Chapter

Towards Innovative and Sustainable Construction of Architectural Structures by Employing Self-Consolidating Concrete Reinforced with Polypropylene Fibers

Wael Zatar and Hai Nguyen

Abstract

Self-consolidating concrete (SCC) has been successfully employed to reduce construction time and enhance the quality, performance, and esthetic appearance of concrete structures. This research aimed at developing environmentally friendly fiber-reinforced concrete (FRC) consisting of SCC and recycled polypropylene (PP) fibers for sustainable construction of city buildings and transportation infrastructure. The addition of the PP fibers to SCC helps reducing shrinkage cracks and providing enhanced mechanical properties, durability, and ductility of the concrete materials. Several mix designs of self-consolidating fiber-reinforced concrete (SCFRC) were experimentally examined. Material and esthetic properties of the SCFRC mixtures that include micro silica, fly ash, and PP fibers were evaluated. Trial-and-adjustment method was employed to obtain practically optimum SCFRC mixtures, mixtures that are affordable and easy to make possessing enhanced compressive strength and esthetic properties. Slump flow and air content testing methods were used to determine the fresh properties of the SCFRC mixtures, and the esthetic properties of the mixtures were also evaluated. The hardened properties of the SCFRC mixtures were examined using three- and seven-day compression tests. The amount of fine/coarse aggregate, water, and other admixtures were varied while the Portland cement content in all mixtures was maintained unchanged. The maximum three-day compressive strength was 43.17 MPa and the largest slump flow was 736.6 mm. Test results showed enhanced material properties such as slump flow, air content and compressive strength values of the SCFRC mixtures and their excellent esthetic appearance. The favorable seven-day compressive strength of the SCFRC mixture, with 4.8 percent air content and 660.4 mm slump flow, is 39.26 MPa. The mixtures' in this study are proven to be advantageous for potential SCFRC applications in architectural structures including building façades and esthetically-pleasing bridges.

Keywords: self-consolidating concrete (SCC), fiber-reinforced concrete (FRC), mix designs, enhanced material properties, esthetic appearance

1. Introduction

Architectural applications often require concrete components with defect-free surfaces, colorful and esthetic appearance (e.g., beautiful appearances of concrete structures made of architectural colored or white concrete), and good compressive strength. Self-consolidating concrete (SCC) appears to be an excellent candidate for these applications. SCC is a highly flowable concrete that can flow under its own weight and attain good consolidation without using any external vibration for compaction and in the absence of segregation and bleeding [1]. SCC was first developed by researchers at the University of Tokyo, Japan in 1988 to obtain sustainable concrete structures [2–5]. Since then, SCC has been applied for construction of building, bridge, and tunnel throughout Japan, Europe, United States, and the rest of the world [6–8].

The term fiber-reinforced concrete (FRC) often refers to a concrete containing dispersed randomly oriented fibers [9]. FRC was first developed in early 1960s that brought it to the attention of both academia and industry around the world [10]. The inclusion of fibers (e.g., steel, polypropylene, polyvinyl chloride, nylon, carbon, glass, etc.) into the mix design of FRC can enhance mechanical properties and ductility of concrete though they can adversely affect workability of FRC mixtures. In this study, polypropylene (PP) fibers were used because they can provide a restrained shrinkage cracking and an improved spalling resistance for concrete (when the PP fibers melt, they provide channels that allow evacuating the vapor and relieving the internal pressure to avoid explosive spalling and loss of concrete cross-section in fire) [11].

Mix-design method plays critical roles in mechanical properties of SCC, which largely affected by the characteristics of constituent materials and mix proportions. The workability, passing and filling abilities, and segregation resistance are important characteristics of well-designed SCC mixtures. The filling ability of SCC (a.k.a. unconfined flowability or deformability) can be defined as the ability of concrete to flow into and fill in all spaces of the formwork under its own weight. The passing ability, on the other hand, is the ability to flow through tight openings under its own weight [12]. ACI committee 237 [13] developed standard test methods to measure the main characteristic of SCC, as shown in **Table 1**. Slump flow, V-shaped funnel, Orimet, and T50 are common methods to characterize the filling ability of SCC. The J-ring test method is used to determine the passing ability of SCC through reinforcing steel [14]. L-box and U-box tests are used to characterize both the passing and

