RESEARCH AND APPLICATION OF SELF-COMPACTING CONCRETE

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Abstract

In recent years, self-compacting concrete (SCC) has been developed very rapidly in China due to its favorable properties in fresh and hardened state. It has gained wide use in civil engineering and achieved remarkable economic and social benefits. This paper reports some advancements of SCC in laboratory research and field application achieved by our group, including mix-proportion design, test method of workability, mechanical behavior, fire resistance and the corresponding application technology. Some suggestions in future study are also proposed in this paper.

Keywords: self-compacting concrete; mixture proportion design; workability; mechanical behavior; time-dependent behavior; fire resistance

1. INTRODUCTION

Self-compacting concrete (SCC), first developed in Japan [1] in the late 1980s and adopted in Europe and the rest of the world recently, is one of the most significant advances in concrete technology for decades. It can flow and compact in a formwork under its own weight without vibration.

Research into shrinkage and creep property of self-compacting concrete is of significant importance to realize the control of construction of bridge and ensure good structural working performance. There is still no general agreement regarding the shrinkage and creep behavior of SCC. While study[2] indicate that the shrinkage and creep compliance of SCC are higher than that of CC. Other studies[3,4] conclude that there is no significant difference between the shrinkage and creep behavior of SCC and CC.

So far, more attention has been paid to the mix proportioning, test methods of workability and mechanical properties of SCC. Little information is available about the structural performance of SCC. Study[5] investigated the Structural behavior of SCC prestressed girders. The research indicated that the deflection histories are similar for SCC and CC beams. Study[6] reported the results of experiment and F.E modelling of SCC-T-Beams and it was found that the experimental behavior of prestressed self-compacting concrete beams can be modeled with a good accuracy with the ANSYS software package.

To further promote the use of self-compacting concrete in civil engineering, Central South
University has carried out systematically deep research on the structural behavior of self-compacting concrete elements including properties of SCC beams under combined actions, long-term performance of SCC beams, properties of SCC columns. Some primary achievements are summarized as follows in this paper.

2. MIX PROPORIONING OF SELF-COMPACTING CONCRETE

Mixture proportion design of SCC has been one of the research focuses since the SCC was developed in the late 1980s. Although many mixture design methods for SCC have been proposed by researchers[1,7,8,9], each of them has its disadvantages and advantages respectively, and there is no mixture design method for SCC, which is widely recognized as the mix proportion design method for ordinary Portland concrete until now. SCC was designed by a combinative method of experience and experiment, especially for the determination of volume of aggregate for SCC.

Based on the analysis of the relationship between properties and composition, microstructure of concrete, an aggregate-space model was proposed which was supposed to benefit the design of SCC and a new mix proportion design was thereafter developed [10]. Figure 1 shows the preliminary model of SCC mixture.

\[
\frac{4(1 - V)}{D} = \Delta, \text{ spacing coefficient}
\]

\[
D = \frac{(6V)}{S}
\]

where
- $S$ — specific area of particles;
- $V$ — volume fraction of particles;
- $d$ — the mean space between particles;
- $D$ — the mean diameter of particles.

\[
\Delta = \frac{2(1 - V)}{3V}
\]
Where \( V \) — volume fraction of aggregate in SCC mixture;

It can be seen from equation (3) that there is a close relationship between volume content of aggregate and aggregate-space coefficient in mixture. Therefore, the volume of aggregate in mixture will be obtained if one can establish the relationship between aggregate-space coefficient and properties of SCC and thus the range of aggregate-space coefficient for SCC with specified properties. In our research, the relationship between the aggregate-space coefficient and the workability in fresh concrete and durability of hardened SCC was established [10]. Figure 2 gives the results of effect of aggregate-space coefficient on slump flow of fresh SCC. One can see that the slump flow of fresh SCC decreases rapidly with reduction of space coefficient when space coefficient is not more than 2. In addition, it can be also found that the slump flow of mixture is more than 500mm when the space coefficient ranges from 1.0 to 2.0. Therefore, one can preliminarily determine the aggregate space coefficient, satisfying the specified requirements of workability and durability of SCC. The reasonable space coefficient is about 1.0 to 1.7 for coarse aggregate and about 0.6~1.0 for fine aggregate in SCC mixture [8].

