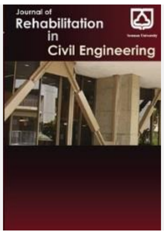
Journal of Rehabilitation in Civil Engineering 13-4 (2025) 1-24



Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Estimating the Increase in the Mechanical Characteristics of Self-Compacting Lightweight Concrete Incorporating Pumice and Steel Fibers

Masoud Dadkhah [1,*]; Reza Rahgozar [2]; Ehsan Barahouei Pasandi [3]; Peyman Rahgozar [4]

1. Ph.D. Candidate, Department of Civil Engineering, Shahid Bahonar University, Kerman, Iran
2. Professor, Faculty of Civil Engineering, Shahid Bahonar University, Kerman, Iran
3. M.Sc., Department of Civil Engineering, Islamic Azad University, Zahedan Branch, Iran
4. Ph.D., Clark Construction Group, California, Los Angeles, United States

* Corresponding author: *m.dadkhah@eng.uk.ac.ir*

ARTICLE INFO

Article history:
Received: 10 July 2024
Revised: 25 December 2024
Accepted: 15 January 2025

Keywords:
Mechanical properties;
Steel fiber;
Pumice;
Self-compacting concrete;
Lightweight concrete.

ABSTRACT

The incorporation of lightweight concrete significantly reduces the weight of structures. However, achieving proper density and ensuring the ease of concrete placement in structures with dense reinforcement has driven the development of self-compacting lightweight concrete (SCLC). Despite its advantages, SCLC exhibits brittleness similar to that of normal concrete. To address this limitation, steel fibers (SFs) can be integrated into SCLC to enhance its properties. In this study, SCLC was first produced using pumice aggregate. Fresh concrete properties were evaluated through Slump Flow, T_{50}, V-Funnel, and L-Box tests, leading to the selection of an optimal mix design. Subsequently, SFs were added to the SCLC at proportions of 0.125%, 0.25%, and 0.5% by volume. The effects of SFs on the mechanical properties of SCLC were assessed through hardened concrete tests, including compressive strength, splitting tensile strength, and flexural strength tests. The results demonstrated that adding SFs to SCLC containing pumice aggregate improves mechanical strength, with the enhancement continuing up to 0.5% fiber content by volume. A predictive method for estimating the strength development of hardened samples at varying SF percentages was proposed. According to the findings, the addition of 0.25%, 0.125%, and 0.25% SFs achieved the most significant enhancements in compressive, tensile, and flexural strengths, respectively. Furthermore, incorporating pumice and SFs in concrete contributes to reduced environmental impact, improved durability, and cost reduction, promoting sustainable and efficient construction practices. Finally, three equations were developed to estimate the 28-day compressive, tensile, and flexural strengths based on SF content. Additionally, two equations were provided to predict tensile strength and modulus of rupture from the 28-day compressive strength.

E-ISSN: 2345-4423

How to cite this article:
Dadkhah, M., Rahgozar, R., Barahouei Pasandi, E. and Rahgozar, P. (2025). Estimating the Increase in the Mechanical Characteristics of Self-Compacting Lightweight Concrete Incorporating Pumice and Steel Fibers. Journal of Rehabilitation in Civil Engineering, 13(4), 1-24. https://doi.org/10.22075/jrce.2025.34222.2109

1. Introduction

A significant challenge in the design and implementation of reinforced concrete structures, particularly tall buildings and bridges, is their substantial weight. Furthermore, due to the direct impact of a structure's weight on the absorption of dynamic vibrations, it is essential to focus on reducing the weight of these structures. Concrete, being a widely used material, can help achieve an optimal structure weight by making it lighter. The advantages of lightweight concrete include a reduction in the overall weight of structures, smaller dimensions of structural sections, lower transportation costs, and a decrease in earthquake forces acting on structures. One method for producing lightweight concrete is the use of lightweight materials and aggregates such as pumice, perlite, and lightweight expanded clay aggregate (LECA). Over the years, research has led to the development of self-compacting concrete (SCC), followed by self-compacting lightweight concrete (SCLC). SCC, with its high workability and lack of segregation, can fill mold spaces and encapsulate reinforcements without the need for mechanical compaction after being poured into the desired location [1–9]. Beigi et al. conducted comprehensive research to investigate the behavioral, mechanical, and durability characteristics of SCC incorporating fibers and silica fume. They performed tests on fresh concrete (such as Slump and T_{50} tests) and hardened concrete (including compressive, flexural, and tensile strength). To assess the durability of concrete, tests for water absorption and chloride ion penetration were carried out on samples containing 2% to 6% nano-silica, along with glass, plastic, and steel fibers (SFs), maintaining a fixed superplasticizer ratio. The results showed that both the flexural and tensile strengths improved with increasing fiber content. Furthermore, the compressive strength and durability of all samples exhibited favorable enhancement. The addition of nano-silica increased the paste viscosity but decreased the durability of the samples [10]. Vakhshouri et al. demonstrated that SCC flows under the influence of its own weight, and the use of light aggregates, in contrast to natural aggregates, reduces the internal energy required for movement in SCC [11]. Sivakumar et al. examined the effects of metakaolin (MK) and glass fibers (GFs) on SCC. They found that workability decreased as fiber content increased. Moreover, while glass fibers did not significantly enhance the compressive strength, they did increase tensile and flexural strength. Durability tests indicated that even small amounts of glass fibers made the samples more resistant to chloride ions and water absorption. Additionally, the simultaneous use of MK and GF significantly improved both the mechanical properties and durability of SCC [12]. Samimi et al. demonstrated that pumice and zeolite significantly enhance resistance to chloride penetration under critical moisture conditions and improve chemical resistance to acid attacks. They found that samples containing 15% pumice and 10% zeolite were optimal [13,14]. Hedayatinia et al. conducted a life cycle assessment of SCC mixtures, examining their compliance with Eurocode requirements and rheological properties. They also found that emissions of air pollutants decreased by 3.6% to 29.9% [15]. Ghasemi et al. investigated the fresh and hardened properties of SCC containing zeolite and pumice. Their results indicated that samples with zeolite had a shorter setting time compared to those with pumice [16]. Azad et al. studied the influence of zeolite and pumice on the physical properties of porous concrete and their role in improving its capacity to mitigate urban and industrial runoff pollution. They found that pumice showed superior physical performance, while zeolite improved the environmental function of green porous concrete for wastewater quality enhancement [17]. Ghafor et al. derived equations governing the compressive, flexural, and tensile strengths for samples containing silica fume [18]. Al-Farttoosi et al. explored the mechanical properties of hardened SCLC containing pumice [19].