Test method	Category	Characteristic	Measurement
Slump flow	Free flow	Filling ability	Flow distance
V-shaped funnel and Orimet	Confined flow	Filling ability	Flow rate
T_{50}	Free flow	Filling ability	Flow rate
J-ring	Confined flow	Passing ability	Flow rate
L-box	Confined flow	Passing and filling abilities	Flow rate and distance
U-box	Confined flow	Passing and filling abilities	
Visual stability index (VSI)	Static condition	Segregation resistance	Visual stability of the mixture
Column segregation test	Confined flow	Segregation resistance	Segregation of aggregates

Table 1.
Standard test methods for SCC (reproduced from ACI 237R-07 [13]).

filling abilities of SCC. The visual stability index (VSI) and column segregation test methods are developed to assess the segregation resistance characteristics of SCC. The VSI test involves the visual examination of the SCC slump flow spread and is used to evaluate the relative stability of SCC mixtures. Highly stable batches (VSI value = 0) show no evidence of segregation in slump flow spread while highly unstable batches (VSI value = 3) clearly indicate large segregation (i.e., large aggregate pile in the center of the concrete spread and/or large mortar halo). The VSI values for stable and unstable SCC batches are 1 and 2, respectively [13, 15].

Su et al. (2001) [16] proposed a new mix design method, which was economical, less time-consuming, and simpler than the traditional Japanese Ready-Mixed Concrete Association. The amount of aggregates, water/cement ratio, and type/dosage of superplasticizer were proved to significantly affect the properties of SCC. High quality SCC can be produced through trial mixtures and tests including slump flow, V-funnel, L- and U- boxes, compressive strength tests. The packing factor of aggregate (the aggregate content), defined as the ratio of mass aggregate in tightly pack state to that of loosely packed state, influenced the strength, flowability, and self-compacting ability of SCC. The passing ability through narrow spaces of rebars was enhanced because the designed SCC mixtures contained less coarse aggregates and more sand. The volume of sand to mortar was approximately 54–60%. The cement contents used in the proposed mix design method was smaller than that required by other mix design methods (because of the increased amount of sand), which result in a cost saving.

Sonebi et al. (2007) [17] carried out a composite factorial design study to investigate the influence of three key parameters of mixture composition on filling and passing abilities of SCC. The examined parameters were the dosages of water and high-range water-reducing admixture (hereafter called HRWR), and the volume of coarse aggregates. Slump flow, T50, T60, V-funnel flow time, Orimet flow time, and the blocking ratio (L-box) were employed to measure both passing and filling abilities. The results revealed that dosages of water and HRWR and the volume of coarse aggregate significantly affected the slump flow at 5, 30, and 60 minutes. T50 tests showed an insignificant influence of all investigated parameters including dosages of water and HRWR and volume of coarse aggregate. On the other hand, T60 test exhibited a significant influence of dosages of water and HRWR. The L-box blocking ratio was found to be substantially affected by dosages of water and HRWR and the volume of coarse aggregate. The L-box test was proved to be suitable for assessment of the passing ability of SCC through closely spaced rebars.

Felekoğlu et al. (2007) [18] investigate the effects of water/cement ratio and dosages of superplasticizer on the fresh and hardened properties of SCC. Slump flow, V-funnel, and L-box tests were carried out to determine optimum SCC mixtures. The results showed that optimum water/cement ratios for best SCC mixtures were in the range of 0.84–1.07 by volume. The ratios beyond this range may result in segregation or blocking of the mixtures. Trial-and-error method was recommended to produce proper concrete mixtures. Higher splitting tensile strength and lower modulus of elasticities were obtained from the SCC mixtures compared to conventional vibrating concrete.

Uysal and Sumer (2011) [19] presented experimental investigations on the performance of SCC. Conventional Portland cement was substituted with fly ash, granulated blast furnace slag (GBFS), and limestone/basalt/marble powders. The compressive strength, density, ultrasonic pulse velocity, and sulphate resistance of SCC were characterized by the amount of mineral admixtures. The results revealed that the workability and compressive strength of SCC mixtures were significantly increased with the addition of the fly ash and GBFS mineral admixtures. The compressive strength reached 105 MPa at 400 days when substituting 25% of Portland cement with the fly ash. The added mineral admixtures yielded favorable effects on the strength loss because of sodium and magnesium sulphate attack.

