance and mature construction technology. However, in the continuous use process, it also exposed the problems of large steel consumption, low production efficiency, brittle failure and high local damage rate. Adding steel fiber into concrete can significantly improve the tensile properties of concrete, enhance the toughness of segment, make up for many problems of ordinary segment, and then improve the economic benefits of segment use. At present, although the research on the mechanical properties of SFRC segment and its application in subway tunnel engineering have achieved rich results and experience\cite{1-2}, there is no relevant content about SFRC segment in domestic subway traffic quota\cite{3-4}. Taking the application of SFRC segment in Xiaobei tunnel and Ruiqi tunnel of Qingdao Metro Line 1 as an example, the manufacturing technology and engineering cost are analyzed.

2. Manufacturing technology of SFRC segment

Comparison between SFRC segment and ordinary reinforced concrete segment, there is no significant difference between them in transportation, driving and assembling. The difference in the production and construction process is mainly segment manufacturing\cite{5-6}.

The manufacturing technology of SFRC segment is shown in Figure 1.
The Manufacturing technology of SFRC segment is the same as that of ordinary reinforced concrete in the aspects of mold application, pouring and vibration, plastering and finishing, maintenance and other links. The main differences are concrete mix proportion adjustment, steel fiber feeding, steel fiber concrete mixing, reduction or cancellation of reinforcement framework manufacturing and installation.

The concrete mix proportion of SFRC segment can be adjusted according to the geometric characteristics and strength of steel fiber. When the length diameter ratio of steel fiber is 35-55, the sand ratio should be increased by 3% - 5% and the water consumption should be increased by 4-7kg for every 0.5% increase of steel fiber volume. The amount of cementitious material should be increased with water consumption, and the amount of admixture should be increased with the amount of cementitious material.

The feeding sequence of SFRC is as follows: ① belt transportation of sand and stone materials → ② mechanical distribution and addition of steel fiber → ③ putting cement, fly ash, water and water reducing agent into mixing tank → ④ mixing → ⑤ finished steel fiber concrete → ⑥ unloading.

The mixing time of SFRC is at least 30s longer than that of ordinary concrete. The total mixing time of SFRC shall not be less than 90s and not more than 3 minutes.

According to the engineering geological characteristics and formation pressure, the SFRC segment can be divided into two types: one is to completely cancel the reinforcement configuration and the other is to partially cancel the reinforcement configuration. The fabrication and installation process of
reinforcement framework can be cancelled or simplified in the production process of the two types segment[7].

3. Cost group price of SFRC segment
Since there is no existing engineering quota available, the supplementary quota of SFRC segment is formulated with reference to ordinary reinforced concrete segment. The supplementary quota group price is shown in Table 1.

Table 1. Cost norm of SFRC segment

| Segment type | Group price quota | Quota number | Quota name | Quota unit | Job content |
|--------------|------------------|--------------|------------|------------|-------------|
| Unreinforced SFRC segment | 3-143 (instead) | Segment fabrication \(\phi \leq 7000\) | m3 | Production, installation, disassembly, cleaning and painting of steel formwork; measurement and inspection; mixing, lifting, pouring and vibrating of concrete; steam curing, stacking and inspection of segment. |
| | BC-001 | Steel fiber addition | 100kg | Transportation and mechanical addition of steel fiber in site. |
| Less reinforced SFRC segment | 3-143 (instead) | Segment fabrication \(\phi \leq 7000\) | m3 | Production, installation, disassembly, cleaning and painting of steel formwork; measurement and inspection; mixing, lifting, pouring and vibrating of concrete; steam curing, stacking and inspection of segment. |
| | 3-144 | Reinforcement of segment | t | Fabrication, welding and molding of reinforcement; placement of embedded parts. |
| | BC-001 | Steel fiber addition | 100kg | Transportation and mechanical addition of steel fiber in site. |

