Research Status and Development Trend of Self-Compacting Concrete technology

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Abstract: The definition of self-compacting concrete is briefly introduced. The research process of self-compacting concrete in various countries in the world is studied, from the initial test to the final formation of the preliminary application specification, and it is constantly improved. The mix proportion design, working performance, testing method, application and research status of self-compacting concrete are discussed in detail, and the problems to be solved in the future and the development prospect are prospected.

1 Introduction

Self-Compacting Concrete (SCC) has high fluidity, non-segregation, uniformity and stability, which can fill the formwork space uniformly under the action of self-weight, without external vibration[1]. SCC can improve concrete quality, save cement, reduce noise, improve production efficiency, save labor, speed up project progress, improve working environment and reduce project cost. After years of research and engineering practice, good results have been achieved in the mix design, evaluation method and engineering application of SCC[2-4].

The research on workability and other aspects of SCC has aroused great interest from researchers all over the world. The United States, Japan and other countries have carried out systematic research on this kind of concrete, including workability measurement and rheological properties of SCC, mix design, admixture and admixture of SCC, and durability and structural properties of SCC. In March, 2002, EFNARC published a guide on the design and application of SCC, which is the first design and application specification of SCC[5]. In the same year, American ASTM C09 Committee began to formulate the standard of SCC[6]. Central South University, Tsinghua University, Shandong Institute of Civil Engineering and Architecture, Suzhou Institute of Concrete and Cement Products, Fuzhou University, Wuhan Institute of Urban Construction and other scientific research institutions have studied SCC, but each has its own emphasis: Central South University mainly carried out research on admixture, workability and durability[7]; In Tsinghua University, the engineering test of SCC with compressive strength of 80 MPa was carried out[8]; Suzhou Institute of Concrete and Cement Products has conducted research on preparation methods[9]; Fuzhou University has conducted research on mix design, etc.[10]; On the basis of a large number of studies, China has also issued codes and standards for the design and application of SCC. In 2004, China civil engineering society issued the Guide for the Design and Construction of SCC, in 2006, China Engineering Construction Standardization Association issued the Technical Specification for the Application of SCC, and in 2012, it issued the national industry standard, Technical Specification for the Application of SCC. SCC has been used in many projects since it was developed. 240000 m³ and 150000 m³ 25 MPa SCC were used for two anchorages of Akashi Strait Bridge in Japan[11]. In Taiwan's TC Tower, all 240 hollow columns below the 60th floor are poured with SCC from bottom to top to ensure the compactness of concrete columns[12]. The 62-story concrete-filled steel tubular column of Shuanglian Square in Seattle, USA, adopts the 115 MPa SCC pumped from the bottom layer by layer, which ensures the pouring quality and integrity[13]. Due to the difference of raw materials and construction conditions, China can't copy the Japanese mix proportion. In 1995, Chen Enyi of Tsinghua University made an experiment with the raw materials on the market, and successfully poured C25 fluid concrete on the site of Qinghe602 residential district in Beijing for wall construction, and the pouring height increased from 2 m to 4 m[14]. In September, 1996, the mixing station of Component Factory of Beijing Urban Construction Group Corporation carried out the appraisal of SCC technology, in which C30 concrete was used in practical engineering, and the pouring capacity was 3000 m³. In 1996 and 1997, Beijing Second Construction Company respectively tried to pour columns, beams, floors and foundations with SCC in three projects[15]. After that, many scientific research institutions, enterprises and even universities in China put into research and development and application. Since

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1995, the amount of irrigation has exceeded 40000 m³. It is mainly used for underground excavation, dense reinforcement, complex shape and other parts which cannot be poured or which are difficult to be poured. At the same time, it also solves the problems such as construction disturbing people, shortens the construction period and prolongs the service life of structures. The representative engineering examples include: the simplified wall of the new terminal building of Beijing Capital Airport, the reconstruction project of the commercial district on the east side of Xidan North Street, the construction project of nuclear waste containers in Daya Bay Nuclear Power Station, the protection project of historical buildings in Jimei, Xiamen, the diversion tunnel of several hydropower stations such as the Three Gorges of the Yangtze River and the diversion project of the left factory dam on the left bank, the construction project of Runyang Yangtze River Bridge and the tunnel project of Wansongguan in Fujian[14], all of which have achieved good technical, economic and social benefits. In recent 10 years, with the continuous improvement of the technical specifications for the application of SCC in China, the application of SCC has entered a full-scale outbreak stage, and its application scope has been further expanded, involving almost all engineering categories such as nuclear energy, railway, water conservancy, municipal and civil use, etc. Besides underground excavation, dense reinforcement, complex shape and other parts that cannot be poured or are difficult to pour, it also includes various reinforcement projects, shield segments, centrifugal molding and other prefabricated components. SCC mixed with steel fiber and organic fiber, lightweight aggregate molding and other prefabricated parts. The four-layer system composed of solid and liquid phases, it is proposed to set the coarse aggregate content in concrete per cubic meter and the sand volume content in mortar, and put forward an improved theoretical calculation method of fixed sand volume content according to the principle of maximum packing compactness. The four-layer system design method is generally based on the preparation of medium and low strength SCC, and for high strength SCC, the volume content of coarse aggregate should be appropriately increased; (4) Aggregate specific surface area method: Wang[22] put forward the method according to the aggregate specific surface area method and the theoretical study of surplus pulp volume.