Recently, colored SCC (C-SCC) for architectural concrete has been developed [20–22]. López et al. (2009) [20] conducted an experimental investigation on C-SCC and presented advantages of using a mortar-based mix design method for C-SCC. Determination of the optimum proportions of SCC mixtures (consisting of various types of pigments, cements, and mineral/chemical admixtures) were quick and easy by using the mortar-based approach. The colorimetric parameters, color homogeneity, surface finishing, and the effects of pigments on the viscosity of C-SCC were effectively evaluated with this approach.

2. Research significance

The aims of this study are two folds: (1) To develop optimum SCC mixtures using trial-and-error method; and (2) To create architectural concrete with excellent surface finish (i.e., free of honeycombing or signs of discoloration and bleeding). First, several trial batches were conducted to obtain optimum SCC mixtures with adequate balance between filling and passing abilities. An experimental program was implemented to investigate the influence of the key mixture parameters (e.g., the volume of fine and coarse aggregate, dosage of water, high-range water reducing admixture, and viscosity-modifying admixture) to the material properties of self-consolidating fiber-reinforced concrete (SCFRC). Second, several mix designs of SCFRC were tested to achieve finest characteristics of architectural concrete (e.g., smooth appearance, defect-free surface, reduced cracks, improved durability, and good compressive strength). With the use of environmentally friendly products in SCFRC (i.e., recycled PP fibers and mineral admixtures such as fly ash and micro silica), the developed SCFRC can provide excellent environmental and esthetic solutions for sustainable construction of architectural structures such as bridges and buildings.

3. Experimental program

3.1 Materials and methods

Portland cement used for this study conformed to ASTM C150 [23]. Coarse aggregates with a maximum size of 12.5 mm were conforming to ASTM C33 [24]. Supplementary cementitious materials, such as fly ash and micro silica (a.k.a. micro silica fume) were added to the SCFRC mixtures to improve the workability, strength, and durability. Fly ash added to the SCFRC mixtures was conforming to ASTM C618 [25]. Micro silica was used for the SCFRC mixtures to enhance segregation and bleeding resistance. The HRWR admixture conformed to ASTM C1017 [26]. Superplasticizer was added to the SCFRC mixtures to enhance the flowability of concrete. In addition, viscosity-modifying admixture (VMA) was used to improve the stability of the SCFRC mixtures. The amount of VMA was adjusted after each SCFRC batch to obtain the designed level of stability. Furthermore, Air-Entraining Admixture (AEA), conformed to ASTM C260 [27], was used for the SCFRC mixtures to improve the freeze–thaw resistance of the concrete.

Polypropylene (PP) fibers were added to the SCFRC mixtures (0.25 to 0.5 percent by volume of concrete) to prevent concrete cracking due to plastic shrinkage. The use of PP fibers in the SCFRC mixtures has advantages including no water demand and high resistance to chemical attack. The material properties of the PP fibers are presented elsewhere [28]. Mixture proportions for 14 selected batches of the SCFRC mixtures (per 1/20 yd^3 or 0.038 m^3) are shown in **Table 2**.

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Batch	Cement (kg)	Fly ash (kg)	Micro Silica (kg)	Sand (kg)	Gravel (kg)	Fibers (kg)	Water (kg)	AEA (ml)	HRWR (ml)	VMA (ml)
1	17	4.54	1.09	28.94	30.07	0.14	8.16	2.3	125.0	5.0
2	17	4.54	1.09	27.35	28.49	0.14	7.03	3.0	125.0	5.0
3	17	4.54	1.09	25.99	30.89	0.14	8.16	4.0	155.3	10.4
4	17	4.54	1.09	25.99	30.89	0.14	8.16	3.5	155.3	10.4
5	17	4.54	1.09	25.99	30.89	0.14	6.80	3.5	165.0	10.4
6	17	3.45	2.18	25.99	30.89	0.14	7.48	3.0	165.0	10.4
7	17	4.54	1.09	25.99	30.89	0.14	7.48	1.8	165.0	10.4
8	17	4.54	1.09	25.99	30.89	0.14	7.48	5.9	165.0	14.8
9	17	4.54	1.09	25.99	30.89	0.14	7.48	3.5	170.0	20.0
10	17	4.54	1.09	25.99	30.89	0.14	7.48	3.5	165.0	20.7
11	17	4.54	1.09	25.99	30.89	0.14	7.48	3.5	180.0	20.0
12	17	4.54	1.09	38.96	46.36	0.14	12.25	3.5	255.0	50.0
13	17	4.54	1.09	38.96	46.36	0.14	12.25	3.5	248.4	31.1
14	17	4.54	1.09	25.99	30.89	0.14	7.94	3.5	180.4	20.7

Table 2.
Mix proportions of SCFRC (per 0.038 m^3 or 1/20 yd^3).