The SCLC mixture is much more fluid than conventional concrete. The inclusion of light aggregates in SCLC reduces the kinetic energy of concrete, causing the mixture to flow more slowly than conventional concrete, particularly in sections with heavy reinforcement. However, this same property allows SCLC to be more evenly distributed throughout structural elements and provide enhanced density [20]. To achieve optimal SCLC mixtures, precise proportions of cement, aggregates, additives, and water must be adhered to, as outlined in the EFNARC guidelines [21–26]. The use of fillers in SCLC mixtures helps maintain the viscosity and flowability of the concrete. Excessive cement content in concrete increases both cost and heat generation during mixing, an issue that can be alleviated by replacing part of the cement with fillers. Among the fillers commonly used in SCLC are limestone powder, silica fume, and others [27]. As a brittle material, hardened concrete possesses low tensile strength. One method to enhance uniformity, reduce brittleness, and increase ductility is the incorporation of fibers. Fibers, typically made of steel, glass, or polymer, are uniformly dispersed throughout the mixture, a key characteristic of fiber-reinforced concrete. Fibers can also be made from natural materials. Studies have shown that SFs in concrete can significantly alter its behavior by reducing cracking and increasing durability. Fiber-reinforced concrete has high energy absorption capacity and is less prone to failure under impact loads [28–36]. Research has demonstrated that incorporating SFs into pumice concrete improves compressive strength, with greater improvements observed as the fiber content increases. Notable enhancements in both compressive and flexural strength were observed compared to conventional concrete mixtures [37].

Incorporating pumice as a partial replacement material in concrete offers significant environmental benefits, as it reduces the demand for natural aggregates and the carbon footprint associated with cement production. Furthermore, using SFs enhances concrete's durability and mechanical properties, potentially lowering maintenance costs and increasing the lifespan of structures, thus contributing to economic sustainability. These combined advantages underline the practical significance of this study in advancing sustainable construction practices. This study investigates the effect of SFs on the mechanical performance of SCLC incorporating pumice aggregates. The goal is to develop optimal mix designs and predictive models for compressive, tensile, and flexural strengths. A specific SCLC mix using pumice aggregates was selected, and the impact of SFs on the mechanical behavior of steel fiber-reinforced SCLC (SF-SCLC) was analyzed, with a focus on compressive, tensile, and flexural strengths. A total of 108 SF-SCLC specimens were produced with fiber contents of 0.125%, 0.25%, and 0.5%. Both fresh and hardened concrete properties were tested. Fresh concrete tests included V-Funnel, L-Box, Slump, and T_{50} tests. Hardened concrete properties were evaluated for compressive strength based on BS 1881 Part 116, tensile strength according to ASTM C496, and flexural strength following ASTM C78. The specimens were prepared using Sistan Type II Portland cement, Zahedan sand, Taftan pumice, Qom stone powder, silica fume, and a superplasticizer. After casting, the specimens were cured in a controlled environment using Zahedan drinking water for periods of 7, 14, and 28 days.

2. Materials

The coarse aggregate materials used in this project include lightweight aggregate, Taftan pumice, and sand from Zahedan grains. According to the ASTM C33 standard, the sand has a particle size range of approximately 0–4.75 mm. For specimen preparation, pumice and sand aggregates were utilized in a saturated surface dry (SSD) condition. In this process, the aggregates were saturated in water for 24 hours, after which they were removed from the water, and the surface moisture was dried. The water absorption of pumice is 43%, while that of sand is 2.8%. Additionally, based on the ASTM C33 standard, the specific gravity of sand is 1400 kg/m³. The sieve analysis results for the sand used in this research are presented in Table 1, and the sand grading curve, showing the permissible range based on ASTM C33, is illustrated in Figure 2.

