

Chapter 2

Self-Compacting Concrete

Abstract Self-compacting concrete is the highly flowable, non-segregating concrete that can spread into place, fill formwork, and encapsulate even the most congested reinforcement by means of its own weight, with little or no vibration. It delivers these attractive benefits while maintaining or enhancing all of customary mechanical and durability characteristics of concrete. Adjustments to traditional mix designs and the use of superplasticizers create this concrete that can meet flow performance requirements. The self-compacting concrete is ideal to be used for casting heavily reinforced sections or be placed where there can be no access to vibrators for compaction and in complex shapes of formwork which may otherwise be impossible to cast, giving a far superior surface to conventional concrete.

Keywords Concrete • Self-compacting • Mix-design • Test methods

2.1 Introduction

Compaction of concrete is often seen as the Achilles' heel of traditional concrete. No matter what type of building structure it is, the concrete used should be sturdy enough and well compacted. The principal objectives for compacting concrete are as follows: (1) to ensure attaining maximum density by removal of any entrapped air and (2) to ensure that the concrete used is in full contact with both the steel reinforcement and the formwork. Ensuring the above two points not only provides additional strength to the structure, but also does benefit to the appearance of final product. The compacting of conventional concrete is performed through external force of vibrators. However, the vibrators are incapable in reinforced intensive engineering, deep structural members, and wall element, where the concrete block, segregation, bleeding, and settlement will take place. As a result, mechanical properties, durability, and quality of surface finish of the concrete are reduced. Furthermore, if the workability is poor, high quality of infrastructure construction depends more on the skilled workers and the more energy is needed to form

concrete shapes. Therefore, it is important to develop a concrete with good workability, especially self-compactability.

This chapter will provide a systematical introduction to the self-compacting concrete (SCC) with attentions to its definition, classification, principles, research progress, and applications.

2.2 Definition and Classification of Self-Compacting Concrete

SCC is also named as self-consolidating concrete, self-leveling concrete, or vibration-free concrete. It has low yield stress, high deformability, and moderate viscosity. These are necessary to ensure uniform suspension of solid particles during transportation and placement until the concrete sets with little or no vibration. SCC can densely fill into every corner of a formwork, totally by means of its own weight without the need for vibrating compaction. The prototype of SCC was completed by Okamura for the first time in 1986 and was used for settling the durability problems due to the reduction in the numbers of skilled workers available in Japan's construction industry. SCC has the advantages of high liquidity, no segregation, and bleeding phenomenon compared with normally vibrated concrete (NVC). Besides, the application of SCC in a large amount will accelerate the construction and shorten the duration of construction because of the elimination of time-consuming mechanical vibrating procedure. The advantages of SCC over NVC are illustrated in Fig. 2.1 [1]. According to the raw materials used to fabricate SCC, the classification of SCC is summarized in Table 2.1.



Fig. 2.1 Advantages of SCC over NVC

Table 2.1 Classification of SCC

Criteria	Categories
Type of mineral mixtures	SCC incorporated with fly ash
	SCC incorporated with silica fume
	SCC incorporated with limestone powder
	SCC incorporated with marble dust
	SCC incorporated with blast powder
	SCC incorporated with metakaolin
	SCC incorporated with palm oil fuel ash
	SCC incorporated with rice husk ash
	SCC incorporated with sawdust ash
	SCC incorporated with bagasse ash
Type of fibers	SCC incorporated with steel fiber
	SCC incorporated with polypropylene fiber
	SCC incorporated with hybrid fiber
Type of aggregates	SCC with normal aggregate
	SCC with lightweight aggregate
Size of minimum particle	Normal SCC
	SCC incorporated with nanomaterial

2.3 Principles of Self-Compacting Concrete

2.3.1 Raw Material Selection Principles

The raw materials used for fabricating SCC include cement, water, sand, gravel, and chemical admixtures, and they are almost the same as those of NVC. The use of chemical admixtures is essential to increase workability and reduce segregation during the production of SCC. As shown in Fig. 2.2, superplasticizer (SP) is always necessary to get high flowability with little change in viscosity. If needed, low dosages of viscosity-modifying admixtures can be used to eliminate the unwanted bleeding and segregation phenomenon. The quality and type of cement used to fabricate SCC are similar to those used in NVC. The maximum size of aggregates in SCC is always limited to 20 mm to decrease segregation. For example, the maximum size of the aggregates depends on the particular application and is usually limited to 20 mm in the European standard, whereas in the Chinese standard, it is defined that the maximum size of the aggregates should not exceed 20 mm and even not more than 16 mm for complex shape structures, vertical compact structures, and other particular applications. In addition, the Chinese standard also provides some requirements about the content of aggregate shape, silt, and clay (as listed in Table 2.2) [2].

Many types of fillers may be used to increase the viscosity of SCC such as fly ash, glass filler, silica fume, stone powder, quartzite filler, and ground blast furnace slag. It should be noted that the particle sizes of the used fillers should be less than

Fig. 2.2 Role of SP

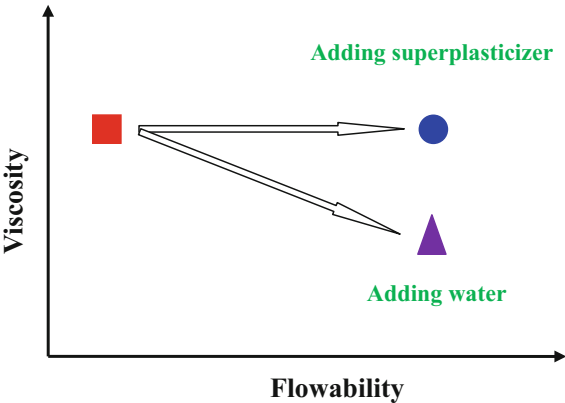


Table 2.2 Performance indicators of aggregates of SCC in Chinese standard [2]

Items	Flat-elongated particles content	Silt content	Clay content
Indicators	≤ 8%	≤ 1.0%	≤ 0.5%

0.1 mm, while their specific surface area should be more than 2500 cm²/g. Small particle size may cause alkali–silica reaction. In addition, some nanomaterials, such as nanosilica, are also introduced into SCC to increase the viscosity.

2.3.2 Mix Design Principles

Mix design plays a very important role in preparing SCC. Under the precondition of guaranteeing sufficient strength, a proper mix design can not only obtain mortar or paste with high compacting property, but also enhance the resistance of concrete to segregation between coarse aggregate and mortar when the concrete flows through the confined zone between the reinforced bars.

More water, higher ratio of paste to aggregates, and more content of water-reducing agent are necessary to get higher flowability. However, these factors will increase the possibility of segregation of fresh mixture. An increase in water/cement ratio can improve the flowability of fresh concrete, but does harm to the strength of harden concrete. Therefore, an effective mix design of SCC is needed to balance the properties of fresh and hardened concrete.

