International Journal of GEOMATE, Aug., 2021, Vol.21, Issue 84, pp.24-33
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.84.j2122
Geotechnique, Construction Materials and Environment

OPTIMIZING MIXTURE OF SELF-COMPACTING CONCRETE FOR CONSTRUCTING A SPILLWAY SURFACE STRUCTURE

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*Corresponding Author, Received: 22 Feb. 2021, Revised: 27 April 2021, Accepted: 12 June 2021

ABSTRACT: A spillway apron is a popular hydraulic work with congested reinforcement and complex shapes. Self-compacting concrete (SCC) with excellent workability can meet the technical requirements for the work. This study focuses on determining the SCC optimal mix for efficient use of local coarse aggregates and 100% crushed sand to construct a spillway surface structure. For the purpose, research steps were carried out as follows: (1) optimize mix ratio of coarse aggregates ; (2) determine the saturated content of superplasticizer, (3) design SCC preliminary mix; (4) set up an experimental plan; and (5) analyze test data to point out the optimal SCC mix. The investigation of fresh SCC was conducted by slump flow test, slump flow time test, L-box test, and segregation resistance test. Compressive strength, water tightness, and underwater abrasion of hardened SCC were also evaluated. The abrasion tests follow the ASTM C1138-19 method and Yu-Wen Liu's method. The results show that the optimal SCC with slump-flow of 72 cm, the H_2/H_1 ratio of 0.85, compressive strength at 28 days of 42.5 MPa, abrasion resistance of 0.34 g/cm^2; and water tightness of B10 meets specifications of a spillway surface structure. Besides, the abrasion depth measured by Yu-Wen Liu's method of water-borne sand was about four times greater than that of ASTM C1138-19.

Keywords: Self-Compacting Concrete, Spillway, Crushed Sand, Slump-Flow, Abrasion Resistance

1. INTRODUCTION

SCC is defined as concrete that can flow under its weight to fill formwork even with congested reinforcement and produce a dense and adequately homogenous material without a need for vibrating compaction [1, 2]. Based on providing viscosity, SCC can be divided into three categories: the powder type, viscosity modifying agent type, and combination type [3].

SCC was first developed in Japan in 1988 [4]. Then the concrete spread to Europe, the USA, and many other countries. SCC is applied mainly for heavily reinforced structures, where conventional concrete would not fill out formworks. This type of concrete is more widely used in civil and transportation construction rather than in irrigation works.

Vietnam has a dense river network with more than 2360 rivers having a length of over 10 km. Therefore, the Government of Vietnam is particularly interested in the construction and development of irrigation systems [5]. The spillway is one of the essential items of irrigation frequently affected by water currents with high velocity. A spillway surface is a structure with complex shapes with many angles, heavy reinforcement. Consequently, SCC is a suitable choice for spillway surface structures.

Due to its smooth, round surface, natural sand is often used to produce SCCs to enhance workability. However, the management has recently improved the efficiency of mineral exploitation and environmental protection in Vietnam [6]. That causes the production of natural sand to decrease instead of the commonly used manufactured sand. This artificial aggregate has a rough surface and varied shapes. Therefore, it is necessary to study adjusting SCC proportion with crushed aggregate to meet SCC technical requirements.

A significant number of previous studies have been carried out replacing natural sand aggregate with crushed sand at a replacement range of about 25-100% to make SCC [7, 8, 9]. As a result, it is reported that river sand can be replaced by 100% artificial sand. However, Vinayak S. and Popat K. suggested that it remain satisfactory workability and compressive strength and reduce the appearance of cracks with a maximum replacement ratio of 60% [10]. Besides, only a few studies mention the combination of coarse aggregates to produce SCC [7, 9].

Due to the high content of powders, mineral admixtures such as limestone, fly ash, silica fume are often used as partial substitutes for cement to reduce the heat of hydration, reduce shrinkage, and increase the durability of SCC [7, 8, 9]. Limestone replaces fine aggregate with a 0-20% content, reducing slump flow but still meeting the SCC flowability requirement while enhancing the segregation resistance [9]. Fly ash replaces the binder at the rate of 0-40%, and the higher fly ash content is, the better workability is [11]. Silica fume replaces cement at a ratio of up to 20%, which increases strength and elastic modulus for SCC with an appropriate content of about 6% [8].

The abrasion resistance is an essential property for hydraulic works; however, a few investigations mentioned this property of SCC [12]. Underwater abrasion test is often used to evaluate the performance of concrete materials for constructing erosion-resistant structures [13, 14]. Apart from the standard method ASTM C1138 [15], the method proposed by Yu-Wen Liu [16] is also used to measure abrasion resistance. The second method uses water-borne sand to simulate the abrasion resistance of concrete under the impact of water flow with suspended sand particles. This method has the advantage of adjusting the flow rate for the model closer to reality condition. However, a few studies compare the differences in determining abrasion according to these two methods.