3.2 Mixing procedure

First, the ingredients (i.e., Portland cement, sand, coarse aggregate, water, fiber, and mineral/chemical admixtures) were weighed to the specifications of the mix design (**Table 1**). The air entrainer was placed into the sand before mixing was started. The gravel and air entrained sand were added to the mixer first. Then, three-quarters of the total water was added in order to saturate the aggregate and form slurry. The remaining water was used for saturation of the cementitious materials. Once the aggregate was saturated, the micro silica was added along with one-third of the remaining water. Once the micro silica was saturated and mixed into the slurry, the cement was added with another one-third of the remaining water. Then, the fly ash was added along with the remaining one-third of the water. At this point, all aggregate, cementitious material, and water was in the mixer. Once the ingredients were well mixed, the fibers were added. Once the fibers were well distributed throughout the concrete, the superplasticizer was added and left to mix for approximately five minutes. Once the superplasticizer took effect, the viscosity-modifying admixture was added and allowed to mix for five minutes before tests were performed.

3.3 Mix designs and specimen preparations

In order to ensure the quality of our concrete, tests were performed to test the compressive strength, and sample molds were poured to test the ability of the concrete to mold to the forms. As mentioned above, inverted slump tests and air content tests were also performed. The target range for the slump of the fresh concrete is 50.8 to 63.5 centimeters. The target range for air content in the fresh concrete is 3 to 5%. The target 28-day compression strength of the cured concrete is 55.2 to 68.9 MPa.

Because of the unique characteristics of SCC, new testing techniques must be used. The slump flow test measures the relative flow ability using an inverted slump cone. The slump cone was filled on a flat surface with no rodding or other consolidation methods and then lifted from the floor allowing the concrete to flow outward. The diameter of the concrete was measured in various directions in order to obtain an average value for the slump. The edge of the slump was inspected for segregation. If segregation was present, a halo of segregated water would be observed. The traditional compression testing procedures were followed except for in the preparation of the specimens. The specimens were prepared by filling the cylinders without rodding. The only other test performed was the air content by pressure method. No alterations were made to the traditional air content testing procedures. In addition to these tests, a sample of concrete was poured into a rubber mold that simulates the inside of the column form to assess the esthetic qualities of the mix.

4. Results and discussions

4.1 SCFRC mixtures

As can be seen in **Table 2**, for the first batch, the mix proportions of SCFRC (per 0.038 m^3) included 2.3 ml of AEA, 125 ml of HRWR, and 5 ml of VMA. The amount of gravel was set to 54 percent of the total aggregate to achieve a higher compressive strength. The water/cement ratio was 0.36 to attain complete hydration while reducing the water content to gain adequate strength. Batch 1 exhibited acceptable slump flow, air content, and compressive strength.

In batch 2, the AEA was increased from 2.3 ml to 3.0 ml, the water was reduced from 8.16 kg to 7.03 kg to gain more strength. The sand and gravel was reduced to

27.35 kg and 28.49 kg, respectively. The rest of the mix proportions was identical to batch 1. Batch 2 exhibited a total slump flow reduction of 88.9 mm (i.e., the slump flow diameter of batch 2 was approximately 508 mm). The air content was lower than batch 1 with an additional 0.7 ml of AEA, which may result from a quicker mix time than batch 1. The reduction of water resulted in a decreased slump flow without affecting the compressive strength.

It is worth mentioning that the performance of the SCFRC mixtures in batch 5 was close to ideal with a slump flow of 584.2 mm and an amount of air content of six percent. The three-day compressive strength of batch 5 was highest among all the tested mixtures. This batch exhibited the least desirable esthetic characteristics of all the mixtures. Based on the results from previous batches, the water in batch 14 was reduced to 7.94 kg to improve strength. The superplasticizer was increased to 180.4 ml to achieve a larger diameter slump flow and increased workability. The test results from this batch showed a good slump flow, air content, and compression values with an acceptable esthetic appearance.