The new consumption of labor, materials and machines in the manufacturing process of SFRC segment is the man hour of adding steel fiber and the One-Shift Machinery. According to the field test, 5 workers and 1 vibration machine are needed to add steel fiber. According to the steel fiber content of 40kg/m3, the total amount of steel fiber in each segment is 322.2kg. If 8 ring segment are made every day, the man hour and one-shift machinery for adding 100kg steel fiber are as follows: 0.194 working day and 0.0388 one-shift machinery\((5/(8\times322.2))\times100=0.194; 1/(8\times322.2)\times100=0.0388\). In addition, because mixing steel fiber concrete needs to adjust the mix proportion and prolong the mixing time, the labor and machinery costs in the quota are multiplied by the efficiency reduction coefficient of 1.2. The specific consumption of labor, material and machine is shown in Table 2.

Table 2. Consumption of labor, material and machine in the process of segment production

| Quota number | 3-143 (instead) | 3-144 | BC-001 |
|--------------|----------------|------|--------|
| Name         | Unit           | Segment fabrication \(\phi \leq 7000\) (m3) | Reinforcement (t) | Steel fiber addition (100kg) |
| man-day      | Working day    | 4.24 | 20.640 | 0.194 |
| Ready mixed concrete | m3 | 1.015 | - |
| Ironware    | kg             | -    | 39.900 |
| steel bar \(\phi \leq 10\) | kg | - | 0.210 |
| steel bar \(\phi > 10\) | kg | - | 0.860 |
| Steel fiber | 100kg | - | - | 100.1 |
| Steel membrane | kg | 9.725 | - |
| Screw of grouting hole | a | 1 | - |
| welding rod | kg | - | 16.896 |
| admixture SN-2 | kg | 3.938 | - |
| Release agent | kg | 0.515 | - |
| Electric | kw.h | 1.052 | - |
| Other material cost | % | 0.5 | 1.000 | 1 |
In Table 2, the material measurement error of steel fiber is calculated as less than 1%. 4-ton truck is used for material transfer in the site, and the one-shift of the truck is the same as that of the steel bar of the same weight. According to the calculation in Table 2, the Entire-cost unit price of SFRC segment can be obtained, as shown in Table 3.

Table3. entire-cost of SFRC segment

| Quota number | Quota name                  | Quota unit | The entire-cost unit price (yuan) |
|--------------|----------------------------|------------|----------------------------------|
| 1-143 (instead) | Segment fabrication ø≤7000 | m3         | 2228.56                          |
| 1-144         | Reinforcement of segment   | t          | 7602.72                           |
| BC-001        | Steel fiber addition (100kg) | 100kg     | 1756.13                           |

4. Cost comparison of SFRC segment in engineering test section

Xiaobei tunnel of Qingdao Metro Line 1 is laid northward along Renmin Road to the junction of Ruichang road. The buried depth of the tunnel is 25-36 meters. The tunnel mainly passes through slightly weathered granite (some tunnels pass through granite porphyry, lamprophyre and fine-grained granite). The tunnel is constructed by TBM method, in which 280m(K40+900~k41+180, class-Ⅲ surrounding rock) is made of SFRC segment. The tunnel adopts a circular segment with an outer diameter of 6m. The concrete grade is C50, and the steel fiber content is 40kg/m3. The reinforcement content is reduced from 98kg/m3 of ordinary reinforced concrete segment to 5kg/m3.

Ruiqi tunnel of Qingdao Metro Line 1 is laid northward along Chongqing road to north bus station. The buried depth of the tunnel is 24m, and the tunnel is mainly passes through silty clay, rhyolite and volcanic breccia. The tunnel is constructed by shield method, in which 150m(K57+380~K57+530, class-Ⅳ surrounding rock). The size and concrete grade of the tunnel are the same as those of Xiaobei tunnel, the steel fiber content is 30kg/m3, and the reinforcement content is reduced from 167kg/m3 of ordinary reinforced concrete segment to 86kg/m3.

