COMPARISON OF FRESH AND HARDENED PROPERTIES OF SELF-COMPACTING CONCRETE MIXTURE FROM DIFFERENT ASPECT RATIO OF STEEL FIBER VIEW POINT

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ABSTRACT

Self-compacting concrete (SCC) is a type of concrete which is frequently preferred in different applications due to its advantages such as its fluidity and transition in tight openings between steel reinforcing bars. However, it is vital that SCC maintains its fresh state characteristics when its transportation phase is taken into consideration. Fiber reinforced in SCC affects the properties of fresh concrete negatively while it had a positive effect on its dynamic properties. In this study, the effect of steel fibers having different aspect ratios on the time dependent fresh properties and mechanical properties of self-compacting concrete mixtures was investigated. In addition to the control mixture without fiber, in the mixtures containing fiber, three different twin-hook steel fibers with aspect ratios of 54, 64 and 50 were used as 0.6% of total volume. In all of the SCC mixtures, the water/cement ratio, cement dosage and slump-flow value were kept constant. The time dependent rheological properties of the mixtures were investigated. The compressive, split-tensile and flexural strengths as well as fracture energy, the load deflection relation under flexural load and load-crack opening displacement, modulus of elasticity of SCC mixtures were also investigated. Besides, the water absorption capacity and depth of penetration of water under pressure of mixtures were measured. On the basis of the results, the fiber utilization and its aspect ratio had no significant effect on compressive strength and modulus of elasticity of the SCC mixtures. The split-tensile, flexural strengths and fracture energy of SCC mixtures increased by using fiber; the permeability properties of SCC mixture increased by fiber utilization.

KEYWORDS

self consolidating concrete, steel fiber, aspect ratio, fresh state properties, mechanical properties.

1. INTRODUCTION

The properties of the concrete mixtures due to technological necessity are developing continually. However, various problems arise when the design, placement and compacting of concrete

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do not occur properly [1]. The energy required for placement and compaction during the preparation of concrete mixtures is one of the main difficulties of concrete production. The placement and compacting of concrete are performed with consuming compression energy with vibrators in construction sites and vibrating tables etc. in concrete factories. These processes are important for producing concrete with optimum strength and durability [2].

With the development of concrete technology, in order to solve the compacting problems which are encountered in the application of conventional concrete, homogenously settled under its own weight in the mold and having high fluency, self-compacting concrete (SCC) was first suggested by Okamura in studies at Tokyo University [3]. Many European countries have realized the advantages of the SCC developed in Japan and focused on this new concrete.

EFNARC was established in 1989, which includes companies in Europe, Asia and Australia and their associate members. From this date on, EFNARC published many technical reports and guidelines and had played a major role in the construction industry related to conform with European Norms. In 2002, specifications and guidelines for the design and use of SCC were prepared by EFNARC and the use of SCC began to grow and develop rapidly. SCC became important for prefabs and ready-mixed concrete production [4,5].

SCC has been widely used in different construction and composing load-bearing systems in many countries. By comparison with conventional concrete, SCC reduces labor cost and has high performance in terms of durability with its vibration-free compacting properties. The reason why SCC exhibits high strength and durability performance from conventional concrete is due to its high content of fine aggregates, binders and superplasticizers.

As known, cementitious materials have very low tensile strength and stress deformation capacity. In order to improve these weak properties of concrete, fibers produced from materials such as glass, plastic, polypropylene and steel can be reinforced to the mixture [6]. Nowadays, fibers are used in concrete production in different types, sizes and ratios and they can improve the compressive, tensile, flexural and impact strength, ductility, energy absorption capacity and crack development characteristics of the concrete mixtures in which they are reinforced. However, it has been observed that the use of fiber has adversely affected the fresh-state properties of the mixtures [7–9].

The workability of the fresh concrete changes with the amount, length and shape of the fibers used. On the other hand, the durability and mechanical performance of the hardened fiber reinforced concrete changes depending on the workability of the mixture and its ability to be placed into the mold without any gaps [10].

Fiber reinforced concrete (FRC) and SCC technologies have been developing continually. A new research area in concrete technology has recently evolved that combines the advantages of both fiber reinforcement and self-consolidation. This new concrete is named fiber-reinforced self-consolidating concrete. In order to provide sufficient flowability, improve fiber ratio and reduce the risk of entrapping gaps, the FRC is often proportioned to be fluid enough to reduce the need for vibration consolidation and facilitate placement. An improvement of this approach can involve the use of self-consolidating concrete (SCC) to eliminate, or greatly reduce, the required energy for vibration and better casting of concrete into mold [10,11]. In this context, fiber reinforced SCC is eco-friendlier than traditional concrete because energy saving is achieved in SCC applications [2,12–15]. On the other hand, the utilization of fiber positively affected durability performance and the dimensional stability of the concrete mixture [15,16]. The long service life of concrete mixture is depended on high durability performance. Therefore, waste materials consisting of destruction of the concrete structure having long service life are decreased. In this way, the reconstruction process is delayed and both economic benefits are provided and cement consumption is indirectly reduced [16,17]. Note that roughly 1.2 tons of raw material and about 130 kWh of energy are required for the production of 1 ton of cement. In addition, roughly 1 ton of CO_2 will be released [18]. Therefore, the decrease in cement consumption is of great importance in reducing the environmental problems caused by concrete production.

In a study by Corinaldesi et al. [19], thin prefabricated elements were produced with SCC mixtures. In this regard, 10% by weight steel fiber was used instead of rebar. As a result of the study, it was reported that SCC mixtures are a suitable option for the production of fine prefabricated elements in non-structural applications. Ding et al. [20] examined the workability properties of steel and polypropylene fiber reinforced SCC mixtures. In the study, it was determined that the transition ability results of J-ring and L-box tests was parallel.

In this study, the effect of the reinforced steel fiber with different aspect ratio on the fresh and some hardened state properties of SCC mixtures was investigated. For this purpose, in addition to the control mixture containing no fiber, fiber reinforced SCC mixtures were prepared by using 3 different two-end hooked steel fibers with 54, 64 and 50 aspect ratios up to 0.6% of the total volume. Slump-flow, U-box, L Box, J Ring, V-funnel tests were performed as time dependent in fresh concrete mixtures. The compressive, split-tensile and flexural strengths as well as fracture energy, the load deflection relation and load-crack opening displacement of SCC mixtures under flexural load were also investigated.

2. MATERIALS AND TEST PROCEDURES

2.1 Materials

In the experimental study, CEM I 42.5R type cement with specific surface area and specific gravity of 3530 cm^2/g and 3.15 was used, respectively. Chemical, physical and mechanical properties of the cement provided by the manufacturer are given in Table 1.

The crushed limestone aggregate with the maximum aggregate size of 12 mm was used in SCC mixtures. The specific gravity and water absorption capacity of the aggregates obtained according to TS EN 1097-6 standard are given in Table 2 and according to the same standard. The results of sieve analysis of aggregates are given in Figure 1. Thirty-five percent of the total aggregate volume was 0–4 mm (fine aggregate) and the residual of volume was 4–12 mm crushed limestone aggregate was used in SCC mixtures.

Polycarboxylate-ether based high range water-reducing admixture was used to provide the desired slump-flow values in the SCC mixtures. Some properties of the water reducing admixture provided by the manufacturer are shown in Table 3.

In the mixtures containing fiber, three different steel fibers with two ends hooked with length/diameter, 30/0.55, 35/0.55 and 50/1 were used and aspect ratios of fibers were calculated as 54, 64 and 50 (Figure 2).

The fiber utilization ratio in the mixtures containing fiber was chosen as 1% of the total volume of the mixture. However, the mixtures containing 1% fiber did not meet the criteria proposed by EFNARC [21] for SCC mixtures. For this reason, based on the experimental results performed in the preliminary study, the fiber utilization ratio in the fiber reinforced mixtures was determined as 0.6% of the total volume of the mixture. Some mechanical and physical properties and appearance of steel fibers are given in Table 4 and Figure 3, respectively.