4.2 Slump flow and air content

Figure 1 exhibits the experimental results from the slump flow test. The slump flow diameters of all the batches ranged between 508 mm and 736.6 mm, which was in line with the recommendation of Nagataki and Fujiwara [29] for high flowable concrete. The slump flow varied significantly from batch to batch. The record low of slump flow was 508 mm for the SCFRC mixtures in batch 2. The reason for this low might be due to the reduction of water in the mixtures while other ingredients remained constant. A maximum slump flow of 736.6 mm was found in batch 12 and the increase of slump flow may be attributed to the fact that VMA was increased while other mixing components were kept constant.

Test results of the air content tests are presented in **Figure 2**. As can be seen from the figure, the air content of the SCFRC mixtures varied in the range of 5 ±2 percent. The wide range of air content is due to the large amount of HRWR used in the SCFRC mixtures. The air content of the SCFRC mixtures in this study, however, was within the expected range. It is worth mentioning that a maximum air content of 6.2 percent

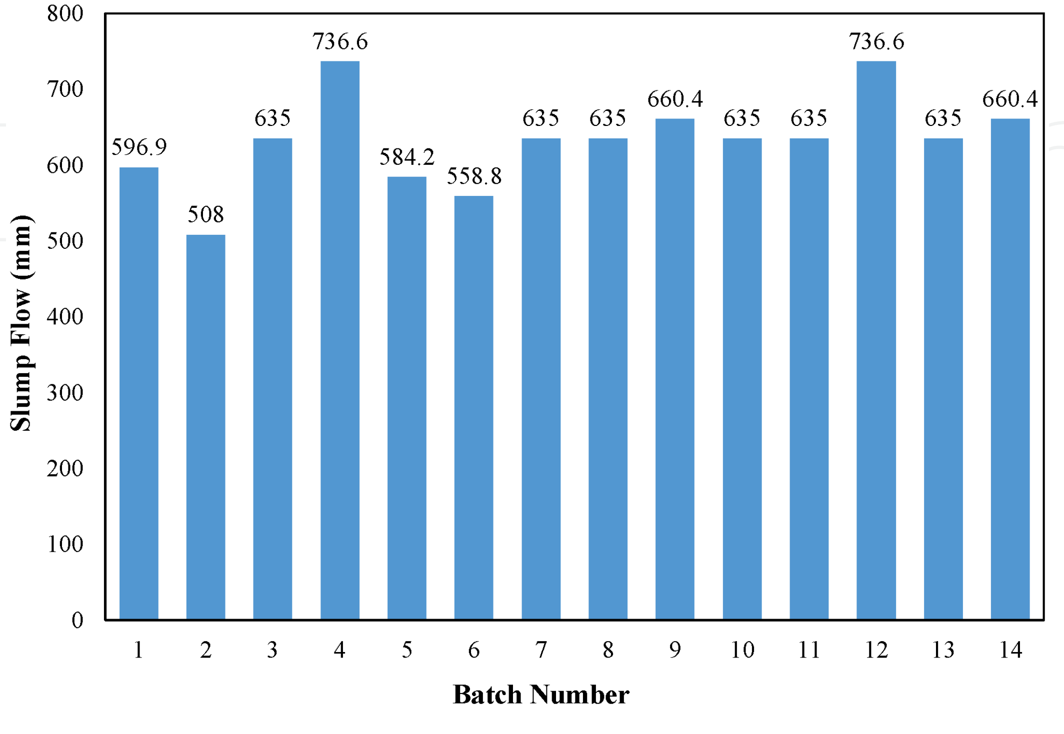

Figure 1.
Slump flows of SCFRC batches.

was recorded for batch 3. This air-content values were favorable, as compared to the results reported elsewhere [30]. The experimental results from batch 14 showed an excellent slump flow of 660.4 mm with an air content of 4.8 percent.

4.3 Compressive strength

The compression tests were carried out for the SCFRC cylinders to obtain the three-day and seven-day compressive strengths. **Figure 3** shows the compressive