Pumice is an igneous aluminum silicate with a cellular structure characterized by numerous voids. Notable properties of pumice that contribute to its use in construction include its low specific weight, cellular structure, lightness, sound insulation, heat insulation, and wear resistance. According to ASTM C330, lightweight aggregates have a maximum size of 9.5 mm, passing through a 3/8-inch sieve and remaining on a No. 8 sieve. The density of pumice powder is approximately 2.6 g/cm³, while the density of aggregates ranging from 1 to 16 mm is approximately 1 to 1.5 g/cm³. The porosity of pumice aggregates is around 85%, consisting of 15% solid material and 85% air. Another important characteristic of pumice is its high deformation temperature, which prevents structural damage due to the overheating of steel materials in concrete during a fire [22]. Based on the ASTM C330 standard, the specific gravity of pumice is 473 kg/m³. The chemical composition of pumice is shown in Table 2 [25]. The sieve analysis results for pumice used in this study are presented in Table 1, and the pumice grading curve, based on the permissible range defined in ASTM C330, is shown in Figure 2.

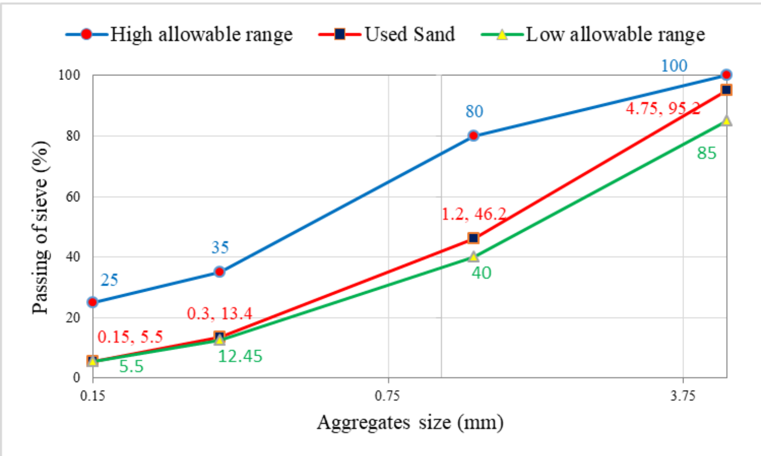


Fig. 1. Sand-grading curve and allowable range according to (ASTM C33).

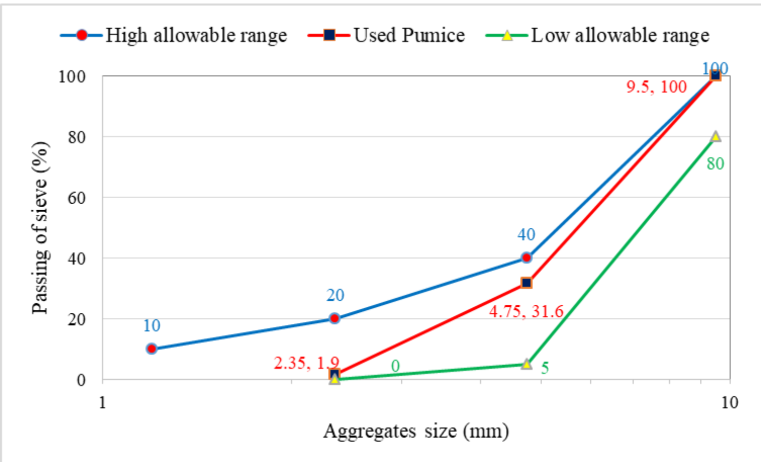


Fig. 2. Pumice-grading curve and allowable range according to (ASTM C330).

Table 1. Characteristics of sand- and pumice-grading systems.

Sieve number	Sieve size (mm)	Remaining weight (gr)				Remaining (%)		Volume passing (%)	
		All sieve		One sieve					
		Sand	Pumice	Sand	Pumice	Sand	Pumice	Sand	Pumice
4	4.75	54	684	54	684	5.40	68.40	95.20	31.60
8	2.36	366	981	312	297	36.60	98.10	68.30	1.90
16	1.18	607	-	241	-	60.70	-	46.20	-
30	0.60	768	-	161	-	76.80	-	28.40	-
50	0.30	888	-	120	-	88.80	-	13.40	-
100	0.15	951	-	63	-	95.10	-	5.50	-
Tray	-	1000	1000	49	19	-	-	0.00	0.00
Total weight		-		1000	1000	363.4	166.5	-	-

Cement, as the primary binder in concrete, plays a crucial role in holding the concrete materials together. This research utilized Sistan Type-II Portland cement. The specific gravity of Sistan cement is 3150 kg/m³, while the Blaine fineness is 3159 cm²/g. The chemical composition of the cement used in this study, as provided by the manufacturer, is listed in Table 2. Stone powder is a common additive in SCC that is used to adjust the viscosity of fresh concrete. In this research, Qom stone powder was selected due to its high quality and uniform granulation. This powder constitutes approximately 60% by weight of the cement used in the main mixing plan. The specific gravity of the stone powder is approximately 2700 kg/m³, and its specific surface area is around 500–550 m²/kg. The chemical composition of the stone powder, based on the information provided by the manufacturer, is shown in Table 2.