TABLE 1. Chemical composition, physical and mechanical properties of the cement.

Item	(%)	Physical properties		
SiO_2	18.86	Specific gravity C2S (%) C3A (%) C4AF (%)		3.15
Al_2O_3	5.71	**Mechanical properties**		
Fe_2O_3	3.09	Compressive strength (MPa)	1-day	14.7
CaO	62.7		2-day	26.8
MgO	1.16		7-day	49.8
SO_3	2.39		28-day	58.5
Na_2O+0.658 K_2O	0.92	**Fineness**		
Cl^-	0.01	Blaine specific surface (cm^2/g)		3530
Insoluble residue	0.32	Residual on 0.045 mm sieve (%)		7.6
Loss of ignition	3.2			
Free CaO	1.26			

TABLE 2. Physical properties of aggregates used in SCC mixtures.

Type	Dimension (mm)	Specific Gravity	Water Absorption Capacity (%)
Crushed Limestone	0–4	2.67	1.2
	4–12	2.7	0.7

FIGURE 1. Gradation curve of aggregates used in experiments.

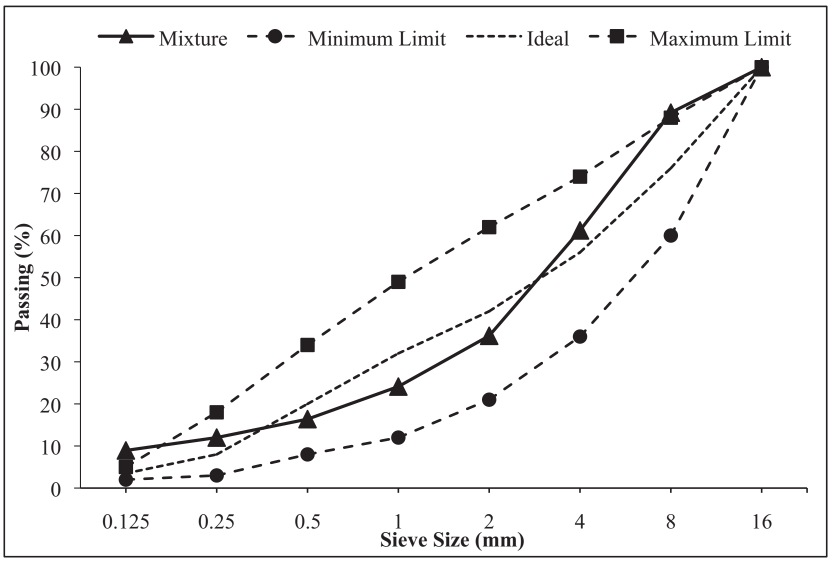


TABLE 3. Properties of water reducing admixture.

Tip	Density (g/cm^3)	pH value	Chloride Content (%)	Alkali Content, Na_2O (%)
Polycarboxylate Ether Based	1.023–1.063	5–8	<0.1	<10

FIGURE 2. Aspect ratio calculation of fibers.

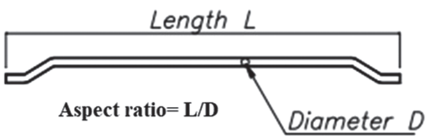
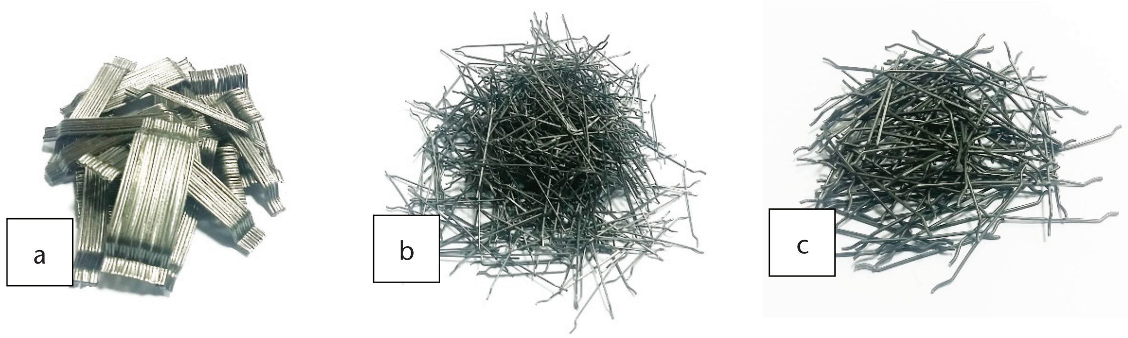


TABLE 4. Mechanical and physical properties of steel fibers.

Type	a	b	c
Aspect ratio	54	64	50
Length (mm)	30	35	50
Diameter (mm)	0.55	0.55	1
Density (gr/cm^3)	7.8	7.8	7.8
Tensile strength (N/mm^2)	1500	1500	1100

FIGURE 3. Appearance of steel fibers with two ends hooked; a. Aspect ratio 54; b. Aspect ratio 64; c. Aspect ratio 50.



2.2 Mixture Preparation

In addition to the control mixture without fiber, three different fiber reinforced SCC mixtures were produced. Water/cement ratio, cement content and slump-flow values of all mixtures were kept constant at 0.40, 480 kg/m^3 and 65 ± 2 cm, respectively. A high range water reducing admixture is used at different ratios in order to provide the desired 65 ± 2 cm slump flow value. The amounts of theoretical and corrected materials for production of 1 m^3 SCC are given in

Table 5 and Table 6, respectively. Designation of mixtures was written according to the fiber use and the length of the fiber used.

As shown in Table 6, the need to admixture increased with the use of fiber to ensure an intended flow value (65 ± 2 cm) regardless of fiber slenderness. In fiber mixtures, the fiber was used by volume instead of aggregates. The increase in unit weight of the mixtures is expected because the specific gravity of the fiber used is about three times greater than that of the aggregate.

2.3 Test Procedures

In order to determine fresh concrete state properties, T50 flow test, T50 time determination, V funnel, U box, L box, J ring and fresh unit weight tests were performed on SCC mixtures in accordance with EFNARC [21] standard, respectively. The experiments were repeated every 20 minutes for 1 hour to determine the time-dependent variation of the test results. Within the scope of this study, each experiment was repeated three times to determine the fresh state properties of mixtures.

SCC mixtures prepared in the mixer were placed into the molds without any compacting process according to the standard. The samples were removed from the mold after 24 hours and kept in a curing pool at a constant temperature of 22 ± 2°C. The 7-and 28-day compressive strength, 28-day 4-point flexural strength, modulus of elasticity, water absorption, and depth

TABLE 5. Theoretical mix amount for 1m³ SCC.

Code of Mixture	Cement (kg)	Water (kg)	Aggregate (kg)		Fiber (kg)			Admixture (kg)	Slump-flow(cm)	Unit weight (kg/m³)	
			0–5 mm	4–12 mm	30 mm	35 mm	50 mm			Theoretical	Measured
C	480	192	1097	597	0	0	0	10	67	2376	2440
L30	480	192	1087	592	46.8	0	0	11.30	66	2409	2466
L35	480	192	1087	592	0	46.8	0	10.87	65	2409	2465
L50	480	192	1087	592	0	0	46.8	10.43	64	2408	2467

TABLE 6. Corrected mix amount for 1 m³ SCC.

Code of Mixture	Cement (kg)	Water (kg)	Aggregate (kg)		Fiber (kg)			Admixture (kg)
			0–5 mm	4–12 mm	30 mm	35 mm	50 mm	
C	494.3	196.5	1129.8	614.8	0.0	0.0	0.0	10.3
L30	491.3	196.5	1112.7	606.0	47.9	0.0	0.0	11.6
L35	491.2	196.5	1112.4	605.8	0.0	47.9	0.0	11.1
L50	491.7	196.7	1113.5	606.4	0.0	0.0	47.9	10.7

of penetration of water under pressure were performed according to TS EN 12390-3, TS EN 12390-5, ASTM C 469, ASTM C642-97 and TS EN 12390-8, respectively. In order for the compressive strength, tensile strength and water absorption capacity tests of mixtures, 10 cm cube specimens were used. Flexural strength, modulus of elasticity and depth of penetration of water under pressure of the mixtures were determined on a 10 × 10 × 50 cm prism, 10 × 20 cm cylinder and 15 cm cube specimens, respectively.