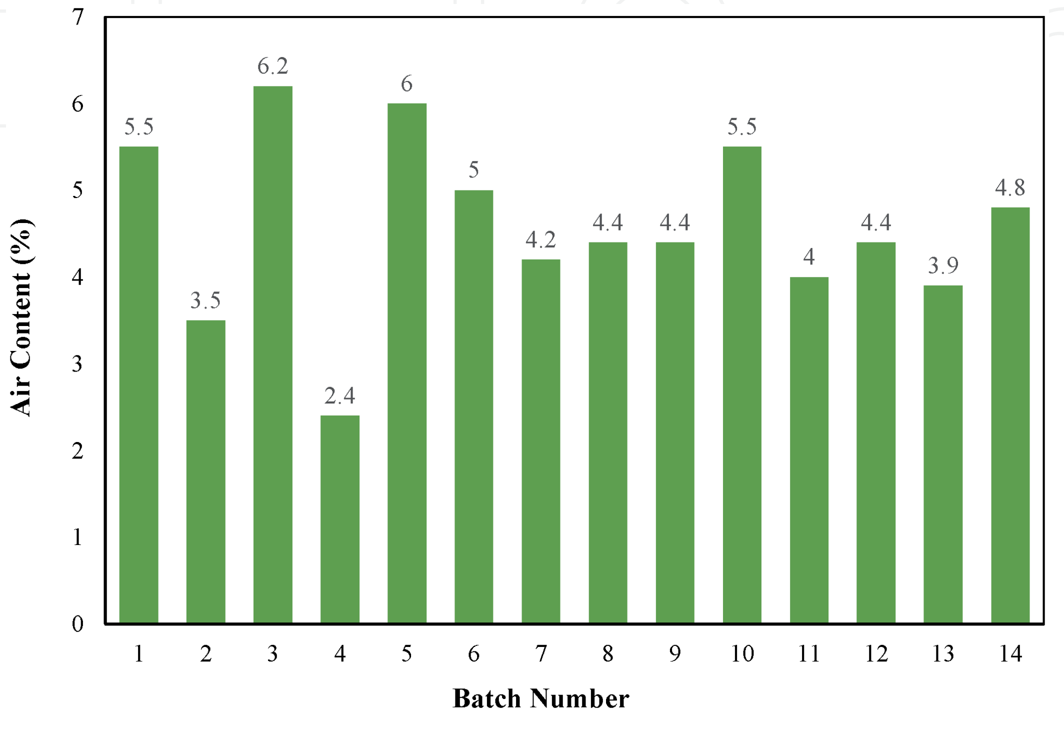

Figure 2.
Air contents of SCFRC batches.

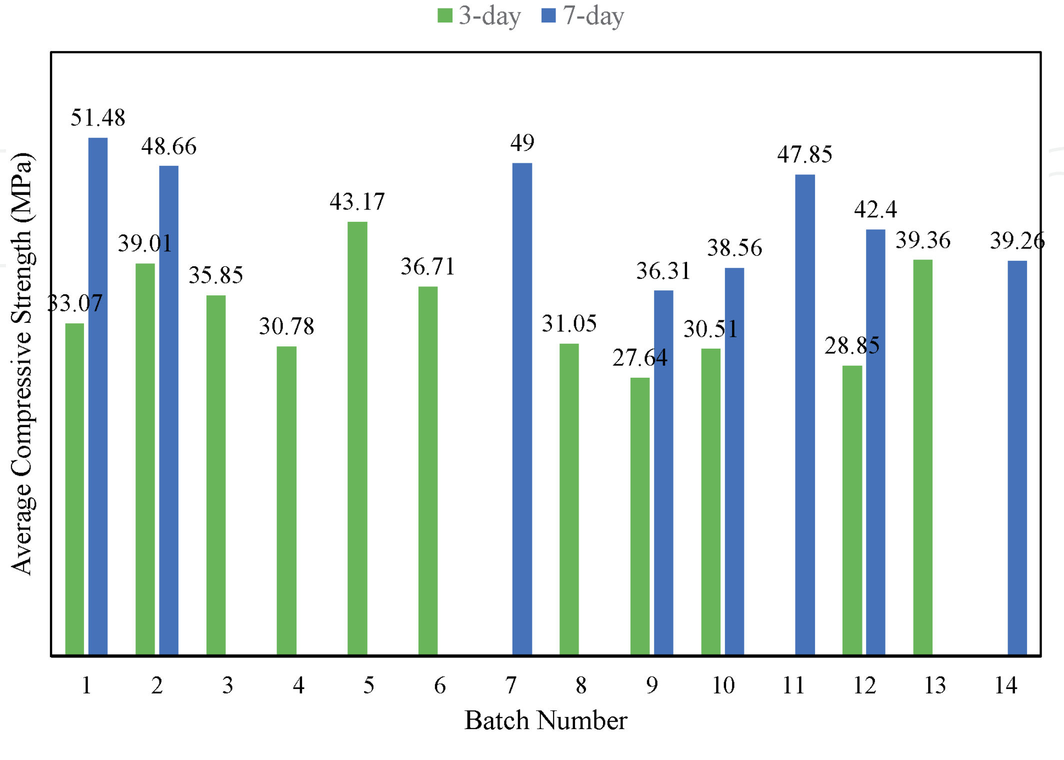

Figure 3.
Average compressive strengths of SCFRC batches.

