Construction and Building Materials 124 (2016) 167–176

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Sealed-space-filling SCC: A special SCC applied in high-speed rail of China

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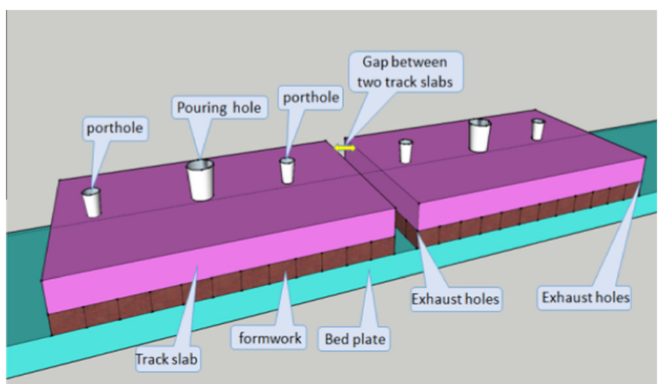
HIGHLIGHTS

- Seal-spaced-filling SCC (SSFSCC), a special SCC applied in high-speed rail, was introduced.
- The property requirements of SSFSCC and corresponding testing methods were elaborated.
- Raw material and mix proportioning of SSFSCC were presented.
- The construction technology of SSFSCC was addressed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form 27 June 2016
Accepted 15 July 2016
Available online 25 July 2016

Keywords:
High-speed rail
Mix proportioning
Sealed-space-filling self-compacting concrete
Workability

ABSTRACT

Sealed-space-filling self-compacting concrete (SSFSCC) is used in China Rail Track System (CRTS) III ballastless slab track of high-speed rail, which has been originally developed in China recently. In this track system, SSFSCC needs to be grouted into a flat, narrow, and sealed space (90 mm × 2500 mm × 5600 mm) which is enclosed by above prefabricated slab and bottom base plate. Good bonding between SSFSCC filling layer and above prefabricated slab has to be secured since these two layers are required to work as a composite plate. SSFSCC presents some special characteristics in comparison with normal SCC. This paper elaborated the property requirements of SSFSCC and the structural characteristics of SSFSCC layer of CRTS III ballastless slab track of high-speed rail. The compositions and mix proportioning of SSFSCC as well as construction technology were briefly introduced. The challenges of the application of this special SCC were also addressed.

1. Introduction

High-speed rail (HSR) refers to the rail operated by high-speed trains with much higher speed than conventional trains. According to the definition of some countries, newly built lines with speed higher than 250 km/h, and upgraded lines with speed higher than 200 km/h can be classified into HSR [1–4]. For the past decades, two types of HSR technology have been developed, i.e. wheel-rail technology and Magnetic levitation (Maglev). China Shanghai Maglev train became the world's first commercially operated high-speed maglev in 2004. A new line with moderate-speed Maglev in Changsha of China is being built and planned to be open in 2016 [5]. Japan is going to build a new line connecting Shinagawa and Nagoya with high-speed Maglev [6,7], which is

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http://dx.doi.org/10.1016/j.conbuildmat.2016.07.093
0950-0618/

planned to be open in 2027. Compared to Maglev, HSR based on wheel-rail technology is more popular and has been widely used around the world. HSR based on wheel-rail technology is the subject of this contribution.

Since the open of Tianjin-Beijing HSR line [8], Chinese government embarked on an ambitious campaign to build the largest HSR network. The total lines with speed higher than 250 km/h in the world network, including lines under construction and in operation, are 35,708 km. China has the largest HSR network of 19,057 km, accounting for 53% of the world total network [9], and including circa 10,000 km passenger-dedicated lines with the speed over 300 km/h. Through tremendous systematic researches and engineering practices, China has become a technology leading country in HSR.

The ballastless track has been widely implemented in HSR around the world [10]. Despite high initial investment and noise problems, it has obvious advantages over ballast track system, such as (1) increase capacity, (2) increase speed, (3) reduce maintenance and life cycle costs, and (4) reduce the number of track maintenance operations and thereby increase safety [11]. In order to implement ballastless track wider and better, many countries are developing new ballastless track form [10–13]. For the last decade, China has established China Rail Track System (CRTS), which includes five types of ballastless tracks, including CRTS I and II double-block ballastless tracks, CRTS I, II and III slab ballastless tracks. The first four types of track are developed by Chinese railway companies based on the transferred technology from Germany and Japan, and CRTS III Slab ballastless track is independently developed by Chinese railway companies. It is believed that it combines the advantages of CRTS I and II types slab tracks.

The structure section and layout of CRTS III slab ballastless track are shown in Fig. 1 [14,15]. It can be easily observed that the track structure consists of four layers, which are, from top to bottom, prefabricated pre-stressed slab, filling layer, isolated geotextile layer, and base plate. Concrete, instead of the cement emulsified asphalt mortar applied in CRTS I and CRTS II track, is used to construct the filling layer of CRTS III track system. The concrete filling layer is cast-in-place, and is required to have strong bonding with the above prefabricated pre-stressed concrete slab, as a consequence the two layers function as a composite plate. The loadings of the high-speed train are transferred to the roadbed by the composite plate. Therefore, the interface bonding between prefabricated slab and filling layer should be strong and durable enough to secure the serviceability of slab track. The thickness of the filling layer, which is cast-in-place, can be adjusted within a range according to the presetting elevation position of above prefabricated slab position. By doing so, the high smoothness of track line can be attained. The track form implements a concept of "decreasing stiffness from top to bottom".

