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Experimental Study on the Workability and Stability of Steel Slag Self-Compacting Concrete

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Featured Application: Steel slag self-compacting concrete (SSCC) with relatively ideal workability was prepared by substituting steel slag for natural fine aggregate to realize solid waste resource utilization. It is beneficial to solve the problems of steel slag abandonment, land occupation, environment pollution and low utilization rate, and realize utilization of a large amount with low-energy consumption for traditional material saving and sustainable development. SSCC has very high application value and economic significance.

Abstract: There is important application value and economic value in exploring the potential use of steel slag to prepare self-compacting concrete (SCC) and make full use of solid waste resources. In this paper, steel slag self-compacting concrete (SSCC) with relatively ideal workability is prepared by using steel slag instead of natural fine aggregate based on mix proportion optimization and SSCC performance research. The filling ability, passing ability and resistance segregation were tested to evaluate the workability of SSCC. The results show that when the content of steel slag sand is 20%, the workability performance of SSCC is similar to that of SCC with natural aggregates. When the content of steel slag sand is less than 60%, the performance of SSCC can also meet the workability requirements after adjusting the amount of raw materials.

Keywords: steel slag; self-compacting concrete; workability; dynamic stability; static stability

1. Introduction

In the process of iron and steel smelting, as one of the by-products, steel slag emission is about 15%–20% of the total crude steel production and is increasing rapidly along with the increase of steel production in the world. Taking China as an example, according to the China economic network, crude steel output in 2018 was 928 million tons, and the steel slag output was about 150 million tons. As a kind of solid waste, steel slag stacking not only takes up land, but also brings a series of ecological environmental pollution problems, and also causes the waste of precious resources to a certain extent. With the increase in its total amount, it has greatly hindered the sustainable development of the environment.

Self-compacting concrete (SCC) is one of the key research directions of the high-performance concrete industry because it flows under its own weight, can completely fill the formwork without mechanical compaction, and has the advantages of fast construction, easy pouring, high efficiency, etc. The research and application of SCC have attracted attention all over the world [1–3]. The concept of

SCC and related scientific tests were first proposed and tested in Tokyo University, Japan, by Okamura et al. [4,5], and they also started to analyze and study the design method of SCC mix proportion through conducting a lot of experimental research. This mix proportion design method of SCC is called the 'Japanese prototype method' or 'step-by-step method'. In this method, the target performance of SCC is determined, firstly, by the mix proportion of the mixture being initially designed, secondly after selecting the raw materials required in construction, and then the mix proportion is adjusted to meet the performance and construction requirements according to the related experiment. Petersson et al. [6,7] proposed the liquid criterion theory and blocking criterion theory, based on the interaction between aggregate particle system and cement paste in SCC, to design the mix proportion of SCC. Su et al. [8] proposed the SCC mix proportion design method based on the compactness between aggregates by introducing an aggregate compaction factor. Moreover, other SCC design methods have been proposed including the fixed aggregate content method [9], the computer-aided design method [10,11], and the mathematical statistics factor method [12], etc.

It is difficult to use a single index or test method to assess the workability of fresh SCC mixture comprehensively. Generally, the workability of SCC mainly comprises filling ability, passing ability, and segregation resistance. The segregation resistance is often considered as the index of stability of SCC, which also can be classified as static stability and dynamic stability. At present, the evaluation and test methods of the workability of SCC mainly includes a slump flow (SF) test incorporating slump flow time (T500) measurements [13–26], a V-funnel test [14,15,17,19–22,24,26], a L-box test [13,15,19,21,23,24,26], a U-shape meter test [14,17,22], and a J-ring test [15–19,24,25], etc. Stability tests conducted for SCC mixture involved a sieve analysis test [15,17,20,25], flow table test [27], segregation probe test [20], and static settlement column test [20,23], etc. Zhu et al. [13] studied the influence of manufactured sand and lightweight sand on the workability of fresh self-compacting lightweight concrete (SCLC) by the slump flow test incorporating T500 measurement and the L-box test. The experimental results indicated that higher manufactured sand and lightweight sand ratios can reduce the flowing ability of SCC. Rios et al. [27] used a flow table test to investigate the self-compacting properties and the consistency of fresh SCC using air-cooled blast furnace slag to replace coarse and fine natural aggregate. The results show that with the increase of slag content, the self-compacting performance of concrete gradually reduces, and when the replacement rate is low, the self-compacting performance of concrete still remains. Valizadeh et al. [18] used magnetite aggregate to replace the natural coarse aggregate of SCC and general concrete with the volume ratio of 50%, 75% and 100% in the study of heavyweight SCC. The slump test and J-ring test results show that the workability of fresh concrete decreases gradually with the increase of the amount of magnetite aggregate. Khan et al. [19] used the slump flow test, V-funnel test, L-box test and J-ring test to study and analyze the workability of SCC with ethylene vinyl acetate (EVA) and ladle furnace slag (LFS) instead of cement and natural sand. The results show that adding EVA increases the workability of SCC, while LFS decreases that.

