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RESEARCH ARTICLE

Importance of pumice amount in the design of self-compacting lightweight concrete

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Abstract

Although concrete has high compressive strength values, it has a heavy unit volume and low tensile strength. In this study, the normal-weight aggregate, which takes up the most space in concrete by volume and mass, was partially replaced with pumice aggregate, and macro steel fiber (30 mm) was also added to the mixtures. This experimental work aims to investigate the effect of pumice aggregate amount on the fresh and hardened properties, as well as the flexural performance of the self-compacting lightweight concrete (SCLC). The replacement proportions of pumice aggregate with crushed sand were arranged as 45%, 50%, and 55% of the entire aggregate by weight. Three mixtures, each with 1% macro steel fiber reinforcement and without fiber, were prepared for each mixture scenario. The mix design of these six mixtures was arranged to achieve the self-compacting ability and the workability tests recommended by EFNARC (slump-flow, T50, J-ring) were taken into account. To investigate the mechanical properties (compressive, splitting tensile, and flexural strengths) and flexural toughness of the samples, the specimens were cured in water at 23±2 °C for 28 days. As a result, the unit volume weights of the specimens produced from pumice-substituted mixtures decreased with the increase in the pumice dosage, while the compressive, splitting tensile, and flexural strengths decreased. However, it has been determined that all SCLC mixtures including pumice aggregate provided workability properties in general and had enough compressive strength to be used in the production of structural bearing elements, regardless of fiber content. As a result, the optimum pumice aggregate replacement percentage with crushed sand was found to be 45% and the best flexural performance values of the specimens having macro steel fiber were observed in the ones having 45% pumice aggregate substitution.

1. Introduction

Self-compacting concrete (SCC), developed by Okamura in 1986 [1], emerged to solve the durability problems in structural concretes. Due to the advantages of SCC, its usage is becoming widespread today.

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This type of concrete is known as high-performance concrete which can flow under its weight, takes the shape of the mold, maintains its uniform structure, and is resistant to segregation [2]. In addition to cement, fine-grained mineral additives such as granulated blast furnace slag and fly ash are used in SCC mixtures. These materials increase the workability of fresh concrete and reduce the hydration heat by reducing the cement dosage. Fine mineral additives such as silica fume are also used in SCC mixtures and the amount of plasticizer can be increased to enhance the workability.

To reduce the amount of coarse aggregate and avoid the use of high dosages of cement, it is well known that SCC includes a significant percentage of very small-sized, fine aggregates. Approximately 60% of the volume of SCC consists of aggregates [3]. Research on the usability of volcanic materials, especially pumice, in the production of lightweight concrete is increasing. Pumice reduces the dead loads of the structures and has high insulation properties due to its low density so in the production of lightweight concrete, it causes an advantage.

Lightweight concrete has a lower density, higher strength/weight ratio [4], lower coefficient of thermal conductivity [5,6], good fire resistance [7], and improved durability [8] than normal-weight concrete. Besides, it reduces the dead load of structures, which reduces the cross-section of columns, beams, walls, and foundations, resulting in the reduction in earthquake loads and the risk of buildings being damaged against earthquake forces. This can be explained by the fact that the higher self-weight of the structure causes it to oscillate more during an earthquake. Since the weight of the total structure decreases in load-bearing systems constructed by the lightweight aggregate, less load is transmitted to the building foundation. This situation causes the inertial forces that occur during the earthquake to decrease as the building load decreases. It means that buildings constructed with lightweight materials reduce the destructive effects of earthquakes on structures.

Steel fiber can be added into concrete to eliminate the disadvantages of concrete such as brittleness and low tensile strength. The aim of using steel fibers is to increase the tensile and flexural strength of hardened concrete and to limit the formation of cracks in concrete [9]. Besides, it allows the concrete to have a more homogenous and isotropic structure. Therefore, concrete changes from a more collapsible material to a more malleable material. When concrete cracks, randomly oriented fibers stop the microcracking mechanism and limit the propagation of cracks, resulting in an enhancement in both strength and durability.

In this study, three different mixtures were prepared by partial replacement of crushed sand with pumice aggregate at 45%, 50%, and 55% by mass to produce self-compacting lightweight concrete. In all mixtures, Portland Cement (PC), fly ash (FA), and silica fume (SF) were used as binders and their dosages were kept constant. For each mixture proportions having a different ratio of pumice, the samples were obtained with and without macro steel fiber so in total, six mixtures were designed. Then, fresh and hardened concrete properties of these SCLC mixtures and their flexural properties were determined via laboratory tests.

2. Materials and method

2.1. Materials

2.1.1. Binders

In this study, in accordance with TS EN 197-1, CEM I 42.5 R type Portland Cement (PC) was used. Besides, as mineral additives, F-Class fly ash (FA) from İsken-Sugözü Thermal Power Plant and silica fume (SF) were added. The physical and chemical properties of PC, FA, and SF are given in Table 1.

Table 1. Properties of binders

(%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cr_2O_3	LOI	Surface area (cm^2/g)	Specific gravity (g/cm^3)
PC	19.41	5.58	3.67	58.85	2.12	3.16	0.69	0.61	-	6.07	4552	3.17
FA	63.09	21.63	6.77	1.07	-	0.10	-	2.79	-	2.68	2900	2.35
SF	91.57	0.38	0.15	0.32	4.05	0.29	1.67	-	0.32	-	220000	2.2

Table 2. The chemical properties of pumice

(%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TIO_2	MN_2O_3	LOI
Pumice	59.6	18.36	5.2	4.31	1.77	0.01	2.96	4.51	0.8	0.21	2.26

2.1.2. Aggregate

In this study, three different types of aggregate groups were utilized for the production of fiber-reinforced self-compacting lightweight concrete (F-SCLC) mixtures. These aggregate groups consist of 0-4 mm pumice 0-4 mm crushed sand as fine aggregate and 4-8 mm crushed stone as coarse aggregate. The specific gravity and water absorption percentages of these aggregates were found to be 1.2 g/cm^3 and 16.85% for pumice, 2.41 g/cm^3 and 2.18% for crushed sand, and 2.67 g/cm^3 and 0.43% for crushed stone, respectively. These three different types of aggregate were used in different proportions to determine the best mixture in terms of hardened concrete, as well as providing full filling and appropriate workability properties. The chemical properties of pumice aggregate are given in Table 2.