The CRTS III ballastless slab track is constructed as the steps shown in Fig. 2. It can be seen that the construction procedures mainly include four steps. The first step is to place the bottom parts in the sequence of base plate, geotextile layer and reinforced mesh. Secondly, the prefabricated slab is put on the top of base plate, and adjusted to its design position with tolerance of 0.5 mm. Then, the space between the base plate and slab is sealed, and the position of the slab is secured by clamps. Finally, SCC is cast into the sealed space from the pouring hole. SCC applied in the slab track is required to fill up the sealed space between slab and base plate under its own weight. It is a special type of SCC, but different from normal SCC because of the following reasons: (1) Normal SCC is often cast into an open formwork. The top surface of SCC can be smoothed by the process of finishing, so slight bleeding and rising of bubbles are acceptable. However, SCC applied in the slab track is grouted into a flat, narrow and sealed space with the dimension of 90 mm $\times$ 2500 mm $\times$ 5600 mm. A strong bonding between the top surface of the SCC layer and prefabricated slab is required. Thus, bleeding and rising of bubbles should be strictly controlled. (2) Normal SCC is often flow on a rigid surface. However, SCC applied in the slab track system flows on a flexible geotextile. It increases the flow resistance. In addition, geotextile may absorb the water from SCC, and affect the flow of SCC. (3) A HSR line is often hundreds of kilometers, and it is usually one-time completion. Construction sites along HSR line may extend hundreds of kilometers, and various raw materials will be used, they may present large variations in properties and compositions. It's quite challenging for the quality control of concrete because of the variation in local raw materials.

Due to the above-mentioned characteristics, SCC for CRTS III slab ballastless track is different from normal SCC and puts forward stricter requirements for SCC. Since the first characteristic is the most important and unique one, hence, we name this type of SCC as sealed-space-filling self-compacting concrete (abbreviated as SSFSCC).

Up to now, CRTS III slab ballastless track has been implemented in the HSR network of circa 900 km in China, including Cheng-Guan line, Wuhan metropolitan area intercity line, Panjin-Yingkou line, and Zhengzhou-Xuzhou line [13–16]. Thousands km of HSR lines in planning are going to be built in the near future, and CRTS III slab ballastless track will be implemented in the newly built HSR lines in China. SSFSCC is used in the construction of CRTS III slab ballastless track, and millions m^3 of SSFSCC for CRTS III slab track could be consumed in China in the near future. In the following sections, the property requirements in fresh and hardened states, mix proportioning and construction technology of SSFSCC are introduced.

2. The property requirements of SSFSCC

The hardened concrete fulfills the structural functions in a system, depending on its mechanical properties, durability, and volume stability. Fresh properties of concrete significantly affect the quality of hardened concrete. The fresh properties of SSFSCC

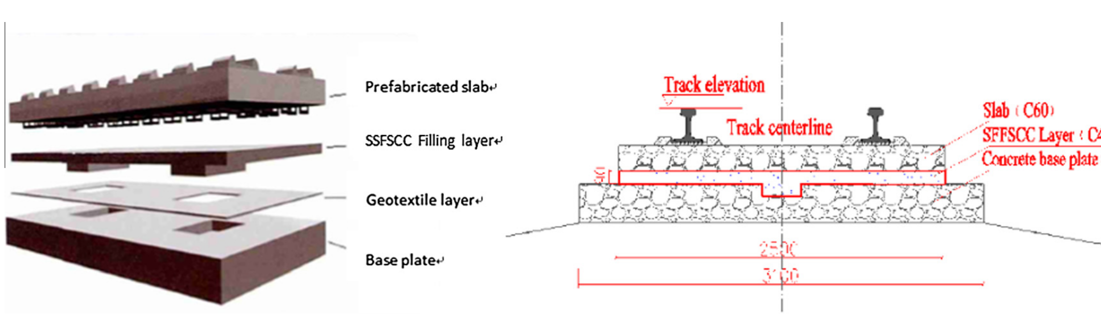


Fig. 1. The structure section and layout of CRTS III slab ballastless track [14,15].

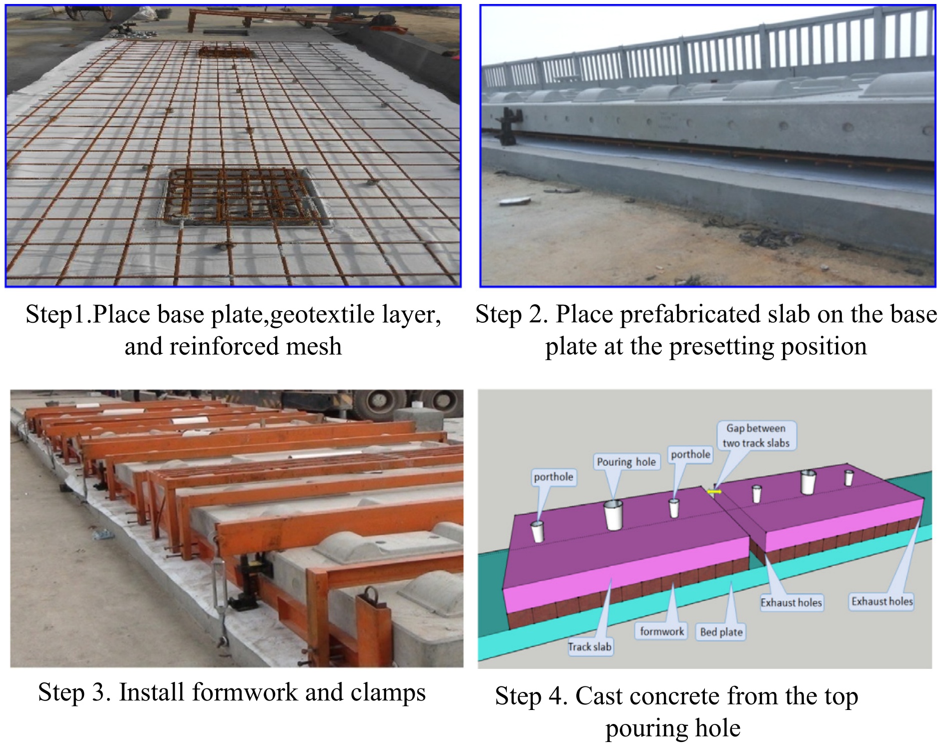


Fig. 2. The main construction steps of CRTS III slab ballastless track.

are particularly important since the intricate slab track system put forward some special requirements as stated above.