In recent years, quite a few researchers have begun to explore the application of steel slag in the preparation of SCC [20–26]. Sheen et al. [20] developed SCC containing stainless steel oxidizing slag (SSOS, partial substitution of fine and coarse aggregate) and stainless steel reducing slag (SSRS, partial substitution of cement). Results showed that the stainless steel slag-based SCC can accelerate the hardening process, the compressive strength of SCC prepared with SSOS replacement in full exhibits slightly better or at least similar results to that of the control while potentially volumetric instability. Santamaría et al. [21,23], investigated the mix design, in-fresh and hardened properties of SCC incorporating electric arc-furnace steelmaking slag as aggregate, and concluded that it is possible to prepare SCC using electric arcfurnace slag as coarse and fine aggregate, using appropriate doses and compatible chemical admixtures. Hisham [22] investigated the effect of steel slag replacing natural aggregate on SCC, and the slump flow test, V-shaped funnel test, column segregation test, sieve analysis test, segregation probe test and U-shaped box test were used to comprehensively evaluate the influence. The results show that steel slag aggregate can be used in SCC, but the workability of SCC will be greatly affected when the substitution rate of steel slag is over 50%. Rehman [24], investigated the combined influence of glass powder and granular steel slag on fresh and mechanical properties of SCC, and found that the workability of SCC decreases with the increase in granular steel slag content which may be attributed to the porous and rough texture of steel slag. Pan et al. [25] investigated the effects of steel slag powder on the properties of SCC with recycled aggregates and found that steel slag powder improved the filling ability and passing ability of SCC, but adversely affected segregation resistance. Sosa et al. [26] investigated the feasibility of high-performance SCC prepared with electric arc furnace slag (EAFS) aggregate and cupola slag powder based on the rheological and physical-mechanical experiments of SCC. The experimental results showed that it is possible to obtain a very homogeneous, symmetrical, and stable distributed mixture without segregation or concentration of coarse aggregates. EAFS reduces concrete slump and passing ability by 10%, reduced the flow rates more noticeably compared to reference mixes due to their high viscosity.

Use of industrial wastes as cement or aggregate replacement can play vital role in reducing the utilization of natural resources, besides decreasing land and air pollution [24]. Although there are many works on steel slag use as aggregates or mineral admixture in concrete and its advantageous properties have been reported, the research on the utilization of steel slag in SCC preparation has only begun in recent years to some extent because the high water absorption of steel slag is unfavorable to the fluidity of the concrete mixture. Moreover, it is not enough to encourage the use of a steel slag in the construction industry without misgivings or concerns if the technical opinion is not supported by sufficient characterization and performance testing [28]. Analyzing the aforementioned research on the use of steel slag in SCC, it found that the steel slag was mainly used to replaces the coarse aggregate [22,26] or both coarse and fine aggregate [20,21,23]. Meanwhile, the substitution rate is relatively high, for instance, all coarse aggregate was replaced [21–23,26], the substitution rate is of 0%, 50%, 100% for both coarse and fine aggregates [20]. The steel slag was also used as powder replacing the cement (fixed substitution rate of 30%) [25], as a fine aggregate (substitution rate is 0, 40%, 60%, 80%) together with the glass powder [24]. The research work that has been carried out mainly focuses on workability and mechanical properties of steel slag self-compaction concrete (SSCC). However, the expansion potential of steel slag has always been an important factor restricting its large-scale application in building materials [28], and it is easier to cause inhomogeneous expansion stress for large-size coarse aggregates.

Therefore, this paper focuses on the use of steel slag as fine aggregate, and the aged steel slag used in incorporating fly ash in SSCC, which is of benefit to reduce the expansion effect of steel slag and inhomogeneous expansion stress. The present work is to investigate the filling ability, passing ability, dynamic stability and static stability of a fresh mixture of SSCC with steel slag as the fine aggregate, and is expected to systematically investigate SSCC workability to promote the wide application of steel slag in SCC for traditional material saving and sustainable development.

2. Materials and Methods

2.1. Raw Materials

2.1.1. Cement

Chinese standard ordinary Portland cement (PO, similar to ASTM C150 Type I cement) of P.O.42.5 produced by Anhui Conch Co., Ltd. (Anhui, China) was adopted. The composition of the cement is listed in Table 1. The basic properties of cement are listed in Table 2.

Table 1. Chemical composition of cement and fly ash.

Constituent/wt %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
Cement	20.52	5.95	2.75	59.65	2.58	2.47	3.02
Fly ash	52.7	25.8	9.7	3.7	1.2	0.2	2.04

Table 2. Basic properties of cement.

Fineness/(m^2/kg)	Setting Time/min		Compressive Strength/MPa		Flexural Strength/MPa	
	Initial	Final	3d	28d	3d	28d
≥350	≥60	≤280	24.5	49.0	4.8	8.4

2.1.2. Mineral Admixture

Generally speaking, fly ash, silica fume and ground mineral powders are the most used admixtures in ordinary SCC. The addition of fly ash and other admixtures can not only improve the performance of concrete, and prevent concrete bleeding, but also decrease cement consumption. The mineral admixture used in this test was the secondary fly ash produced by a power plant in Ma'anshan, China. The composition of fly ash was listed in Table 1. The main physical properties of the fly ash were listed in Table 3.

Table 3. Main physical properties of fly ash.

Moisture Content/%	Loss of Ignition/%	Alkali Content/wt %	Density/(g/cm^3)	Fineness/(m^2/kg)
0.10	2.04	0.75	2.32	460

2.1.3. Water-Reducer

The polycarboxylic high-performance superplasticizer agent with the commercial name of JMPCA produced by Sobute New Materials Co., Ltd. (Nanjing, China), an industry-leading supplier of new construction materials in China, was used to adjust the workability of the steel slag self-compacting concretes. Because this kind of admixture has the advantages of low dosage and high water reduction rate, the water reduction rate can reach 30%, which greatly reduces the water demand of concrete, thus reducing the segregation rate of SCC. The basic performance parameters and recommended dosage are listed in Table 4.

Table 4. Basic performance parameters of the polycarboxylic high-performance superplasticizer (JMPCA).

Admixture State	Solid Content/wt %	PH Value/%	Alkali Content/wt %	Water Reducing Rate/%	Dosage Range/wt % (Proportion to Binder)
Liquid	2.04	0.75	≤2.0	30%	0.8–1.5

2.1.4. Aggregates

Natural gravel particles with grading of 5–16 mm were used as coarse aggregate. Some basic properties of coarse aggregate were listed in Table 5.