The frequency of contact and stacking of coarse aggregates will increase when the concrete with high flowability is deformed, particularly near steel bars or other obstacles. In the mortar with low viscosity, sand will be blocked by coarse aggregates and only paste and water can pass through the interspace among aggregates. Therefore, the SCC with high flowability should have two characteristics, i.e., limited content of coarse aggregate and enough viscosity. The volume

content of coarse aggregates is an important parameter to control segregation of SCC. The mortar of SCC is mainly composed of sand and cement paste. Previous research results have shown that the probability of blocking increases sharply with the volume content of sand when the volume content of sand in mortar exceeds 42%. Moreover, the probability of blocking has reached up to 100% when the volume content of sand in mortar more is more than 44% (as shown in Fig. 2.3) [3]. Therefore, the volume content of sand in mortar should not exceed 42%. In general, the mechanism for achieving self-compacting ability is shown in Fig. 2.4.

In 1995, Okamura and Ozawa first came up with the method for SCC design as shown in Fig. 2.5. The principles mainly include three aspects, i.e., the limited aggregate content, the low water-to-powder ratio, and the use of SP. A comparison between the mix proportion of SCC and that of conventional concrete is shown in Fig. 2.6 [4]. The “Standardized mix design method of SCC” in China starts with the packing of all aggregates (sand and gravel together) and then fills the gaps between aggregates with paste. This method is easier to be carried out, and the adopted paste dosage is relatively low. The “Specification and Guidelines for Self-compacting Concrete” in European gives typical ranges for proportions and

Fig. 2.3 Relationship between the volume content of sand in mortar and the probability of blocking

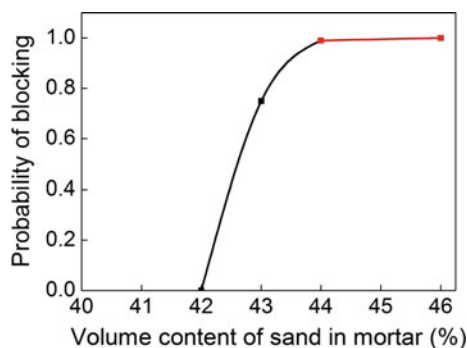
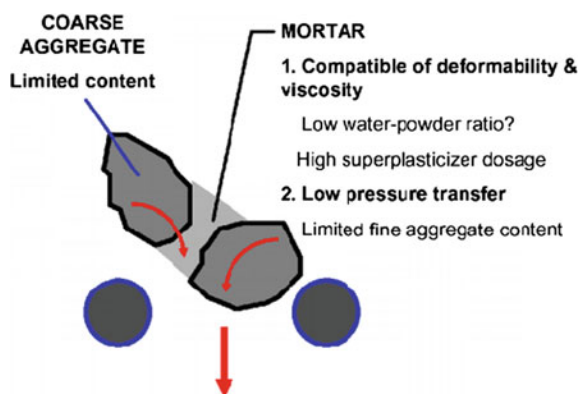


Fig. 2.4 Mechanism for achieving self-compacting ability. Reprinted from Ref. [4], with permission from ACT



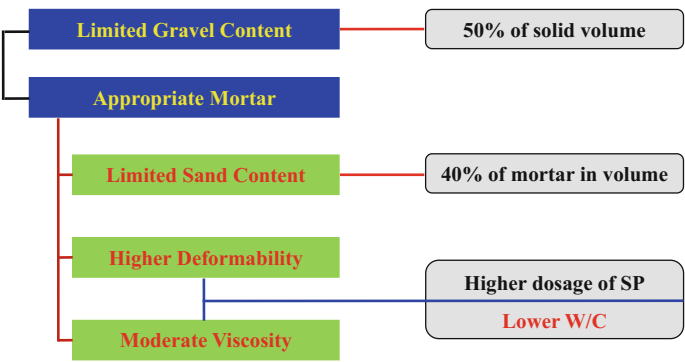


Fig. 2.5 Methods for achieving self-compactability

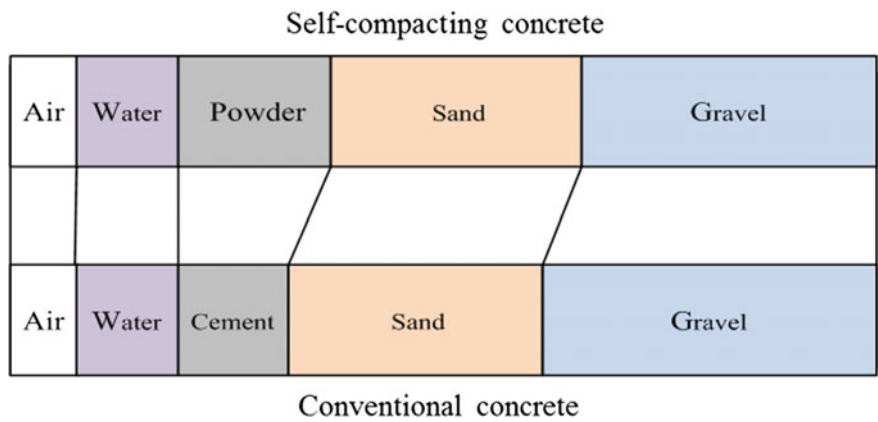


Fig. 2.6 Comparison between the mix proportion of SCC and that of conventional concrete. Reprinted from Ref. [4], with permission from ACT

quantities of raw materials in order to obtain the self-compactability and provides a sand content to balance the volume of other components.

2.4 Current Progress of Self-Compacting Concrete

SCC has been described as “the most revolutionary development in concrete construction for several decades.” The research and application of SCC has grown tremendously since its inception in the 1980s. It is mainly focused on three aspects: test methods of self-compacting property, property of fresh self-compacting concrete, and properties of hardened self-compacting concrete.

2.4.1 Test Methods of Self-Compacting Property

Workability is a key performance of SCC, which indicates the self-compacting property of SCC and is the index for mixture design adjusting in SCC preparation. The workability of SCC is also called the self-compacting ability, and it includes filling ability, passing ability, and segregation resistance. The filling ability is that SCC can densely pack itself in the formwork by its own weight. The passing ability means that SCC can smoothly flow through narrow openings without blocking and packing. The segregation resistance refers to that SCC has enough cohesive force to keep aggregates and mortar together, remaining homogeneous during the process of transporting and pouring.

Because most of the test methods for the workability of NVC are not available for SCC, some specialized methods have been successively developed to test the self-compacting ability of SCC. These specialized test methods are summarized in Table 2.3 and will be detailed as follows.

(1) Slump flow test method

Slump flow is used to assess the horizontal free flow of SCC in the absence of obstructions. It was first developed in Japan for assessment of underwater concrete [5]. Slump flow is an average value of the maximum diameter and the diameter perpendicular to the maximum diameter when the flow stops. The diameter of the concrete circle is a direct test index for characterizing the filling ability of the concrete. Besides slump flow, the slump flow time is also an acquired index to be tested when slump flow gets 500 mm (remarked as T500). The detailed test process of the slump flow and the slump flow time is illustrated in Fig. 2.7. The bigger the slump flow value, the greater its ability to fill formwork under its own weight. A value of at least 650 mm is required for SCC. The T500 time is a secondary indicator for characterizing SCC. A shorter time indicates greater flowability. Brite

Table 2.3 Test methods for self-compactability of SCC

Properties	Methods	Eurocode	Chinese code
Filling ability	Slump flow Abrams cone	650–800 mm	550–850 mm
	T ₅₀ cm slump flow	2–5 s	2–5 s
	V-funnel	8–12 s	–
	Orimet	0–5 s	–
	U-box	H ₂ –H ₁ = 30 mm max	–
Passing ability	J-ring	0–10 mm	25–50 or 0–25 mm
	L-box	H ₂ /H ₁ = 0.8–1.0	–
Segregation resistance	GTM screen stability	≤ 15%	≤ 20% or ≤ 15%