The particle size distribution curves of crushed sand and pumice aggregates are seen in Fig. 1. The fineness moduli of fine aggregates were calculated as 2.83 and 4.03 for crushed sand and pumice, respectively, indicating that the substituted pumice is finer than crushed sand. However, the fact that the curves are parallel to each other and both aggregate groups are fine aggregates shows that substitution is correct.

2.1.3. Fibers

In this study, 30 mm long hooked steel fibers, shown in Fig. 2, were used. The tensile strength of the macro steel fiber is 1200 MPa, the modulus of elasticity is 200 GPa, the specific gravity is 7.85 g/cm^3, and the slenderness value is 40.

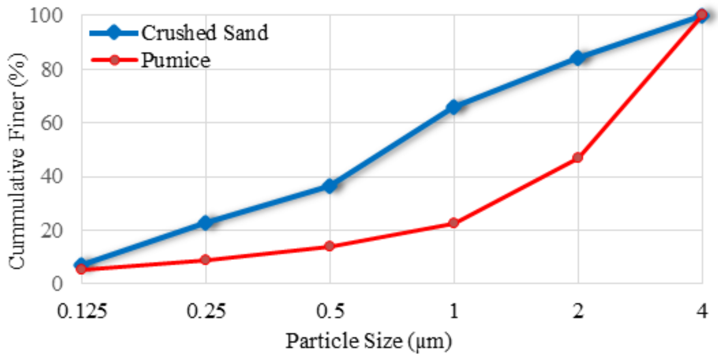


Fig. 1. Particle size distribution of fine aggregates

Fig. 2. The macro steel fiber used in this study

Table 3. Mixture proportions (kg/m^3)

Mix ID	PC	FA	SF	W/B	HP	Aggregate (0-4) mm crushed sand	Aggregate (0-4) mm pumice	Aggregate (4-8) mm crushed stone	Macro steel fiber
REF_P0.45	450	350	50	0.27	6	275	300	95	-
REF_P0.50	450	350	50	0.27	6	230	322	95	-
REF_P0.55	450	350	50	0.27	6	187	343	95	-
MAC_P0.45	450	350	50	0.27	6	265	295	90	78.5
MAC_P0.50	450	350	50	0.27	6	225	315	90	78.5
MAC_P0.55	450	350	50	0.27	6	185	335	90	78.5

2.1.4. Chemical additive

To meet the self-compacting criteria determined by EFNARC [10] in all mixtures, to reduce the negative effect of fibers on the workability properties of concrete, and to reduce the water/binder ratio, a high rate of water-reducing polycarboxylic polymer-based hyperplasticizer (HP) with a specific gravity of 1.06 was used.

2.2. Mix proportions

In this study, six mixtures having 800 kg/m^3 total binder content and a water/binder ratio of 0.27 were designed, as given in Table 3. Besides, 6 kg/m^3 of HP was used in each mixture and the amount of coarse aggregate was kept constant by weight. Within the scope of the study, three different mixtures were designed by the substitution of 45%, 50%, and 55% by weight of the total aggregate as pumice aggregate. The mixtures in which pumice was replaced with crushed sand were produced both without fiber and by adding macro steel fiber. 1% macro steel fiber by volume was used for the self-compacting fiber-reinforced lightweight concrete mixtures. In Mix ID, REF symbolizes the mixtures having no fiber, MAC is the mixtures having 1% macro steel fiber by volume and the letter 'P' refers to pumice. The numbers written next to the abbreviation of 'P' indicate the percentage of pumice content by weight of all aggregates in the mixture. For example, REF_P0.45 is the fiberless lightweight SCC having 45% pumice by weight of total aggregate.

2.3. Method

2.3.1. Preparation of mixtures

A drum-type concrete mixer with a capacity of 30 liters was used in the mixing process. All aggregates were added to the mixture as oven dry. At first, lightweight aggregate (pumice) was moistened with a sufficient amount of water and left for approximately 10 minutes to stabilize the absorption of water into the aggregate and thus, the pumice aggregate was saturated with water. Then, all aggregates and macro steel fibers in the mixture were mixed with 2/3 of the mixing water for 3 minutes. Meanwhile, the HP and the remaining 1/3 of the mixing water were mixed homogeneously in a separate container. At last, the remaining water with HP and all binders were added to the mixture and it was mixed for an additional 10 minutes to reach the homogeneity.

2.3.2. Fresh concrete tests

In this study, workability tests were carried out based on the criteria determined by EFNARC to determine the filling ability of fresh concrete, its ability to pass through obstacles, and its resistance to segregation. To attain the fresh properties of SCLC mixtures, slump-flow, T500, and J-Ring tests were performed.

Slump-flow and T500 tests were carried out to determine the flowability and viscosity of the produced SCLC mixtures (Fig. 3). In these experiments, SCLC mixtures were homogenously taken from the mixer and placed in Abram's cone without being subjected to compression, then spread on a moistened table. The time when the fresh SCLC mixture reached to 500 mm diameter circle on the table was determined. Besides, the diameter of the fully dispersed mixture was calculated by taking the average of the diameters measured from two perpendicular directions. Thus, the slump-flow diameter (Df) and T500 values for each SCC mixture were obtained.

J-Ring test was conducted to evaluate the ability of SCLC mixtures to pass between obstacles. This test consists of a J-ring placed in a 300 mm diameter circle, in addition to the apparatus used in the slump-flow test. Metal bars on the J-ring were adjusted according to the longest fiber length used [11]. In the J-Ring test, it was expected that the SCC mixture would pass through the obstacles and complete its diffusion by lifting Abram's cone. Then, the heights on the inner (H1) and immediately outer (H2) sides of the ring were measured, and the average of the inner and outer height differences was calculated as the J-ring height difference (ΔH). Besides, the time to reach 500 mm (T500J) and flow diameter (Df) were also measured (Fig. 4).