test results of the SCFRC specimens from selected batches at three and seven days. In some batches, due to the premature failure of some cylinders, the results at the three- and seven-day compressive testing were not reported in the figure. The compressive strengths ranged from 27.64 and 43.17 MPa for three-day testing specimens while the seven-day testing results showed compressive strengths ranging from 36.31 to 51.48 MPa, which well fulfilled the application needs.

The average three-day compressive strength of batch 3 (35.85 MPa) was lower than that of batch 2 (39.01 MPa). The reduction in the three-day compressive strength of cylinders in batch 3 was due to the increase of water and the coarse aggregate adjustments. The SCFRC strength of the three-day compressive test results of batch 5 (43.17 MPa) exhibited the highest compressive strength among all the tested batches. Several trials were conducted after this batch, and the desired mixture was attained in batch 14 with the seven-day SCFRC compressive strength of 39.26 MPa.

Figure 4 shows the compression failure of selected cylinders from four batches. As can be seen in **Figure 4a**, the cylinder broke along the edge, not through the center. The failure is attributed to a minor defect in the bottom surface of the cylinder molds. The mold irregularity effect on the compressive strength were taken care of while producing subsequent batches, as seen in **Figure 4b**. The cylinders in batch 3 failed at the middle section and concrete splitting at the bottom of the cylinder was observed.