![Figure 2: Effect of space coefficient of coarse aggregate on flow spread of SCC](image)

So, combining the above results with equation (3), one can calculate the volume content of coarse aggregate and fine aggregate in SCC mixture according to equation (4) and equation (5) respectively [10]. And then the water to binder ratio can also be obtained according to the design strength of SCC and the cement type, mineral admixture type and replacement of cement and etc. and finally the mix proportion of SCC can be determined. This mix proportion design method was verified through our experiments and compared with the existing mix proportion methods; this method has many advantages for the aggregate content can be calculated reasonably according to the specified requirements of properties of SCC mixture.

\[
V_{oa} = \frac{2}{3\Delta_a + 2} \quad (4)
\]

\[
V_{os} = (1 - V_{oa}) \frac{2}{3\Delta_s + 2} \quad (5)
\]
Where, $V_{oa}$ and $V_{os}$ are the volume fraction of coarse and fine aggregate in SCC mixture, and the $\Delta_a$ and $\Delta_s$ are the space coefficient for coarse and fine aggregate respectively.

### 3. RECENT RESEARCHES ON PROPERTIES OF SCC

#### 3.1 Workability of fresh SCC and its assessment

As a special new type of concrete with excellent workability, how to evaluate reasonably the workability of fresh SCC mixture is of great importance. Many efforts are focused on developing a reasonable test method to test and thus assess workability of fresh SCC due to the need of application in industry and engineering and etc. Presently, there are many methods developed to test workability of fresh SCC in the world, such as slump and slump-flow test, Orimet test, V-funnel test, J-ring test, L-apparatus test, U-apparatus test, wet-sieving segregation test and penetration test and etc[9,12,13]. However, in order to evaluate fully the workability of fresh SCC, combination of two or three test methods must be used at present. This is also the reason why so many test methods have been developed. Therefore, it is complicated to test and assess the workability of fresh SCC.

Numerous works were carried out to study the factors affecting workability of SCC as well as the assessment of workability by Xie et al [14]. Some new apparatus were developed, such as bounding-table test [15] and the integrative apparatus [10, 16]. The new test method used by integrative apparatus can test and evaluate well the workability of SCC and is characterized by simplicity and convenience. Based on above achievements and extensive experimental research, the alternative test methods and the acceptance criteria for SCC with a maximum aggregate size up to 20mm are shown in Table 1 [17]. For highly congested reinforced structures and strengthening engineering with thickness of 100mm, the criterion is in accordance with that of Class I. For reinforced structures with minimum spacing of reinforcement less than 5 times size of coarse aggregate and concrete filled steel tube structures, the criteria is in accordance with that of Class II.

<table>
<thead>
<tr>
<th>Test methods</th>
<th>Criteria</th>
<th>Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td>slump-flow</td>
<td>class I: 650mm ≤ SF ≤ 750 mm class II: 550mm ≤ SF &lt; 650 mm</td>
<td>Filling ability</td>
</tr>
<tr>
<td>T₅₀₀ time</td>
<td>2s ≤ T₅₀₀ ≤ 5 s</td>
<td>Filling ability</td>
</tr>
<tr>
<td>L-box (H₂/H₁)</td>
<td>class I: Gap 40mm class II: Gap 60mm</td>
<td>Passing ability Segregation resistance</td>
</tr>
</tbody>
</table>

| U-box (Δₙ)            | class I: Gap 40mm class II: Gap 60mm | Passing ability Segregation resistance |
| vibration table test  | $f_m$ ≤ 10%                  | Segregation resistance |

$V_{oa}$ and $V_{os}$ are the volume fraction of coarse and fine aggregate. $\Delta_a$ and $\Delta_s$ are the space coefficient for coarse and fine aggregate.
3.2 Mechanical properties of SCC

Since self-compacting concrete (SCC) was introduced into the construction industry in the early 1990s, much of extensive research and development work has been concerned with the achievement and assessment of fresh properties. It is, however, the hardened properties that are of paramount interest to structural designers and users, and much data have also been obtained on all aspects of these, including compressive and other strength, elastic modulus, creep, shrinkage, bond to steel [8,13,18–21]. These data obtained are useful. However, many of these numerous investigations have been limited to a relatively small number of mixtures with a limited range of properties.