Table 2. Content of chemical compositions of stone powder, cement, and pumice (%).

Elemental makeup	CaO	SiO2	Al2O3	Fe2O3	MgO	SO3	NaO2	Others
Stone powder	71.39	8.1	2.30	0.8	0.88	0.26	0.14	16.13
Cement	62.70	21.38	5.37	3.84	1.69	2.48	-	2.54
Pumice	6.69	61.57	18.00	4.93	2.63	0.14	1.65	4.39

POWERPLOST-RM, a new generation of superplasticizers, is specifically designed for making SCC without the need for vibration or additional energy for compaction, and without any separation. The recommended dosage range for this superplasticizer is 0.3-0.9% by weight of cement. The exact amount of consumption depends on the desired effect, the characteristics of the materials, and weather conditions. To determine the precise dosage, preparing test mixtures is recommended. To produce SCC, the same common materials used for conventional concrete are employed, but particular attention must be paid to the mixing process and method to achieve the desired SCC characteristics. The aggregate grading is adjusted by reducing the sand content to a certain extent and increasing the softness factor of the material. The water-to-cement ratio in SCC is always low, typically less than 0.4. Due to its unique properties, SCC requires different testing procedures compared to ordinary concrete, with a greater variety and number of tests. In this research, POWERPLOST-RM, based on polycarboxylate, was used as the superplasticizer, with 2.5% by cement weight.

In addition to enhancing the rheological properties of the paste, the incorporation of silica fume improves the quality of hardened concrete by increasing compressive strength and reducing water absorption. It is particularly useful for producing high-strength concrete without the need for vibration or additional energy for compaction. The recommended usage of silica fume is between 3% and 8% by cement weight. The precise amount of silica fume varies depending on the expected effect, the characteristics of the materials, and weather conditions. To determine the optimal usage, preparing test mixtures is advised. In this study, silica fume was used at 10% by cement weight. The SFs used in this research, according to the ASTM C-1116 standard, have a length of 12 mm and are used per unit volume. The specifications of these fibers are provided in Table 3.

Table 3. Specifications of SF.

Appearance	Melting point (C°)	Specific weight (kg/m^3)	Modulus elasticity (GPa)	Tensile strength (MPa)	Fiber length (mm)	Fiber diameter (mm)
Wavy fibers	1200	7800	200	280	35	0.5

3. Mixing scheme

This study utilized the absolute volume method to develop the initial SCLC mix designs. The absolute volume method calculates the required material quantities by considering their specific volumes and densities, ensuring a precise and balanced concrete mix.

Initially, the required cement quantity for each cubic meter of concrete was estimated, with its corresponding volume determined from its density. In the selected mix designs, 450 kg of cement per cubic meter was used. The water content was adjusted to meet both hydration requirements and workability criteria, maintaining a water-to-cement ratio of 0.35. Additionally, the air content was assumed to be 4%, in line with the typical range of 4% to 9%.

To meet the fresh SCC properties outlined by the EFNARC standard, stone powder, silica fume, and superplasticizer were incorporated at 55%, 10%, and 2.5% by cement weight, respectively. Using the absolute volume formula, the total aggregate volume was calculated by subtracting the volumes of water, cement, stone powder, silica fume, superplasticizer, and confined air from the total volume of one cubic meter of concrete. This value was then allocated between coarse and fine aggregates to finalize the mix design.

The fresh concrete was then subjected to various tests, including the V-Funnel, Slump, L-Box, and T_{50} tests, to verify its acceptability and ensure compliance with the design requirements. Figure 3 illustrates the percentage by material weight used in the initial design.

3.1. Fresh concrete experiments

Among the properties of SCC, filling ability and stability play a significant role in the cost of production, strength, durability, and overall quality of the concrete. These features are characterized by four key properties: flowability, viscosity, permeability, and enhanced resistance to segregation. The properties of fresh concrete, including fluidity, viscosity, and segregation, are evaluated using the T_{50}, V-Funnel, and L-Box tests [38].

In the EFNARC 2002 standard, criteria for assessing fluidity, viscosity, and segregation in concrete samples are provided [21]. In this study, the criteria outlined in the EFNARC 2002 standard were used to evaluate the properties of fresh concrete. To this end, Slump, T_{50}, V-Funnel, and L-Box tests were conducted on the manufactured specimens. All tests were performed at 20°C.