Table4. comparison of engineering cost between SFRC segment and ordinary reinforced concrete segment

| project name | Segment type              | Segament specification | Steel fiber content (kg/m3) | Reinforcement content (kg/m3) | Unit price composition | The entire-cost unit price (yuan/ ring) | Cost comparison |
|--------------|---------------------------|------------------------|----------------------------|------------------------------|------------------------|----------------------------------------|----------------|
| Xiaobei tunnel | ordinary reinforced concrete segment | outer diameter is 6m, inner diameter is 3.4m and width is 1.5m | -                          | 98                          | Segment fabrication:8.05×2031.74=16355.51 + Reinforcement:8.05×0.098×7602.72=599 7.9 | 22353.30 | Reduce d by 15.2% |
| Ruiqi tunnel | ordinary reinforced concrete segment | -                      | 167                        | Segment fabrication:8.05×2228.56=17939.91 + Reinforcement:8.05×0.167×7602.72=102 20.72 | 26576.23 | Reduce d by 10.7% |

Through monitoring the whole process of manufacturing and construction of SFRC segment of the above two tunnels, the consumption of labor, material and machine is calculated, and then the
engineering price comparison list of steel fiber concrete segment and ordinary reinforced concrete segment is obtained. The details are shown in Table 4.

5. Conclusion and Prospect
As a new type of composite building material, SFRC has obvious advantages in improving the strength and toughness of segment structure. In 2007, the Ministry of Construction issued a notice on the promotion of scientific and technological achievements in the national construction industry, which clearly defined "making SFRC shield segment" as a promotion project. In the production process of ordinary segment, the production of steel skeleton takes up a large proportion of working hours, so the application of SFRC segment can significantly reduce the amount of steel, but also simplify the production process. The application results of Qingdao line 1 test tunnel show that under the same geological conditions, the steel fiber concrete segment of TBM tunnel can save the project cost by 15.2%, and the steel fiber concrete segment of shield tunnel can save 10.7% of the project cost. Because the material mechanical properties of SFRC segment need to be further studied, the steel fiber and reinforcement design redundancy of Qingdao Metro Line 1 test tunnel segment are large. It can be predicted that with the more and more extensive application of SFRC segment, the steel consumption and cost can be further reduced. To sum up, the popularization and application of SFRC segment not only produce huge economic benefits, but also have important significance for energy conservation and emission reduction and low-carbon environmental protection.

References
[1] CUI Guang-yao, SUN Ling-yun, ZUO Kui-xian, et al. Review of researches on mechanical behaviors of tunnel fiber reinforced concrete lining[J]. Modern Tunnelling Technology, 2019, 56(03):1-7.
[2] ZHENG Ai-yuan, XU Bin, CHEN Xiang-sheng. Study on Material Performance of SFRC segment for Subway Shield Tunnels in Marine Straturn[J]. Modern Tunnelling Technology, 2019, 56(05):211-217.
[3] WANG Hui, LIU Yun-liang. Study on Civil Engineering Cost Index of Large-diameter Shield Subway Tunnel[J]. Railway Standard Design, 2016, 60(04):95-98.
[4] XIAO Shihui. Analysis of Cost of Super Large-diameter Subsea Shield Tunnel[J]. Tunnel Construction, 2018, 38(06):907-914.
[5] LIU Ming-yue. Production technology and quality control measure of large-diameter railway shield tunnel segment[J]. China Building Materials Science & Technology, 2020, 29(02):119-120.
[6] HUO Man-lin, DU Yue-lei 1, CAO Yu-xin. Experim entalstudy on m ix proportion optim ization ofshield segm entconcrete[J]. Concrete, 2018(12):126-128+132
[7] WElying Wangyongan. Calculation of reinforcement of normal section of FRC shield segment with asymmetric reinforcement[J]. China concrete and cement products, 2019(02):30-35.