Based on the achievements documented, some extensive experiments were carried out to investigate the influence of the main parameters, such as water to binder ratio, sand to mortar ratio, volume content of coarse aggregate and curing conditions on compressive strength, elastic modulus and the stress-strain characteristics of SCC. The experimental results indicate that the water to binders ratio has great influence on the compressive strength and elastic modulus of SCC, which is very similar to that of normal concrete. The compressive strength and elastic modulus of SCC increase with the decrease of water to binder ratio. The development of compressive strength for SCC under steam curing and standard curing condition are almost the same. According to the statistical analysis of about 200 data as shown in Figure 3, it can be found that the compressive strength of SCC depends strongly on the paste. And further the relationship between compressive strength of SCC at 28 day and the water to binder ratio and other parameters was established as equation (6).

![Figure 3: The effect of paste on compressive strength of SCC](image)

\[
f_{cu} = 0.42 f_{ce} \frac{b(1-\beta)}{w} + b \cdot \beta \cdot \gamma - 1.2
\]

Where, \( f_{cu} \) and \( f_{ce} \) are the compressive strength of SCC and cement at 28 day, respectively, \( b \) represents the amount of binder used in per stere SCC. \( \gamma \) is the equivalent cementitious
coefficient of mineral admixture, such as 0.2 for limestone powder, 0.4 for class F fly ash and 0.9 for slag according to existing documents. \( \beta \) and \( w \) represent the replacement content of mineral admixture and water demand in per stere SCC designed.

In addition, with the increasing application of self-compacting concrete, it is necessary to appraise reasonably the compressive strength of self-compacting concrete in actual structure. For the sake of developing a method to inspect and appraise compressive strength of SCC in actual structure, numerous experiments were carried out and the nondestructive method and local destructive method were combined to test the compressive strength of self-compacting concrete (SCC) with two strength levels in actual structure and cubic sample by experiments in job site and laboratory. Results indicated that the compressive strength of SCC in actual structure can be appraised by the existing Rebound Test Method with modification. Other documents in this conference can be referred for details. Further works should be done to verify appraisements of mechanical properties of SCC in actual structure.

5. STRUCTURAL PROPERTIES OF SCC

5.1 Properties of SCC beams under combined actions

6 beam specimens with length of 4230mm were made including 1 normal reinforced concrete beam and 5 self-compacting concrete beams, among which beam WJN-1 is the control specimen. For self-compacting concrete beams under torsion plus bending and shear, the test results indicated that [22]

1) The cracking load and the ultimate load of the self-compacting concrete beam are almost the same as that of the normal concrete beam.

2) The failure of the beams developed as shear-torsion failure pattern. The crack developed firstly at one side and then spreaded across the four sides of the beam. Finally the cracks at the adjacent sides were connected which contributed to the failure of the beam specimens.

3) The failure surface formed at the mid-span location of the beam. There is a major crack at the mid-span location, with two cracks developing symmetrically beside the major crack.

4) The structural properties of the beam specimens during loading period can be well simulated using ANSYS software.

5.2 Long-term performance of SCC beams

Since 1999, Central South University has carried out systematic research on long-term performance of self-compacting concrete beams. Two groups of self-compacting concrete beams were investigated [23-26]. The first group consisted of 13 prestressed self-compacting concrete beams, which were tested continuously for 1580 days. The second group consisted 12 reinforced concrete beams, which were tested for 512 days. Experimental study and theoretical analysis indicate (1) the variability of test results for the same group of SCC beams is very small, which is attributed to good quality of SCC. (2) under the same environmental conditions, the shrinkage-time curve of self-compacting concrete beam is very similar to that of normal concrete beam. (3) Tensile reinforcing ratio and degree of indeterminacy have great impact on long-term behavior of self-compacting concrete beams. (4) The deflection creep coefficient of SCC beams is almost the same as that of normal concrete beams. Extra precautions considering shrinkage and creep behavior are probably not needed for the use of SCC in engineering practice. (5) the test beams were modeled by section analysis using modified MC 90 creep and shrinkage model and age-adjusted effective modulus method. The
calculated results correlate well with the test ones. The extended grey dynamic model considering the influence of loading time on creep of concrete was used to predict the long-term deformation of 6 self-compacting concrete beams on the basis of short-term experimental data. The predicted values by extended grey dynamic model are in good agreement with the tested ones.