Table 5. Physical properties of coarse aggregates.

Apparent Density/(kg/m^3)	Crushing Index	Needle and Flake/wt %	Nud Content/wt %	Water Content/wt %
2678	11.8%	6.3%	0.2%	0.6%

Steel slag sands, which were accumulated a long time for aging, and natural river sand were used as fine aggregates. According to Chinese standard GB/T 14684-2011 [29], the physical properties of both natural and steel slag aggregates were measured and are given in Table 6; a sieve analysis was conducted and the results are shown in Figure 1. The chemical composition of steel slag is presented in Table 7. The X-ray diffraction (XRD) analysis results are shown in Figure 2a.

Table 6. Physical properties of fine aggregates.

Type of Fine Aggregates	Apparent Density/(kg/m^3)	Fineness Modulus	Nud Content/wt %	Water Content/wt %
Natural river sand	2580	2.4	1.2	2.8
Steel slag sand	3590	3.9	-	1.2

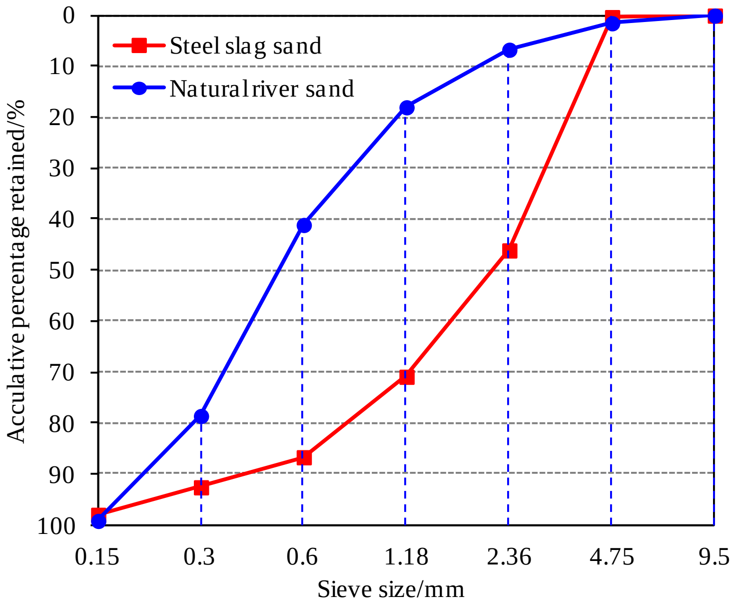
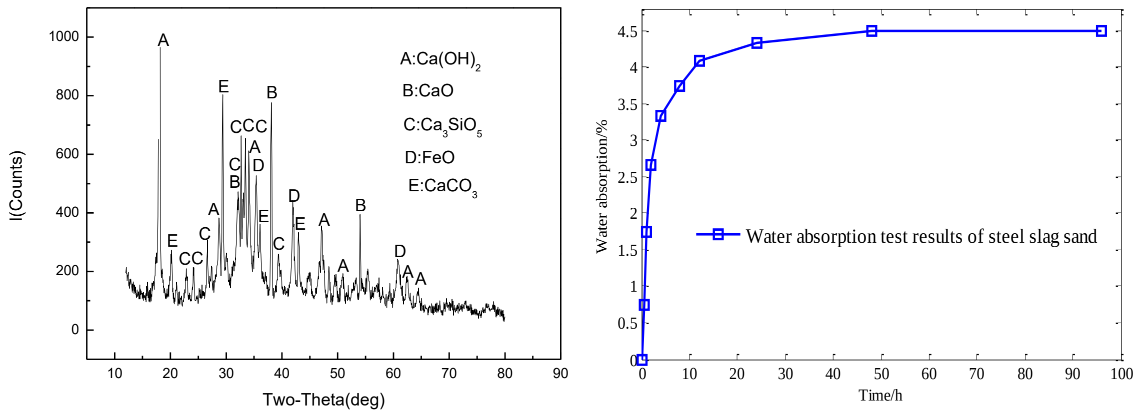


Figure 1. Grading of fine aggregates according to sieving analysis test.

Table 7. Chemical compositions of steel slag.

CaO	SiO_2	Fe_2O_3	Al_2O_3	P_2O_5	MgO	NnO	SO_3	Others
50.32	13.06	23.4	1.53	3.02	4.05	2.21	0.3	2.11



(**a**) (**b**)

Figure 2. X-ray diffraction (XRD) and water absorption experimental results of steel slag used as fine aggregates in self compaction concrete: (**a**) XRD test results; (**b**) water absorption.

As the surface of steel slag sand is rough and porous, which has better water absorption than natural sand, it will have a greater impact on the workability of SSCC. Therefore, it is necessary to measure the water absorption of steel slag sand before the experiment. We took 1200 g of dried steel slag sand as a sample for the test and measured water absorption of the sample. The test results are shown in Figure 2b.

According to Table 7 and Figure 2a, the steel slag used is basically composed of crystalline minerals, and the content of amorphous material is very low. The main mineral components of the steel slag aggregate were calcium silicate, $Ca(OH)_2$, f-CaO, RO phase (RO phase is a broad solid solution formed by melting FeO, MgO, and other divalent metal oxides such as MnO) and $CaCO_3$. Because the steel slag has been stored in the open air for a long time, some f-CaO has reacted with water to form $Ca(OH)_2$, and some has carbonated to $CaCO_3$. The decrease of f-CaO reduces the expansion effect when being used in concrete, which is beneficial to the volume stability of SSCC.