Fig. 3. Slump-flow and T500 tests

Fig. 4. J-Ring test

2.3.3. Hardened concrete tests

For the 28-day compressive strength test, three samples from each mixture were cast into molds measuring 100×100×100 mm. The test was carried out on a load-controlled press machine in accordance with ASTM C39 [12] standard (Fig. 5). Compressive strength values of the samples were calculated by dividing the maximum load by the sample cross-sectional area.

To determine the 28-day splitting tensile strength of SCC samples, the ASTM C496/C496M-17 [13] standard was used and three cylindrical samples with the dimensions of 100×200 mm were prepared. As seen in Fig. 6, the splitting tensile strength (f_{ct}) values of the samples subjected to increasing loads was calculated using Eq. 1.

$$f_{ct} = \frac{2F}{\pi I d} \tag{1}$$

where F is the maximum load (N), I is the contact line length of the sample to the loading part (mm) and d is the cross-sectional size of the sample (mm).

To determine the flexural strength of all SCLC samples, two prismatic samples with the dimensions of 100×75×400 mm were produced for each mixture and a four-point bending test was applied to these samples according to ASTM C1609 [14]. The experimental setup was given in Fig. 7. The net span length was 300 mm and the applied singular loads were arranged as 100 mm far from the supports. The average deflection of the beam was calculated through two reciprocal displacement meters (LVDT) placed vertically in the middle of the span. The flexural strengths (f_{cf}) of the mixtures were calculated using Eq. 2.

$$f_{cf} = \frac{M}{I} y = \frac{\left(\frac{PL}{6}\right)}{\left(\frac{bh^3}{12}\right)} \frac{h}{2} = \frac{PL}{bh^2} \tag{2}$$

where M is the maximum moment at midspan (N.mm), I is the moment of inertia (mm^4), y is the neutral axis depth (mm), P is the maximum load (N), L is the displacement between two supports (mm), b and h are the section dimensions of the sample (mm).

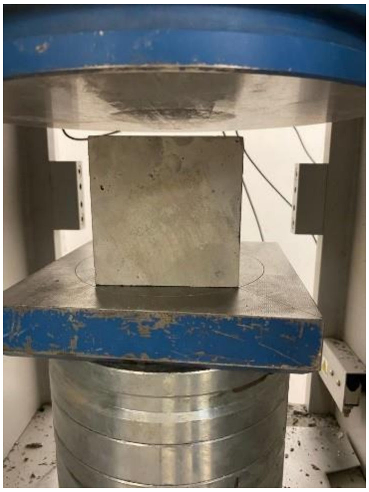


Fig. 5. Compressive strength test

Fig. 6. Splitting tensile test

Fig. 7. Four-point bending test

2.3.4. Flexural performance

Load-deflection curves drawn as a result of the four-point bending test provide information about the bending behavior of F-SCLC. In Fig. 8, the deflection hardening and deflection softening behavior of fiber-reinforced concrete are determined based on the LOP point where the first crack occurs and the fracture modulus defined as the MOR point. Deflection-hardening behavior occurs when the P_{MOR} corresponding to the MOR point is greater than the P_{LOP} value corresponding to the LOP point, and if it is smaller, deflection-softening behavior occurs. $\delta_{LOP.}$

In this study, the energy absorption capacity (toughness) of the samples was determined by calculating the area under the load-deflection curve. For the F-SCLC samples subjected to four-point bending, the loads corresponding to deflections of L/600 (0.5 mm) and L/150 (2 mm) were determined and the flexural strengths at these points were calculated using Eq 2. Besides, for all F-SCLC samples, the toughness values up to MOR, L/600, and L/150 deflection points were calculated based on ASTM C1609 and JSCE, respectively, and the flexural toughness factor (FTF) was computed using Eq. 3.

$$FTF = \frac{T_{(L/150)}L}{\frac{L}{150}bh^2} \tag{3}$$

where $T_{(L/150)}$ is the area under the load-deflection curve up to 2 mm deflection (N.mm), L is the distance between two supports (mm), b and h are the section dimensions of the sample (mm).

The deflection capacity is an important parameter for fiber-reinforced concrete so ductility index (D) values were also calculated for all F-SCLC samples using Eq. 4.

$$D = \frac{\delta_{MOR}}{\delta_{LOP}} \tag{4}$$

where δ_{MOR} is the deflection value at MOR (mm) and δ_{LOP} is the deflection value at LOP (mm).

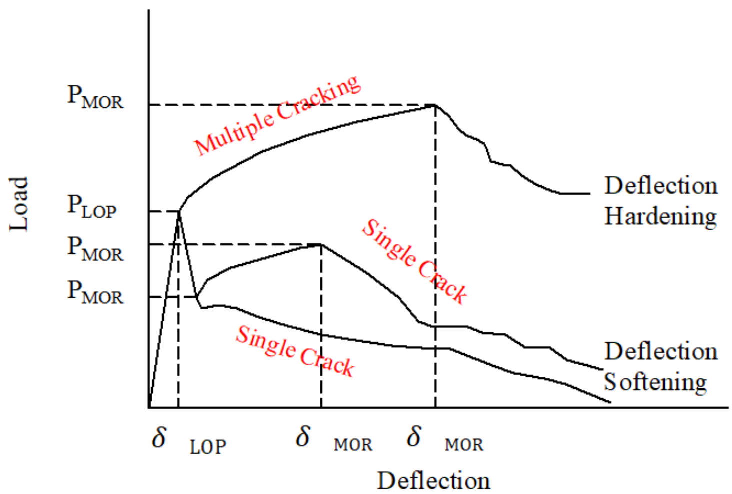


Fig. 8. Typical load-deflection curve fiber reinforced concrete under bending [15]

3. Experimental results and discussion

3.1. Fresh concrete unit weight

The weighing process was performed to determine the fresh concrete unit weights of MAC_P0.45 and MAC_P0.50 mixtures. As can be seen in Fig. 9, the unit weights of all fresh SCLC mixtures with/without fiber were found to be in the range of 1875-1959 kg/m^3 and the fresh mixtures with no fiber had lower unit weight than the F-SCLC mixtures. The reason for this fact is the replacement of aggregate with macro steel fibers, which are included at a rate of 1% by volume in all F-SCLC mixtures. Because the specific gravity of the macro steel fiber (7.85 g/cm^3) is higher than the specific gravity values of the aggregates (2.67 g/cm^3 for crushed stone, 2.41 g/cm^3 for crushed sand, and 1.2 g/cm^3 for pumice). Besides, as the amount of pumice in the mixtures increases, the unit weight of fresh SCLC decreases. This can be attributed to the fact that the specific gravity value of crushed sand is greater than the specific gravity of pumice. Similar results were also obtained by different researchers [16-18] in studies where pumice was replaced with fine aggregate.