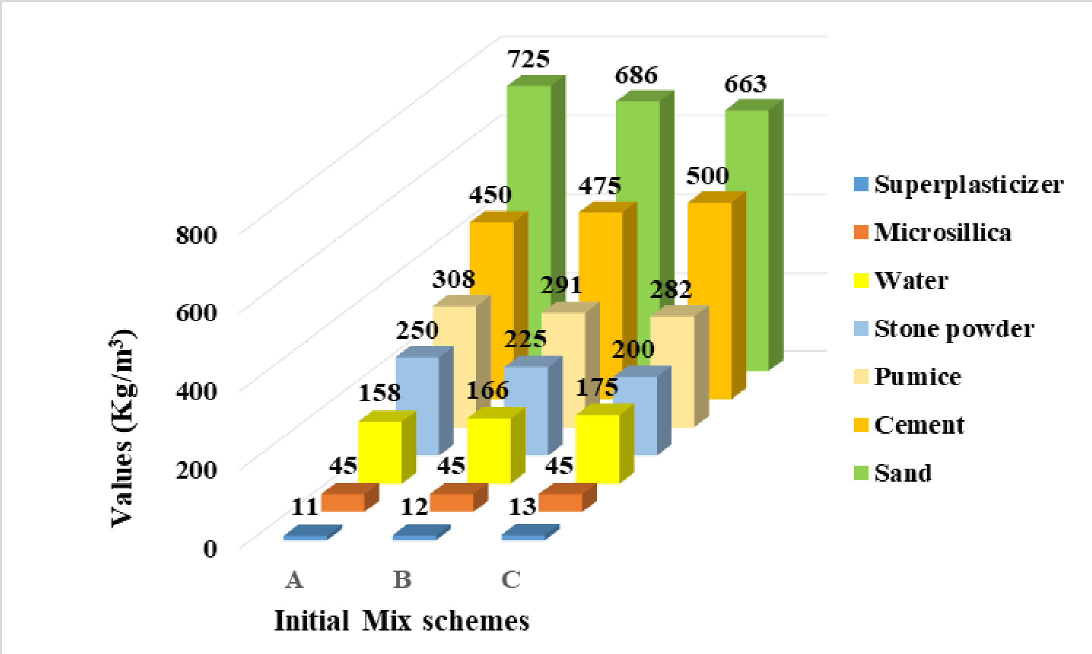


Fig. 3. Initial mixing schemes.

The L-Box test is employed to assess the ability of SCC to flow in confined spaces and through dense reinforcement. First, the L-Box device is leveled, and its inner surface is cleaned and moistened. Fresh concrete is then poured into the mold, and the surface is leveled using a trowel. After approximately 10-60 seconds, the valve opens uniformly. Once the concrete settles, the average depth of the concrete in the vertical part (H1) and the horizontal part (H2) is measured. The permeability ratio is calculated as H2/H1.

The V-Funnel test is used to evaluate the flowability of fresh concrete and its ability to change direction. This test measures the passage of concrete through obstacles, such as reinforcements or confined spaces, without material separation or flow blockage. After leveling the V-Funnel device, approximately 12-14 liters of concrete is poured into it. The lower valve of the device is opened after a 10-second delay, and the concrete discharge time is recorded. This procedure is repeated, and the discharge time is measured after a 5-minute interval.

The T_{50} test is a crucial test for SCC, designed to evaluate the flowability of fresh concrete under its own weight without external constraints. During this test, the diameter of the circle formed after lifting the cone (slump flow) is measured to assess fluidity. The viscosity of the concrete is determined by measuring the time it takes for the concrete to spread and reach a diameter of 50 cm. The time is recorded from the moment the cone is lifted until the concrete reaches the specified diameter. The final diameter is the average of two perpendicular measurements.

The EFNARC 2002 standard classifies the viscosity of SCC into two categories: VS1/VF1 and VS2/VF2, based on the results from the Slump Flow and V-Funnel tests. The VS1/VF1 category indicates excellent filling capacity, even in the presence of dense reinforcements, along with self-levelling ability and a good surface finish. However, concretes in the VS1/VF1 range may also experience separation and water shedding. In contrast, concretes in the VS2/VF2 range exhibit increased thixotropy over time, reducing pressure on molds and improving resistance to segregation.

In this study, all SCC mixtures met the acceptable limits for SF2 and VS2 classifications. The V-Funnel test conducted on the fresh concrete produced flow times of 11 seconds for mixture A, 13 seconds for mixture B, and 13 seconds for mixture C. Similarly, the T_{50} times were recorded as 4 seconds, 5 seconds, and 5 seconds for mixtures A, B, and C, respectively. The Slump Flow test results indicated spread values of 660 mm, 690 mm, and 710 mm for the respective mixtures. Additionally, the L-Box test yielded ratios of 0.82, 0.84, and 0.84 for mixtures A, B, and C.

Based on the fresh SCC tests, mixing scheme A was found to be acceptable and was selected as the primary concrete mix design in this research, incorporating varying percentages of fibers. The final mix designs are illustrated in Figure 4.

The selected SF percentages of 0.125%, 0.25%, and 0.5% have been based on previous research and standard practices in concrete studies. These percentages fall within the range commonly investigated for steel fiber-reinforced lightweight concrete. For instance, Wang et al. (2020) reported enhancements in mechanical performance for SF contents ranging from 0.1% to 1.5%, highlighting the significance of this range for improving compressive strength [39].