Okamura's method and the European Guidelines for Self-Compacting Concrete (EFNARC) are often used to design SCC composition. Besides, there are many other methods to purposed for SCC design [17, 18]. These methods are used for preliminary design, and then the mix is adjusted by experiment. The limitation of these methods is that the obtained composition is satisfied but may not be optimal. Experimental planning is an effective method to determine the optimal mix within the research scope.

This paper presents the research results on determining the SCC optimal mix using local coarse aggregates and 100% crushed sand for constructing a spillway surface structure. In addition, a comparative evaluation of abrasion measured by ASTM C1138-19 and Yu-Wen Liu's method is also determined. The results would be applied to the Hieu River Reservoir Spillway project in Quang Tri province, Vietnam.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Binder

Binder mixtures (B) were used in the study, including cement (C), fly ash (FA), and silica fume (SF). The PC40 cement from But Son cement factory has the physical properties that meet the ASTM C150-20 requirements of type I cement [19]. The fly ash from Pha Lai thermal power plant can be classified as F class according to ASTM C618-19 [20]. The physical properties and the chemical compositions of the cement, the fly ash, and the silica fume are given in Table 1, Table 2, and Table 3, respectively.

Table 1 Physical properties of the PC40 cement

Properties	Unit	Result
Specific gravity	g/cm^3	3.1
Fineness		
- Retained 0.09 mm	%	1.0
- Average particle size	µm	16.64
Normal consistency	%	28.5
Soundness	mm	1.0
Setting time		
- initial setting time	minutes	135
- final setting time	minutes	195
Compressive strength		
- 3 days	MPa	31.4
- 28 days	MPa	49

Table 2 Physical properties of the FA and SF

Properties	FA	SF
Specific gravity, g/cm^3	2.34	2.45
Strength activity index at the age of 28 days, %	89.3	108
Average particle size, µm	18.79	0.16

Table 3 Chemical compositions of the C, FA, and SF (%)

	C	FA	SF
SiO_2	21.94	54.01	92.1
Al_2O_3	5.16	27.90	0.96
Fe_2O_3	3.29	5.53	1.92
CaO	63.70	1.17	0.34
MgO	2.04	1.48	0.86
Na_2O	0.13	-	0.38
K_2O	0.72	4.44	1.21
SO_3	1.01	0.38	0.3
TiO_2	0.06	-	-
LOI	1.47	4.46	1.7

2.1.2 Aggregates

In the study, crushed sand (CS) and two coarse aggregates of maximum diameter at 10 mm (D10) and 20 mm (D20) were mined and crushed on site of the Hieu River Reservoir Spillway project. Besides, natural sand (NS) was also used as a control sample. The physical properties of the four aggregates are shown in Table 4, and the particle size distributions are presented in Fig. 1 and Fig. 6.

2.1.3 Superplasticizer

TC-F1 is a polycarboxylate type of superplasticizer, a high-range water reducer up to 45%. TC-F1 has a 38 ± 2% solids content and a density of 1.1 ± 0.02 kg/liter. The recommended use of TC-F1 is 0.6-1.2 liters/100 kg binder.

Table 4 Physical properties of the four aggregates

Properties	CS	NS	D10	D20
Specific gravity, g/cm^3	2.76	2.65	2.76	2.76
Bulk density, kg/m^3	1520	1550	1439	1457
Voids, %	44.9	41.5	47.9	47.2
Fineness modulus	3.2	2.63	-	-
Content of stone powder, %	13.5	-	1.2	0.23
Elongation and flakiness index, %	-	-	5.8	7.6
Resistance to degradation, %	-	-	26.5	28.3
Crushing value, %	-	-	12.9	13.3

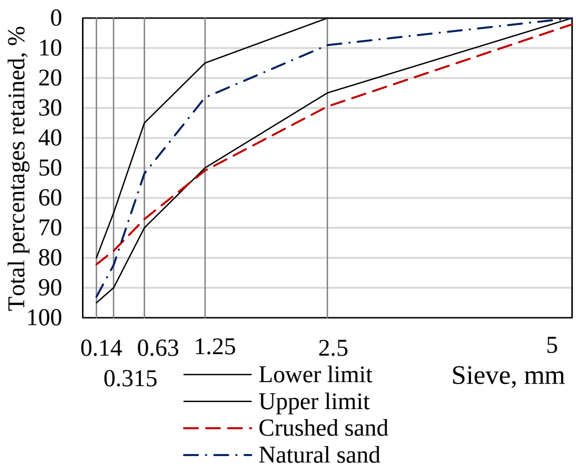


Fig. 1 Particle size distribution of the CS and NS

2.1.4 Viscosity modifying agent

Viscoma-02 is a viscosity modifying agent-based polymer hydroxylate. It has solid contents of 17.5±1% and a density of 1.06 ± 0.02 kg/liter. Viscoma-02 works efficiently in the range of 0.1÷0.3 liters/100 kg binder.