In order to evaluate the hardened state properties, three specimens were produced for each experiment. Each value was determined by calculating the average of 3 different specimens.

3. TEST RESULTS AND DISCUSSION

3.1 Fresh State Properties

The results of fresh state experiments of the SCC mixtures are given in Table 7.

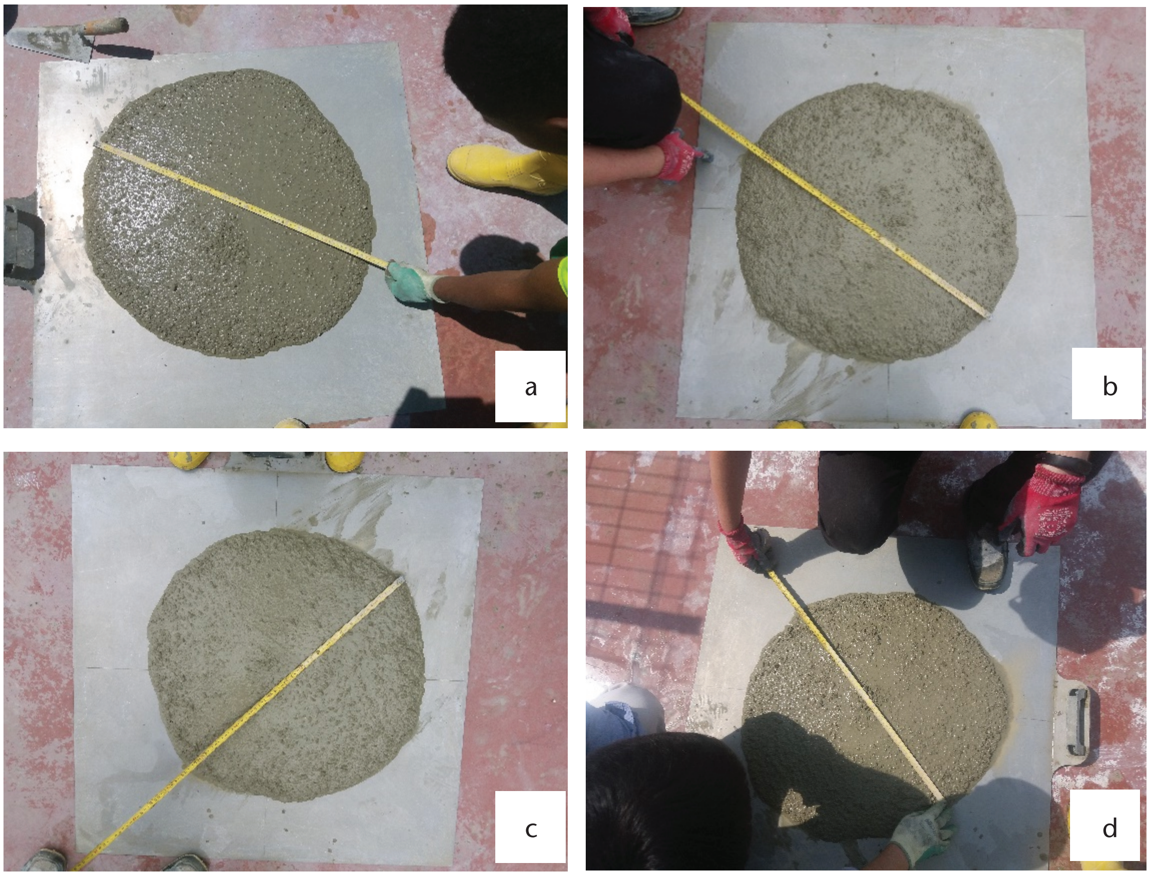
T50 slump-flow test and flow time results

In order to investigate the T50 slump-flow test and flow time properties, the slump flow value of the SCC mixtures was kept constant as 65 ± 2 cm and the passing time of the concrete over the 50 cm circle on the slump flow table was measured by elapsing time. All measurements were repeated every 20 minutes during one hour. The slump-flow measurements of the SCC mixtures are shown in Figure 4.

TABLE 7. Fresh state test results of SCC mixtures.

Mix	Time (min)	Slump Flow (cm)	T_{50} Time (s)	V-funnel (s)	L Box (H2/H1)	L Box T20 (s)	L Box T40 (s)	U-box (cm) (H2-H1)	J Ring Level Difference (mm)
C	0	67	2.69	7.32	0.8	1.36	3.56	2	3.5
	20	59	4.9	10.76	0.75	1.49	3.79	9	4
	40	53	6.43	14.07	0.71	1.67	4.68	19	5.5
	60	50	8.39	17.33	0.61	1.89	4.91	26	7
L30	0	66	4.92	46	Block	—	—	Block	8.5
	20	58	5.3	69	Block	—	—	Block	9
	40	52	9.63	Block	Block	—	—	Block	10.5
	60	47	—	Block	Block	—	—	Block	13
L35	0	65	3.46	35.83	Block	—	—	Block	9
	20	57	5.12	67.89	Block	—	—	Block	10.5
	40	52	7.48	Block	Block	—	—	Block	11.5
	60	43	—	Block	Block	—	—	Block	15
L50	0	64	2.71	26.8	Block	—	—	Block	11
	20	54	4.9	59.63	Block	—	—	Block	12.5
	40	48	6.43	95	Block	—	—	Block	15
	60	Block	—	Block	Block	—	—	Block	Block

FIGURE 4. T50 slump-flow measurements of SCC mixtures; a. Control Mixture (C); b. L35 Mixture; c. L35 Mixture; d. L50 Mixture.

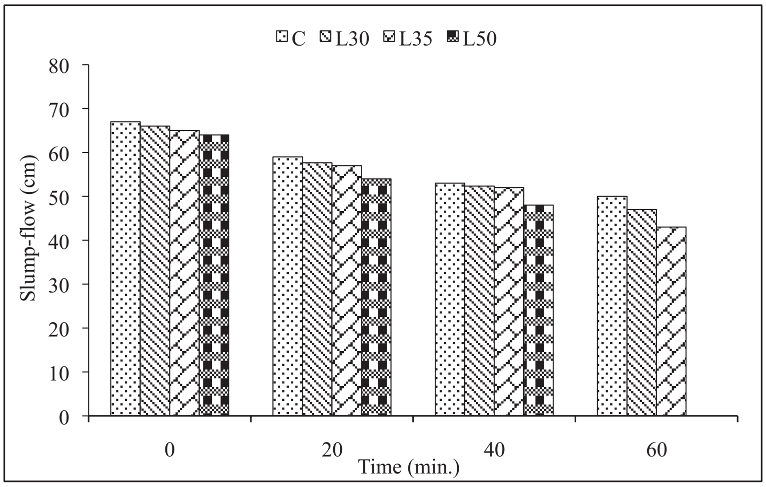


The time-dependent slump flow values of the mixtures and the T50 times are shown in Figure 5.

As seen in Figure 5, the highest slump flow value was observed for the control mixture without fiber. According to the SCC mixture criteria proposed by EFNARC [21], the slump flow value of the concrete mixture should stay between 55 cm and 85 cm. Thus, all mixtures were found to meet the slump flow requirements of SCC at 0 minutes.