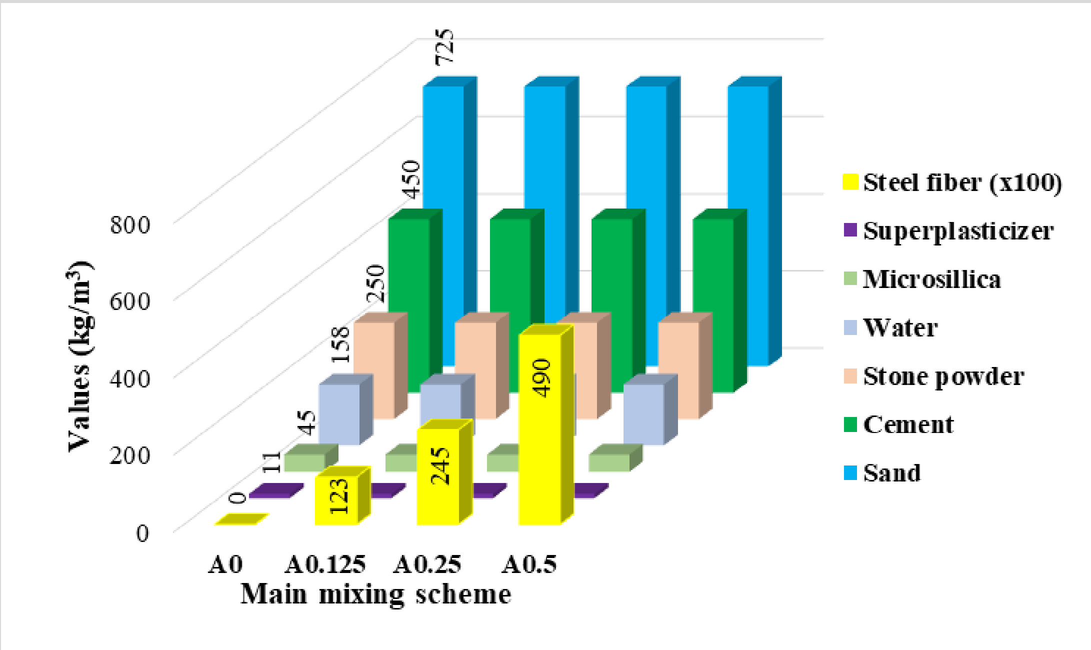


Fig. 4. Main mixing schemes.

Similarly, Zhang et al. (2019) examined SF percentages from 0% to 2.0% and found significant improvements in stress-strain behavior at moderate fiber contents, particularly around 0.5% [40]. Iqbal et al. (2015) also noted that incorporating SF at low to moderate levels improved both compressive strength and ductility in lightweight self-compacting concrete [41]. The chosen percentages in this study ensure a comprehensive evaluation of SF influence while aligning with established benchmarks in the literature.

3.2. Hardened concrete experiments

The compressive strength test was performed on 150×150×150 mm cubic specimens, following the guidelines of BS 1881 Part 116. Prior to testing, the samples were removed from the curing pond and surface-dried. The cubic specimens were placed between the two plates of the loading device, ensuring that the surface of the sample was aligned with the surface of the cubic mold. A vertical force was then applied to the cube specimen at a constant speed, causing the concrete cube to fail under the compressive force, rendering it incapable of transmitting any further load. A total of 36 samples were tested for compressive strength at 7, 14, and 28 days with varying percentages of fibers, all stored under controlled environmental conditions.

For the tensile strength test, conducted in accordance with ASTM C496, cylindrical specimens measuring 150×300 mm were used. The test followed the Brazilian split method, where the cylindrical samples were placed horizontally in the machine, and a vertical load was applied to the surface of the sample using two plates. The force was applied at a constant speed, causing the cylinder to fail due to tensile stress, preventing it from transmitting further force. Similar to the compressive strength test, 36 cylindrical samples with different fiber percentages were tested at 7, 14, and 28 days, all stored under controlled environmental conditions.

The flexural strength test was conducted on 150×150×750 mm prism specimens, in accordance with ASTM C78. A key step after removing the samples from the water basin is to ensure that the surface of the specimens is dried before testing. The samples were then placed on the support plate, which was mounted on the concrete breaker jack. A vertical force, applied at a constant speed, was directed at the center of the sample until it failed due to the applied load. Flexural strength tests were performed on 36 samples at 7, 14, and 28 days, with varying percentages of fibers, all stored under controlled environmental conditions.

(a) (b) (c)

Fig. 5. Broken specimens in the test: (a) Compressive strength (b) Tensile strength (c) Flexural strength.

Table 4 presents the standard deviation (SD) of the tested categories. These categories are based on the percentages of SFs added, concrete age, and the hardened concrete test results. A deviation of less than 20% was considered acceptable.

Table 4. The standard deviation of compressive, flexural and tensile strength tests.

Category	Compressive strength (%)			Flexural strength (%)			Tensile strength (%)		
	SD-7	SD-14	SD-28	SD-7	SD-14	SD-28	SD-7	SD-14	SD-28
A0	8.52	13.11	15.68	16.12	17.81	11.09	10.55	9.73	12.24
A0.125	15.33	18.41	13.08	9.36	14.20	11.89	10.37	14.07	11.88
A0.25	8.66	7.39	13.62	13.44	15.51	14.75	16.34	12.55	18.69
A0.5	13.77	16.22	14.35	12.99	13.87	12.91	15.46	13.80	17.78

4. Research results

In this study, compressive, tensile, and flexural strength tests were conducted on SCLC samples containing pumice at the ages of 7, 14, and 28 days. The samples included SFs at percentages of 0.125%, 0.25%, 0.5%, as well as a control group without SFs. The results of the hardened concrete tests are presented in Figures 6 to 17. The outcomes of these experiments are discussed below. The compressive strength trends observed in this study are consistent with findings from similar research. For instance, our results align with those reported by [3] and [5], where including nano-silica and metakaolin improved the mechanical properties of lightweight concrete. Additionally, [7] and [37] highlighted the effectiveness of pumice and steel fibers in enhancing compressive strength, trends that parallel the observations made in this work. By comparing these results, it becomes evident that the combination of these materials yields synergistic benefits, further emphasizing the innovative contributions of the present study.