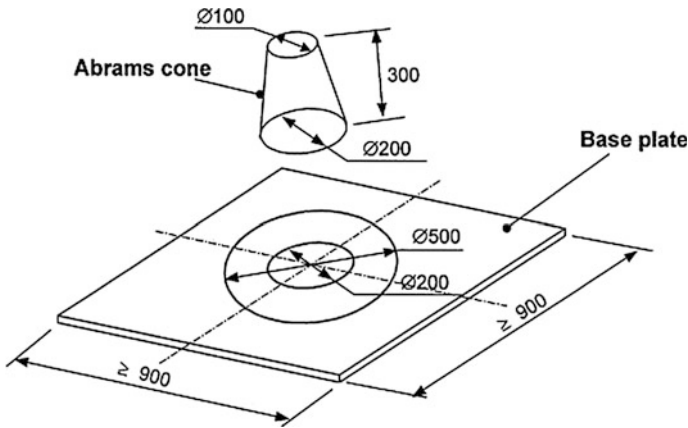
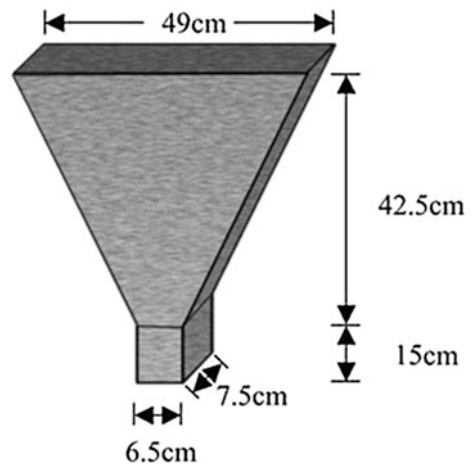


Fig. 2.7 Slump flow test method. Reprinted from Ref. [7], Copyright 2009, with permission from Elsevier

Fig. 2.8 V-funnel apparatus



EuRam's research suggested that a time of 3–7 s is acceptable for civil engineering applications and 2–5 s for housing applications [6].

(2) V-funnel test method

V-funnel test method was developed in Japan by Ozawa et al. [8]. The test equipment is a V-funnel as shown in Fig. 2.8. This method can be used to characterize the filling ability (flowability) of the concrete with the maximum aggregate size of 20 mm. The V-funnel is filled with about 12 L of concrete, and the time taken for it to flow through the apparatus is measured. Later, the funnel can be refilled with concrete and left for 5 min to settle, and the flow time is measured again. The shorter flow time indicates the greater flowability. The concrete with a

flow time below 10 s can be considered as SCC. After 5 min of settling, segregation of concrete will show a less continuous flow with an increase in flow time. Therefore, the longer the flow time, the more serious the segregation.

(3) Orimet test method

Orimet test method, put forward by Bartos, also has been used to test the workability of SCC [9]. The apparatus is shown in Fig. 2.9. The principle of test is that the Orimet flow rate under deadweight in standpipe is mainly affected by the viscosity coefficient of mixture. The test condition is that the concrete with high flowability does not segregate during the test process. The mixture flow rate is marked as V_0 and can be calculated by using Eq. (2.1). The higher the V_0 , the smaller the viscosity coefficient. The concrete with a flow time of 5 s or less can be considered as SCC.

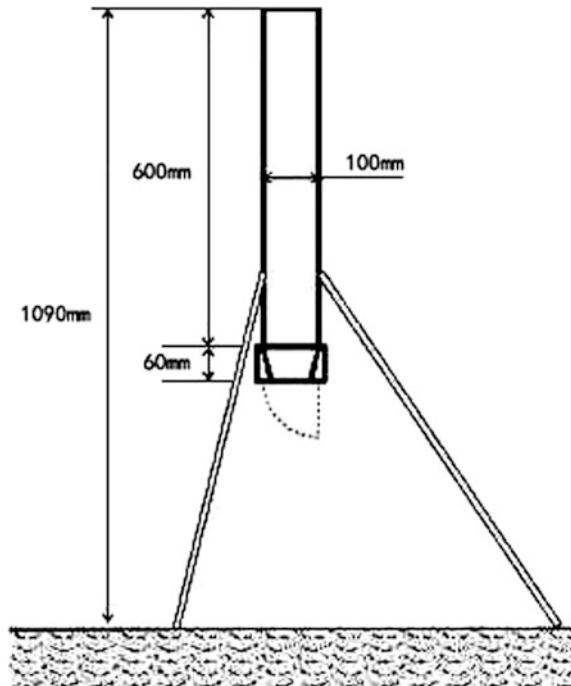
$$V_0 = V_m/t \quad (2.1)$$

where V_0 is the mixture flow rate, V_m is the total volume of concrete in standpipe, and t is the time of concrete in standpipe.

(4) U-box test method

U-box test method was developed by the Technology Research Centre of the Taisei Corporation in Japan for characterizing the filling ability of SCC [9]. The

Fig. 2.9 Orimet test method



equipment (as shown in Fig. 2.10) consists of a vessel that is divided by a middle wall into two compartments. The left-hand section is filled with about 20 L of concrete, and then, the gate lifts and concrete flows upward into the other section. The height of the concrete in both sections can be measured. If the concrete can flow through a height over 320 mm, the concrete can be judged as SCC.

(5) J-ring test method

J-ring (as shown in Fig. 2.11) is composed of a steel ring with sixteen evenly spaced steel bars and used to check the passing ability of SCC. The test parameters are the maximum diameter and the diameter perpendicular to the maximum diameter

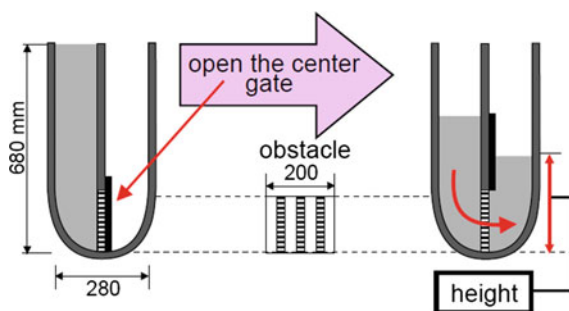


Fig. 2.10 U-box test method. Reprinted from Ref. [4], with permission from ACT

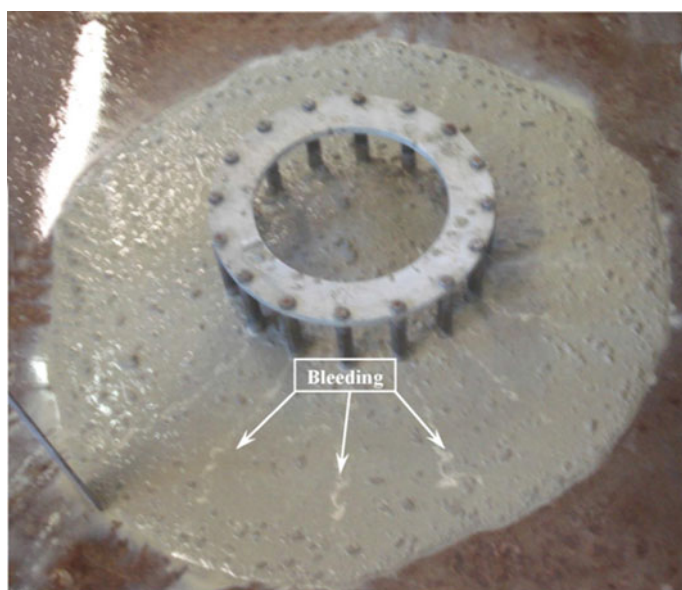


Fig. 2.11 J-ring test method. Reprinted from Ref. [10], Copyright 2015, with permission from Elsevier

when SCC stops flowing. The J-ring test method can also be used in conjunction with the slump flow test method. The difference value between the slump flow and the average value of the two diameters is called the passing ability indicator. In Chinese standard, the passing ability indicator of SCC is less than 50 mm. In addition, obvious blocking of coarse aggregates around the reinforcing bars can be detected visually by using this method.