From Figure 2b, it can be seen that the water absorption rate of steel slag sand increases rapidly in the first 4 h. Therefore, it has a great influence on the workability of SSCC, especially the fluidity and anti segregation performance of a fresh concrete mixture. It is necessary to control the time interval from mixing to pouring the concrete mixture.

2.1.5. Water

Common tap water was used as mixing water.

2.2. Mix Proportion

Considering the influence of steel slag sand on the workability of concrete, the volume percentage of steel slag (VPS) replacing natural sand was used as a variable parameter to design the mix proportion of concrete. The volume replacement rate of steel slag used in mix proportion were 0.0%, 20%, 40%, 60%, 80% and 100% respectively. In the experiment, the influence of steel slag on the workability of SSCC was investigated keeping concrete mix proportion unchanged by changing the amount of steel slag in each group of concrete specimen. The codes of different groups relating to the mix proportion of concrete were explained according to the substitution rate of steel slag to natural san, as shown in Table 8.

Table 8. Substitution of steel slag mixture in different groups.

Group	Code	Name
A	S_0SCC	Ordinary self-compacting concrete
B	S_{20}SCC	Self-compacting concrete with equal volume of steel slag sand instead of 20% natural fine aggregate
C	S_{40}SCC	Self-compacting concrete with equal volume of steel slag sand instead of 40% natural fine aggregate
D	S_{60}SCC	Self-compacting concrete with equal volume of steel slag sand instead of 60% natural fine aggregate
E	S_{80}SCC	Self-compacting concrete with equal volume of steel slag sand instead of 80% natural fine aggregate
F	S_{100}SCC	Self-compacting concrete with equal volume of steel slag sand instead of 100% natural fine aggregate

After the analysis, calculation and adjustment of the preliminary experiments, mix proportion of the reference group (S_0SCC) of SSCC was determined as shown in Table 9. Then, the mix proportion of each group of SSCC can be preliminarily designed according to the different VPS as shown in Table 8.

In the workability experiment of fresh SSCC prepared with the reference mix proportion, the workability of SSCC declined with the gradual increase of the steel slag sand amount (substitution rate). When the amount of steel slag sand was more than 20%, the fresh SCC mixture made it difficult to achieve the design goal of workability.

Table 9. Mix proportion of steel slag self-compaction concrete (SSCC, /kg/m^3).

Group	W/B	Water	Cement	Fly Ash	Gravel	Natural Sand	Steel Slag	Superplasticizer
S_0SCC	0.40	192	312	168	836	656.0	0.0	4.80
S_{20}SCC	0.40	192	312	168	836	525.0	131.0	4.80
S_{40}SCC	0.40	206	334.5	180.5	807	380.6	253.6	6.18
S_{60}SCC	0.40	215	349.4	188.1	807	235.7	380.5	8.06
S_{80}SCC	0.40	220	357.5	192.5	807	126.8	507.4	8.25
S_{100}SCC	0.42	231	357.5	192.5	739	0.0	580.0	8.25

The reason is that the water absorption of steel slag sand is larger than that of natural sand and the particle surface is rough, so the free water in the mixture is relatively lower under the same water consumption, which makes the flow performance of the concrete worse. The void fraction of accumulated steel slag sand particles is bigger, and needs more cement slurry to wrap particles' surface and fill the gap between and particles, so that when the content of steel slag sand was 100%, the anti segregation performance of concrete mixture decreased obviously, and the mixture almost fell into scattered particles.

Therefore, based on the preliminary experiment and cause analysis of the influence of the VPS on the S_0SCC, guided by the predetermined workability design goal, the mix proportion of SSCC with ideal workability under different VPS was finally obtained after constantly changing the proportion of raw materials in SCC. In adjusting mix proportion, the water–binder ratio (W/B) remained unchanged as much as possible. Being trial mixed mainly by adjusting the amount of superplasticizer, the volume of cement slurry and the slurry-aggregate ratio of the mixture, the basic workability of the SSCC with different VPS was tested and analyzed. It should be pointed out that when design mix proportion was S_{100}SCC, which is due to the large water demand of the mixture, it was difficult to meet the workability goal if keeping unchanged the original mix proportion (W/B = 0.40). Therefore, the water binder ratio of the S_{100}SCC groups was adjusted to 0.42. The mix proportion of SSCC which satisfied the workability design goal after adjustment i shown as Table 9.

2.3. Test Methods

The stability of SCC, including dynamic stability and static stability, is an important index of its workability [30–32]. Static stability refers to the ability of the coarse aggregate to stably suspend in the mortar from the completion of concrete pouring to the initial setting. Dynamic stability refers to the ability of the coarse aggregate to keep the synchronous flow with the mortar in the transportation, pouring, pumping and other engineering operations of the fresh self-compacting concrete.

There are many experimental instruments and methods for measuring and evaluating the workability of SCC. The slump flow test, J-ring test, sieve analysis and visual stability index were selected after comprehensive consideration to evaluate the workability of SCC with different substitute rate of steel slag as fine aggregates. So these methods can be divided into three categories: basic workability, static stability and dynamic stability. The selected test methods and evaluating indexes are shown in Table 10.

Table 10. Test and evaluation method of workability for SCC.

Method Types	Evaluating Method	Evaluating Indicator	Workability
Basic workability	Slump flow test	Slump flow diameter (SF)	Filling ability
	T500 test	Slump flow time (T500)	Filling ability
	J-ring test	J-ring spread diameter (SF_J) J-ring height difference (Δh)	Passing ability
Dynamic stability	Visual stability	Visual stability index (VSI)	Segregation resistance
Static stability	Sieve analysis	Segregation rate (SR)	Segregation resistance

As is known, the slump flow test is one of the earliest test methods evaluating the workability fresh SCC mixture, which evolved from the slump test for concrete fluidity. The slump flow method is a relatively simple and effective method to evaluate the filling performance of fresh SCC from three parameters of SF, filling velocity and T500.