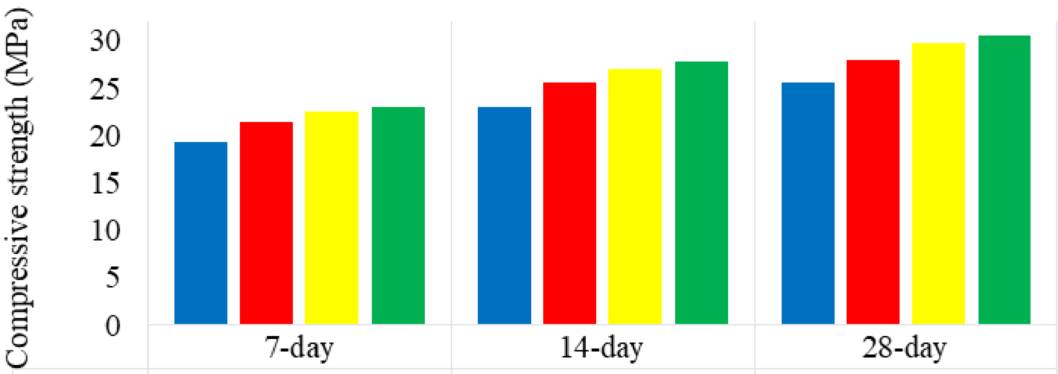
4.1. Compressive strength experiment outcomes

The outcomes of the compressive strength experiments for SCLC with pumice are presented in Figures 6 to 9. Hardened concrete samples containing 0%, 0.125%, 0.25%, and 0.5% SFs were tested at the ages of 7, 14, and 28 days.

Figure 6 displays the values obtained from the compressive strength test. As shown, the compressive strength increases with the percentage of SFs and the concrete age.

Figure 7 illustrates the compressive strength of concrete based on the samples' age index. It demonstrates the impact of concrete age on the compressive strength of mixtures containing varying amounts of SFs. The data indicates that the inclusion of SFs improves the compressive strength of concrete, with enhanced results observed at different ages.

Figure 8 depicts the relationship between compressive strength and the proportion of SFs incorporated into the concrete. The figure shows how the addition of SFs influences the compressive strength at various curing ages. It was observed that, as the concrete aged, its compressive strength increased. Furthermore, an increase in SF content led to a higher compressive strength, with the maximum strength observed in the 28-day samples.



	7-day	14-day	28-day
A0	19.36	23.04	25.61
A0.125	21.36	25.65	27.98
A0.25	22.49	27.1	29.68
A0.5	23.01	27.86	30.48

Fig. 6. Compressive strength at various SF percentages and different ages.

Figure 9 presents the percent variations in compressive strength (VCS) at different ages. This figure evaluates the progress in compressive strength of samples containing SFs compared to those without SFs, expressed as a percentage.

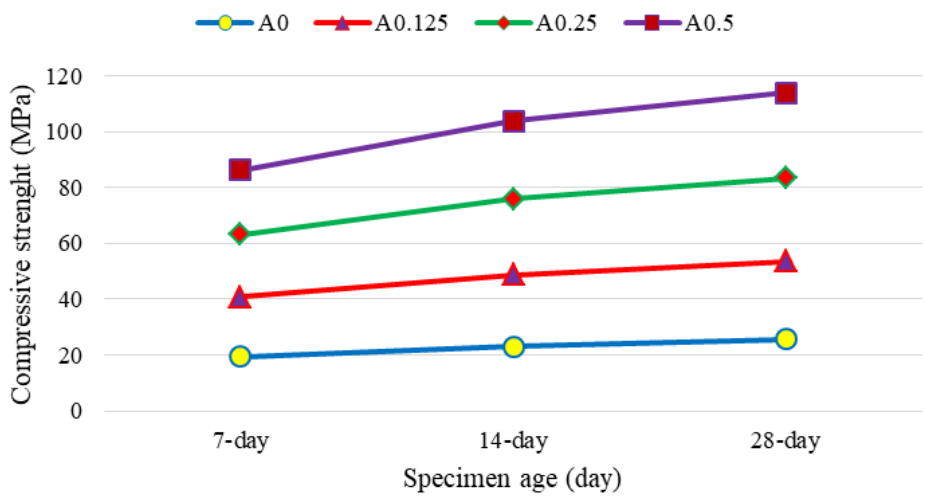


Fig. 7. VCS at different ages.