(6) L-box test method

L-box (as shown in Fig. 2.12) consists of a rectangular-section box in the shape of an “L,” with a vertical and horizontal section, separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted. The test procedures are as follows: (1) Fill the vertical section with concrete; (2) lift the gate to let the concrete flow into the horizontal section; (3) measure the time taken to reach 200 and 400 mm at horizontal section, and mark the time as T200 and T400, respectively; and (4) record the height (H_1 and H_2 in Fig. 2.12) of the concrete at the end of the horizontal section when the flow stops. The T200 and T400 are taken as indicators to characterize the filling ability of SCC, while the proportion of H_2/H_1 is an indication of the passing ability or the degree to which the passage of concrete through the bars is restricted.

The L-box test is a widely used test method, suitable for laboratory and perhaps site use. It can assess the filling and passing ability of SCC and can visually detect serious lack of stability (segregation). Moreover, obvious blocking of coarse aggregates behind the reinforcing bars can also be detected visually. However, it is unfortunate that the dimension and arrangement of L-box is unified. The minimum acceptable value of H_2/H_1 is 0.8 for SCC [6].

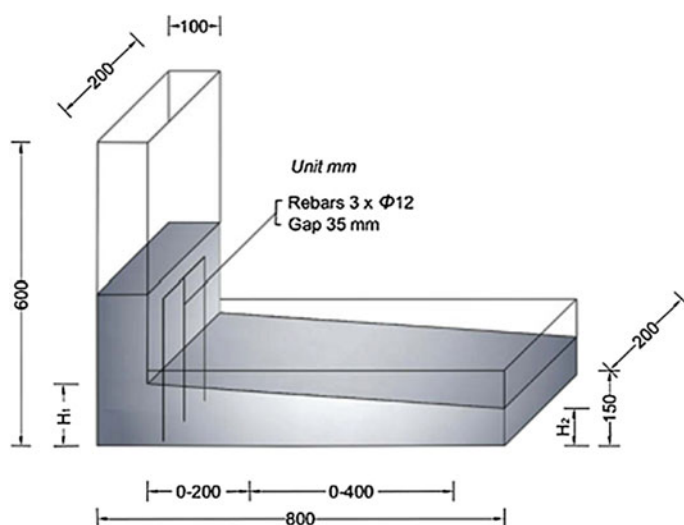


Fig. 2.12 L-box. Reprinted from Ref. [7], Copyright 2009, with permission from Elsevier

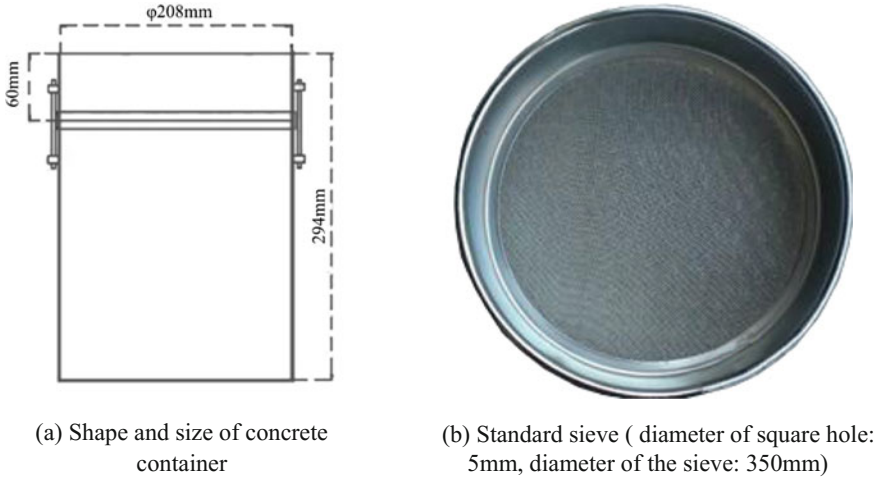


Fig. 2.13 Test instruments of GTM screen stability

(7) GTM screen stability test method

GTM screen stability can be used to check the segregation resistance of SCC. Its test procedures are as follows: (1) Put 10 ± 0.5 L concrete into the container which is shown in Fig. 2.13a, must be installed in a horizontal position, and stands for 15 ± 0.5 min; (2) put the stand sieve shown in Fig. 2.13b on a scale together with a pallet; (3) take 4.8 ± 0.2 kg concrete from the upside of the container into the stander sieve, and mark the mass of the taken concrete as m_0 ; (4) remove the stand sieve and the concrete in the stand sieve after a standing of 120 ± 5 s; (5) weigh the slurry in the pallet and mark its mass as m_1 ; and (6) use m_1 and m_0 to assess segregation resistance of SCC.

The static segregation percent (SR) of the concrete can be calculated from Eq. (2.2), and it is suggested to be less than 20% [2].

$$SR = (m_1/m_0) \times 100\% \quad (2.2)$$

where m_1 is the mass of the slurry thought the stand sieve and m_0 is the initial mass of concrete in the stander sieve.

2.4.2 Property of Fresh Self-Compacting Concrete

The property of fresh SCC, i.e., self-compactability, is very important to adjust mix proportion and to assess the self-compacting degree of SCC. The self-compactability is affected by many factors, such as water/cement ratio, types and amount of aggregates, types and dosage of chemical admixtures, types and amount of mineral

mixtures, fibers, nanomaterials, and rubber. The detailed effect of the above-mentioned factors on the self-compactability of SCC will be subsequently introduced as follows.

(1) Effect of water/cement ratio on self-compactability

Water/cement ratio is a key factor in the design and proportioning of SCC mixture and should be set in a proper range. Sonebi et al. investigated the fresh properties of SCC with limestone powder, including the filling ability measured by the slump flow test method, the flow time measured by the Orimet test method, and the plastic fresh settlement measured in a column [11]. They found that the slump flow of all SCC specimens with limestone powder and ground granulated blast furnace slag is greater than 580 mm, and the time in which the slumping concrete reaches 500 mm is less than 3 s. In addition, the settlement of the fresh SCC increases with the increase in water/powder ratio and slump. Felekoglu et al. also explored the effect of water/cement ratio on the fresh properties of SCC. All the slump flow, V-funnel, and L-box test methods were used in this study. It was found that the optimum water/cement ratio for producing SCC is in the range of 0.84–1.07, with which the SCC mixture would not cause blocking or segregation [12].