Soon after the J-ring test used to evaluate the performance of SCC appeared, it became a common method of scholars all over the world. The J-ring test can fully reflect the viscosity of fresh SCC and its ability to pass through a narrow space, so which can better reflect the passing ability of SCC. Two parameters, J-ring spread diameter (SF_J) and J-ring height difference (Δh), were used to characterize the passing ability of fresh SCC. According to the Chinese Standard JGJ/T 283-2012 [33], the difference between SF_J and SF is used as evaluation indicator of passing ability (PA) and can be divided into two grades: PA1 (25 mm < PA ≤ 50 mm) and PA2 (0 ≤ PA ≤ 25 mm). PA1 is applicable to structures with reinforcement spacing between 80 mm and 100 mm. PA2 is applicable to structures with reinforcement spacing between 60 mm and 80 mm

The visual stability index, as the only standard test method at present, was incorporated into the American Society for Testing and Materials (ASTM) Standard in 2009 and accepted by the American concrete field [34]. This method is mainly combined with the slump flow test. The surface condition of the mixture is observed and evaluated by combining the evaluation standards. The degree of segregation is qualitatively divided into four grades based on the personal subjective judgment in the VSI method, which has higher requirements for testers. VSI evaluation criteria are shown in Table 11.

Table 11. Visual stability index (VSI) values for SCC.

VSI Value	Evaluation Description
0 = Highly stable	No evidence of segregation or bleeding
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass
2 = Unstable	A slight mortar halo (≤10 mm) and/or aggregate pile in the of the concrete mass
3 = Highly unstable	Clearly segregating by evidence of a large mortar halo (>10 mm) and/or aggregate pile in the of the center of the concrete mass

The sieve analysis test [35], as a typical static stability test method, is one of the methods commonly used to evaluate the segregation resistance of fresh SCC objectively by quantifying and evaluating the probability of segregation between mortar and coarse aggregate in SCC. According to Chinese Standard JGJ/T 283-2012 [33], the segregation resistance of SCC can be divided into two grades: SR1 (the segregation resistance index ≤20%) and SR2 (the segregation resistance index ≤15%). SR1 is applicable to vertical structures and thin plates with reinforcement spacing greater than 80 mm and flow distance less than 5 m. SR2 is applicable mainly to the vertical structures and thin plates with reinforcement spacing greater than 80 mm and flow distance more than 5 m.

In this paper, the workability of SSCC is mainly tested and evaluated by filling ability, passing ability and segregation resistance. Based on the Chinese Standard JGJ/T 283-2012 [33] and the previous relevant research results, the basic requirement of SSC workability was determined as follows: 550 mm ≤ SF ≤ 750 mm; 3 s ≤ T500 ≤ 25 s; 0 ≤ PA ≤ 50 mm; 0 mm ≤ Δh ≤ 25 mm.

3. Experimental Results and Workability Evaluation

3.1. Basic Workability of the Reference Group (S_0SCC)

The basic workability of the reference group concrete (S_0SCC, as shown in Table 9) was tested first. The experiment results are listed in Table 12. The basic workability test of S_0SCC is shown in Figure 3.

Table 12. Basic workability of the reference group (S_0SCC).

Slump Flow	T500	J-Shaped Ring		Stratification	Bleeding Condition
		Δh	PA		
700 mm	8.2 s	14 mm	30 mm	Fine	No

(a) (b)

Figure 3. The basic workability test of S_0SCC. (**a**) Slump flow test (SF = 700 mm); (**b**) J-ring test (SF_J = 670 mm).

According to observation in the experimental process and the test result listed in Table 12, the basic workability of S_0SCC concrete can be obtained and shown as follows: (1) the SF result is 700 mm of fresh SCC and belongs to SF2 Grade according to JGJ/T 283-2012 [33], indicating that the fluidity of SCC mixture is ideal; (2) the T500 result is 8.2 s, within the range of 3–25 s, meeting the requirements; (3) the Δh result is 14 mm of fresh SCC, within the range of 0–25 mm, meeting the requirements; (4) the PA result is 30 mm, qualified as Grade PA1. There is no bleeding and stratification phenomena of fresh concrete, easy to form and compact. The hardened SCC showed high early strength, which indicated that the polycarboxylate superplasticizer can improve the early strength of SCC, while very less strength increased later. These test phenomena and data show that the performance of SCC, prepared with the reference mix proportion, fulfilled the preset requirements and met the corresponding construction and specification standards.

3.2. Basic Workability of Steel slag Self-Compacting Concrete (SSCC) with Different VPS

The basic workability experimental results of SSCC with different VPS are shown in Figure 4.

The test results show that when VPS = 20%, due to the small amount of steel slag sand, it has little effect on the fluidity and filling performance of the fresh mixture, and the performance of S_{20}SCC in the test group is similar to that of SCC in the reference group. However, about 40%, 60% and 80% replacement ratios of steel slag sand, the total sand amount used in SSCC mixture is 634.2 kg/m^3, and then by adjusting the amount of water reducing agent, SSCC with ideal workability and meeting the specification requirements can be trial prepared. In particular, when the VPS is 60% and 40%, the filling and fluidity of fresh SSCC are relatively high, which meet the specification requirements. The minimum value of SF is 690 mm, which belongs to the first-level standard. The maximum value of PA is 30 mm, which can meet the requirements of relevant standards and specifications. Δh meets the requirements of experience summary less than 25 mm. When VPS is 80% and 100% respectively, although it can meet the expected requirements, due to its large flow time of T500, the maximum value is about 18.2 s, which will have a certain hidden danger to the filling and passing ability of concrete mixture. The analysis shows that when the replacement ratio of steel slag sand is large, the ground friction resistance between coarse aggregate and fine aggregate increases, which results in a large flow time of T500 and general filling performance of fresh SSCC. Therefore, when testing SCC with steel slag sand instead of natural sand, it is reasonable to suggest that VPS should not be more than 60% under the same conditions.