3.2. Fresh properties of SCLC mixtures

The results regarding the fresh concrete properties of SCLC mixtures with and without macro steel fiber are given in Table 4, Fig. 10, and Fig. 11. The workability properties of all SCLC mixtures were approximately similar as intended, namely, slump-flow diameter values varied between 690±25 mm, T500 values were between 5.4±0.9 sec, and J-ring height difference values were in the range of 1.25 and 8.25 mm. The results indicated that all workability values, except for T500 values, meet the limit values recommended by the EFNARC, which is valid for SCC with no fiber, and the slump-flow diameter values of all mixtures were in SF 2 class (660-750 mm), as given in Fig. 10 and Fig. 11.

Observing Table 4, as the pumice dosage increased, a decrease in slump-flow diameter values and an increase in T_{500} values were observed, while the J-Ring height difference values increased for all SCLC mixtures. It was found that substituting 55% pumice as fine aggregate into the mixture caused a greater reduction of the fresh properties of SCLC mixtures with and without fiber. As a result of the visual inspection of pumice, this may be due to its roughness and porous surface structure, resulting in having a high water absorption percentage concerning other aggregates used in this study. Since its porous structure is quite high, it can absorb up to 55% of water [19]. In the designed mixtures, the pumice content of the mixtures was increased by keeping the amount of mixing water constant, resulting in a reduction in the workability of the mixtures. Karthika et al. [20] also prepared the lightweight concrete mixtures by replacing the coarse aggregate with pumice aggregate by 50%, 80%, and 100% and found that the slump values decreased by 69.2%, 75.4%, and 76.9% compared to lightweight concrete without pumice aggregate, respectively.

Considering Fig. 12, it was obtained that as the fresh unit weight of SCLC with and without fiber increased, the flowability of the mixtures also increased. This is an expected result since the placing and flowing features of self-compacting concrete are provided by its weight. Increasing the unit weight of the mixture will increase its spreading capacity at the fresh state. The linear regression analysis performed for slump flow diameter and unit weight of fresh SCLC showed that the prediction ratio of unit weight via slump-flow diameter was so high for both SCLC with and without macro steel fiber due to having R-squared values of 0.96 and 0.87, respectively. However, it can be concluded that the formulation to correlate the unit weight of fresh macro steel fiber reinforced SCLC with slump-flow diameter made more sense due to having a higher correlation of coefficient value.

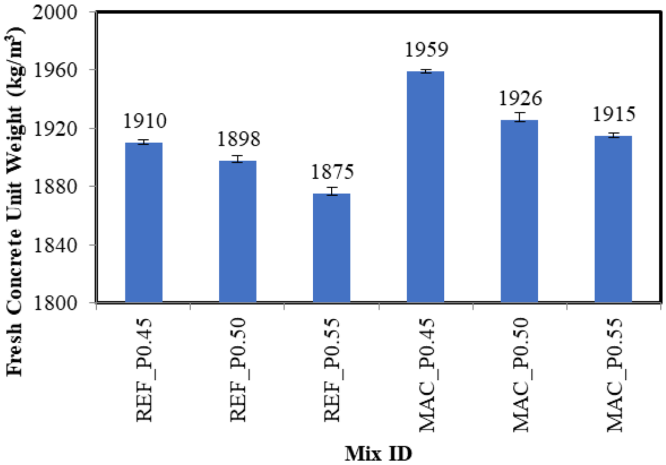


Fig. 9. Fresh concrete unit weights of the SCLC mixtures

Table 4. Workability test results of the mixtures

Mix ID	Slump-flow		J-Ring		
	Df (mm)	T500 (sec)	Dj (mm)	T500J (sn)	ΔH (mm)
REF_P0.45	715	4.5	700	5.2	1.25
REF_P0.50	695	5.5	685	6.3	2
REF_P0.55	685	6	665	7.2	4.50
MAC_P0.45	700	5.4	690	7.4	2.25
MAC_P0.50	680	5.7	665	7.8	4.50
MAC_P0.55	665	6.3	650	8.3	8.25
Workability Limits based on EFNARC	650 – 800	2 –5	-	-	0 –10