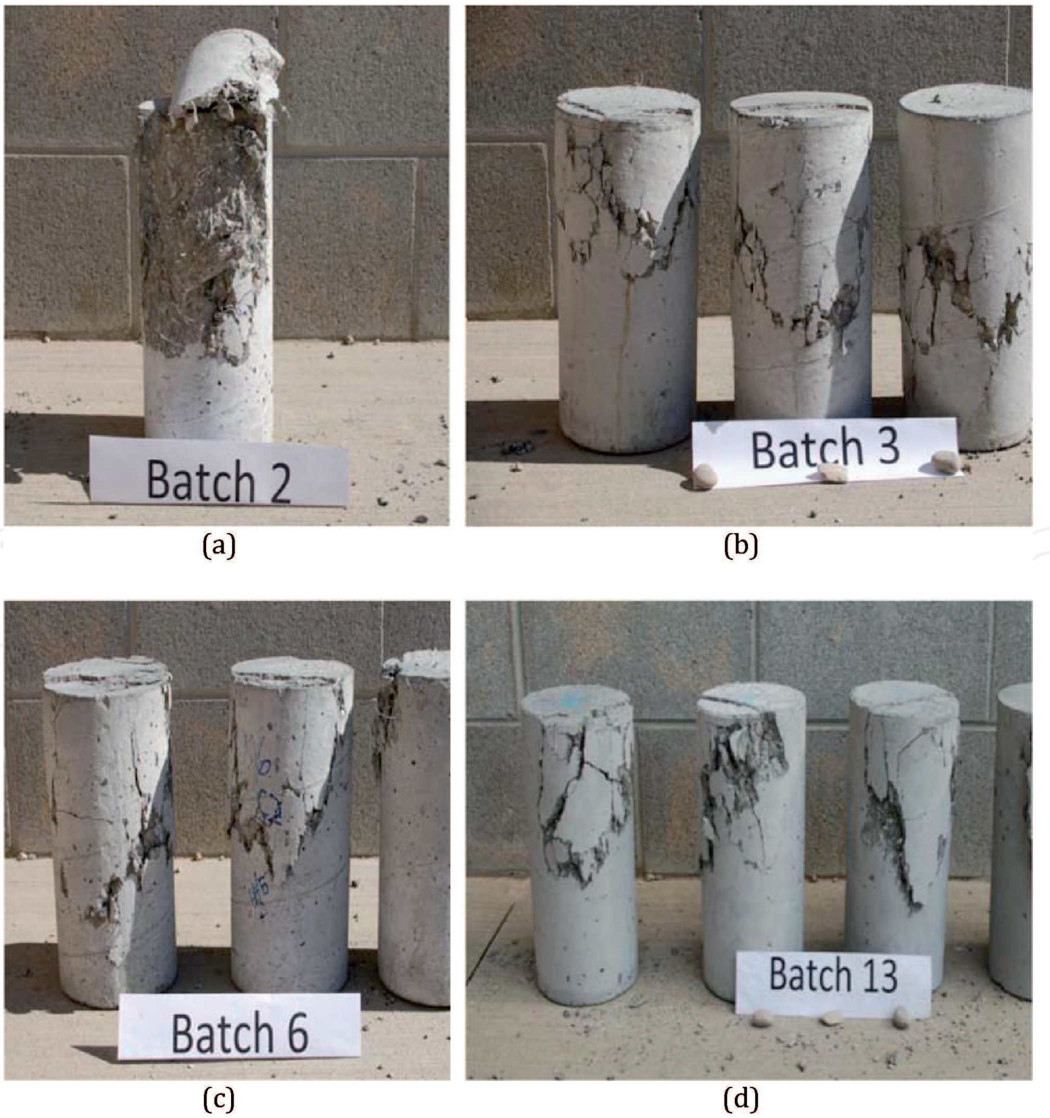

Figure 4.
Compression failure of SCFRC specimens from four batches (a) batch 2, (b) batch 3, (c) batch 6, (d) batch 13.

4.4 Esthetic characteristics

Production of esthetically pleasing SCFRC mixtures was a major objective of this study. For each SCFRC batch, several samples were cast to evaluate the esthetic characteristics of SCFRC. **Figure 5** shows a desired surface appearance of the SCFRC samples made from the selected batches. Overall, the color variation from a specimen to another was negligible. The specimens were easily removed from the molds, but the quality of the artworks in terms of sharpness and details varied significantly among the concrete batches.

As can be seen in the SCFRC specimen from batch 5 (**Figure 5a**), the artwork was clear but some minor surface voids were present. The quality of the artwork was significantly improved after several trials. Slight air voids on the surface of concrete from batch 7 were observed (**Figure 5b**). Excellent results were obtained for the concrete shapes made from the SCFRC mixtures in batch 9. As shown in **Figure 5c**, the artwork had almost no surface voids and a smooth finish. **Figure 5d**

Figure 5.
Smooth finish appearance of SCFRC samples made from different batches: (a) batch 5, (b) batch 7, (c) batch 9, (d) batch 14.

exhibited the esthetic results of the specimen from batch 14. The specimen looked flaw free with a smooth finish and virtually no surface voids.

5. Conclusions and future works

Several mix designs of self-consolidating fiber-reinforced concrete (SCFRC) were experimentally examined. Properties of SCFRC mixtures made from micro silica, fly ash, and PP fibers were evaluated. The trial-and-adjustment method was employed to seek finding favorable performances of the SCFRC mixtures. The fresh concrete properties, including filling ability and air content, were evaluated. In addition, both the hardened concrete properties and esthetic characteristics of the mixture designs were examined. The trial-and-adjustment process produced SCFRC mixtures with desired material properties and esthetic appearance. The seven-day compressive strength of SCFRC ranged from 36.31 MPa and 51.48 MPa, and the average air content was approximately 4.5 percent. The developed mixture designs in this study were proven to be advantageous for potential SCFRC applications in architectural structures including building façades and esthetically-pleasing bridges.

Future work will focus on building a comprehensive database for desired SCFRC mixtures taking into account additional variables including fiber type (natural fibers, synthetic fibers, or the combination thereof) and chemical admixtures (e.g., plasticizers and superplasticizers). Such a study could assist with mass application of SCFRC in sustainable architectural structures.

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Conflict of interest

The authors hereby declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Abbreviations

ACI	American Concrete Institute
AEA	Air-entraining admixture
ASTM	American Society for Testing and Materials
C-SCC	Colored self-consolidating concrete
FRC	Fiber-reinforced concrete
GBFS	Granulated blast furnace slag
HRWR	High-range water-reducing admixture
PP	Polypropylene
SCC	Self-consolidating concrete
SCFRC	Self-consolidating fiber-reinforced concrete
VMA	Viscosity-modifying admixture
VSI	Visual stability index

Author details

Wael Zatar* and Hai Nguyen
College of Engineering and Computer Sciences, Marshall University, One John Marshall Drive, Huntington, WV, USA

*Address all correspondence to: zatar@marshall.edu

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