During the test, at least a 54 cm slump flow value was measured up to 20 minutes for all SCC mixtures. This value decreased by elapsing time due to the loss of consistency of the SCC mixtures. After 40 minutes, regardless of fiber presence and fiber aspect ratio, steel reinforced SCC mixtures could not provide a minimum 55 cm spread value which is recommended for slump flow by EFNARC [21]. The slump flow values of all mixtures at the 40th minute showed a loss of about 20 to 25% with respect to their initial values. After 60 minutes, the L50 mixture containing the longest fiber did not flow from the Abraham cone and the slump flow value of this mixture could not be obtained. In addition to the loss of consistency by elapsing time, due to interlacing of fibers depending on the length of the fiber used (50 cm) in the mixture, agglomeration became inevitable.

FIGURE 5. Results of time-dependent slump-flow test.



According to the results, the decrease of the slump flow values due to the loss of consistency of the mixtures containing fiber was more pronounced compared to the control mixture. The slump flow values of the SCC mixtures at the end of 60 minutes according to the slump flow values measured immediately after the casting (0 minutes) is shown in Figure 5. At the end of 60 minutes, a slump flow loss of 26% was observed in the control mixture, while it was determined as 29% and 33% in the L30 and L35 mixtures, respectively.

Initial T50 times of SCC mixtures were measured between 2–5 seconds. These values correspond to the requirements of EFNARC [21], which recommends a flow time of 2 to 6 seconds for the SCC mixture. In general, an increase in T50 flow times was observed due to the loss of consistency by elapsing time.

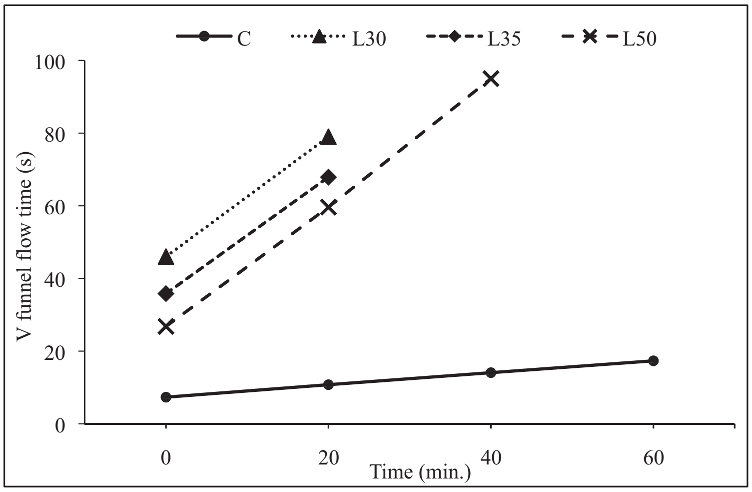
The T50 flow time values of SCC mixtures containing fiber were increased independent of the fiber aspect ratio. This increase became more apparent by elapsing time. While the L50 mixture showed the lowest performance compared to the other fiber reinforced SCC mixtures, the T50 flow time measurement could not be obtained after 40 minutes since it could not reach the 50 cm spread limit value.

When the control mixture performed at maximum at approximately 8 seconds of T50 flow time of up to 60 seconds, L30 and L35 mixtures performed 9.63, 7.48 seconds T50 flow time, respectively, 40 minutes after casting. However, T50 measurements could not be obtained as the L30 and L35 mixtures did not reach 50 cm in the 60th minute. From the beginning, the L35 mixture had a lower T50 flow time compared to the L30 mixture. This situation was more apparent over time. It is also understood from the results that T50 flow time of the L35 mixture at the 40th minute was 23% lower than the L30 mixture. For this reason, among the fiber reinforcement mixtures, the L35 mixture containing the fiber having a length of 35 mm was chosen as the most suitable mixture in terms of T50 flow time.

V-funnel test results

The V-funnel flow time provides information on the viscosity properties of the mixtures. The V-funnel flow time of the mixtures was repeated every 20 minutes for 1 hour. The results of time-dependent V-funnel test of the SCC mixtures are given in Figure 6.

FIGURE 6. Time-dependent V-funnel test results.



The control and L50 mixtures were compatible with the criteria by showing a value below the maximum flow time (27 sec) specified in the guidelines criteria of EFNARC [21] in terms of the initial V-funnel values, while the L30 and L35 SCC mixtures were not in the appropriate range with the V-funnel flow times of 35 and 46 seconds, respectively. As shown in Figure 6, V-funnel flow is provided in the control mixture for up to 60 minutes. On the other hand, as expected, the change in the fresh state properties of the mixtures containing steel fibers over time is worse compared to the control mixture. As the fiber length decreased in the steel fiber-containing mixtures, it was seen that the V-funnel flow time increased. In the L50 mixture with the longest fiber, V-funnel flow was achieved up to 40 minutes, and it was determined that it did not flow from the V-funnel after 60 minutes. In the L30 and L35 mixtures, blockage occurred in the V-funnel after 40 minutes and thus, it could not take measurements (Figure 7). In the

FIGURE 7. V funnel flow time measurements of SCC mixtures a. providing to V funnel flow of control mixture (C) for up to 60 minutes b. Blocking of L30 mixture after 40 minutes from V funnel.

(a)

(b)

FIGURE 8. Blockage of SCC mixtures containing steel fibers in L-box.

first 20 minutes, V-funnel flow performance in the control mixture decreased by 40% compared to the starting V-funnel flow times. When the identical comparison is performed in mixtures containing fiber, it stayed between 73–123%. According to the result, it is thought that the viscosity of the SCC mixtures increased with the fiber length decrease. It is seen that the amount of fiber in the mixture increased by decreasing the fiber length if fiber amounts are fixed and the same in volume in fiber mixtures. For this reason, the viscosity of the mixture increased.

L-box test results

The results of the time-dependent L box test for all SCC mixtures are given in Table 7. According to EFNARC [21], it is recommended that H2/H1 ratio should be in the range of 0.8–1. As shown in Figure 8, only the control mixture provided the recommended EFNARC [21] criteria for SCC. In fiber reinforced mixtures, the fibers that did not pass through the L box rebars, formed a blockage which disrupted the uniformity and continuity of flow of the SCC mixture. For this reason, the L-box test for fiber reinforced mixtures could not be performed.

Also understood from Table 7, after 60 minutes there was a 40% increase in flow time of the control mixture.

U-box test results

According to EFNARC [22], it is recommended that the H1-H2 difference is in the range of 0–30 cm in the U-box experiment. The results of the time-dependent U-box test that was performed for all SCC mixtures are given in Table 7 and Figure 9.

According to the results obtained in the U-box experiment, the U-box criterion of EFNARC [22] was provided only in the control mixture. It is seen that the U-box H2-H1 value of the control mixture changed to 2–26 cm until 60 minutes. However, as can be seen from the results, the 60-minute U-box H2-H1 value of control mixture is increased by 13-times compared to the 0th minute. The U-box H2-H1 values of mixtures containing fiber could not be measured because there was no flow between rebars in the U-box, regardless of the fiber aspect ratio. As shown in Figure10, the U-box transition zone is blocked by steel fibers. It is

FIGURE 9. Result of H2-H1 difference of U Box.