2.1. Properties in hardened state

The designed service life of CRTS III slab track is 60 years. During service, the slab track requires maintaining its original properties without major repair. In order to fulfill its function, the hardened properties of SSFSCC have been proposed based on the structural design requirements [17], as shown in Table 1. These properties include mechanical properties, durability, and volume stability. More importantly, the strong interface bonding between the prefabricated slab and SSFSCC layer needs to be ensured during the whole service life.

2.2. Workability in fresh state

Properties of fresh SSFSCC determine the performance of hardened matrix. Hence, it is very important to choose some existing testing methods, or even develop new testing methods, to evaluate the fresh properties of SSFSCC. Of course, appropriate testing results should be specified as the acceptance criteria for the purpose of practice. As stated above, bleeding, segregation, surface settlement and instability of air bubble of SSFSCC have to be minimized. On one hand, very flowable SSFSCC is required to fill up the sealed, narrow and flat space under the action of gravity; on the other hand, very stable SSFSCC is required to avoid the above-mentioned defects.

There are many testing methods has been developed to evaluate the properties of fresh SCC for the past decades, for example, slump flow, J-ring, V-funnel, L-box, sieve segregation test, settlement column, penetration test for segregation, and *U*-test etc. [18–20]. It is generally accepted that SCC needs to have the three key abilities: filling ability, passing ability, and anti-segregation ability, which can be evaluated by different methods. Some single test can evaluate two or more abilities. Take the J-ring test for instance, filling ability by measuring the spread diameter as in the slump-flow test, passing ability by measuring the blocking step B_J, flow-rate by measuring the time to reach 500 mm, segregation ability can be visually judged. The selection of testing methods for evaluating properties of fresh SCC needs to take the specific conditions and circumstance into account, including reinforcement ratio, formwork, and other special requirements.

2.2.1. Filling ability

Filling ability is one of the most important properties of fresh SSFSCC. It ensures SSFSSC can fill up the flat, narrow, and sealed space with a large area. Slump-flow value can well describe the flowability of a fresh mixture in unconfined conditions. Visual observations during the test and measurement of the T_{500} can give additional information on the segregation resistance and uniformity of each delivery. Therefore, the slump-flow test is employed to evaluate the filling ability of SSFSCC. The appropriate slump-flow value and flow rate of fresh SSFSCC are 570 mm to 650 mm and 3–7 s based on the results from laboratory experiments and jobsite applications.

Table 1
Properties requirement of hardened SSFSCC for CRTS III slab ballastless track (56 days).

Properties	Value
Compressive strength, (MPa)	⩾40.0
Flexural strength, (MPa)	⩾6.0
Elastic modulus, (GPa)	30–38
6-h charge passed, (c)	⩽1000
Spalling under salt solution freezing and thawing test, (g/m^2)	⩽1000
Shrinkage, ($\times10^{-6}$)	⩽400

2.2.2. Passing ability

Passing ability describes the capacity of the fresh mixture to flow through confined spaces and narrow openings without segregation, loss of uniformity or causing blocking. Passing ability is mainly influenced by the size of confinement gap, maximum aggregate size and the flowability/filling ability. For the thin plate-like filling layer, there is a row steel bar at the center of sealed-space of layer, and the confinement gap is only 40 mm. SSFSCC must have a very good passing ability which makes it smoothly pass the narrow gap and flow on geotextile readily.

The L-box with three bars test is used to assess the passing ability of SSFSCC to flow through tight openings between reinforcing bars without segregation and blocking. Passing ability specifications are set as PA2 according to the European guidelines for self-compacting concrete [21].

2.2.3. Stability

Due to density difference among the constituents of SSFSCC, it is easy to suffer from instability. In this paper, the term stability, instead of segregation used in normal SCC, since segregation, bleeding, rising of bubbles, and surface settlement should all be addressed. Segregation and bleeding lead to very high w/c ratio in the top surface of SSFSCC and thus weak interface bonding between the prefabricated slab and SSFSCC layer. Rising of bubbles entrapped in the interface results in a bubble layer, as a consequence, very weak interface bonding is resulted. Obviously, the surface settlement of SSFSCC layer may result in incomplete contact with slab, and thus weak bonding. Thus, special attention should be paid to the stability of SSFSCC.

There are several testing methods developed to evaluate the segregation resistance properties of fresh SCC for the past decades, such as sieve segregation test, settlement column, penetration test etc. [21–23]. These test methods are not enough to secure the good interface bonding between the slab and SSFSCC layer. Three tests, i.e. top surface paste thickness measurement, bleeding test and expansion rate test, are employed to evaluate the stability of fresh SSFSCC. The bleeding test conducted according to Chinese standard GB/T 50080 is used to evaluate the bleeding resistance and water-holding abilities of fresh SSFSCC. In order to ensure the complete contact between the fresh SSFSCC and slab during hardening, expansion agent is added to generate a certain expansion rate and to avoid surface settlement or shrinkage of concrete within 24 h. The expansion rate test are conducted according to Chinese standard GB 23439. The top surface paste thickness measurement is a novel and newly developed test method [24]. It is used to assess the segregation degree between paste and aggregate in fresh mixture. The testing setup of the top surface paste thickness is given in Fig. 3. It consists of three parts, i.e. steel testing cross, cylindrical container, and bracket. In this test, fresh SSFSCC is placed into a cylindrical container with the height of 110 mm and diameter of 200 mm, and let the concrete rest for 15 min. Afterwards, the steel testing cross, with the thickness of 1 mm, length of 150 mm, and height of 10 mm, is fixed right on the top of the surface of concrete, followed by releasing the steel testing cross suddenly, then measure the penetration depth of the cross within 30 s. It is believed that the surface paste thickness test is appropriate to evaluate the segregation degree of fresh SSFSCC. The segregation resistance is very good and acceptable when the surface paste thickness is no more than 7 mm which is about equal to the thickness of mortar layer enwrapped coarse aggregate. There is no method specially designed for the bubble stability of SSFSCC. However, SSFSCC passed bleeding and top surface paste thickness tests is quite sticky, and should have good stability of bubble.