5.3 Properties of SCC columns

Utilizing the strength criterion based on damage Poisson’s ratio and axial compressive stress-strain relations for laterally confined concrete under axial compression, based on continuum mechanics, the mechanical model of concentric cylinders of circular steel tube with concrete core was determined. The elasto-plastic analysis method of CFST stub columns both at room temperature and at high temperatures was proposed, and a computer program was developed. Through analyzing the behavior of CFST stub columns, it was pointed out that the confinement effect decreased when axial pre-stress in steel tube, and for the concrete confined steel tube, the confinement effect strengthened but the composite elastic modulus diminished.\[27-30\]

Based on elasto-plastic analysis method, the numerical constitutive model for the concrete filled steel tubes was determined, the practical calculation formulas of composite axial stiffness and axial ultimate capacity for CFST stub columns were proposed, and the practical calculation methods of axial force-strain relations for the composite section were presented. Based on plane section assumption, layered method was applied to calculate the axial force-moment-curvature relations for the composite section of CFST beam-columns, the practical calculation formulas of composite flexural stiffness, flexural capacity, axial force-moment interaction equation were proposed, and practical calculation methods of axial force-moment-curvature relations for the composite section of CFST beam-columns were presented. Fiber model method based on partial sinusoidal shape was applied to calculate the load-deformation relations of CFST columns under eccentric loading with equal or unequal end-moment, and the practical calculation formulas of load bearing capacity for CFST columns under eccentric loading were presented. Good agreement is obtained between these predicted results and experimental results.\[31-34\]

17 CFST stub columns under concentric compression, 4 CSFT members under pure bending, and 8 CFST columns under eccentric compression with equal end-moment were investigated, the behavior of load capacity, load-deformation relations, and load-strain ratio relations of the specimens were discussed. Combined with the test results by other researchers, the reliability of the elasto-plastic analysis method, layered method, fiber model method, the practical calculation formulas and the practical calculation methods was verified.\[33-35\]

5.4 Properties of SCC columns under fire

A total of 11 circular concrete-filled steel tube stub columns shown in Fig.9 were tested. During the experiment, the loads were kept constant while the temperature rises. The measurements include the change of temperature at the surface of steel tube and the change of longitudinal deformation and lateral displacement at the midpoints of the specimens with the time under fire. The experiment was carried out on the large-size assembled multi-function electronic furnace developed by the research center of structural and municipal engineering in Central South University. The test setup was shown in Fig. 4.

The typical failure pattern of self-compacting concrete column after fire is flexural failure.
with local buckling and wrinkle, which are shown in Fig.5. When the experiment was finished, the protective layer of the elements which is still under the duration of fire resistance remains integrity with only local cracks, while the protective layer of the mid-part of specimen spalled off and completely fell off with the cooling of the specimen, which was shown in Fig 6.

The test results indicate that

1. The protective layer can slow down the velocity of temperature rise of the surface of steel tube, thereby increasing the duration of fire resistance of the self-compacting concrete column.

2. The concrete filled steel tube can easily burst, but the protective layer can effectively prevent it.

3. The eccentric ratio and the axial-compression ratio have great influence on duration of fire resistance, longitudinal deformation vs. time and lateral displacement vs. time, while the influence of steel ration is relatively small.

6. APPLICATION OF SCC

Self-compacting concrete has gained wide use in strengthen engineering of reinforced concrete structures, for it is difficult to vibrate concrete with the existing concrete construction technologies. The use of SCC can make the construction convenient, and also improve the construction quality. Compared with other strengthen techniques, the construction cost can also be reduced obviously. So far, self-compacting concrete has been widely used in civil engineering [37-48]. Fig.7, 8 shows the application of SCC in Xiangya hospital in Changsha city in China, which is an old building with more than 90 years use. The hospital must be kept to be a memorial of Sino-America friendship and it needs strengthening for it cannot meet the current design code. Other applications include Strengthening of main arch rib of Bayi road arch bridge in Chansha city, strengthening of shear walls of Mingyuan building in Chenzhou city, and also the pouring of concrete in the prestressing of beams of the underground chamber in Chongqing opera house, etc. The use of SCC made the strengthen construction and the pouring of concrete into densely reinforced area easier and achieved both social and economic benefits.
7. CONCLUSION

Self-compacting concrete has optimized performance characteristics. The durable and reliable concrete structures can be achieved through lower water to cementitious ratio and use of larger amounts of mineral fillers.

New mix-proportion design and new test method of workability for SCC were developed. Extensive experiments and theoretical analysis indicate that the existing structural design and analysis method for normal concrete are applicable to SCC.

Relevant techniques should be developed and rational training and qualification systems for engineers should be established to promote the rapid diffusion of the techniques for the production of self-compacting concrete and its use in construction.

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REFERENCES


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