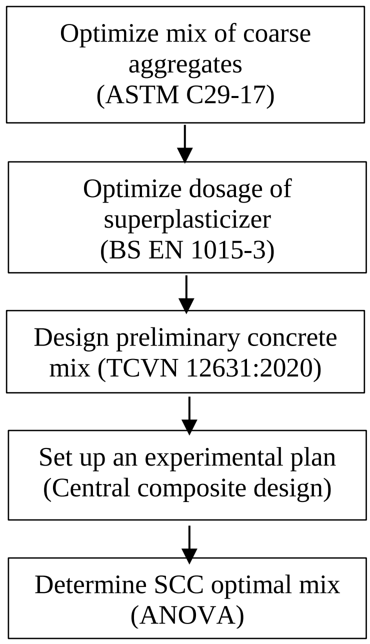
2.2. Methods

In the study, a combination of methods to determine the SCC optimal mix. The research process is described in detail in Section 2.2.1. The properties of SCC mixes such as slump flow (by inverted mold), slump flow time (t_{500}), H_2/H_1 ratio (L-box test), and segregation resistance were measured according to TCVN 12209: 2018 [1]. A compressive strength test was conducted with cubes of 150× 150× 150 mm in size. The watertightness of the concrete was determined according to TCVN 3116: 1993 [21]. Some other tests are described in Sections 2.2.2 and 2.2.3.

Fig. 2 Slump flow test (Inverted Mold)

2.2.1 Optimizing procedure

The procedure of optimizing the SCC mix in five steps is shown in Fig. 3.



2.2.2 Determine the saturated dosage of the superplasticizer

The method of determining the saturated dosage of superplasticizer proposed by Nguyen Nhu Quy [22] was used. It is based on BS EN 1015-3 [23]. The superplasticizer content increases gradually until water separation appears at the edge of the mortar mass while measuring the diameter. That is the saturated dosage of the superplasticizer. At this dosage, the flow is usually in the range of 25- 30 cm.

2.2.3 Determine abrasion resistance of SCC

In the study, two methods were used to assess the abrasion resistance of SCC, including ASTM C1138-19 [15] and the method proposed by Yu-Wen Liu [16] (see Fig. 3).

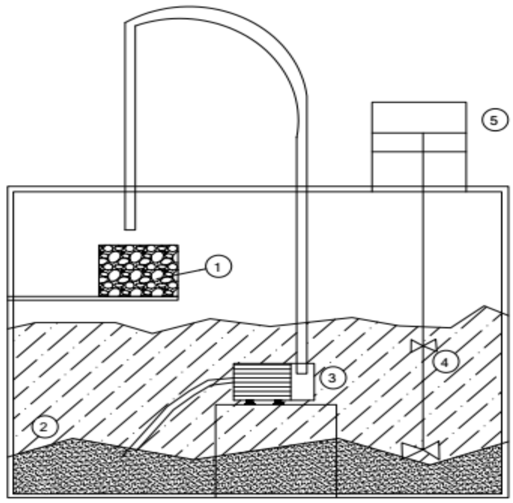


Fig. 3 The model of concrete abrasion test
1- Concrete sample with h× ϕ = 100×100 mm; 2- Sand with d= 0.15-0.30 mm; 3- Pump with capacity of 2m^3/h; 4- Water; 5- Agitator.

Test cylinder specimens were cast with 300 mm in diameter and 100 mm in height. After being tested according to ASTM C1138-19 [15], a sample was drilled at the center with a diameter of 100 mm. That sample was investigated according to Yu-Wen Liu's method [16] (see Fig. 4).

Fig. 4 Drill sample to test concrete abrasion

The sand used for the experiment had a particle size from 0.15- 0.315 mm, and sand content was 400 kg/m^3 mixture [16, 24]. The abrasion resistance was tested under the most unfavorable conditions with an impact angle of 90°. Specifications of pumps and pipes used in the test are given in Table 5.

The abrasion resistance index is measured according to ASTM C1138-19 [15] and calculated by the below formula:

$$ARI = \frac{m_1 - m_2}{A} 100\% \quad (1)$$

In which ARI is abrasion resistance index, %; m_1 and m_2 are the mass of SCC specimen before and after testing, g; A is the area of the top surface of a specimen.

Table 5. Specifications of pumps and pipes

Type of pumps	Nominal capacity, m^3/h	The actual capacity, m^3/h	Design speed, m/s	Pipe cross-section, mm
The pump generates friction	3	2.571	15	7.78
The pump generates a vortex	2	1.565		

2.2.4 An experimental planning method

Based on the central composite design, Design Expert 7.0 software was used to define the experimental plan. The experimental data were used to carry out analysis of variance (ANOVA) to develop a regression model for compressive strength at the age of 28 days. The SCC optimal mix was pointed out according to the maximum value of compressive strength at 28 days.