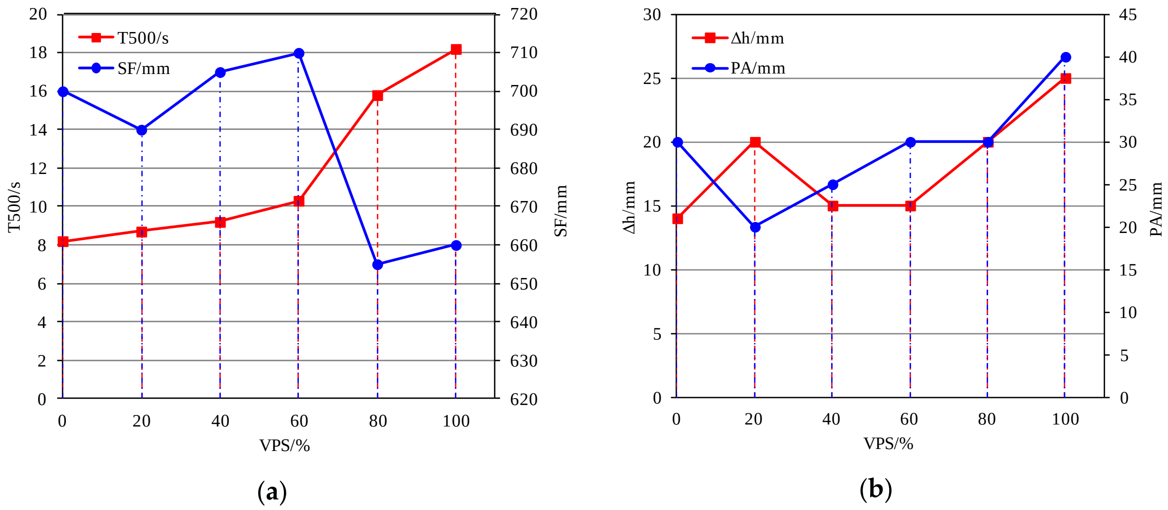


Figure 4. Effect of steel slag sand on the basic workability of SSCC after mix proportion adjustment. (**a**) slump flow (SF) and T500; (**b**) passing ability (PA) and Δh.

3.3. *Dynamic Stability Test of SSCC (Visual Stability Index, VSI)*

The visual stability index method was used to analyze and evaluate the dynamic stability of fresh SSCC. According to the experimental study and analysis, the VSI value of the SSCC with different VPS after adjustment is 0, that is, highly stable. The VSI results of SSCC are shown in Figure 5.

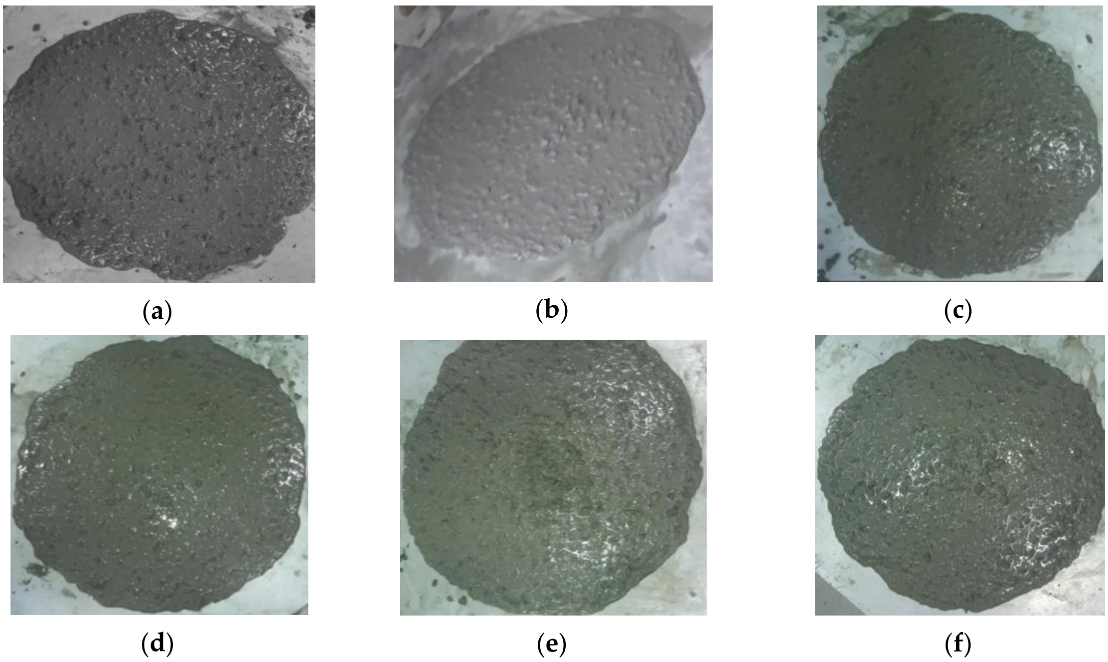


Figure 5. VSI evaluation of SSCC after adjustment. (**a**) S_0SCC (VSI = 0, SF = 700 mm); (**b**) S_{20}SCC (VSI = 0, SF = 690 mm); (**c**) S_{40}SCC (VSI = 0, SF = 705 mm); (**d**) S_{60}SCC (VSI = 0, SF = 710 mm); (**e**) S_{80}SCC (VSI = 0, SF = 655 mm); (**f**) S_{100}SCC (VSI = 0, SF = 660 mm).