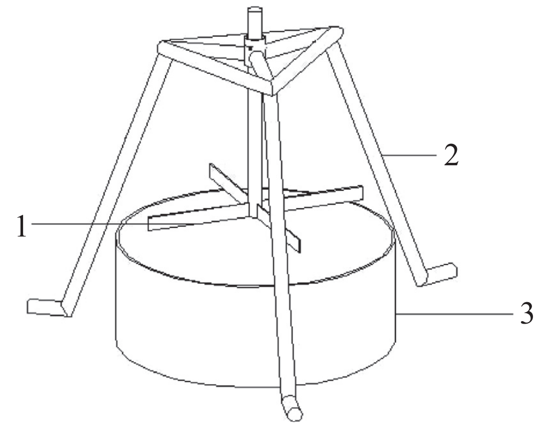


Fig. 3. Testing setup for top surface paste thickness measurement, 1 – steel testing cross, 2 – cylindrical container, 3 – bracket.

The property requirements of fresh SSFSCC for CRTSIII slab ballastless track were proposed in Table 2 based on comprehensive laboratory tests and full-scale job-site tests.

3. Mix proportioning of SSFSCC

Raw materials and their fractions in the mix are the key factors influencing the properties of concrete. In past decades, mix proportioning method has been one of the focuses in SCC research and application fields. More than 10 mix design methods for SCC have been proposed by researchers from different countries and regions around the world such as Japan, the Laboratory Central Des Ponts et Chausses (LCPC), the Swedish Cement and Concrete Research Institute (CBI) and research groups in both Mainland China and Taiwan [25–37]. Each method has its own characteristics, which basically meets the specific demands in practice. Most of them gave only general guidelines and ranges of quantities of materials to be used in proportioning SCC, in the meantime, the specific conditions and objective properties of SCC in fresh and hardened states had to be taken into account. In addition, these existing methods were normally developed based on experiences and specific experimental results. They may not be applicable to other scenarios with different conditions. Especially for SSFSCC applied in the sealed-space-filling layer of ballastless slab track system in HSR, some special requirements of SSFSCC in fresh and hardened states have been put forward. In order to realize the optimum properties and minimum cost for SSFSCC, an optimal mix proportioning method

Table 2
Property requirements of fresh SSFSCC for CRTS III slab ballastless track.

Properties	Parameters	Typical values	Testing methods
Filling ability	Slump flow, (mm)	570–650	Workability test in GB/T 50080 (Chinese standard)
	Flow rate $T_{500,}$ (s)	3–7	
Passing ability	P A	⩾0.8	L-Box test
Stability	Top surface paste thickness, (mm)	⩽7	Surface paste thickness test as shown in this paper
	Bleeding, (%)	0	Bleeding test GB/T 50080 (Chinese standard)
	Expansion rate, (%)	0–1.0	Expansion test in GB 23439 (Chinese standard)

has to be established. For a good mix proportion of concrete, some basic requirements have to be taken into consideration collectively:

(1) Workability in fresh state.
(2) Designed mechanical properties.
(3) Designed durability when subjecting to specific environment.
(4) Economic and environment-friendly consideration.

Of course, an optimal mix proportioning of concrete should be highly robust given that the variation in raw materials of SSFSCC along high-speed rail construction sites occurs. The design of SSFSCC should meet the above-mentioned considerations.

3.1. The key parameters of mix proportion

Generally speaking, concrete can be seen as a binary system consisting of coarse aggregate and mortar, and mortar can also be considered as a binary system including paste and fine aggregate. In the concrete level, concrete can be ideally modeled as a suspension system with two phases of coarse aggregate and mortar as shown in Fig. 4(a). In this model, the coarse aggregate is idealized as a large spherical particle and uniformly dispersed in the continuous mortar phase. The mortar, as a continuous phase, enwraps the coarse aggregate. t_m represents the average space between neighboring coarse aggregates and is equal to the thickness of mortar layer enwrapping the surface of the coarse aggregate. In a similar way, mortar can be described by the physical model shown in Fig. 4(b). The fine aggregate is idealized as a small spherical particle and evenly dispersed in the paste. The paste, as a continuous phase, enwraps fine aggregate, t_p represents the average space between neighboring fine aggregates and is equal to the thickness of paste layer coating the surface of the fine aggregate.

The properties of concrete are determined by the properties and volume fraction of paste and aggregates. The fresh paste contributes to the workability of the mixture. Its consistency and volume fraction are the main factors determining the properties of fresh mixture. The paste enwraps aggregates and thus a lubricative paste layer on the surface of each aggregate is formed. The lubrication layer makes aggregates move easily with low friction if the paste has appropriate viscosity. After setting and hardening, the hardened paste binds the dispersed aggregates into a whole body. According to the physical model shown in Fig. 4, the average gap between neighboring aggregates in the mixture is one of the key parameters which greatly affect the properties of fresh and hardened concrete. In the case of SSFSCC, a suitable average gap between neighboring aggregates (the thickness of paste layer) is of great importance for ensuring self-compatibility of fresh mixture and good bonding strength between the SSFSCC filling layer and prefabricated slab. The average gap between aggregates is closely related to the volume fraction of aggregate in unit mixture. Of course, the properties of fresh paste are also the key parameters affecting the workability, mechanical and durability of SSFSCC. It depends on the water-to-powder ratio, dosage of superplasticizer, and compositions of binder powder etc. Hence, in order to meet the requirements of SSFSSC, the following key mix parameters should be carefully considered:

(1) The volume fractions of coarse and fine aggregates. They determine the average gap between neighboring aggregates. The volume fraction of aggregates can be easily obtained if the average gaps (t_m, t_p) are determined. Based on the concept of mean free path proposed by Fullman and the aggregate gradation which is assumed to follow Fuller function, the average gaps can be obtained [38]:

$$\text{For concrete system}: t_m = \frac{2(1-V_{ca})}{3V_{ca}} \times \sqrt{D_{ca,\max} \times D_{ca,\min}} \quad (1)$$

$$\text{For mortar system}: t_p = \frac{2(1-V_{fa})}{3V_{fa}} \times \sqrt{d_{fa,\max} \times d_{fa,\min}} \quad (2)$$

where V_{ca} *and* V_{fa} are the volume fractions of coarse aggregate and fine aggregate in corresponding system, $D_{ca,\max}$, $D_{ca,\min}$, $d_{fa,\max}$ *and* $d_{fa,\min}$ are the maximum and minimum diameters of coarse and fine aggregates, respectively.
(2) Water-to-binder/powder ratio. It is a basic parameter in the mix design of concrete, and closely related to the compressive strength of SSFSCC and the consistency of fresh paste. In order to obtain a high viscosity of paste, relatively low water-to-binder/powder ratio is adopted.
(3) Type and amount of powder. Apart from cement and expansive agent, mineral powders including cementitious materials and inert powders are necessary constituents for SSFSCC. They positively affect the fresh and hardened properties, and greenness of concrete. Generally, powder materials applied in SSFSCC include cement, mineral admixture and expansive agent.
(4) Type and dosage of admixtures. Superplasticizer and viscosity-enhanced agent are both used in SSFSCC. It improves the rheological properties of concrete and also remarkably improves the robustness of fresh SSFSCC.

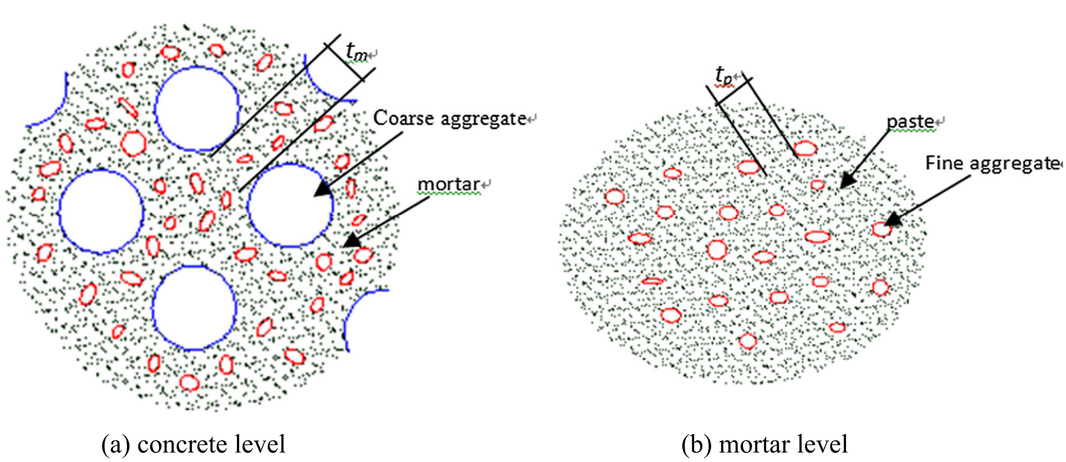


Fig. 4. Schematic diagram of physical models for concrete and mortar.

3.2. The procedures of mix proportioning of SSFSCC

Based on the above considerations and experiences, the procedures of mix proportioning of SSFSCC are summarized in the following steps.

3.2.1. Step 1: select raw materials and calculate the volume content of aggregates

The raw materials used for producing SSFSCC includes crushed limestone with a maximum diameters of 16 mm and continuous gradation, river sand with a fineness modulus ranging from 2.3 to 3.0, Portland cement, fly ash (FA) with specific area of 450~500 m^2/kg, ground granulated blast furnace slag (GGBS) with specific area of 450~500 m^2/kg, expansive agent (EA), viscosity-enhanced agent (VEA), and polycarboxylic acid superplasticizer. VEA is a compound composing of cellulose polymer and inorganic ultrafine calcareous and siliceous powders.

A reasonable volume of aggregates is crucial to the filling ability, passing ability and segregation resistance of fresh SSFSCC, and the volume stability of hardened SSFSCC. As shown in Fig. 4, the volume of aggregate is closely related to the average gap between neighboring aggregates in a mixture. Therefore, it is very important to select the optimal gap between aggregates according to Eqs. (1) and (2). The optimal average gap t_m between neighboring coarse aggregates in a concrete system is 13 mm~14 mm for coarse aggregate with the diameter ranging from 4.75 mm~16 mm and thus 0.28~0.32 is determined for the volume fraction of coarse aggregate. For the mortar system in concrete, the optimal average gap t_p between neighboring fine aggregates is 1.2 mm~1.4 mm for fine aggregate with the diameter ranging from 0.15 mm~4.75 mm. 0.29~0.31 is the volume fraction of fine aggregate in unit SSFSCC mixture. The optimal total volume fraction of coarse and fine aggregates ranges from 0.60 to 0.62, which is a reasonable value for good workability in fresh state and good volume stability in hardened state of SSFSCC. It is worth to mention that the aggregate gradation should meet fuller function. When the fineness modulus of sand is at the low limit, a small volume fraction of sand should be selected.