3. RESULTS AND DISCUSSION

3.1 Determine the Appropriate Combining Ratio of Two Coarse Aggregates

Based on ASTM C29-17 rodding procedure [25], the bulk density coarse aggregate mixtures with combined ratios of D10/ (D10 + D20) = 0, 30, 40, 50, 60 and 100% were measured.

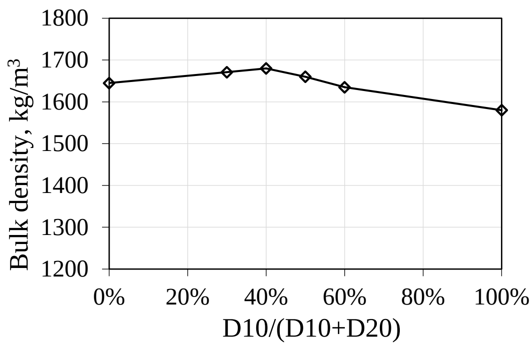


Fig. 5. Relationship between bulk density and coarse aggregate mixing ratio

The experimental results are shown in Fig. 4. It can be seen that the maximum bulk density was at the ratio of D10/D20= 40/60. However, some preliminary tests showed that the passing ability to L-box mold and slump flow of SCC mixtures with D10/ D20 = 40/60 was worse than that with the ratio of D10/D20= 45/55. Simultaneously, the bulk density at the ratio of 45/55 is only slightly smaller than that of the 40/60 ratio. As a result, the ratio D10/D20=45/55 was chosen as the coarse aggregate mixed ratio for the subsequent SCC mixtures. The particle size distribution of D10, D20, and the coarse aggregate mix is presented in Fig. 6.

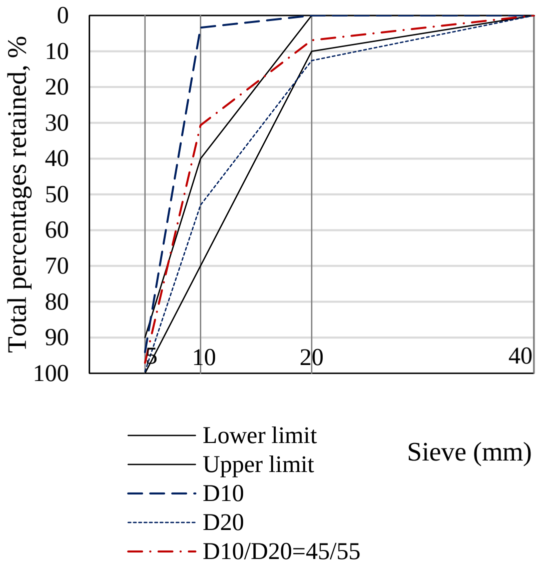


Fig. 6 Particle size distribution of coarse aggregates

3.2 Determine the Saturated Dosage of Superplasticizer

The experiments were carried out on fresh mortars with ratios of W/ B = 0.30, 0.33, and 0.36; a range of CS/B= 1.6-2.0; a range of TC-F1/B= 0.6-1.2 liters/100 kg B; and constant ratio of Viscoma-02/B at 0.1%. The binder used in a batch was 500 g of the PC40 cement and 250 g of the fly ash. That is corresponding to the SCC proportions calculated preliminarily according to TCVN 12631: 2020 [26]. Results of the consistency of the fresh mortars are presented in Fig. 7, 8, 9.

It is clear that the flow of the mortars increases proportionally with the TC-F1 content and inversely to the ratios of CS/B. This relation could be explained that the higher amount of TC-F1, the more modifying efficiency on the surface of the cement particles when interacting with water. As a result, the mobility of the mortar increases accordingly. In contrast, the amount of paste did not change because the content of binder, water, and TC-F1 was kept constant. Therefore, the higher ratio of CS/B is, the higher amount of crushed sand is, the thinner thickness of the paste layer between aggregate particles is. Thus, the higher CS/B ratio causes a decrease in the workability of the mortar.