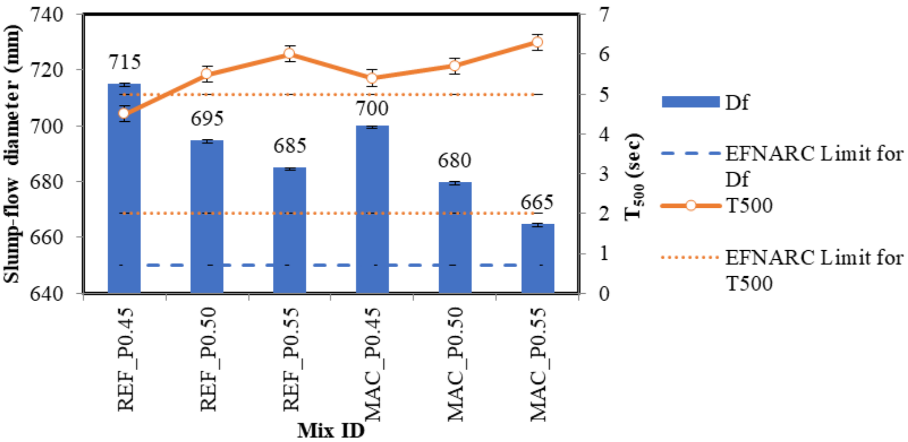


Fig. 10. Slump flow diameter and T500 values of SCLC mixtures

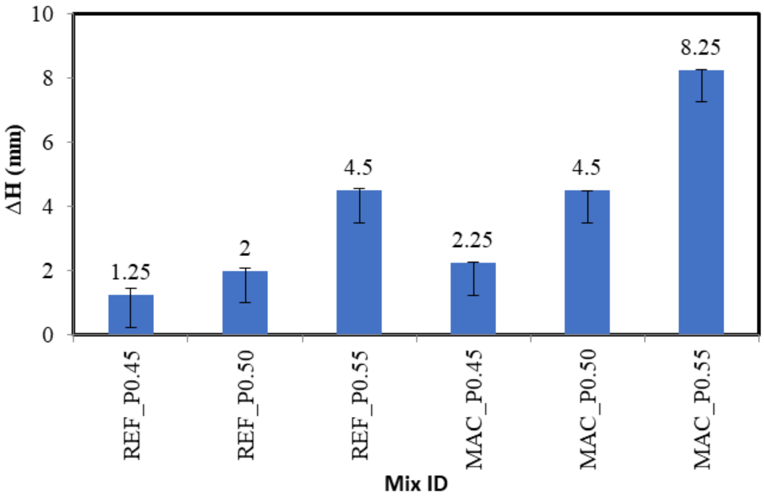


Fig. 11. The height difference values of SCLC mixtures in J-Ring test

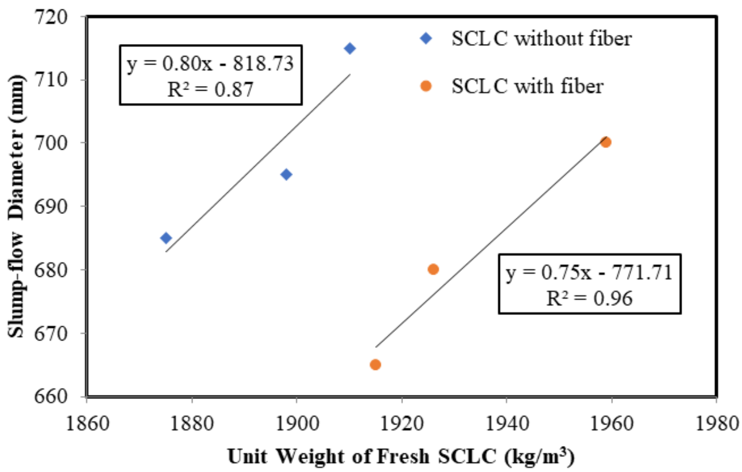


Fig. 12. Effect of fresh SCLC unit weight on slump-flow diameter

Visual Stability Index (VSI) values specified in ASTM C1611 [21] were used to evaluate the stability of SCLC mixtures. Accordingly, no segregation or bleeding was observed in the mixtures and the VSI values of all SCLC mixtures were determined as 0. Therefore, it was concluded that all mixtures were resistant to segregation.

3.3. Hardened properties of SCLC mixtures

The results regarding the hardened concrete properties of SCLC mixtures with and without macro steel fiber are given in Table 5.

3.3.1. Compressive strength

The compressive strength results of the samples are given in Table 5 and Fig.13, and it is seen that the compressive strength values of all SCLC mixtures with and without macro steel fiber varied between 37.96 MPa and 44.43 MPa. Therefore, this study revealed that all produced SCLCS mixtures can be used in the production of structural load-bearing members. It was observed that the compressive strength of macro steel fiber-reinforced SCLC samples was less than the ones produced with no fiber. This can be attributed to the fact that steel fibers reduce the flowability of concrete mixtures, resulting in not being distributed homogeneously in the mixture, and thus, the amount of voids increases due to the poor settlement of the mixture compared to concrete without fiber. In the studies about SCC available in the literature [22–25], it was concluded that the use of single macro steel fiber reduces compressive strength.

As can be seen in Fig. 13, considering SCLC mixtures with and without macro steel fiber, it was observed that the increase in pumice dosage caused a reduction in compressive strength. Namely, the highest compressive strength value was obtained from the SCLC mixtures containing 45% pumice instead of crushed sand regardless of the fiber content. In addition to this, it was determined that substituting pumice aggregate at 50% of the total aggregate weight instead of crushed sand in F-SCLC samples caused a 4.3% decrease in the compressive strength of the F-SCLC samples containing 45% of the total aggregate weight. This may be attributed to having higher porosity of pumice aggregate than other aggregates used in this study. In the study of Kurt et al [26], the effect of fly ash, water/binder ratio, and the replacement of pumice with natural aggregate on SCLC was examined and they also found that the increase in replacement percentage of pumice aggregate caused a significant decrease in compressive strength. Besides, Floyd et al. [27] and Grabois et al. [28] proved that lightweight aggregates are generally weaker than mortar although the lightweight aggregates used by these researchers were different.

Table 5. 28-day hardened properties of SCLC mixtures

Mix ID	Compressive Strength (MPa)	Splitting Tensile (MPa)	Flexural Strength (MPa)
REF_P0.45	44.43	4.37	6.65
REF_P0.50	41.32	4.05	6.27
REF_P0.55	38.83	3.72	6.02
MAC_P0.45	42.63	5.53	10.31
MAC_P0.50	40.8	4.56	9.62
MAC_P0.55	37.96	4.13	9.39