(2) Effect of aggregates on self-compactability

Different types of aggregates have been used to fabricate SCC, and their proper or optimum amount has been investigated. Su et al. determined the amount of the required aggregates and then filled the voids of aggregates with the paste of binders to ensure that the concrete thus obtained has targeted flowability [13]. Zhu et al. made SCC with 30, 31, 32, 33, and 34 vol% of coarse aggregates and studied the effect of the coarse aggregate content on the fresh properties of SCC by measuring such parameters as slump flow, T500 time, V-funnel flowing time, and U-box filling height. It was found that both the T500 time and the V-funnel flowing time decrease, while the U-box filling height increases, with the reducing content of coarse aggregates. The optimal content of coarse aggregates is 33% regarding the workability and drying shrinkage of SCC [14]. Kou et al. evaluated the fresh properties of SCC with 100% recycled coarse aggregates and different levels of recycled fine aggregates. Recycled fine aggregates are used to replace river sand by weight of 0, 25, 50, 75, and 100%. The slump flow of the SCC fabricated with recycled aggregates increases with the content of fine recycled aggregates as shown in Fig. 2.14. This is because the actual water/binder ratio increases with the content of recycled fine aggregates in SCC due to the recycled fine aggregates in the air-dried condition, and the higher water/binder ratio results in the increase in slump flow of SCC [15].

Kou et al. fabricated SCC with recycled glass (RG) aggregates and studied the fresh properties of the recycled glass-SCC (RG-SCC) [16]. The replacement ratio of conventional aggregates by the RG aggregates is 10, 20, and 30%, respectively. The experimental results show that the slump flow, blocking ratio, and air content of the RG-SCC mixtures all increase with the recycled glass content. The feasibility of

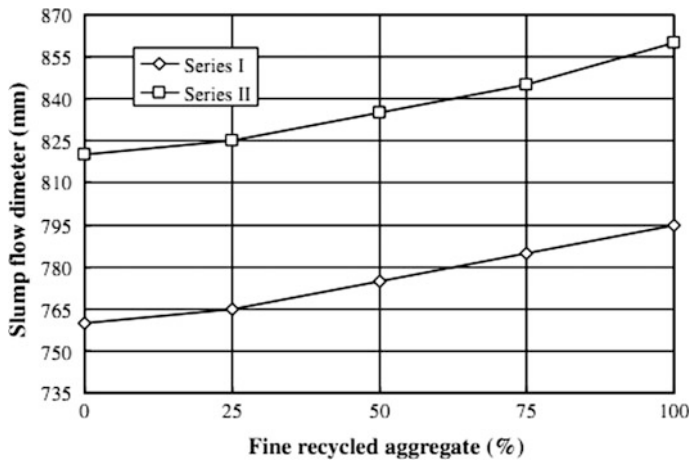


Fig. 2.14 Effect of fine recycled aggregates on slump flow diameter of SCC with recycle aggregate in Series I and II (water/binder ratios (W/B) were 0.53 and 0.44 for SCC mixtures in Series I and II). Reprinted from Ref. [15], with permission from Elsevier

fabricating RG-SCC gets good supports from the test results of fresh and hardened properties of the concrete. Choi et al. studied the fluidity properties of high-strength lightweight SCC, which include flowability, segregation resistance ability, and filling ability of fresh concrete. It is found that the high-strength lightweight SCC can satisfy the second-class standard of Japan Society of Civil Engineers (JSCE) when the mix ratio of lightweight fine aggregates to lightweight coarse aggregates is less than 50 and 75%, respectively [17]. Bignozzi et al. fabricated SCC with different contents of untreated tire waste and studied its fresh properties. The rubberized SCC mixed with 22.2 and 33.3 vol% of tire waste has the same water/cement ratio and water/(cement + filler) ratio. The slump flow test results are all more than 600 mm, and the J-ring test results also show that the mixtures all have high flowability in the presence of obstacles. It is also should be noted that the rubberized SCC needs more SP than the control SCC when both the water/cement ratio and the water/(cement + filler) ratio keep constant [18]. Topçu et al. also investigated the usage of ground elastic wastes such as rubber in SCC. Rubber replaced aggregates at the contents of 60, 120, and 180 kg/m³ by weight. The results show that the optimum content of rubber is 180 kg/m³ in order to obtain sufficient fresh and hardened properties [19].

It can be concluded from the above research results that an optimum amount of aggregates can endow SCC with favorite self-compactability. Moreover, some recycled aggregates, including recycled coarse aggregates, recycled glass, and untreated tire waste, can be used to fabricate eco-friendly SCC. However, the addition of recycled aggregates makes it necessary to increase the dosage of SP to ensure the targeted self-compactability of SCC, and the dosage of the recycled aggregates also should be limited in a proper amount to reduce their negative effects on fresh and hardened performances of SCC.

(3) Effect of chemical admixtures on self-compactability

The chemical admixtures used in SCC mainly include SP and viscosity-modifying admixtures. In recent years, much research efforts have been devoted to exploring the effect of the main parameters of SP and viscosity-modifying admixtures on the self-compacting property of SCC. The investigated parameters include the type of viscosity-modifying admixtures, the interactions between SP and viscosity-modifying admixtures, and the type of SP. For example, Rols et al. studied the influence of different types of viscosity-modifying admixtures (starch, precipitated silica, and a waste from the starch industry) on such main properties of SCC as workability, segregation, and bleeding. They found that the precipitated silica and starch present good performances and can act as good alternatives for welan gum as the viscosity-modifying admixtures for SCC. This provides an effective way to reduce the cost of SCC [20]. Schwartzentruber et al. investigated the interaction between SP and viscosity-modifying admixtures in SCC and explored the relationship between the spread and flow time and the rheological behavior of cement pastes. It is found that the viscosity-modifying admixtures can affect both viscosity and shear yield stress of SCC, but have no effect on the saturation dosage of SP. In addition, the viscosity-modifying admixtures do not modify the rheological behavior of paste when the SP dosage is close to the saturation point, whereas they can enhance the stability of SCC [21]. Felekoglu et al. investigated the action of the chemical structure of polycarboxylate-based SPs (PC-based SPs) on the workability retention of SCC. It is found that the workability retention performance of PC-based SPs will change when the bond structure between main backbone and side chain of copolymer is modified. The PC-based SPs with ester bonding cannot maintain the workability of fresh concrete due to the alkali attack vulnerability of the bond structure, whereas the PC-based SPs with polyoxyethylene side chain can effectively maintain the workability of fresh SCC for a period of 2 h at least. Furthermore, the SP dosage and the water/powder ratios were also responsible for the long-term workability retention performance of SCC [22]. Le et al. studied the effect of SP on the self-compactability of SCC. It was observed that the SP against the SP saturation dosage has no influence on the flowability and plastic viscosity of SCC, but will induce bleeding [10]. Feys et al. used Bingham model and the modified Bingham model to investigate the rheological properties of SCC in steady status and found SCC presenting a lower yield stress than NVC. The type of fillers and the type of SP are two main influence factors of the shear-thickening behavior of SCC. An increase in shear-thickening behavior will bring a decrease in water/paste ratio, while an increase in slump flow. Other parameters also have a little effect on the shear-thickening behavior of SCC [23].