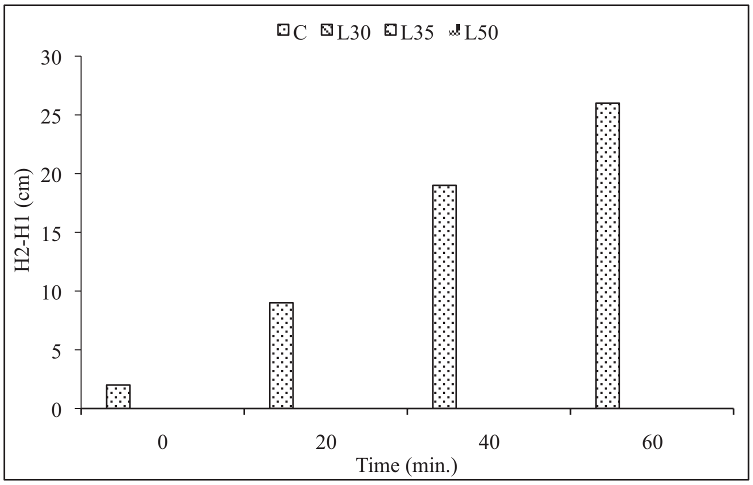
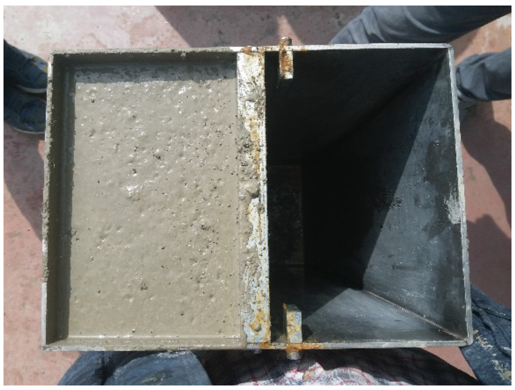


FIGURE 10. Blockage of SCC mixtures containing steel fibers in U-box.



considered to be inconvenient to use the aforementioned steel fiber-containing SCC mixtures in the commonly-equipped regions.

J-ring test results

The time-dependent J-ring test results that was performed for all SCC mixtures are given in Table 7 and Figure 11.

In reference to the J-ring level difference results, it was initially seen that a difference of 3.5 mm was realized for the control mixture. This value is shown in the first measurement and the recommended EFNARC [21] criterion for the SCC mixture is provided. After 60 minutes, the J ring level difference increased by 100% due to loss of consistency in the control mixture. In the case of L30 and L35 mixtures containing short fibers, despite the flowing problems between the rebars of the J ring, it achieved a positive result and complied with the EFNARC [21] criteria. However, it was observed that during the experiment, mixtures of L30 and L35 had lost their consistency over time and exceed this criterion after 40 minutes. In the L50 mixture containing long fibers, the first measurement showed a similar result. The long fibers in the L50 mixture

FIGURE 11. Time-dependent J-ring level difference results.

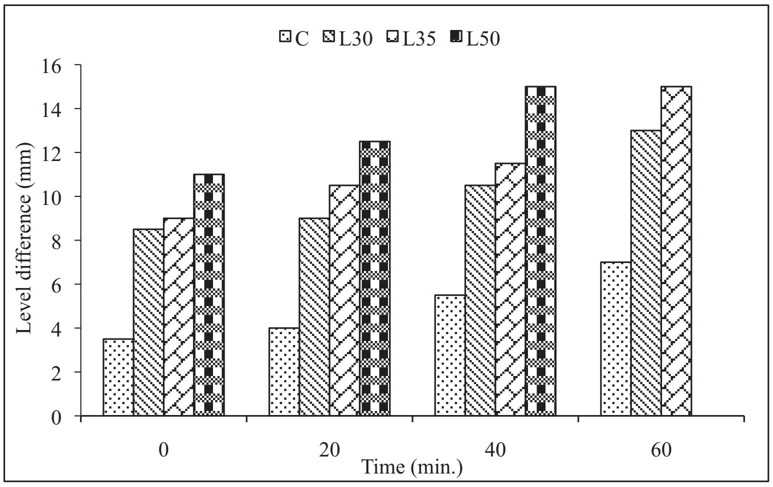


FIGURE 12. Blocking of SCC containing fiber between rebars of J-ring.

prevented the flow of concrete between the rebars of the J ring during the measurements after the 20th minute, and the ability of passing of the mixture was adversely affected. As shown in Figure 12, due to the length of the fiber in the L50 mixture, the mixture did not pass between the J ring rebars.

3.2 Hardened State Test Results

The compressive, splitting tensile and flexural strengths, fracture energy, modulus of elasticity, water absorption and depth of penetration of water under pressure test results of SCC mixtures are given in Table 8.

Compressive strength test results

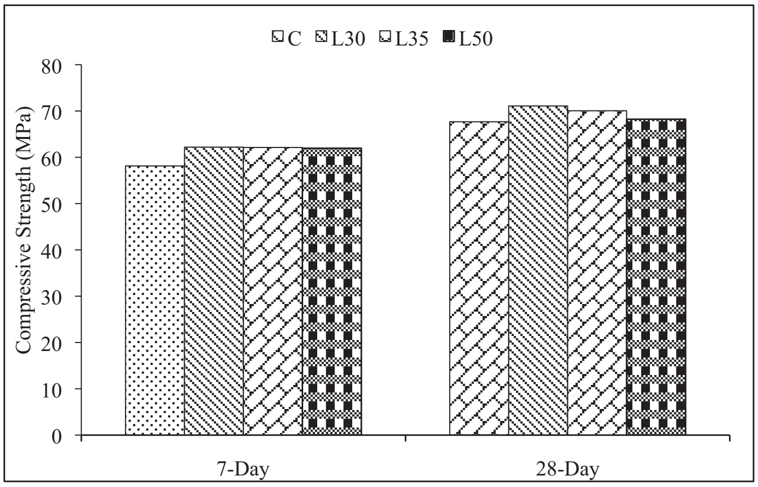
The 7 and 28-day compressive strength test results on 4 different SCC specimens is given in Figure 13.

According to the results, the compressive strengths of the SCC mixtures increased as expected, regardless of the use of steel fibers. As seen in Figure 13, it was found that the 28-day compressive strength for each mixture increased by 10–16% compared with the 7-day strength.

TABLE 8. Hardened state test results of SCC mixtures.

SCC mixtures	Compressive strength (MPa)		Splitting tensile strength (MPa)		Flexural strength (MPa)	Fracture energy (J/m^2)	Modulus of elasticity (GPa)	Water absorption (%)	Depth of penetration of Water (%)
	7d	28d	7d	28d	28d	28d	28d	28d	28d
C	58.13	67.67	3.33	4.1	2.98	131	42.56	6	4.85
L/30	62.19	71.08	5.81	6.78	4.94	4913	39.32	7	5.17
L/35	62.12	70.05	5.21	6.23	3.80	4061	36.82	7	5.24
L/50	61.95	68.22	5.21	6.18	3.65	5582	40.97	9	5.53

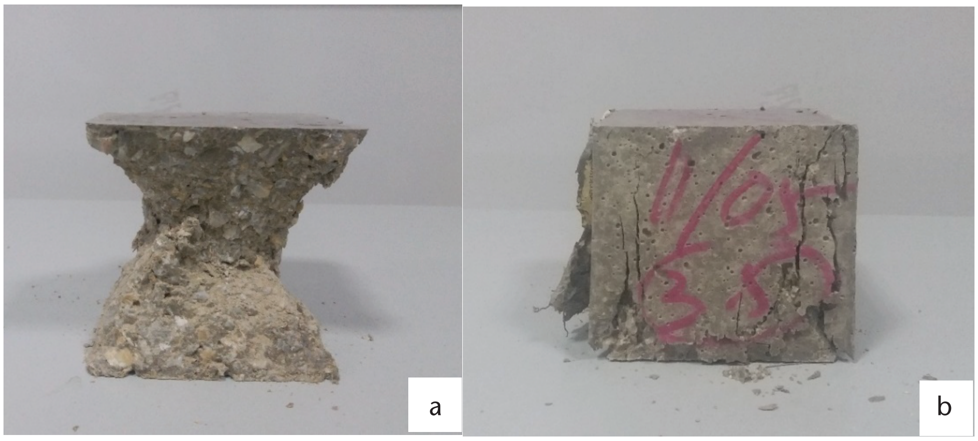
FIGURE 13. The 7 and 28-day cube compressive strength of SCC mixtures.