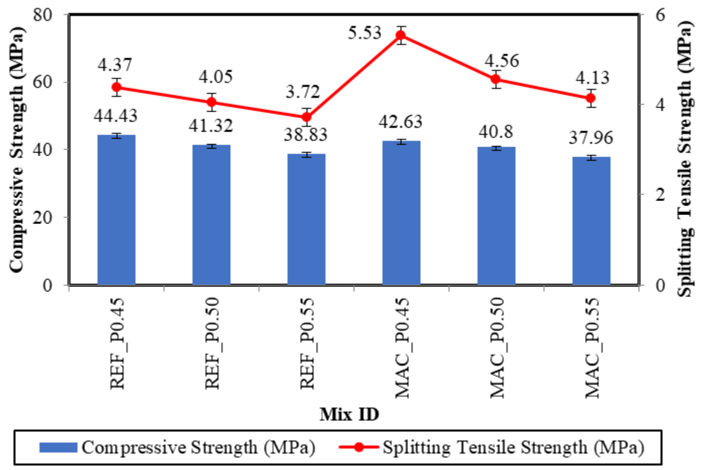


Fig. 13. The compressive and splitting tensile strength values of SCLC mixtures

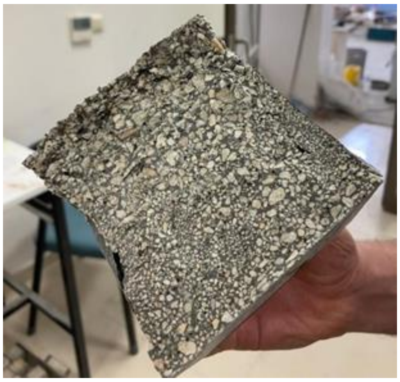


Fig. 14. The cross-section of the cube sample subjected to compressive load

a) SCLC sample with no fiber b) SCLC sample with macro steel fiber

Fig. 15. The pictures of cylindrical samples after splitting tensile strength test

Since the weakest part of the concrete sample is the interface between the hardened cement paste and the aggregate, the fracture axes of concrete samples produced with normal aggregate are generally between the aggregate and hardened cement paste. However, in this study, as seen in the produced SCLC samples (Fig. 14), fracture axes were seen mostly in pumice aggregates. To reduce the fracture cross-section of the pumice aggregate and to transfer the load to crushed stone and crushed sand with higher compressive strength, pumice aggregate was replaced with fine aggregate. Thus, it is aimed to obtain higher compressive strength. As also proven in the other studies [29,30], when finely grounded, pumice aggregate acts as a good filler which is non-hazardous and non-crystalline and also, gives low density and strain resistance.

3.3.2. Splitting tensile strength

The splitting tensile strength results of the mixtures are given in Table 5 and Fig. 13, and it is seen that the splitting tensile strength values of the samples varied between 3.72 MPa and 5.53 MPa. Due to the crack bridging and delaying properties of fibers, the splitting tensile strengths of samples obtained from all F-SCLC mixtures were found to be higher than those of samples obtained from SCLC mixtures with no fiber. As seen in Fig. 15(a-b), the F-SCLC samples behaved more ductile under load in the splitting tensile strength.

Considering Fig. 13, the splitting tensile strength values of the samples decreased as the pumice content increased for all SCLC mixtures with and without macro steel fiber. It can be said that the use of more than 45% pumice aggregate instead of fine aggregate in SCLC mixtures has a significant negative effect on splitting tensile strength. Namely, the substituting 50% of the total aggregate weight of pumice aggregate instead of crushed sand in F-SCLC mixtures caused a 17.5% decrease in the splitting tensile strength of the

SCLC mixture containing 45% of the total aggregate weight of pumice aggregate. The reduction in splitting tensile strength can be explained by the poor tensile strength of pumice aggregate. In other words, the tensile strength of SCLC was controlled by the tensile strength of the pumice aggregate particles. Observing Fig. 15, the failure of SCLC samples occurred in pumice aggregates due to the strong bond strength between the rough surface aggregate and cement matrix. The similar results were found by the other researchers [18,31].

3.3.3. Flexural strength

The flexural tensile strength results of the mixtures are given in Table 5 and Fig. 16, and it is seen that the flexural tensile strength values of the samples varied between 6.02 MPa and 10.31 MPa. As expected, due to the crack bridging and delaying properties of fibers, the flexural strength values of all F-SCLC samples were higher than those of the SCLC samples with no fiber. This finding can also be explained by the reduction of the pumice aggregate fracture caused by the bridging effect of macro steel fibers before cracking. Steel fibers can withstand crack expansion and elongation even after flexural cracking has occurred [32].

As seen in Fig. 16, the increase in the pumice content in SCLC mixtures caused a reduction in the flexural strength of all SCLC samples with and without macro steel fiber. However, substituting pumice aggregate at 50% and 55% of the total aggregate weight instead of crushed sand in F-SCLC mixtures resulted in a 6.70 % and 8.92% decrease in flexural strength compared to F-SCLC samples with 45% pumice aggregate, respectively. Because a higher flow ability results in a homogenous distribution of fibers into concrete in the tensile zone of the section where the fracture occurs [33,34]. However, the low reduction in flexural strength values in F-SCLC would imply that the change in the amount of pumice aggregate in the samples had little to no significant effect on the flexural tensile strength of SCLC samples with macro steel fiber. The findings are consistent with the similar studies available in the literature [18,31,35].

3.3.4. Flexural performance

Table 6 presents the findings obtained from the load-deflection curves drawn as a result of the four-point bending test of samples produced from macro steel fiber-reinforced SCLC mixtures. Accordingly, for each mixture, δ_{LOP}, P_{LOP}, δ_{MOR}, P_{MOR}, flexural strength at the 0.5 mm deflection point ($F_{L/600}$), flexural strength at the 2 mm deflection point ($F_{L/150}$), toughness up to the MOR point (T_{MOR}), toughness up to the 0.5 mm deflection ($T_{L/600}$), toughness up to the 2 mm deflection ($T_{L/150}$), FTF and D values were calculated.

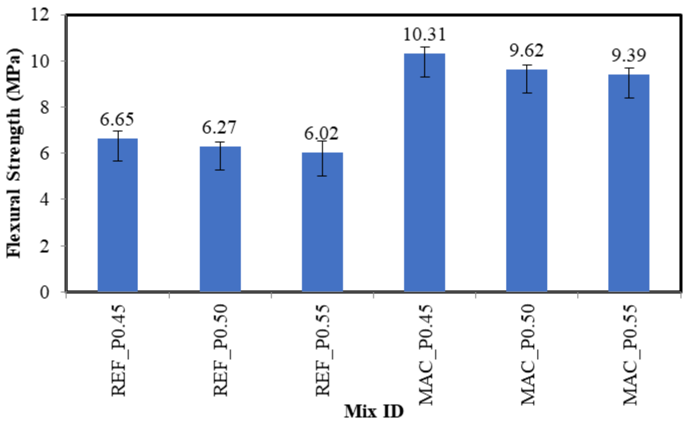


Fig. 16. The flexural strength values of SCLC mixtures

The load-deflection curves of macro steel fiber reinforced SCLC samples showed that the substitution of 45% crushed sand with pumice aggregate caused more ductile behavior and a significant impact on the post-peak response (see Fig. 17). For more than 45% replacement of pumice aggregates, the load carrying capacity was decreased more obviously after peak load. This could be due to the insufficient bridging effect of macro steel fiber in the matrix. Because the weakest component in the matrix is the transition zone between cement and pumice and therefore, the increase in the amount of pumice aggregate particles causes a weaker interfacial zone resulting in low flexural strength [36]. In addition to this, the weak and brittle nature of pumice aggregate may also prevent fiber from bridging, leading to being stripped from the matrix.