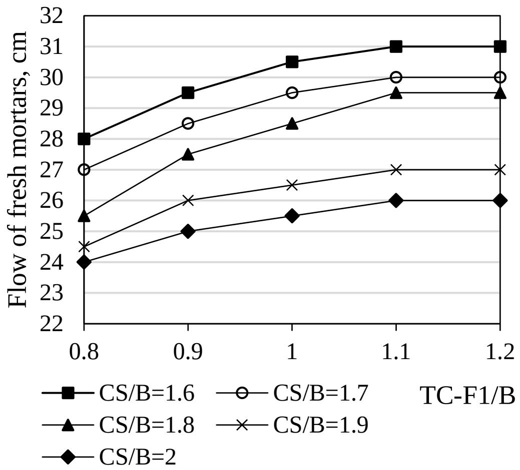


Fig. 7 Effect of CS/B and TC-F1/B on the flow of the fresh mortars with W/B = 0.30

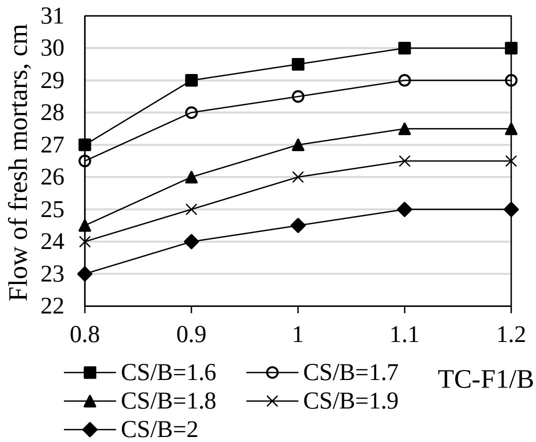


Fig 8. Effect of CS/B and TC-F1/B on the flow of the fresh mortars with W/B= 0.33

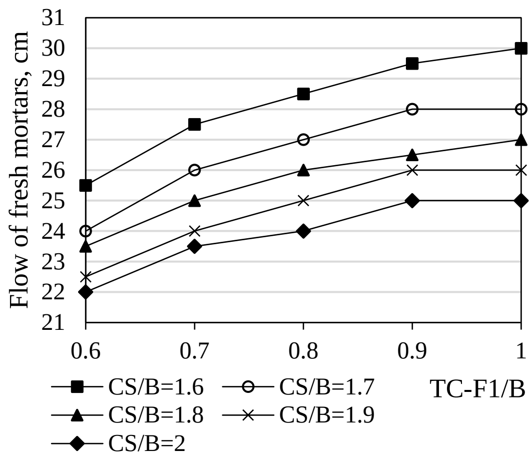


Fig. 9 Effect of CS/B and TC-F1/B on the flow of the fresh mortars with W/B = 0.36

When the amount of the TC-F1 increased to the saturation threshold, the flow did not increase further. If the dosage of the superplasticizer increased continuously, a part of mixed water was released, causing bleeding phenomena. Therefore, the appropriate dosage of superplasticizer is the smallest dosage to achieve the highest flow of fresh mortar. Based on the consistency test results, the ratios of TC-F1/B= 1.1%, 1.0% and 0.9% corresponding to ratios of CS/B= 0.3, 0.33 and 0.36 respectively were chosen to calculate SCC mix in the next research steps.

3.3 Concrete Mixture Design

3.3.1 Preliminary concrete mixture design

Based on TCVN 12631:2020 [26] and referred to the EFNARC, a preliminary SCC mix was calculated with the results shown in Table 6.

Table 6. Preliminary SCC mixture (per 1 m^3)

Cement (kg)	Fly ash (kg)	SF (kg)	Coarse aggregate (kg)
338	157	20	828
CS (kg)	Water (liter)	TC-F1 (litre)	Viscoma-02 (litre)
874	175	5.14	0.54

The properties of the preliminary SCC mix were determined as follows: the passing ability H_1/H_2= 0.80; the slump flow was 68 cm (right after mixing); the slump flow was 65 cm (2 hours after mixing); no segregation or bleeding; the slump flow time t_{500}=4.8 s; and compressive strength at 28 days f'_{c28}= 35.2 MPa. The SCC flowability meets the requirements of TCVN 12209: 2018 [1]. However, the compressive strength was negligibly higher than the required compressive strength (35 MPa) according to the specification of the Hieu River Reservoir Spillway project. Furthermore, the safety overload factor less than 1.1 is not ensured for field construction. Therefore, it is necessary to set up an experimental plan to find the optimal SCC mix that meets all technical requirements.

3.3.2. An experimental plan

Three affecting factors were selected for the experimental plan, including a ratio of water to binder X_1=N/B, a ratio of silica fume to cement X_2=SF/C, and water content X_3=W. In the study, the variation ranges of the three factors are illustrated in Table 7. Besides, the other ingredients were determined according to the research results in the previous steps including Viscoma-02/B= 0.1 liters/100 kg binder, W/C= 1.93, TC-F1/B = 1.1; 1.0; 0.9 corresponding to W/B= 0.30; 0.33; 0.36 respectively; the amount of coarse aggregate was kept at 828 kg/m^3. The experiment plan of SCC mixtures is given in Table 8.