3.2.2. Step 2: calculate the volume content of paste

Based on the volume fractions of coarse and fine aggregates in the mixture, the volume of paste, V_p, can be easily obtained by Eq. (3):

$$V_p = V_c - V_{ca} - V_{fa} - V_{air} \tag{3}$$

where V_c is the volume content of SSFSCC mixture, V_{ca} is the volume content of coarse aggregate, V_{fc} is the volume content of fine aggregate, V_{air} is the volume content of air bubble in the mixture.

3.2.3. Step 3: determine the water-to-binder ratio (m_b/m_w)

The relation between water-to-cement ratio and compressive strength of concrete can be described by classical mathematical equation proposed by Abram or Bolomey. Based on Bolomey equation and experiences, the compressive strength of SSFSCC is correlated with water-to-binder ratio and other factors, as shown in Eqs. (4) and (5). Eq. (5) can be rewritten as Eq. (6), and thus the water-to-binder ratio (m_b/m_w) can be determined.

$$f_{cu,0} = f_{cu,k} + 1.645\sigma \tag{4}$$

$$f_{cu,0} = 0.42 f_{ce}\frac{m_b(1-\beta) + m_b\cdot\beta\cdot\gamma}{m_w} - 1.2 \tag{5}$$

$$m_w/m_b = \frac{0.42 f_{ce}(1-\beta+\beta\cdot\gamma)}{f_{cu,0}+1.2} \tag{6}$$

where $f_{cu,k}$ is the designed compressive strength of SSFSCC, $f_{cu,0}$ is the required compressive strength of SSFSCC during production process by considering the fluctuation of strength, σ is the variation value of compressive strength, f_{ce} is the tested compressive strength of cement at the age of 56 days, β is the percentage of mineral admixture (by the mass of total binder), γ is the cementitious coefficient of mineral admixture at the age of 56-day, 0.4 for fly ash and 0.9 for ground granulated blast furnace slag is used. This is reported by many publications, such as [39].

3.2.4. Step 4: calculate the content of powder and water

Given that mineral admixtures can improve performance, reduce cost, and increase greenness of concrete, FA and GGBS are both used in SSFSCC mixture. Meanwhile, expansive agent (EA) is also used to compensate the shrinkage of concrete. Therefore, the powders used in SSFSCC include cement, FA, GGBS, and expansive agent.

According to the volume content of paste in unit mixture and the apparent density of each powder, the mass content of each powder can be calculated by the following equations:

$$m_b = V_p / \left(\frac{1-\beta_{FA}-\beta_{GGBS}-\beta_{EA}}{\rho_c} + \frac{\beta_{FA}}{\rho_{FA}} + \frac{\beta_{GGBS}}{\rho_{GGBS}} + \frac{\beta_{EA}}{\rho_{EA}} + \frac{m_w}{m_b}\right) \tag{7}$$

$$m_w = \frac{m_w}{m_b}\times m_b \tag{8}$$

$$m_{FA} = \beta_{FA}\times m_b \tag{9}$$

$$m_{GGBS} = \beta_{GGBS}\times m_b \tag{10}$$

$$m_{EA} = \beta_{EA}\times m_b \tag{11}$$

$$m_c = m_b - m_{FA} - m_{GGBS} - m_{EA} \tag{12}$$

where ρ_c, ρ_{FA}, ρ_{GGBS}, ρ_{EA}, and ρ_w are the apparent density of cement, fly ash, GGBS, EA, and water, respectively. β_{FA}, β_{GGBS} and β_{GGBS} are the amount of fly ash, GGBS and EA by mass percent of total binder. m_{FA}, m_{GGBS}, m_{EA}, and m_c are the mass of fly ash, GGBS, expansive agent and cement in unit mixture.

3.2.5. Step 5: determine the dosage of superplasticizers and viscosity-enhanced agent

Superplasticizer (SP) is used in combination with viscosity-enhanced agent (VEA). On one hand, VEA increases the viscosity of the liquid phase and stabilizes the suspension system. On the other hand, SP disperses powder among liquid phase. Thus, a highly dispersed and stable suspension can be achieved by the combined action of VEA and SP. This is desired for highly flowable cement-based materials. In order to produce SSFSCC with satisfactory workability and robustness, a special VEA, which includes organic and inorganic components, is made. The dosage of VEA is 5~6% of the total binder by weight. The dosage of superplasticizers is adjusted by the flow spread of SCC.

3.2.6. Step 6: trial batch

Based on the above mix proportioning steps, the compositions of a mix can be obtained and then a trial batch of SSFSCC can be implemented. The workability of fresh mixture, the mechanical properties, durability and volume stability of hardened concrete are tested according to Tables 1 and 2. If one of the properties fails to meet the proposed value, adjustments should be made until all properties of SFFSCC satisfy the specified requirements.

3.3. Typical mix for SSFSCC

Based on the proposed mix proportion method, three mixes with different powders were designed as shown in Table 3. The raw materials used include Grade 42.5 Portland cement with a

Table 3
Mixing proportions of concretes (kg/m^3).

Mix	Cement	FA	GGBS	EA	VEA	SP	W	CL	S
1	350	80	100	0	0	5.0	175	810	835
2	308	80	100	42	0	5.0	175	810	835
3	308	50	100	42	30	5.3	175	810	835

compressive strength of 49.8 MPa at 56 days, GGBS with specific area of 450 m^2/kg, class F fly ash with specific area of 460 m^2/kg, sulphoaluminate-based expensive agent (EA), crushed limestone (CL) with continuous gradation and a size ranging from 4.75 mm to 16 mm, river sand (S) with a size ranging from 0.15 mm to 4.75 mm and a fineness modulus of 2.6, polycarboxylic acid superplasticizer, and compound VEA. The properties of fresh and hardened concretes are given in Table 4. It can be found that the properties of the mixes with different powders differ from each other. The compositions of powders in a mixture, especial VEA has a significant effect on properties of fresh concrete. The sample without VEA has higher flowability (slump flow), less flow rate, larger surface paste thickness in fresh state compared to sample with VEA. Mix 3 is a typical mix of SSFSCC, which satisfies the corresponding properties specified in Tables 1 and 2. The typical SSFSCC mix has been successfully applied in actual practice. This indicates that the proposed mix proportioning method for SSFSCC is reasonable and feasible.