(4) Effect of mineral mixtures on self-compactability

Proper addition of mineral mixtures can endow SCC with enough filling ability, passing ability, and segregation resistance. Up to now, many types of mineral mixtures have been used for fabricating SCC, such as fly ash, slag, silica fume, limestone

powder, marble dust, blast powder, metakaolin, palm oil fuel ash, rice husk ash, sawdust ash, and bagasse ash. Among these mineral mixtures, fly ash is the most commonly used. Many researches indicated that fly ash can improve viscosity and reduce water requirement of SCC. For example, Xie et al. fabricated high-strength SCC with ultrapulverized fly ash and investigated the fresh properties by using a combination of the slump flow and L-box test methods. It was observed that the ultrapulverized fly ash can improve the viscosity of fresh concrete without decreasing its flowability [24]. Sahmaran et al. studied the fresh properties of fiber-reinforced SCC incorporating with high-volume fly ash. The research results show that adding high volume of fly ash into SCC can reduce the water requirement of the mixture [25]. Dinakar et al. manufactured different types of SCC by adding 0, 10, 30, 50, 70, and 85 vol% of fly ash, respectively. The developed SCC is highly segregation resistant and presents good flowability and passing ability [26]. Khatib et al. also investigated the influence of fly ash on the fresh properties of SCC. Portland cement was partially replaced with 0–80% fly ash. The research results show that the SCC with fly ash possesses high workability with flow spread of over 700 mm, while the flow spread of the control SCC is only 635 mm. It indicates that the fly ash can reduce the water requirement of SCC and increase the workability at constant water/binder ratio. However, Khatib found that the addition of fly ash increases the time recorded for 500 mm diameter, the final spread diameter, and the time in V-funnel [27]. Liu et al. explored the fresh properties of SCC with different levels of pulverized fuel ash. The pulverized fuel ash was used to replace cement by volume level of 0, 20, 40, 60, 80, and 100%, respectively. To keep the slump flow values and the V-funnel time of SCC with pulverized fuel ash constant, an increase in water/powder ratio and a reduction in SP dosage are needed [28]. Alsubari et al. manufactured SCC by using 0, 50, 60, and 70%, respectively, of mass replacement of ordinary Portland cement with treated palm oil fuel ash at a constant water/binder ratio of 0.35 and studied the fresh properties of SCC. The results show that the substitution of ordinary Portland cement with high-volume treated palm oil fuel ash can improve the filling ability and passing ability of fresh SCC (as shown in Fig. 2.15) and bring good visual appearance for the slump flow and J-ring flow tests (as shown in Fig. 2.16). It should also be noted that the segregation index of high-volume treated palm oil fuel ash is increased, but it remains in the range specified by the EFNARC (2002) guidelines. Therefore, the treated palm oil fuel ash can act as a new material to produce economical and eco-friendly SCC [29]. Le et al. studied the effects of SP and mineral admixtures (i.e., fly ash, silica fume, and macro-mesoporous rice husk ash) on the self-compactability of SCC. Unlike fly ash/silica fume, the rice husk ash increases the SP saturation dosage of mortar, slightly decreases the filling and passing abilities, and significantly improves the plastic viscosity, bleeding resistance, and segregation resistance of SCC [10]. Therefore, the rice husk ash can be used as a viscosity-modifying admixture in fabricating SCC. Elinwa et al. assessed the fresh properties of SCC containing sawdust ash. The slump flow test values lie between 665 and 680 mm, and the flow time measured with the V-funnel test method is in the range from 8.2 to 8.4 s. These values indicate that the fresh mixture achieves adequate stability and self-segregation. Moreover, the values measured with the U- and L-box test methods are both within the targets and tolerance

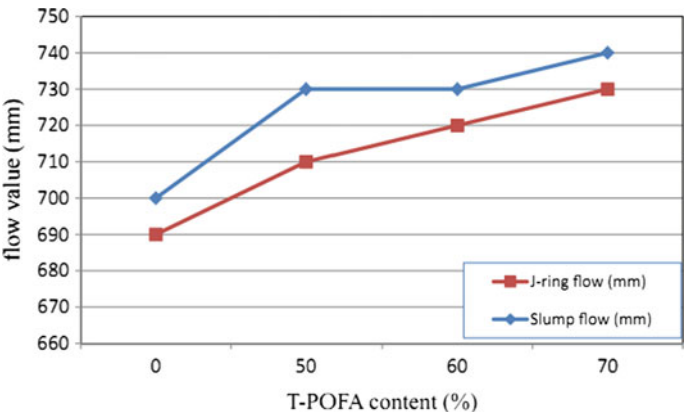


Fig. 2.15 Slump flow and J-ring flow for SCC mixtures. Reprinted from Ref. [29], Copyright 2016, with permission from Elsevier

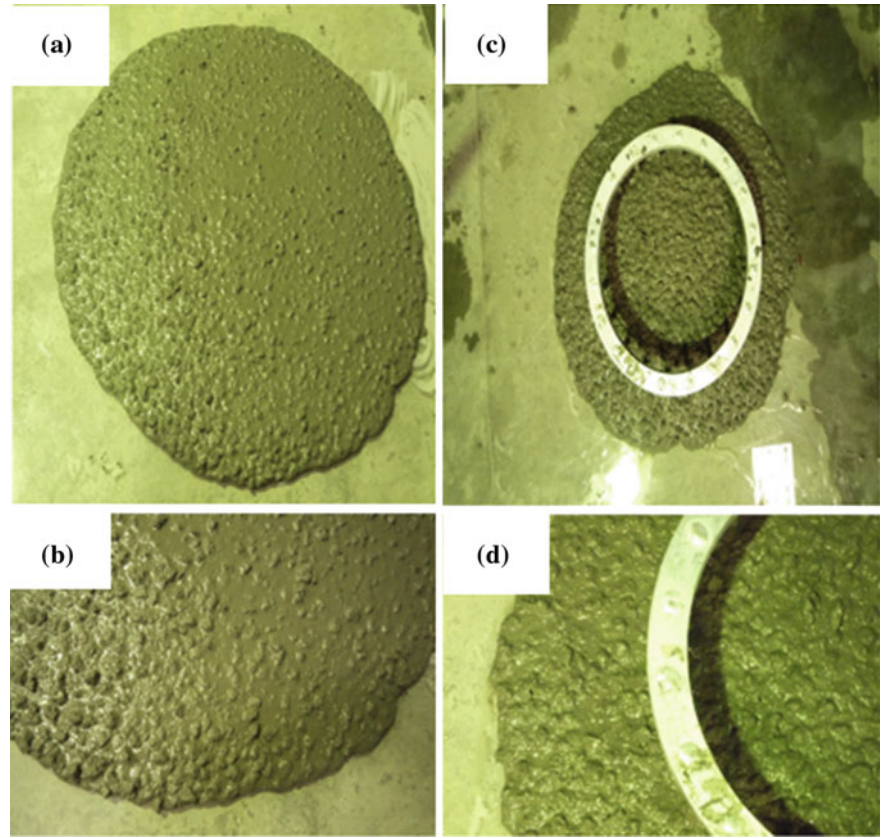


Fig. 2.16 Visual appearance for slump flow (a and b) and J-ring flow (c and d). Reprinted from Ref. [29], Copyright 2016, with permission from Elsevier

values stipulated by EFNAC (2002). All the results show that the SCC mixture has suitable self-compactability, and the sawdust ash can be used as powder material together with cement and superplasticizers to produce SCC [30]. Akram et al. used bagasse ash as viscosity-modifying admixture in fabricating SCC to decrease the cost of SCC. The content of bagasse ash used here varies from 5 to 20% by the weight of cement. They found that the slump flow and the H_2/H_1 both decrease with the increasing content of bagasse ash [31].