Table 7. The variation ranges of the factors

Value	X_1	X_2 (%)	X_3 (liter)
Range of variation	$0.3 \leq X_1 \leq 0.36$	$5 \leq X_2 \leq 8$	$170 \leq X_3 \leq 180$
X^0_j	0.33	6.5	175
ΔX_j	0.03	1.5	5

3.4 Some Properties of SCC

Properties of fresh SCC and hardened SCC are shown in Table 8.

3.4.1 Slump flow

The slump flow of all mixtures was higher than 550 mm, slump flow time $t_{500} \geq$ 2s, and passing ability $H_2/H_1 \geq 0.8$. Those follow the SCC flowability requirements of TCVN 12209:2018. Furthermore, there was not any segregation and bleeding observed.

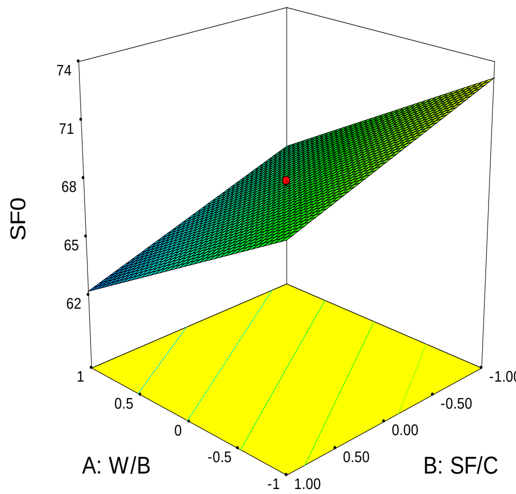


Fig. 10 Diagram of response surface of the slump flow- SF0 (right after mixing)

As shown in Fig. 10, the lower SF/C, the higher slump flow (SF0) agrees with Mahalakshmi and Khed's study [8]. When the amount of silica fume increases, the flow decreases. The tiny particle size of SF makes the amount of water for wetting SF particles increase. Therefore, the amount of free water can be reduced, which causes a decrease in the slump flow of fresh concretes. At the same W/B ratio, the higher amount of binder is, the greater slump flow of the SCC mix is. It could be due to the thicker layer of paste between aggregates.

Table 8. Composition and properties of SCCs

No	Encoded variables			Actual variables			Slump-flow time t_{500}, s	Slump-flow, cm	Passing ability, H_2/H_1	Com-pressive strength f'_{c28}, MPa	Abrasion resistance index ARI, g/cm^2	Water-tightness
	A	B	C	X_1= W/B	X_2= SF/C (%)	X_3= W (kg/m^3)						
1	-1	-1	-1	0.3	5	170	4.16	72	0.87	35.5	0.61	10
2	1	-1	-1	0.36	5	170	5.13	63	0.82	32.8	0.65	8
3	-1	1	-1	0.3	8	170	4.62	67	0.84	36.9	0.50	10
4	1	1	-1	0.36	8	170	5.12	60	0.80	34.5	0.53	8
5	-1	-1	1	0.3	5	180	4.14	78	0.91	36.5	0.54	12
6	1	-1	1	0.36	5	180	4.21	68	0.85	34.0	0.59	10
7	-1	1	1	0.3	8	180	4.13	71	0.89	42.2	0.41	12
8	1	1	1	0.36	8	180	4.98	66	0.86	39.0	0.42	10
9	-1.215	0	0	0.294	6.5	175	4.65	70	0.86	42.0	0.34	10
10	1.215	0	0	0.366	6.5	175	5.62	64	0.82	38.5	0.36	8
11	0	-1.215	0	0.33	4.68	175	5.12	67	0.85	40.5	0.70	8
12	0	1.215	0	0.33	8.32	175	4.98	63	0.81	40.8	0.41	10
13	0	0	-1.215	0.33	6.5	169	411	67	0.83	35.6	0.56	8
14	0	0	1.215	0.33	6.5	181	4.45	70	0.85	38.6	0.41	8
15	0	0	0	0.33	6.5	175	4.65	68	0.82	40.2	0.43	8

3.4.2 Compressive strength

As given in Table 8, the compressive strength at the age of 28 days of SCC samples was in the range of 32.8-42.2 MPa. The ratios of W/B and SF/C influence remarkably on the compressive strength (see Fig. 11). The higher percentage of SF/C, the higher the compressive strength of SCC. As a result, the efficiency of the pozzolanic reaction of SF in a rich-cement environment of SCC improves the strength. However, the increase in compressive strength is not significant compared to the increase in SF/C when the ratio rises from 6.5% to 8%.