According to the evaluation criteria of the visual stability index and the performance of the above graphs, we preliminarily determined that the VSI of each group of SSCC was 0, so its dynamic stability (segregation resistance performance) met the test requirements. This test method is relatively simple and easy to judge, but most of the test results are determined by the subjective performance of the test personnel, so whether it can meet the requirements of construction still needs further test verification.

3.4. Static Stability of SSCC (Segregation Resistance, SR)

The sieve analysis test was used to analyze and evaluate the static stability of fresh SSCC. The sieve analysis test results of SSCC with different VPS are listed in Table 13.

Table 13. Sieve analysis test results.

Group	Total Sampling/kg	Separation Quantity/kg	SR/%
VPS = 0%	5.056	0.350	6.92
VPS = 20%	4.982	0.298	5.98
VPS = 40%	5.040	0.380	7.54
VPS = 60%	4.960	0.270	5.44
VPS = 80%	5.092	0.430	8.44
VPS = 100%	5.032	0.438	8.70

According to Table 13, we can see that with the increase of VPS and paste-aggregate ratio, SR is in a fluctuating trend, the numerical dispersion is large, there is no obvious rule, but the overall trend is increasing. The maximum SR value of 8.7% appears when VPS is 100.0%, the minimum when VPS is 60.0%. According to the analysis of the test phenomenon, the reason for the decrease of VPS = 0% and 20% SR value is that the water demand in the mixture is relatively increased due to the steel slag sand with high water absorption, so the segregation rate of the mixture is relatively reduced. When VPS is 0%, 20%, 40% and 60%, SR value is between 5% and 15%, which belongs to SR2 level, and the flow time T500 of each test group is smaller, which shows that when VPS is 0%, 20%, 40% and 60%, each test group has better liquidity and no segregation. SR value is larger than that of the previous groups when VPS ≥ 80.0%, although S_{80}SCC and S_{100}SCC have higher viscosity and better segregation resistance, indicating that the probability of segregation risk between coarse aggregate and paste increases.

3.5. Compressive Strength of SSCC

The compressive strength of SSCC with different VPS was tested according to Chinese standard GB 50081-2002 [36]. The average value of the measured compressive strengths of three cubic specimens sized 150 × 150 × 150 mm in a group was taken as the final compressive strength result. If either of the differences between the maximum value or the minimum value and the intermediate value exceeds 15%, the intermediate value shall be taken as the strength result, if both the differences exceed 15%, the test results of this group were invalid. The compressive strengths at different age are shown in Figure 6. The microscopic pictures of several different groups of SSCC are shown in Figure 7.

As shown in Figure 6, compared with the group of S_0SCC, the addition of steel slag sand improves the compressive strength of self-compacting concrete at 28 days when the water–binder ratio is constant and the working performance is ideal after the optimization of concrete mix proportion based on workability of fresh SSCC. The difference of compressive strength, at the same age, between SSCC specimen groups with different VPS. With the increase of VPS, the compressive strength of SSCC at 7 days shows a decreasing trend (up to 11% at 100% VPS), and the compressive strength at 28days decreases slightly when VPS exceeds 60%. Combined with the results of the workability test results, it is not recommended to exceed 60% VPS in the preparation of SSCC.

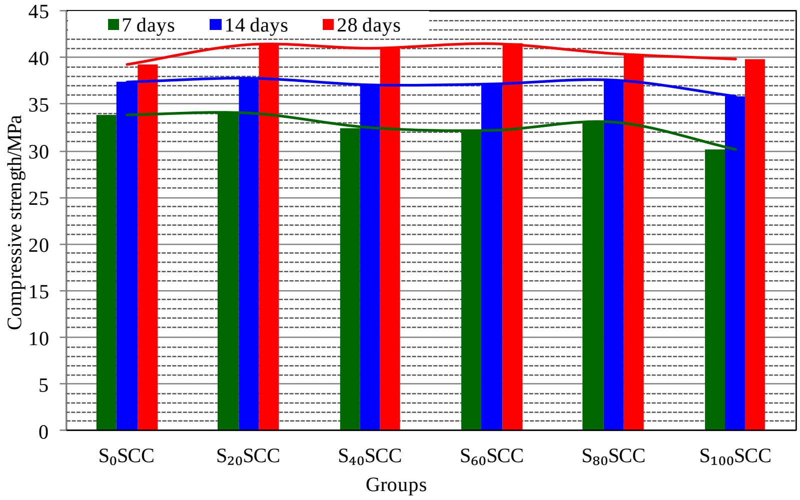


Figure 6. Grading of fine aggregates according to sieve analysis test.