Cassagnabere et al. designed two kinds of SCC incorporating either ordinary Portland cement or slag cement and kept the slump flow values constant by adjusting the dosage of water or SP. Unlike the self-compacting performance of the SCC with the ordinary Portland cement/limestone filler combination, the SCC with the slag cement/limestone filler combination requires no extra addition of water or SP to maintain the self-compacting ability when the mix temperature increases from 20 to 50°C [32]. Bosiljkov studied the influence of finely ground limestone and crushed limestone dust on the properties of SCC in fresh state. The results indicate that the finer and better graded limestone dust significantly increases the deformability of the paste due to filler effect and improved fine-particle packing [33]. Zhu et al. investigated different types and finenesses of limestone and chalk powders as fillers in SCC and explored their effects on the SP demand of SCC. They found that the required dosages of SP in the SCC with chalk powder are higher than that in the SCC with limestone powder, but the fineness of the powders has little effect on the SP demand [34]. Topçu et al. fabricated SCC with high volume of marble dust and investigated the fresh properties of the SCC [35]. Marble dust was used to replace binder of SCC at the contents of 0, 50, 100, 150, 200, 250, and 300 kg/m³, respectively. From the test results of workability, it can be found that all the usage amounts below 200 kg/m³ are suitable for the marble dust. This indicates that the use of marble dust in SCC is an effective way to reduce pollution and produce green concrete. Uysal et al. fabricated SCC with limestone powder, basalt powder, and marble powder, respectively. The three types of powders are used to partially replace Portland cement individually. They found that all the mixtures show good self-compacting properties, and the addition of limestone powder, basalt powder, and marble powder all improves the workability of fresh SCC. Among the three mineral admixtures, the marble powder presents the best modification effect on the fresh SCC [36]. Melo et al. studied the effect of metakaolin's finesses and content and paste's volume on the fresh properties of SCC [37]. They found that increased metakaolin's finesses and content both increase the requirement of SP in SCC, while the increased paste volume can improve the fluidity of the mixtures, thus reducing the demand of SP. Madandoust et al. used different contents (0–20% by the weight of cement) of metakaolin to manufacture SCC with three water/binder ratios of 0.32, 0.38, and 0.45 and investigated the fresh properties of the fabricated SCC [38]. The slump flow values of SCC with metakaolin vary between 660 and 715 mm and can be adjusted by changing the dosage of SP. However, metakaolin is harmful to the slump flow retention. At different water/binder ratios, the SCC with metakaolin can achieve proper stability and passing ability with no other viscosity-modifying admixtures.

In general, 10% is a proper replacement ratio for the metakaolin regarding to the economic efficiency and the fresh and hardened properties of SCC. Vejmelková et al. explored the rheological properties of SCC with the blended binders containing metakaolin and blast furnace slag [39]. It is found that the SCC with metakaolin requires more water and SP than the SCC with blast furnace slag to meet the requirement on the parameters of fresh SCC mixtures. In addition, due to the higher surface area and higher reactivity of metakaolin, the SCC with metakaolin has higher loss of flowability with time and presents a significant yield stress and a relatively low viscosity like typical non-Newtonian fluids. However, the SCC with blast furnace slag exhibits zero yield stress and higher viscosity characteristic like Newtonian fluids.

Apart from the fresh property of SCC with single mineral mixtures, that of SCC with binary, ternary, and quaternary mineral mixtures also has been explored. Mohamed fabricated three types of SCC: fly ash alone, silica fume alone, and fly ash and silica fume together [40]. The research results show that all the SCC mixtures have good filling and passing abilities as well as favorite segregation resistance. It should also be noted that the time recorded for 500 mm diameter, the final concrete diameter, and the time in the V-funnel test method all increase with the percentage of fly ash and silica fume. Gesoglu et al. fabricated SCC incorporating binary, ternary, and quaternary blends of Portland cement, fly ash, ground granulated blast furnace slag, and silica fume with a constant water/binder ratio of 0.44 and a total binder content of 450 kg/m^3 , and studied the fresh properties of the SCC. They observed that the addition of the mineral admixtures can improve the filling and passing abilities of SCC. In addition, mineral admixtures, especially silica fume, can be used to slightly increase the T500 slump flow time. However, criteria of the EFNARC in terms of the V-funnel flow time can be satisfied only when the ternary of Portland cement, fly ash, and ground granulated blast furnace slag is used [41].

(5) Effect of fibers on self-compactability

Fibers also have been added into SCC to make fiber-reinforced SCC. In general, the workability of SCC will significantly decrease when the content of fibers exceeds a specific value. However, it is also possible to make SCC with proper amount of fibers by adjusting the mix proportion. Sahmaran et al. studied the workability of hybrid fiber-reinforced SCC (HFR-SCC). The effect of the fiber properties (including fiber volume, fiber length, and fiber aspect ratio) on the workability of SCC was quantified with the slump flow and V-funnel test methods. They found that it is possible to achieve good self-compaction with considerable fiber inclusion (60 kg/m^3) [42]. Ferrara et al. also studied the fiber-reinforced SCC and put forward a mix design method for steel fiber-reinforced SCC based on the influence of fibers on the grading of solid skeleton, minimum content, and rheological properties of the paste required to achieve the targeted self-compactability and rheological stability [43]. El-Dieb used steel fiber to make ultrahigh-strength SCC and evaluated the effect of the volume fractions of steel fibers on the flowability of SCC. As shown in

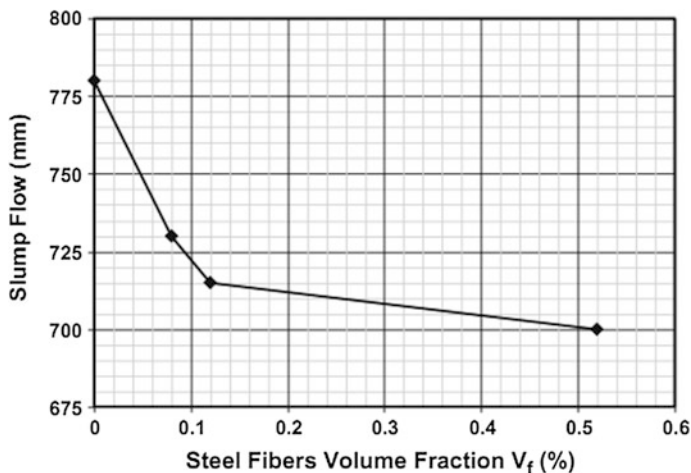


Fig. 2.17 Slump flow of fresh concrete with different steel fiber volume fractions. Reprinted from Ref. [44], Copyright 2009, with permission from Elsevier