It was observed that the use of steel fiber in these SCC mixtures had a positive effect on the 7 and 28-day compressive strength. According to the results, the 7 and 28-day compressive strength of SCC mixtures containing steel fiber did not perform a significant increase compared to the control mixture. In this context, with regard to the results of the 7 and 28-day compressive strength, it was found that fiber reinforced mixtures showed an increase of 1.88–6.98% and 0.81–5.03% compared to the control mixture, respectively. The crack angle in the control mixture, which is 45 degrees, decreased with the use of fiber is shown in Figure 14. With the use of steel fibers of 0.6% by volume and a length of 35 mm, the crack angle of these specimens decreased and showed a nearly parallel crack direction. In addition, in fiber reinforced specimens, under the compression load, fibers behaved as bridge between particles and reduced the failure of the piece.

On the other hand, with the increase of the fiber length in the fiber reinforced mixtures, the compressive strength of the SCC mixtures was adversely affected. In the fiber reinforced SCC mixtures, the L30 mixture, which has the shortest length of fiber compared to the other fibers, showed the highest performance in terms of compressive strength. According to the

FIGURE 14. Specimens of SCC mixtures after compressive strength test; a. A specimen of the control mixture; b. Specimens of L35 mixture.



28-day compressive strength results of the mixtures containing fiber, the L30 mixture increased by 1.5% compared to the L35 mixture and 4.2% compared to the L50 mixture.

Splitting tensile test results

The results obtained from the splitting tensile test of 7 and 28-day specimens are presented graphically in Figure 15.

From Figure 15 there is a time depending increase in the tensile strengths of all SCC mixtures. In general, an increase in the 28-day tensile strength of SCC mixtures compared with the 7-day strength was observed with an increase of between 20% and 23%. Considering Figure 15, it was observed that the use of steel fibers in SCC mixtures had a positive effect on tensile strength.

In fiber-containing mixtures, a slight decrease in the splitting-tensile strength of SCC mixtures was observed with the increase in fiber length. While the L35 and L50 mixtures showed almost the same performance at 7 and 28 days, the L30 mixture had the highest splitting

FIGURE 15. Splitting tensile strength of SCC mixtures on 7 and 28 days.

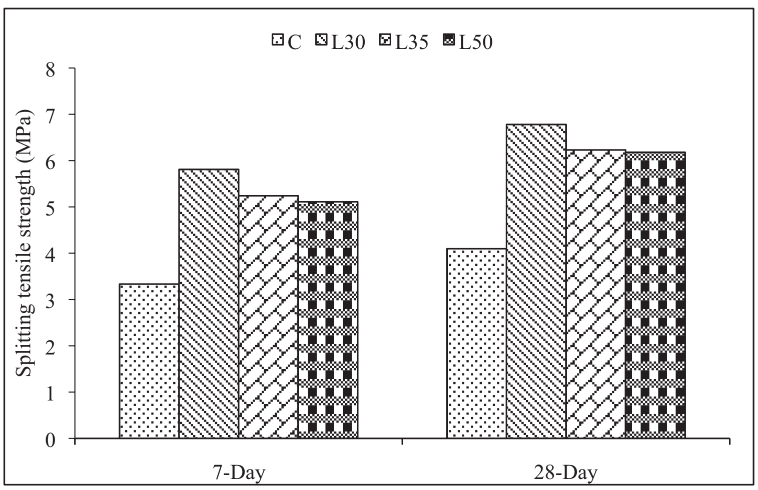
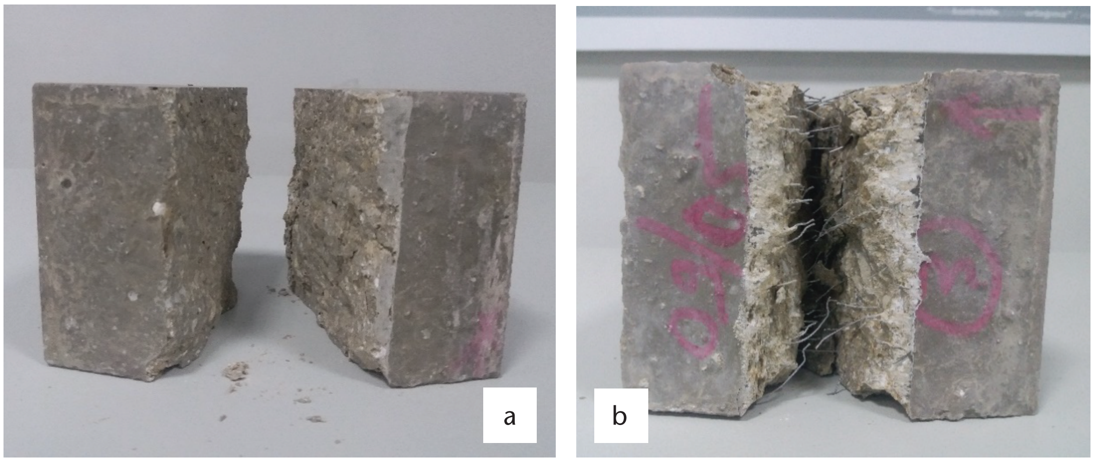


FIGURE 16. SCC mixture specimens after splitting tensile test a. Specimen of the control mixture b. Specimens of the L30 mixture.



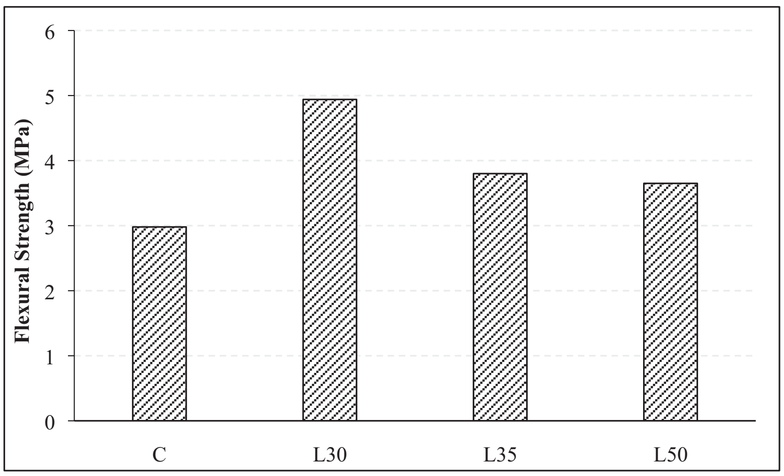
tensile strength performing mixture compared to other fiber-containing SCC mixtures. When the results of the tensile experiment were examined for 7 days, the L30 mixture was found to increase by 8.7% and 9.7% compared to the L35 and L50 mixtures, respectively. Similar ratios were observed for the 28-day specimens. As is known, the use of shorter fibers in the mixtures prevents the growth and development of micro-cracks formed in the specimens during loading and positively affects the properties of the mixtures such as splitting tensile and flexural strength [23–27].

The cube specimens divided into two parts as a result of the splitting tensile test applied to the control mixture specimens are shown as Figure 16. However, there was no complete separation of the specimens in the steel fiber reinforced mixtures.

Flexural test results

The flexural strengths of the mixtures are shown in Figure 17. It was determined that the L30 mixture showed the highest flexural strength performance compared to the other mixtures. As

FIGURE 17. Flexural strength values of SCC mixtures.



mentioned earlier, this mixture contains the fiber length of 30 mm (the shortest). Furthermore, it was determined that the flexural strength of the control mixture was the lowest value compared to the fiber-containing mixtures.

The flexural strength of the concrete mixture increases by decreasing fiber length. Some researchers stated that shorter fiber prevents crack propagation and thus increases flexural strength [17,23–28].

The flexural strengths of the mixtures containing fiber 27% and 46% are higher than the control mixture. When the flexural strengths of fiber reinforced SCC mixtures are examined, the L30 mixture has a higher bending strength value between 30% and 35% compared to the L35 and L50 mixtures.

The 4-point flexural tests were performed on the notched beam specimen and the load-crack mouth opening displacement of the SCC mixtures is shown in Figure 18.