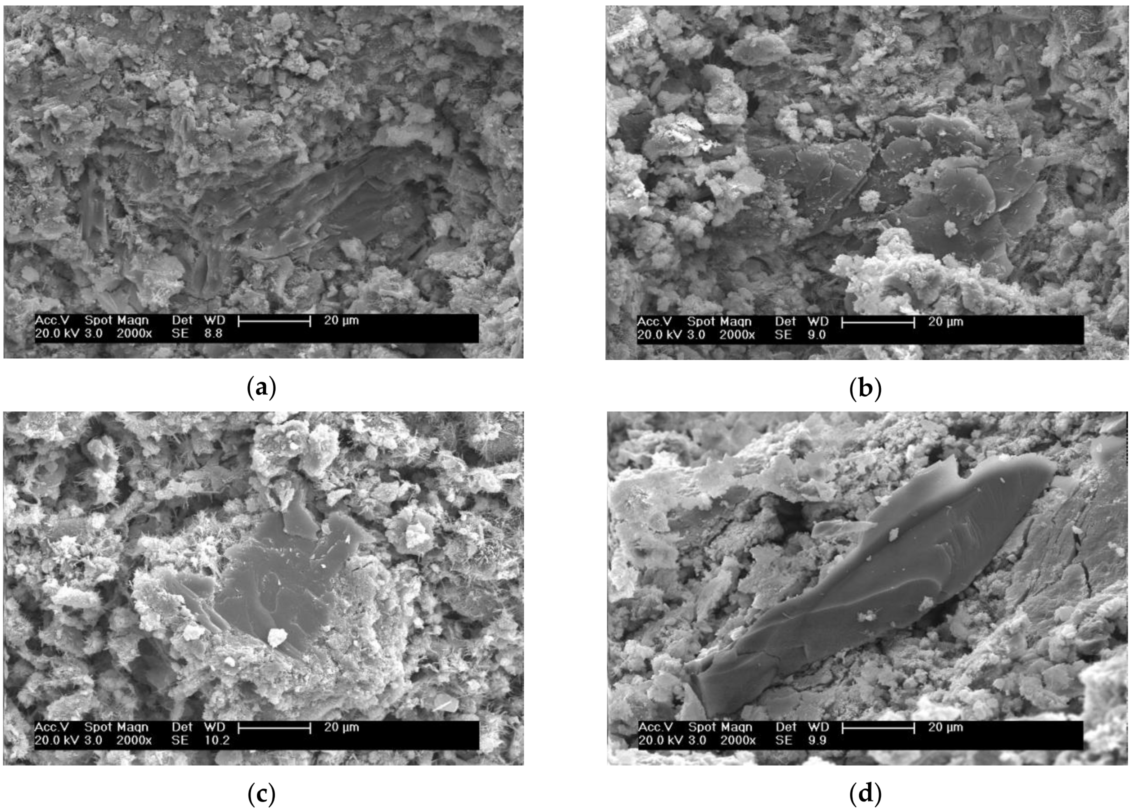


Figure 7. Scanning electron micrograph of hardened SSCC samples with different VPS: (**a**) S_0SCC; (**b**) S_{20}SCC; (**c**) S_{60}SCC; (**d**) S_{100}SCC.

As shown in Figure 7, there is a directional alignment of calcium hydroxide crystal around aggregates in the specimen of Group S_0SCC, and there is less C-S-H gel surrounding the coarse aggregate surface (see Figure 7a); the main characteristic features observed are the reduction of porosity accompanied by the continuous denser matrix of C-S-H along with VPS increase (see Figure 7b,c) and the less obvious alignment of calcium hydroxide crystal, the interface transition zone (ITZ) in concrete is gradually improved and, therefore, concrete shows high compressive strength.

The microcosmic appearance of hydration products as shown in Figure 7d appears in Group S100SCC, presumably caused by the calcium hydroxide produced by f-CaO hydration. The calcium hydroxide crystal from hydration of f-CaO has a large volume and occupies a large space, when compared with that from the hydration of cement clinker, resulting in a large expansion force and cracking.

Therefore, it can be considered that the microstructure and ITZ of SSCC improves, under the same water binder ratio, with the increase of VPS. This may be one of the main reasons for the improvement of concrete strength by the addition of steel slag in the SSCC. The improvement effect of steel slag on concrete strength may also be related to the surface roughness of steel slag aggregate and certain water absorption capacity, and the detailed mechanism needs to be further studied.

4. Conclusions

In this paper, the workability of the fresh mixture and the strength of hardened self-compacting concrete with different substitution rate of steel slag sand were studied. By adjusting the water–binder ratio, paste–aggregate ratio, fine–coarse aggregate ratio and the amount of superplasticizer, steel slag self-compacting concrete with ideal workability can be obtained, which can meet the workability design goal. Moreover, the addition of steel slag sand helps to improve the interfacial transition zone in hardened concrete, which is beneficial to the strength of concrete. It can be concluded that it is one of the effective ways to use steel slag sand as fine aggregate to prepare self-compacting concrete. If SSCC is popularized and applied, it will help to realize the resource utilization of a large amount of steel slag, and finally achieve good economic benefits and environmental value. Based on the above test results and discussion, the following conclusions can be drawn as for the workability of SSCC:

(1) The basic workability of SSCC was evaluated by the experimental results of the slump flow test and J-ring flow test. PA (the difference between SF and SF_J) and Δh (J-ring height difference), were used to characterize the passing ability of fresh steel slag self-compacting concrete. The results show that all the groups of SSCC can meet the workability design goal with the minimum SF, the maximum T500, the maximum PA and the maximum Δh were 655 mm (S_{80}SCC), 18.2 s (S_{100}SCC), 40 mm (S_{100}SCC) and 25 mm (S_{100}SCC), respectively. Along with the increase of VPS, the basic workability of SSCC shows little difference when the VPS is less than 60%, but then it changed rapidly. Generally, VPS less than 60% is preferred for SSCC as regards the basic workability.

(2) The dynamic stability of SSCC was evaluated by the visual stability index. The evaluation result, according to ASTM C1611/C1611M-18, is highly stable (VSI = 0) for all groups of SSCC which performed ideal segregation resistance.

(3) The static stability of SSCC was evaluated by the segregation rate through a sieve analysis test. The SR values of the all groups of SSCC fresh mixtures are far below 15%. The maximum, and the minimum SR values were 8.70 (S_{100}SCC), and 5.44 (S_{60}SCC), respectively.

(4) The comprehensive analysis based on the basic workability, the dynamic stability, and the static stability test results shows that the workability of fresh SSCC will be relatively ideal in all aspects when the substitute ratio of steel slag sand is not more than 60%.

(5) It is necessary to pay attention to the expansibility of steel slag and its influence on the volume stability of concrete in the later stage when SSCC is applied to practical projects, and further research is needed.

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