4. Construction technology of SSFSCC

With proper design and careful production of SCC, bleeding, segregation, surface settlement and instability of air bubble can be reduced to an acceptable level for normal SCC. For a formwork with upper side open to atmosphere, a slight bleeding, surface settlement and air bubble floating of normal SCC is acceptable. Furthermore, it can be smoothed by the process of finishing. However, in the case of filling a flat, sealed and narrow space, no process of finishing is allowed for the top surface of SFFSCC, what's more, the tope surface of SSFSCC filling layer is required to have strong bonding with the above prefabricated slab. Therefore, the defects on the top surface of filling layer shown in Fig. 5 should be minimized. Obviously, bleeding, segregation, surface settlement and air bubble floating should be strictly controlled for SSFSCC of CRTS III ballastless slab track. In order to make the SSFSCC filling layer meet the designed requirement, it is also of great significance to develop proper construction technology besides developing an optimal mix proportioning of SSFSCC.

The construction of CRTS III slab track structure includes a set of steps as shown in Fig. 2. Apart from that, there are several special and important requirements for the construction of SSFSSC filling layer of CRTS III slab track, they are described as follows.

Casting speed of SSFSCC is the first point. SSFSCC flows in the sealed space may be in two different modes as shown in Fig. 6. Mode 1, the SSFSCC is very flowable or casting speed of SSFSCC is slow. SCC first spread out on the base plate, that is to say, the profile of SSFSCC has no contact with the top surface at the beginning. The surface of SSFSCC elevates steadily until fresh SSFSCC has full contact with the slab. In this scenario, the air in the sealed space cannot be totally squeezed out, and some big air bubbles are readily entrapped in the interface between the slab and base plate. Mode 2, the SSFSCC is not highly flowable or casting speed of SSFSCC is fast, the profile of SSFSCC has contact with upper and bottom faces during the flowing of SSFSCC. The air in the sealed space can be squeezed out to its largest extent, and no air bubble could be entrapped in the interface. Therefore, SSFSCC of CRTS III slab track is cast in mode 2. To reach the balance of flowability and casting speed of SSFSCC is crucial for casting SSFSCC. Full-scale tests have been carried out to find the appropriate casting speed of SSFSCC with specified rheological behavior.

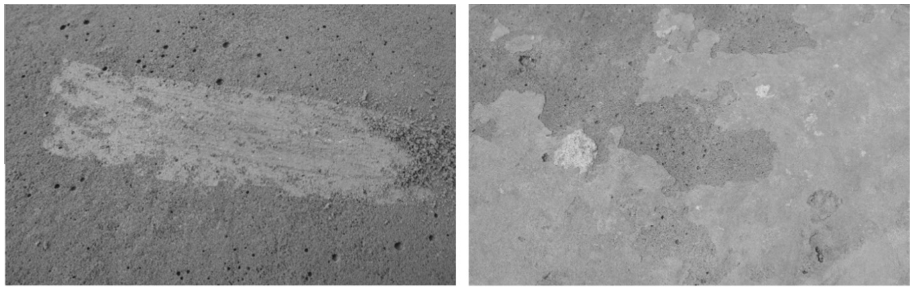
Secondly, the slab has been finely adjusted to its design position, and the change of position cannot beyond 0.5 mm during casting SSFSCC. However, in order to cast SSFSCC in mode 2, the height of SSFSCC in the pouring hole has to be high enough to maintain hydraulic pressure on SSFSCC, and thus the slab can be lifted up easily. Therefore, some clamps are designed to hold slab still, as shown in Fig. 7. However, if the height of SSFSCC in casting hole is too high, the hydraulic pressure exerted on the slab is high, as a consequence relatively large deformation of the clamp is inevitable, and the position of slab may be changed beyond the limit of 0.5 mm. The rheological behavior of SSFSCC, SSFSCC height in the pouring hole, and the clamps jointly affect the position controlling of the slab.

Thirdly, real-time field inspection must be carried out from porthole and exhaust holes during casting. The casting speed and segregation of SSFSCC can be visually judged from the porthole during casting. When the homogenous SSFSCC begins to flow out of the exhaust holes in the corners of the sealed place as shown in Fig. 8, it is believed that the sealed space is full of SSFSCC and casting of SSFSCC should be stopped to avoid lifting the above prefabricated slab by excess fresh SSFSCC. Besides, the quality of SSFSCC can be also visually judged by the observations from porthole and exhaust holes.

In addition, it is worth to mention several other important steps during the construction of SSFSCC filling layer. For example, after the completion of grouting SSFSCC into the sealed space, some fresh concrete in the cylindrical pouring hole should be reserved until the initial setting of concrete to avoid surface settlement. In this way, a little bit hydraulic pressure is maintained to keep SSFSCC in full contact with the above prefabricated slab, and the surface settlement of concrete can be effectively avoided. Prior to casting SSFSCC, the sealed space should be pre-wetted to avoid water loss of SSFSCC absorbed by geotextile and prefabricated slab.

Table 4
Properties of fresh and hardened concretes.