Crack mouth opening displacement reached up to 6 mm in all SCC mixtures containing fiber. In addition, it was determined that steel fiber reinforced SCC are the most energy absorbing mixtures. On the other hand, it was observed that as the steel fiber length decreases, the energy absorption capacity of the SCC containing fiber mixtures decreased. Similar results were reported by some researchers [23–27].

The flexural test was performed on control specimens containing no fiber. A brittle fracture occurred during loading in the beam specimens. However, in specimens containing fiber, the steel fibers acted as bridges between cracks, breaking the crack and preventing brittle fracture. In this regard, as shown in Figure 19, there was no complete separation at the notch level. In the mixtures containing fiber, the long fiber-containing L50 mixture showed the best performance in terms of crack opening.

FIGURE 18. Crack mouth opening displacement-load curves of SCC mixtures.

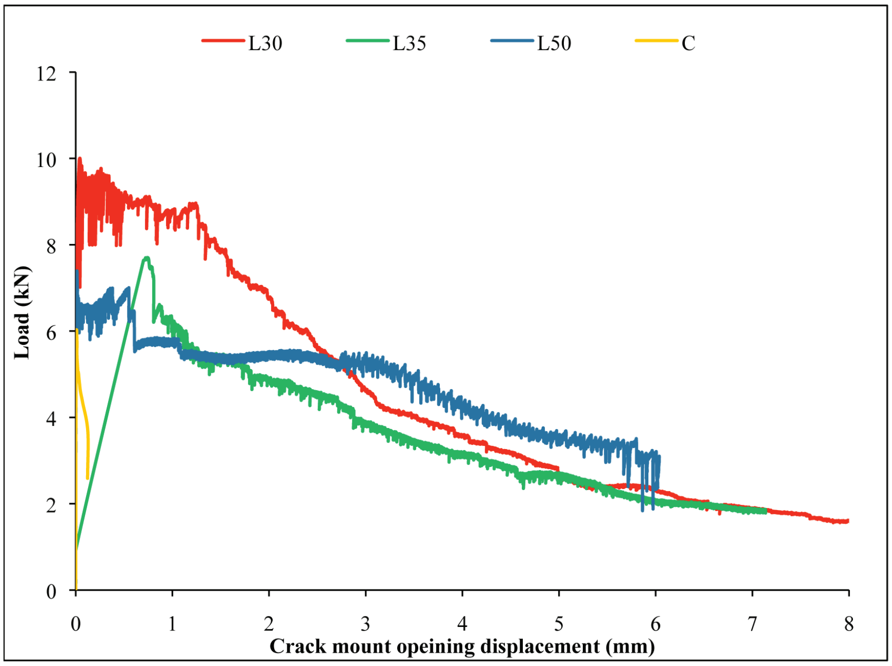


FIGURE 19. Crack opening after flexural test on fiber reinforced SCC.

The load-deflection curves of the SCC mixtures as a result of the flexural test are shown in Figure 20.

The deflection values of all fiber reinforced SSC mixtures except the control mixture reached up to 10 mm. It was found that typical load-deflection curves obtained from fiber mixtures was very close to each other. It was observed that the L30 mixture had a higher load carrying capacity compared with the L35 and L50 mixture. After about 1 mm of mid-point deflection, the L30 and L35 mixtures probably had a decrease in load due to the position of the fibers in the crack plane with regard to the crack plane and the ratio of broken fiber.

When the flexural test was performed on the notched concrete beam specimens, cracks in the matrix phase were formed after the beam showed a particular deflection. It was observed that the crack starting from the notch proceeded with increasing deflection (Figure 19). It is predicted that the crack mouth opening displacement will be greater than the vertical displacement of the midpoint beam.

FIGURE 20. The load-deflection curves of the SCC mixtures.

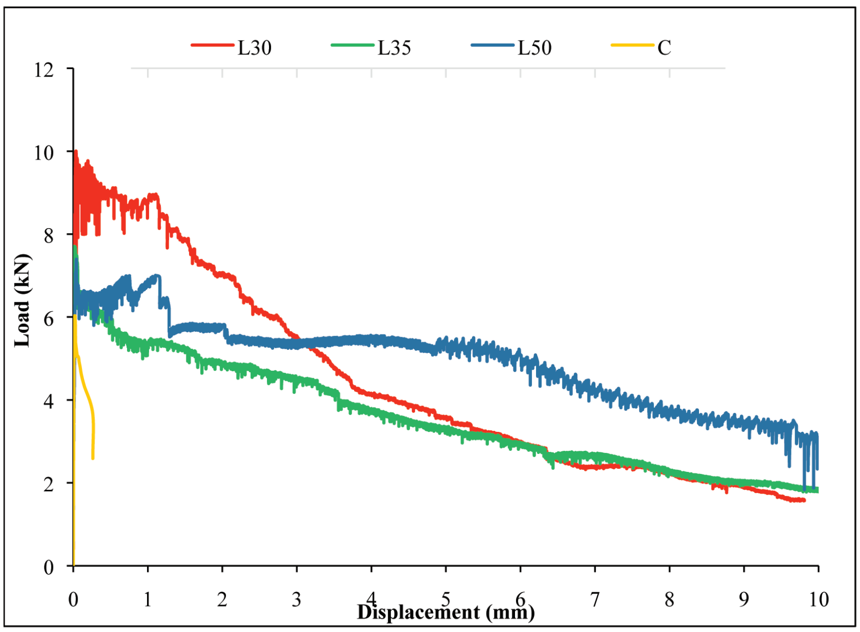
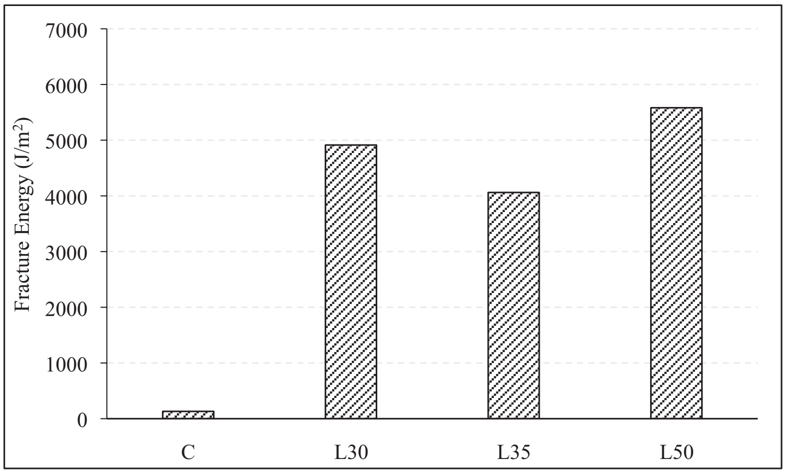


FIGURE 21. The fractural energy of the SCC mixtures.



Fractural energy results

The fractural energy given in Figure 21 was calculated as the area under the load-deflection curve in the flexural test of the specimens.

According to the flexural test results as shown in Figure 21, the fracture energy of the mixtures increased with the steel fiber presence of the SCC mixtures.

Fracture energies of fiber-containing SCC mixtures were determined to be 38 to 43 times higher than the control mixture. The L50 mixture had 14% and 37% higher fracture energy than L30 and L35 mixtures, respectively. The fiber content of the mixtures contributed significantly to the reduction of crack development. In this context, a significant increase in fracture energies of fiber-containing mixtures was observed. This effect became more pronounced with the increase in the length of the fiber. Increased fiber length delays pulling away fibers during loading [23–27].

Modulus of elasticity test results

The modulus of elasticity of the mixtures was calculated from the slope of the rising 40% of the curve in the stress-strain curve obtained under compression loading. The modulus of elasticity of the SCC mixtures is given in Figure 22.

According to the results of the modulus of elasticity applied to SCC specimens, it was observed that the use of steel fibers did not cause a significant change on the modulus of elasticity of the SCC mixtures. As shown in Figure 22, the control mixture had the highest modulus of elasticity. According to the mixtures containing fiber, an increase in the elasticity of modulus of the control mixture was 4% and 15%. The highest performance was the L50 mixture among fiber mixtures. This mixture had a modulus of elasticity of 4% and 11% higher than L30 and L35 mixtures, respectively.