2 Mix proportion design of SCC

The existing methods of preparing SCC are mainly based on experience, and the mix proportion design is mostly based on the experience of Japan, Netherlands, France and Sweden. In the production of SCC, the mix proportion design should ensure that the concrete can achieve the new mixing hardening performance specified in advance, and the components should coordinate with each other to prevent segregation, bleeding and settlement. From the literature of SCC research at home and abroad, the calculation methods of mixture ratio can be generally divided into three categories: the first category is based on the selected solution method of sand and gravel volume content; The second type is the design method based on empirical parameters; The third category is the calculation method of direct reference to the mix design of high performance concrete, as shown in Table 1.

| Table 1. Mix proportion design method of SCC |
| --- | --- |
| Principle | Type |
| The first category | Solution method based on selected sand and gravel volume content | Fixed sandstone volume content method |
| | Simple mix proportion design method | |
| | Four-layer system design method | |
| | Aggregate specific surface area method | |
| The second category | Design method based on empirical parameters | Parameter design method |
| | Orthogonal test method | |
| | Empirical derivation method | |
| The third category | Direct reference to the calculation method of mix design of high performance concrete | Overall calculation method |
| | Improved overall calculation method | |

The first category includes: (1) the method of fixed sand and gravel volume content: this method is adopted by European code[17], Guide to the China Civil Engineering Society[18] and British standard[19], and its principle is improved according to the characteristics of mix design proposed by Okamura; (2) Simple mix proportion design method: This method was put forward by Taiwanese scholar Nan Su et al[20]. Its basic principle is to fill loose aggregate gaps with cementitious material slurry. Compared with other volume methods, its innovation lies in putting forward the concept of compactness factor to control aggregate consumption in SCC, and then to control the fluidity and compactness of the mixture; (3) Four-layer system design method: This method was proposed by Ma et al[21]. By considering SCC as a four-layer system composed of solid and liquid phases, it is proposed to set the coarse aggregate content in concrete per cubic meter and the sand volume content in mortar, and put forward an improved theoretical calculation method of fixed sand volume content according to the principle of maximum packing compactness. The four-layer system design method is generally based on the preparation of medium and low strength SCC, and for high strength SCC, the volume content of coarse aggregate should be appropriately increased; (4) Aggregate specific surface area method: Wang[22] put forward the method according to the aggregate specific surface area method and the theoretical study of surplus pulp volume.

The second category includes: (1) the parameter design method of Wu[23-24]. The basic idea of this mix design method is that concrete is a mixture of various raw materials, and several parameters can be defined as different influencing factors of different raw materials on concrete during mix design, and on this basis, the final consumption of various materials can be obtained by solving simultaneous equations; (2) Orthogonal test method[25-28]. The idea of adopting orthogonal test (or
"factorial method") is to study the influence of different factors such as the total amount of cementitious materials, mineral material content, sand ratio, water-binder ratio, slurry volume and admixture content on the workability and strength of concrete, determine the reasonable dosage range of each parameter, and then calculate the mix proportion according to the ordinary concrete mix proportion design method. Orthogonal test method is used to test the concrete mix ratio, and the results can objectively reflect the law of preparation and optimize the mix ratio conveniently. Using orthogonal table to arrange tests can also avoid blind tests, greatly reduce the number of tests and shorten the development time; (3) Empirical derivation method: pure trial matching method, that is, based on empirical data, the unit coarse aggregate consumption, water consumption and cementing material consumption are determined, and the unit fine aggregate volume is equal to the total volume minus the volume of other materials. On this basis, the initial mixture ratio is determined for trial matching, and the workability and compressive strength are tested, and then the final mixture ratio is obtained after adjustment.