Fig. 2.17, the slump flow value decreases with the increase in steel fiber volume fraction. The reduction in slump flow reaches up to about 12% for the SCC with the highest steel fiber dosage (0.52%). Although the steel fibers reduced the slump flow values, the slump flow values are still larger than the minimum value required for SCC. If the slump value is required to remain unaffected, the admixture dosage should be adjusted [44]. Mazaheripour et al. manufactured fiber-reinforced lightweight SCC and explored the effect of polypropylene fiber on the workability of SCC. It is found that the slump flow of the fiber-reinforced lightweight SCC significantly decreases with the increasing content of polypropylene fibers. The flowability of SCC with 0.1, 0.2, and 0.3 vol% decreases from 720 to 680, 560, and 430 mm, respectively [45]. Aydin et al. explored the fresh properties of the SCC with hybrid steel fibers and carbon fibers of high-volume content [46]. It was found that the fibers are uniformly distributed in SCC and the SCC with 2 vol% steel fibers and carbon fibers has no loss of flow and workability. The amount of paste in the mixture of SCC should be increased to ensure the good dispersion of fibers and the high-level workability of SCC with fibers.

(6) Effect of nanomaterials on self-compactability

Since nanomaterials have huge specific surface area, larger amount of SP is needed to make nanomaterials reinforced SCC. However, excessive addition of SP may lead to bleeding and segregation. Therefore, Sari et al. used a nanometric, amorphous, silica SiO_2 combined with a specific polysaccharide (for its suspending ability) to manufacture SCC without bleeding or segregation at a reasonable cost [47]. The tested flow slump at t_0 (the time of departure from the concrete plant) can reach 615 mm, and the concrete mixture can be placed without any vibration.

Table 2.4 Comparison of hardened properties of SCC and NVC

Properties	SCC	NVC
Compressive strength	No obvious difference	
Tensile strength	No obvious difference	
Shrinkage	High	Low
Bond to steel	High	Low
Modules of elasticity	Low	High
Creep	High	Low
Sulfate resistance	Better	Good
Permeation properties	Better	Good

2.4.3 Properties of Hardened Self-Compacting Concrete

In the meanwhile of concerning the property of fresh SCC, much research efforts also have been devoted to exploring the properties of hardened SCC, such as compressive strength [48–50], tensile strength [12, 44, 45, 51], modules of elasticity [36, 52–55], bond to steel [56–59], shrinkage [16, 53, 60–62], and durability [26, 63, 64]. In general, the compaction and harden properties of infrastructures are more guaranteed through the use of SCC [65]. A comparison of harden properties of SCC and NVC is summarized in Table 2.4.

2.5 Applications

Up to now, significant amount of work has been carried out on SCC all over the world. In several countries including Japan, Sweden, Thailand, and UK, the knowledge of SCC has moved from domain of research to application. Non-requirement of vibration in laying SCC is one of the key factors driving the fast growth of the global SCC market. According to the report released by the market research company Markets and Markets, the global market of SCC is projected to reach USD 15.18 billion by 2026, at a compound annual growth rate of 5.7% between 2016 and 2026.

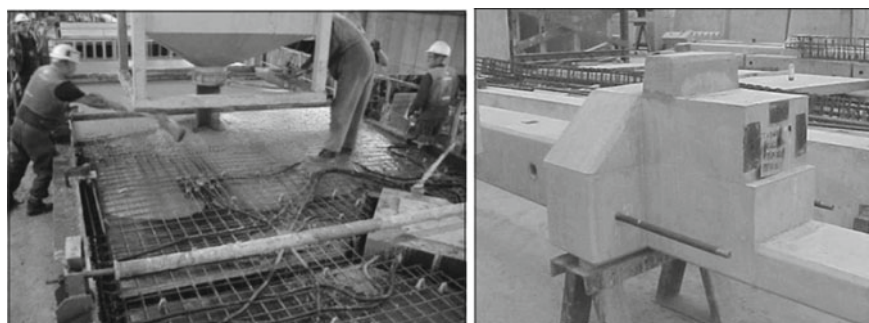
SCC can be used for ready-mixed concrete (cast-in-place) and prefabricated products (precast members) as detailed as follows: (1) cast-in-place application (as shown in Fig. 2.18 [65]), such as construction of bridge, tank, high building, and nuclear power plant. A typical application example of SCC is the two anchorages of Akashi-Kaikyo (Straits) Bridge. The volume of cast SCC amounted to 290,000 m³. In this project, the SCC was mixed on-site and pumped through a piping system to the specified point, located 200 m away. In the final analysis, the use of SCC shortened the anchorage construction period by 20%, from 2.5 to 2 years. SCC was also used in the construction of the wall of a large LNG tank belonging to the Osaka Gas Company, Double Square in Seattle, and Yangjiang Nuclear Power Plant; (2) precast application (as shown in Fig. 2.19, [65]), such as fabrication of super span

Fig. 2.18 Placement of SCC by pump tremie on site, demonstrating the flowable nature of the material (Mott MacDonald Ltd). Reprinted from Ref. [65], with permission from ICE Publishing



prestressed beam, ecological revetment member, and prefabricated square columns. SCC has made it possible to precast quality concrete structures. The use of SCC in the precast market of the UK, Europe, and Asia-Pacific region is continuing to increase with the development of module buildings, especially in Asia-Pacific region.

In addition, the application of SCC is also benefit for making eco-friendly concrete and promoting the development of other types of ultrahigh-/high-performance, ultrahigh-/high-strength, multifunctional, and smart concrete. Self-compacting technology, needing high volume of powder fillers, seems to be promising to use recycling materials or by-product, such as rubber waster, fly ash, coarse recycled concrete aggregate [7], waste marble dust [35], recycled glass aggregate [16], bagasse ash [31], chalk powders [34], treated palm oil fuel ash [29], and rice husk ash [10]. Modern application of SCC is focused on combining SCC matrix with advanced fillers, such as high-performance fibers, nanomaterials [66–68], and self-healing capsules. These fillers may take advantage of superior performance of SCC in the fresh state to obtain a more uniform dispersion, which is



(a) A precast unit being cast in SCC
(Tarmac Precast Concrete Ltd)

(b) A precast column cast in SCC
(Tarmac Precast Concrete Ltd)

Fig. 2.19 SCC is used in precast application. Reprinted from Ref. [65], with permission from ICE Publishing

critical for incorporating these fillers into concrete matrix to achieve favorite reinforcing or modifying effect [43].

2.6 Summary

SCC is a kind of highly flowable concrete that can spread into the mold without the need of mechanical vibration. It can solve the problems brought by poorly compacted concrete, including unsatisfying physical appearance, strength, or durability issues. SCC can also bring the benefit of eliminating operative exposure to potentially harmful levels of noise, vibration, and physical strain. Moreover, SCC includes a diverse range of mix types with both fresh and hardened properties. It has higher filling rate, better deformability, and higher segregation resistance compared with NVC. Up to now, the application of self-compacting concrete has achieved good technical, economic, and social benefits. However, there are still some issues needed to be addressed. For example, the early-age shrinkage of SCC is larger due to the lower water/binder ratio, which may lead to the appearance of cracks. In addition, SCC will give great pressure on molds due to its higher liquidity, and it is easier to spall than NVC when subjected to high temperature.

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