Depth of penetration of water under pressure test results

Depth of penetration of water under pressure test was performed on 15 cm cube specimens of 28-day. Figure 23 shows the results of depth of penetration of water under pressure test of SCC mixtures.

FIGURE 22. Result of modulus of elasticity.

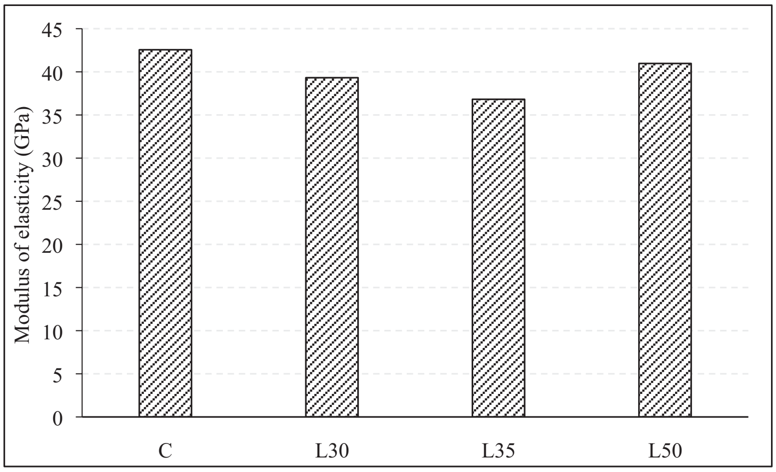
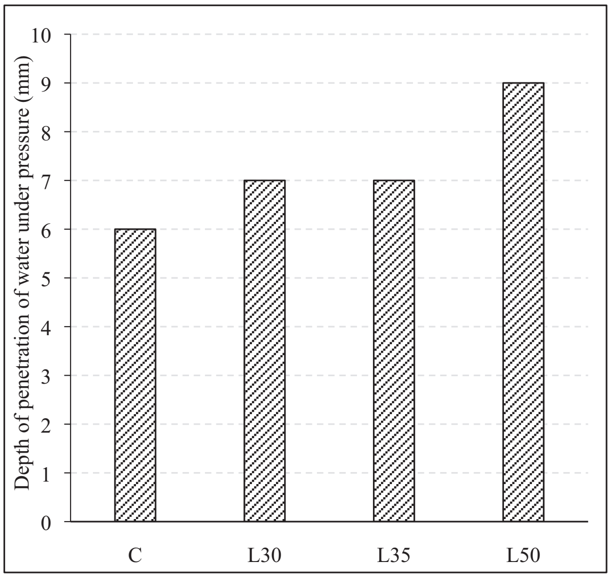


FIGURE 23. Depths of penetration of water under pressure of SCC mixtures



According to Figure 23, the control mixture was the mixture with the lowest water permeability as compared with the mixtures containing the fiber. It had a lower depth of penetration of 14% and 33% compared with other SCC mixtures. The L50 mixture showed 28% more water permeability than the L30 and L35 mixtures. The use of long fibers in the mixtures adversely affected the water permeability performance of the SCC mixtures (Figure 24).

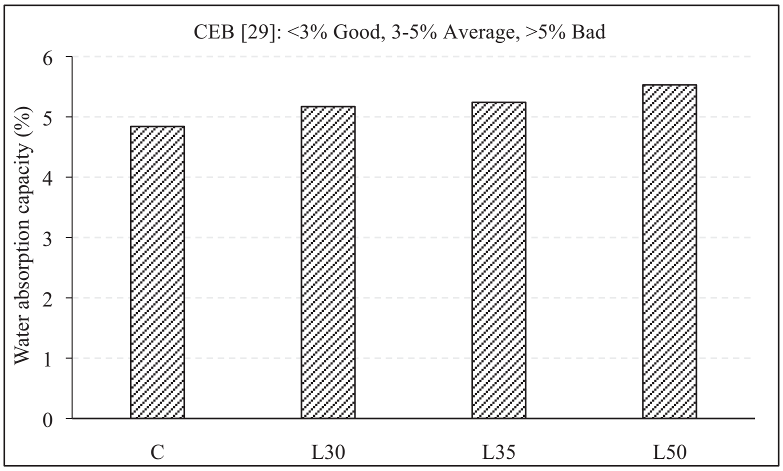
Water absorption test results

The water absorption test was carried out on 10 cm specimens produced from SCC mixtures. The results of the 28-day water absorption test are presented graphically in Figure 25.

As seen from Figure 25, the control mixture containing no fiber had the lowest water absorption rate compared to other fiber-containing mixtures. The water absorption rate of the control mixture was 0.39–0.68% lower than the other mixtures. It was found that adding fiber

FIGURE 24. Measured of the depths of penetration of water; a. Control mixture; b. L30 mixture.

FIGURE 25. Water absorption rate of specimens.



to the SCC mixtures has no significant effect on the water absorption capacity. The L30 mixture with the lowest water absorption rate in the fiber reinforced SCC showed a difference between 0.07% and 0.36% compared to the other L35 and L50 mixtures, respectively. The increase in water absorption rate was observed with the increase of fiber lengths. It is understood from Figure 24 that the water absorption rate of all SCC mixtures is more than 3%. According to the proposed classification for water absorption of concrete mixtures by CEB [29], the control mixture is medium and the fiber reinforced mixtures are classified as poor concrete.

4. CONCLUSION

The results obtained in accordance with the materials used in the SCC mixtures, the fresh state and hardened state experiments are summarized below:

- In SCC mixtures, the use of steel fibers with different aspect ratios adversely affected the time-dependent fresh state performance of the mixtures.
- All mixtures provided the slump-flow requirement recommended by EFNARC [21] criteria at 0 min. However, the time-dependent flow performance of the fiber-containing

mixtures decreased due to loss of consistency. After 60 minutes, it was observed that the SCC mixture containing steel fiber mixture with a length of 5 cm did not flow from the Abraham cone.

- Although fiber reinforced SCC mixtures flow through the V-funnel at 0 minutes, EFNARC [21] compliance criteria were not provided in these mixtures. Furthermore, as fiber length decreased in fiber-containing mixtures, V-funnel flow time increased.
- In the time-dependent L-box and U-box experiments, the measurement could not be taken for fiber reinforced SCC mixtures because there was no flow between rebars in the L and U-box, regardless of the fiber aspect ratio. It is considered that the use of fiber-containing mixtures to be inconvenient in regions containing close rebars.
- In terms of hardened state properties, it has been observed that the use of steel fiber with different aspect ratios in SCC mixtures generally gives positive results.
- In the compressive strength test, the SCC mixtures containing fiber showed leastwise higher strength than the control mixture. Mixtures containing short fiber have the highest performance in terms of compressive strength.
- In SCC mixtures, the use of steel fibers has led to an increase in the tensile splitting strength of the mixtures. In fiber-containing mixtures, a leastwise decrease in the tensile strength of the SCC mixtures was observed with the increase of the fiber length. As mentioned earlier, the use of short fiber prevents the development of micro-cracks that will occur during the loading and thus increase the tensile splitting strength.
- The mixtures containing fiber exhibited higher flexural strength and fracture energy performance than the control mixture. The SCC mixture (L50), which has a fiber length of 5 cm, exhibited a higher load carrying performance compared to other mixtures in terms of crack opening. As with the tensile splitting test, the flexural strength of the SCC mixtures increased with the decrease of the fiber length. However, the energy absorption capacity of the mixtures increased with increasing fiber length.
- Regardless of the fiber aspect ratio, it was found that the use of steel fiber in SCC mixtures had no significant effect on the modulus of elasticity of the mixtures.
- The use of steel fibers in the SCC mixtures adversely affected depth of penetration of water under pressure and water absorption capacity. This became more obvious by increasing fiber length.

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