The third category includes: (1) Overall calculation method: firstly, through mathematical derivation from the assumed concrete volume model, the calculation formulas of water consumption per cubic meter of concrete and sand ratio are obtained; then, combined with the traditional water-cement ratio rule, and on this basis, through the design of composite superplasticizer mixture ratio, the admixture content is obtained. Finally, the amount of each component material in concrete can be obtained comprehensively and quantitatively, thus realizing the full calculation of the mix proportion design of self-compacting high-performance concrete from semi-quantitative to full-quantitative; (2) Improved overall calculation method[29]: when the overall calculation method of concrete mix ratio is directly used to calculate SCC, the calculated sand ratio and slurry collection ratio are both low, which is difficult to meet the requirements of self-compacting. The overall calculation method for SCC has its disadvantages and needs to be improved. According to the characteristics of SCC, combined with the method of fixed sand and gravel volume content, the improved overall calculation method is used to calculate the mixture ratio of SCC. The improved overall calculation method is a more scientific, reasonable and accurate design method of SCC mix proportion.

3 Working performance and test method of SCC

3.1 working performance of Fiber Reinforced SCC (FR-SCC)

He and Yan[30] studied the influence of polypropylene fiber on the workability of SCC. Through experimental tests, it was found that the workability of polypropylene SCC can meet the requirements of self-compacting workability when the volume ratio of polypropylene fiber reaches 0.1%. Under the condition of increasing the dosage of cementitious materials and water reducing agent, the maximum volume ratio of polypropylene fiber can reach 0.15%.

Zhang et al.[31] studies the anti-segregation performance of concrete by adding three different lengths (15 mm, 20 mm and 30 mm) of wave-shaped steel fiber into SCC. The results show that when the length of steel fiber increases to 30 mm, the fluidity and expansion of SCC can no longer meet the workability requirements. With the increase of length and content, the dispersion coefficient of steel fiber in concrete decreases, and the phenomenon of agglomeration appears, which affects the uniform distribution of steel fiber, thus making the fluidity of steel fiber reinforced SCC worse. Three kinds of steel fiber SCC have a volume content of 1.25% for 15 mm steel fiber, 0.5% for 20 mm steel fiber, and a trace amount for 30 mm steel fiber. Hossain et al.[32] mixed polyvinyl alcohol fibers with different volume ratios in SCC, and found that when the volume ratio of polyvinyl alcohol fibers is less than 0.125%, the workability of FR-SCC can meet the requirements of self-compacting.

Although adding fiber into plain concrete can improve the strength, it will correspondingly reduce the fluidity of concrete mixture and affect its self-compacting performance. Therefore, in the research of FR-SCC, there must be a prerequisite which is to ensure its self-compacting requirements. As shown in Table 2, it is the maximum volume content that some different fiber types can add on the premise of ensuring the self-compacting requirements of concrete.

| Fiber type          | Polypropylene fiber | Steel fiber with a length of 15 mm | Steel fiber with a length of 20 mm | Steel fiber with a length of 30 mm | Polyvinyl alcohol fiber |
|---------------------|---------------------|-----------------------------------|-----------------------------------|-----------------------------------|-------------------------|
| Maximum volume ratio| 0.1%                | 1.25%                             | 0.5%                              | trace                             | 0.125%                  |