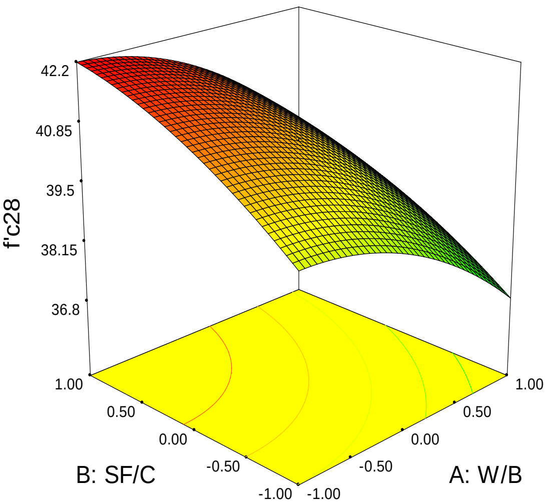


Fig. 11 Diagram of response surface of f'_{c28}

The compressive strength of specimens noted 7, 8, 9, 10, 11, 12, and 15 meets the strength requirements with a safety factor at 1.1, which are more significant than 38.5 MPa (see Fig. 12).

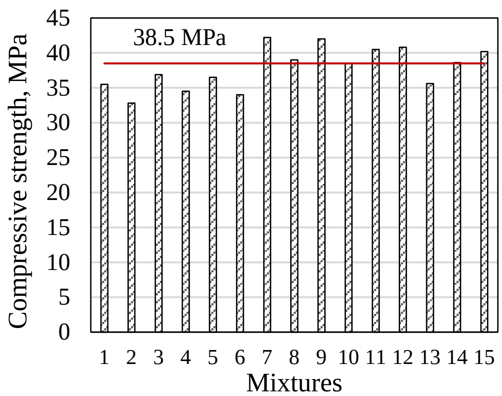


Fig. 12 Compressive strength of SCC samples

3.4.3 Abrasion resistance index

ARI results shown in Table 8 were determined according to ASTM C1138-19. The samples tended to be abrasive at the edge of the piece rather than in the center area. That is caused by the vortex bringing steel balls to the outside.

The ARI of specimens noted 7, 8, 9, 10, 11, 12, 14, and 15 is less than 0.5 g/cm^2 following ARI requirements (see Fig. 14). Those almost corresponded with the samples archiving the requirement of compressive strength.

The ratio of SF/C also considerably influenced

ARI. The ARI was inversely proportional to SF/ C in the range of 5-7%. After that, the increase of SF/C did not decrease the ARI of SCC significantly. Thus, SF can enhance the compressive strength and increase the abrasion resistance to a specific limit for SCC. The results agree with the suggestion that SCC with about 6%SF having good performance [8].

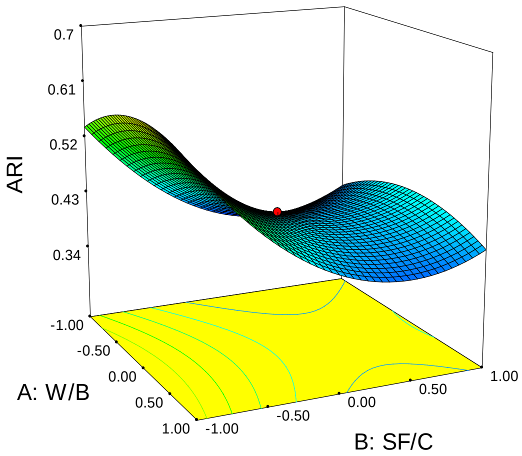


Fig. 13 Diagram of response surface of ARI

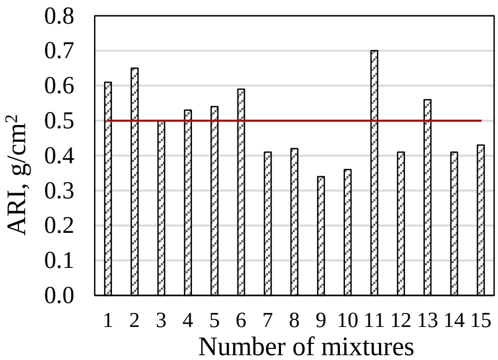


Fig. 14 Abrasion resistance index of SCC samples

3.4.4 Watertightness

Ensuring water resistance is required for hydraulic concretes. Depending on the project specifications, the watertightness of concrete can be used to design. The watertightness of the mixes was from B8-B12. When the quantity of binder and the SF content increases, the watertightness increases accordingly, as Deng-Deng Zheng et al. reported [27]. That accounts for the filling role of SF, making concrete structures denser.

3.5 Optimal SCC Mix and Control SCC Mix

The experimental data of compressive strength at the age of 28 days were analyzed to generate the following regression model and determine the SCC optimal mix (see Table 9)

$$f'_{c28} = 40.55 - 1.37X_1 + 1.29X_2 + 1.43X_3 - 0.05X_1X_2 - 0.08X_1X_3 + 0.95X_2X_3 - 0.67X_1^2 - 0.40X_2^2 - 2.80X_3^2 \quad (2)$$

The Model F-value (Fischer variance) of 15.18 implies the model is significant. There is only a 0.01% chance that a Model F-value this large could occur due to noise.