Table 6. The results obtained from the load-deflection curves of F-SCLC samples

Mix ID	δ_{LOP} (mm)	P_{LOP} (mm)	δ_{MOR} (mm)	P_{MOR} (kN)	T_{MOR} (N.m)	ASTM C1609				JSCE	D (mm/mm)
						FL/600 (MPa)	FL/150 (MPa)	TL/600 (N.m)	TL/150 (N.m)	FTF (MPa)	
MAC_P0.45	0.023	15.77	0.104	19.34	5.39	9.58	5.75	8.22	30.5	8.13	4.52
MAC_P0.50	0.018	12.76	0.078	18.04	2.42	7.76	3.91	7.35	23.68	6.31	4.33
MAC_P0.55	0.015	5.44	0.065	17.61	1.27	7.27	3.37	7.86	21.96	5.85	4.21

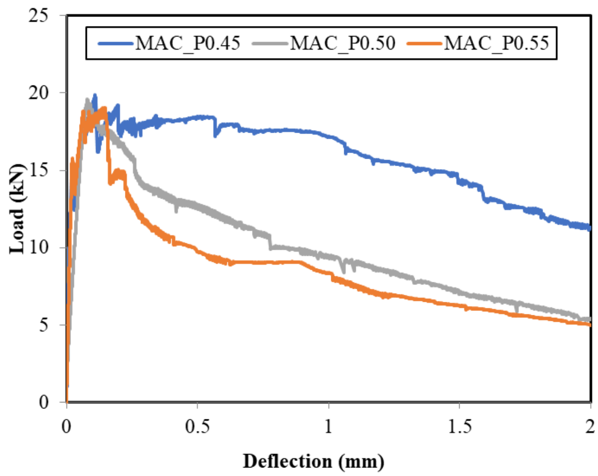


Fig. 17. The load-deflection curves of SCLC samples with macro steel fiber

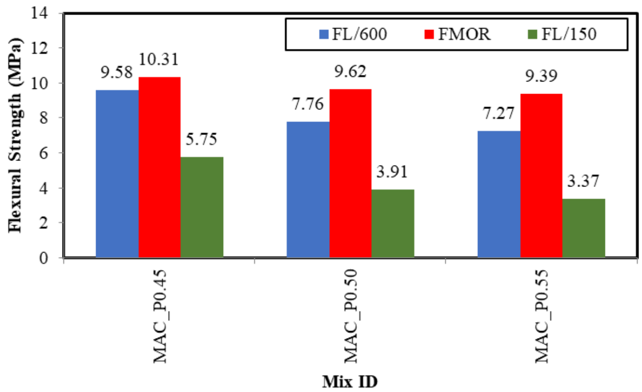


Fig. 18. The flexural performance of SCLC samples with macro steel fiber

The flexural strength values at different deflection points for macro steel fiber reinforced SCLC samples are shown in Fig. 18. It provides information about the flexural performance of the samples at certain points after cracking and maximum load. As the amount of pumice aggregate in the mixture increased, the flexural strength value at the MOR, L/600, and L/150 deflection points decreased. Such that, the highest and lowest flexural strength values for both L/600 and L/150 deflection points were obtained in the MAC_P0.45 and MAC_P0.55 samples, respectively. Besides, it was seen that the flexural strength values of MAC_P0.50 and MAC_P0.55 samples at L/600 and L/150 deflection points were so close to each other, while the obtained values for the MAC_P0.45 sample were significantly higher than those of the other samples.

3.3.4.1. Toughness

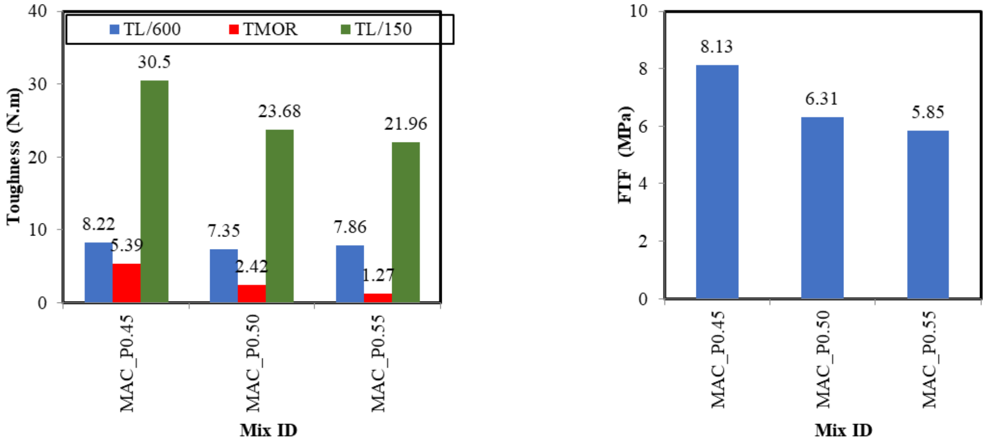
Toughness values up to different deflection points based on ASTM C1609 for macro steel fiber reinforced SCLC samples are shown in Fig. 19(a). It was observed that among all toughness values for different deflection points, the highest and lowest values were obtained for MAC_P0.45 and MAC_P0.55 samples, respectively. Besides, the toughness values of MAC_P0.50 and MAC_0.55 samples were so close to each other at MOR, L/600, and L/150 deflection points. It can be emphasized that the energy absorption capacity of MAC_P0.45 samples was higher than those of the other two samples. This may be attributed to the achievement of better fiber bridging capacity caused by 45% pumice aggregate compared to higher substitution rates. It can be more effective after the first cracks have formed and consequently, after the first peak load has been exceeded [37–39]. In the study of Khaloo et al. [40], it was also proven that the flexural toughness of SCC specimens having high strength was more than those of the other ones.