3.2 Working performance of SCC-filled steel tube

The pouring quality of concrete filled in steel tube, that is, the compactness of concrete pouring, has great influence on the bearing capacity of concrete-filled steel tube columns. According to the obtained test analysis, when bearing long columns, the strength of mechanical vibration is 30% higher than that of artificial vibration, and the elastic stiffness is also 30% higher. Therefore, it is very necessary to configure SCC with higher strength and stiffness by controlling the mixture ratio of SCC in steel pipes[33]. For SCC filled with steel tubes, a slight exudation of concrete will form a considerable slurry layer at the top of components with high height or large span, which will affect the uniform stress of mixed soil.
Therefore, it is necessary to control the exudation of concrete. However, if the configuration is too controlled, the SCC will be too sticky, and the excessively sticky mixture will sometimes be wrapped with more bubbles. Based on this, it is very important to test and study the mix proportion of SCC before the project of SCC with steel pipe. Zhou\textsuperscript{[34]} takes the concrete wrapped with penisstock in the dam section of the left bank powerhouse of the Three Gorges Project as an example, and configures SCC suitable for hydraulic structures. According to the existing experimental research, the working performance indexes of SCC should reach: slump 240–270 mm, expansion ≥600 mm, Orimet method running time 8–16 s, and slump middle edge height difference 20 mm. In the aspect of bearing capacity test, Yu Zhiwu of Central South University studied the influence of different concrete strength grades, whether there are small holes in the middle of steel pipes or transverse grooves with different heights, and different loading methods on the ultimate bearing capacity of SCC filled steel pipes through axial compression test of short columns\textsuperscript{[35]}. However, the test does not completely focus on the change of bearing capacity of SCC compared with ordinary concrete, but mainly obtains the influence of grooving in the middle of steel pipe on its bearing capacity. Yao\textsuperscript{[36]} has done a lot of research on the mechanical properties of SCC-filled steel tubular. Through 18 axial compression members and 20 compression-bending members, experimental research and theoretical analysis have been carried out, taking into account the vibrating mode, section form, diameter-thickness ratio and load eccentricity of core concrete. The research shows that the calculated values of concrete-filled round steel tubular and concrete-filled square steel tubular under different codes (whether for self-compacting or common) are basically the same as the experimental results. All regulations of concrete filled steel tube are suitable for the design and calculation of ultimate bearing capacity of SCC filled steel tube under axial compression and compression and bending, and the mechanical properties of self-compacting high performance concrete filled steel tube under axial compression and compression and bending are basically similar to those of ordinary concrete filled steel tube. Yu\textsuperscript{[37]} have also conducted a series of tests on self-compacting high-strength concrete filled steel tubes, considering the influence of parameters such as cross-section form, slenderness ratio and eccentricity of steel tubes on the bearing capacity of SCC filled steel tubes columns, and comparing the test results with those calculated by AISC, EC4 and DBJ 13-51-2003. It shows that local buckling occurs in square steel tubes, while shear failure occurs in round steel tubes. Compared with ordinary concrete, the ductility of SCC filled with steel tube is worse. The results calculated by each code are also close to or slightly higher than the test results.

3.3 Test method for working performance of SCC

Workability is an important content to ensure the performance of SCC. Some researches have been carried out on the testing methods of SCC at home and abroad, and corresponding standards have been formulated. At present, there are many methods to test the rheological properties of concrete at home and abroad. The commonly used methods are slump and slump fluidity methods, that is, to test the slump height and diffusion diameter of concrete mixture, and to test the outflow time of slump cone\textsuperscript{[38–39]}. However, this method can not reflect the actual application of concrete, such as steel bar permeability and concrete filling. In order to conveniently and effectively evaluate the high fluidity, high stability and ability of SCC to pass through steel gap, some new testing methods were developed, such as inverted slump cone, L-shaped instrument, U-shaped box, V-shaped funnel, J-ring, filling box and so on. As each method has its advantages and disadvantages, a unified and mature detection method has not yet been formed. Comprehensive testing methods at home and abroad should be adopted to judge the workability of SCC, so as to judge the fluidity, clearance passing and segregation resistance of SCC. The fluidity and filling property of self-compacting concrete can be evaluated by slump spread and T500 flow time. V-shaped funnel can be used to judge the filling and viscosity of self-compacting concrete; The filling height of L-shaped meter and U-shaped meter can judge the ability of self-compacting concrete to pass through steel bars; The segregation resistance of self-compacting concrete can be judged by the stability of the mixture jumping off the table\textsuperscript{[40]}.  

4 Conclusions and Prospects

Due to many advantages of SCC, its application prospect is very broad, but its development and application history is short. There are still some problems and contents that need to be further studied:

(1) Early contraction problem. Because of the low water-binder ratio and high dosage of cementitious materials, the early shrinkage of self-compacting concrete is large, especially the early self-shrinkage. At present, the research mainly focuses on the influencing factors and degree of self-shrinkage, while the shrinkage mechanism, calculation formula and detection method of self-shrinkage need further study.

(2) Mix proportion design method. SCC requires high workability, and there are many factors involved in the calculation of mix proportion, so far there is no unified design and calculation method. With the popularization of computers, on the basis of a large number of tests, considering the influence of various factors on the workability, mechanical properties and economy of SCC, it will be possible to use computers to optimize the mix proportion design.
3. Understanding of physical and mechanical properties and durability. The construction performance of SCC has been fully studied. However, whether the physical and mechanical properties and durability of SCC have changed and their changing rules are not well understood at present after adding a large amount of superplasticizer. 

4. Seismic performance of SCC. This is an important problem in the design of concrete structures, which deserves further study. If fiber reinforced materials are mixed into it to make FR-SCC, it will play an important role in structural seismic resistance. 

5. Economic problems. The material cost of self-compacting concrete is slightly higher than that of ordinary concrete, which also becomes the main obstacle to the application of SCC. However, SCC has excellent performance which can't be compared with ordinary concrete, so we should combine SCC with environmental protection, ecological protection and sustainable development to comprehensively investigate its economic indicators, and promote the wide application of SCC in China as soon as possible.

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