To check the error between the regression model and experiment, at the same time, and compare properties of SCC using CS and using NS, the two mixtures with the same composition given in Table 9 were prepared. Their mechanical characteristics were measured as shown in Table 10.

Table 9. The optimal SCC mixture (per m^3)

Cement, (kg)	Fly ash, (kg)	SF, (kg)	Coarse aggregate, (kg)
342	221	27	828
CS or NS, (kg)	Water, (liter)	TC-F1, (liter)	Viscoma-02, (liter)
783	177	6.49	0.59

Table 10. Properties of optimal and control SCCs

Properties	Unit	Optimal sample	Control sample
Passing ability (H_2/H_1)		0.85	0.9
Slump-flow	cm	72	78
Slump-flow after casting 2 hours	cm	69	72
Segregation/ Bleeding		No	No
Slump- flow time (t_{500})	s	4.8	3.5
Compressive strength	MPa	42.5	39.7
ARI	g/cm^2	0.34	0.35
Depth of abrasion (ASTM C1138)	mm	1.51	1.55
Depth of abrasion (Yu-Wen Liu)	mm	6.2	7.2
Watertightness		10	10

The properties of both optimal and control specimens meet specifications according to TCVN 12209:2018 and the project specifications in which the compressive strength f'_{c28} > 38.5 MPa, and watertightness is higher than B8 and ARI < 0.5 g/ cm^2. However, SCC using NS had better slump flow and workability maintenance after 2 hours at 78 and 72 cm than samples using crushed sand at

72 cm and 69 cm, respectively.

The compressive strength of the optimal SCC using the CS was 42.5 MPa, slightly different from that obtained from the model at 42.7 MPa and nearly 7% higher than the value 39.7 MPa of the control specimens using the river sand.

When compared with some studies SCC using 100% CS, it can be seen that the compressive strength of 43.5 MPa of the optimal mix with W/ B = 0.34, SF/ C = 6.6% and FA/ B= 30% is slightly lower than 47.1 MPa of the specimens noted SCC+5%SF with W/B=0.31, SF/C= 5.3%, and FA/B= 20% [8]; and remarkably greater than the 33.79 MPa of M100 sample with W/ B = 0.32, SF/ C = 6.2%, FA/ B = 0% [7]. Both the compared samples have smaller W/B and FA/ B ratios, which indicates the efficiency of determining the optimal mix used in this study.

The SCC sample using CS with the abrasion resistance (ASTM C1138) at the age of 28 days was 1.51 mm, which is better than that of the sample using NS with 1.55 mm. Compared to the two specimens named M40-0 and M50-0 with f'_{c28}= 37.3 MPa and 48.3 MPa, SF/C= 0 and 12.7%, abrasion resistance at 28 days is 3,520 mm and 1,268 mm, respectively [13]. It can be seen that the abrasion resistance of the optimal sample is almost equivalent to the results of another study.

The SCC specimen using the CS had better abrasion resistance than that of the SCC specimen with the NS. The average depth of abrasion measured according to ASTM C1138-19 [15] was about four times less than that of Yu-Wen Liu's method [16]. That figure should be evaluated and used to simulate actual conditions more carefully in further researches.

The watertightness of the two SCC specimens using the crushed sand and the natural sand was similar.

4. CONCLUSIONS

Based on the research results, the following conclusions can be drawn:

This study has come up with a procedure to determine the SCC optimal mix, including (1) determine the appropriate mixture of coarse aggregate with maximum bulk density according to ASTM C 29-17; (2) determine the saturated dosage of superplasticizer following BS EN 1015-3; (4) design preliminary SCC mix based on the guideline of TCVN 12631:2020; (4) design and conduct an experimental plan; (5) generate a regression model and choose the optimal mix based on criteria. The optimal mix based on this process shows a good performance.

The ratio of coarse aggregate at D10/ D20= 45/55, and the dosages of superplasticizer at the ratios of TC-F1/B= 1.1%, 1.0% và 0.9% corresponding to CS/B= 0.3, 0.33 và 0.36 respectively were suitable for SCC using 100% crushed sand.

The optimal SCC mix using the crushed sand was figured out that meets all SCC specifications of the project to construct a spillway surface structure with 72 cm in slump flow, 42.5 MPa in compressive strength at 28 days, and 0.34 g/cm^2 in abrasion resistance index, and B10 in watertightness.

SCC using entirely crushed sand has slightly worse workability but better compressive strength and abrasion resistance than the control specimens using natural sand.

The average depth of abrasion measured by water-borne sand of Yu-Wen Liu was about four times greater than that by ASTM C1138-19.

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