In Fig. 19(b), the FTF for macro steel fiber reinforced SCLC samples was given according to JSCE. The calculated flexural toughness results based on ASTM C1609 and JSCE showed a similar trend for the SCLC samples. In some studies in the literature [41,42] for samples produced from normal-weight concrete, such calculations based on different standards also gave similar results.

The deflection capacity is an important criterion in evaluating ductility so deflection values at LOP and MOR were obtained to determine the ductility of the mixtures. The deflection at LOP (δ_{LOP}) is affected by the first cracking behavior and it is related to the matrix strength rather than the bridging mechanism of fibers [43]. Observing Table 4, the highest δ_{LOP} value was obtained from the MAC_P0.45 mixture. Besides, the highest deflection capacity at MOR was also obtained for the sample having 45% pumice aggregate replacement and δ_{MOR} was higher than those of the other mixtures because of its higher deflection-hardening behavior. Therefore, the highest ductility index value was obtained from the MAC_P0.45 mixture with 4.52, and the MAC_P0.55 mixture had the lowest ductility index value with 4.21, as given in Fig. 20. Besides, it was observed that the ductility values calculated for MAC_P0.50 and MAC_P0.55 were close to each other.

3.3.4.2. Crack patterns

Crack models are very important in understanding the flexural behavior of fiber-reinforced SCLC samples. Observing Fig. 21, the SCLC samples without fiber cracked brittle, while the crack branching was observed in all SCLC samples reinforced with macro steel fiber. The formation of multiple cracks after the first crack in fiber-reinforced SCLC samples indicates deflection hardening behavior. The crack branching that occurred after the four-point bending test proves the lowest energy absorption capacity of MAC_P0.55 due to having less amount of multiple cracks in the mid-span region of the sample. The multiple cracking behavior of MAC_P0.45 and MAC_P0.55 were almost similar. Caggiano et al. [44] also found that an increase in the volume fraction of macro steel fiber from 0.2 to 0.75 resulted in a tougher behavior, resulting in strain-hardening behavior crack response. Besides, in the study of Ghanem and Obeid [45], the use of 65/60 macro steel fiber provided better bond characteristics and energy absorption capacity. The similar results were also found by other researchers [23,46].



a) Based on ASTM C1609 b) Based on JSCE

Fig. 19. The flexural performance of SCLC samples with macro steel fiber

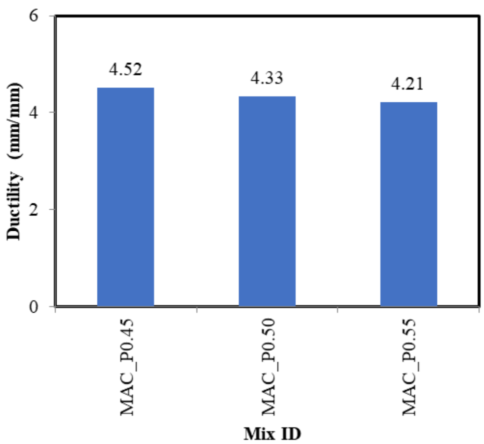


Fig. 20. The flexural performance of SCLC samples with macro steel fiber

Fig. 21. The crack patterns of fiber-reinforced SCLC samples after the bending test

4. Conclusions

In this study, SCLC mixtures with and without macro steel fiber were designed and their fresh and hardened properties were investigated. Based on the findings from the performed tests, the following conclusions can be drawn:

- The inclusion of macro steel fiber into SCLC increased the fresh concrete unit volume weight, while the increase in pumice aggregate content decreased the fresh concrete unit volume weight of both SCLC with and without macro steel fiber.
- The increase in the amount of pumice aggregate reduced the workability of SCLC with and without macro steel fiber by decreasing the slump-flow diameter values and increasing the T500 time and J-ring height difference values. Besides, it has been observed that all SCLC mixtures with and without macro steel fiber meet the workability requirements in terms of self-compacting except for T500 values.
- Considering the compressive strength values of the designed SCLC mixtures with and without macro steel fiber, it is concluded that they are convenient for the production of structural load-bearing elements. Besides, the increase in pumice aggregate content as a replacement for crushed sand and the addition of 1% macro steel fiber into mixtures caused a reduction in compressive strength values.
- The substitution of more than 45% pumice aggregate with crushed sand decreased the splitting tensile and flexural strength values of all SCLC with and without macro steel fiber. Besides, the use of macro steel fiber enhanced both the splitting tensile and flexural strength values of SCLC samples.
- All macro steel fiber reinforced SCLC samples exhibited deflection-hardening behavior in the load-deflection curves but it was more prominent in the MAC_P0.45 sample. The deflection and energy absorption capacity of the MAC_P0.45 sample was the highest among all F-SCLC mixtures.
- According to ASTM C1609, the toughness values of MAC_P0.50 and MAC_P0.55 for three different points were found to be so close, while these values were the highest for MAC_P0.45. The same trend was also obtained from the JSCE.
- The ductility index values of MAC_P0.50 and MAC_P0.55 were close to each other, while the ductility of MAC_P0.45 was the highest.

In terms of fresh and hardened properties of SCLC mixtures, the optimum pumice aggregate replacement percentage with crushed sand was found to be 45%. However, it has been determined that all SCLC mixtures with pumice aggregate provide workability properties in general and have enough compressive strength to be used in the production of structural bearing elements, regardless of fiber content. Besides, the addition of macro steel fiber into SCLC mixtures has a positive impact on splitting tensile strength and flexural performance. Thus, it is thought that the structures to be produced from SCLC having pumice aggregate as a partial replacement can reduce the earthquake effects on the structure by reducing the weight of the structure with ductile behavior.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

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