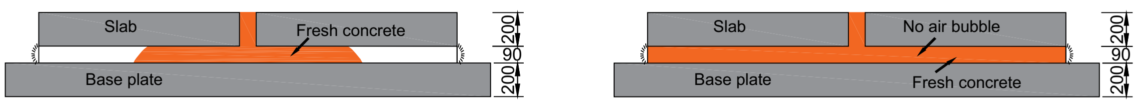
Mix	Air content/%	Slump flow/mm	T_{500}/s	PA	Bleeding rate/%	Top surface paste thickness/mm	Expansion rate within 24 h/%
Properties in fresh state							
1	3.6	670	3.5	0.86	0	12.0	0
2	4.2	655	3.0	0.89	0	9.5	0.40
3	4.8	610	5.0	0.90	0	7.0	0.50
	Compressive strength/MPa	Flexural strength /MPa	Elastic modulus/GPa	6-h charge passed/c	Freezing-thawing resistance/g/cm^2	Shrinkage/10^{-6}	
Properties in hardened state							
1	53.0	6.0	38.0	720	820	395	
2	52.3	5.8	37.2	750	840	335	
3	50.5	6.5	36.0	460	610	310	



(a) (b)

Fig. 5. The top surface of filling layer constructed by SSFSCC with improper workability after removing the prefabricated slab seated above. (a) Paste with very porous structure and low strength on the top surface of filling layer, (b) a very thin paste layer with a bubble layer beneath on the top surface of filling layer.

(a) Mode 1. SSFSCC first spread out, and then the surface is elevated until in contact with the slab. In this way, big air bubbles may be entrapped in the interface.



(b) Mode 2. SSFSCC has full contact with upper and bottom surfaces to squeeze out air to its largest extent. In this way, almost no air bubbles may be entrapped in the interface.

Fig. 6. Two different filling modes of SSFSCC.

Fig. 7. Full-scale field experiment of SSFSCC construction.

(a) Exhaust holes (b) Porthole

Fig. 8. Observation of SSFSCC from exhaust hole and porthole.

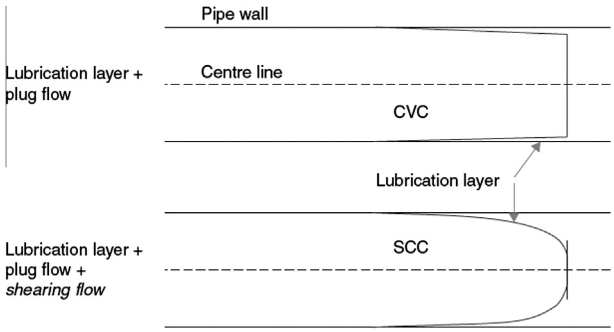


Fig. 9. Estimated velocity profile during pumping of conventional vibrated concrete (CVC, top) and self-compacting concrete (SCC, bottom), showing that the bulk SCC is sheared while CVC is not [40].

It is important to note that, although some successful applications of SSFSCC in high-speed rail have been made, there are still some challenges faced. The first challenge is that the air bubble layer on the top surface of SSFSCC filling layer (see Fig. 5(b)) occurs sometimes. Although bleeding, segregation, surface settlement of SCC can be effectively avoided, as long as SSFSCC meets all the requirements listed in Table 2. However, the thin paste layer with a bubble layer underneath is hard to be completely avoided. This type of interface has low interface bonding between the slab and SSFSCC layer. The fresh SSFSCC flows in the sealed space in mode 2, both upper and bottom surfaces provide friction during flowing. It is similar to the flow of pumping SCC [40]. The velocity profile of SCC flows through the pipe is assumed to consist of plug in the center, a lubrication layer at the wall, and a shear zone. It is believed that the plug is small and the bulk concrete is sheared. However, conventional vibrated concrete has no shear zone (see Fig. 9). When SSFSCC flows in the sealed space, a shear zone may present. If the SSFSCC is shear thinning under the shear rate, depending on the casting rate, the viscosity of SSFSCC may be reduced, and bubbles become unstable. Floating bubbles gather under the lubrication layer. This is exactly what Fig. 5(b) presents. Due to the presence of the bubble layer, the bonding between slab and SSFSCC filling layer is very weak. In practice, the size of the bubble in concrete is decreased by the action of chemical admixture, and the stability of bubbles is verified by small-scale casting test for every new batch of materials prior to application. This helps to prevent the bubbles from rising to the interface in real engineering. However, more works are needed to understand the rising phenomena of air bubbles, in order to find better measures to completely prevent this from happening.

The second challenge is the quality control of SSFSCC for CRTS III slab track. The amplitude of quality fluctuation of raw materials is relatively large, because of the long time and large space spans during the construction of a HSR line of CRTS III slab track. Thus, to further improve the robustness of SSFSCC is extremely important.

5. Concluding remarks

(1) SSFSCC, a special SCC applied in the high-speed rail of China, possesses some prominent characteristics. First, SSFSCC is grouted into a flat, narrow and sealed space (90 mm × 2500 mm × 5600 mm), and good bonding between above prefabricated slab and SSFSCC filling layer is required. Secondly, SSFSCC flows on flexible geotextile, and it increases the flow resistance.

(2) In order to meet requirements of SSFSCC filling layer, a set of parameters were proposed for evaluating the workability of fresh SSFSCC, including slump flow, T_{500} time, PA index, bleeding ratio, surface paste thickness, and expansion rate.

(3) The mix proportioning method proposed in this paper is feasible and has been successfully applied for constructing the SSFSCC filling layer of CRTS III ballastless track structure.

(4) Although SSFSSC has been successfully applied in practice, more works are needed to better understand the flow state of SSFSCC in the sealed space, and the phenomena of bubble rising to the interface between slab and SSFSCC layer. Since construction sites along HSR line may extend hundreds of km, to further improve the robustness of SSFSCC against the variation of raw materials is desired.

Acknowledgements

Financial supports from China Railway Corporations (2016G001-C), National Basic Research Program of China (973 Program) (2013CB036201) and National Natural Science Foundation of China (No. 51208515) are highly appreciated.

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