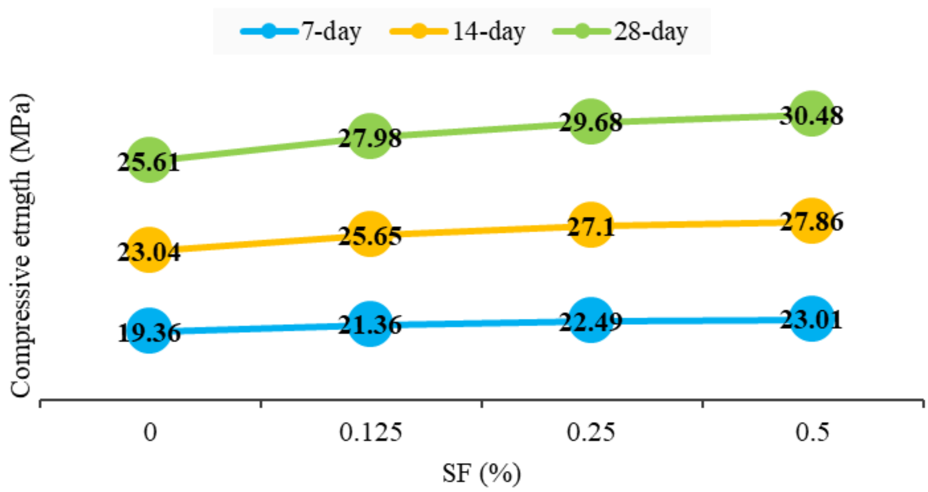


Fig. 8. VCS at various SF percentages.

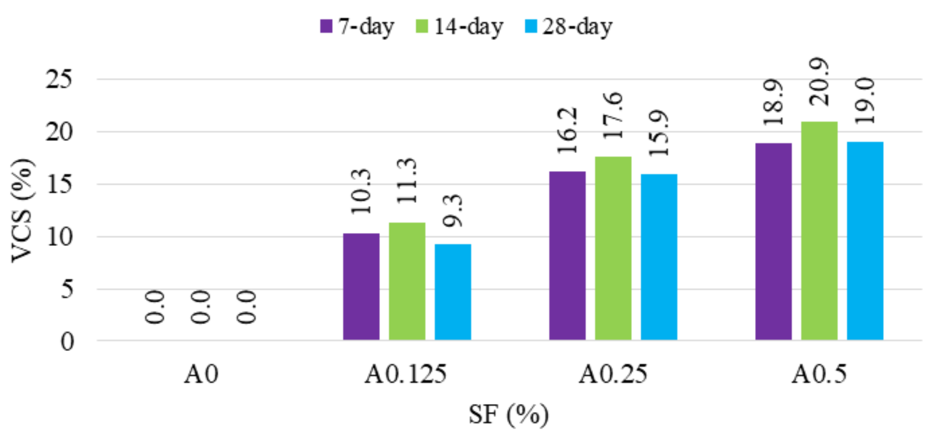


Fig. 9. Percent of VCS at various SF percentages.

The investigations reveal the following:

- The 7-day compressive strength of samples containing 0.125% SFs increased by 10.3% compared to samples without SFs.
- The 14-day compressive strength of samples containing 0.125% SFs increased by 11.3% compared to those without SFs.
- The 28-day compressive strength of samples containing 0.125% SFs increased by 9.3% compared to those without SFs.

Additionally:

- The 7-day compressive strength of samples containing 0.25% SFs increased by 16.2% compared to those without SFs.
- The 14-day compressive strength of samples containing 0.25% SFs increased by 17.6% compared to those without SFs.
- The 28-day compressive strength of samples containing 0.25% SFs increased by 15.9% compared to those without SFs.

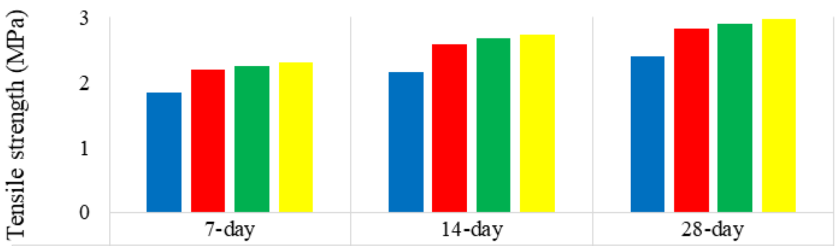
The compressive strength at 7 days for samples containing 0.5% SFs was 18.9% higher than that of samples without SFs. At 14 days, the compressive strength of the samples with 0.5% SFs increased by 20.9% compared to those without SFs. After 28 days, the compressive strength of the samples containing 0.5% SFs was 19.0% greater than that of the samples without SFs.

As observed, the addition of SFs to SCLC containing pumice resulted in an increase in compressive strength.

4.2. Tensile strength experiment outcomes

The results of the tensile strength experiments for SCLC containing pumice are presented in Figures 10-13. Hardened concrete samples with SF ratios of 0%, 0.125%, 0.25%, and 0.5% were tested at the ages of 7, 14, and 28 days.

Figure 10 presents the values obtained from the tensile strength tests. As observed, both the percentage of SFs and the concrete age contributed to an increase in tensile strength.



	7-day	14-day	28-day
A0	1.84	2.17	2.4
A0.125	2.19	2.59	2.83
A0.25	2.25	2.68	2.91
A0.5	2.31	2.74	2.98

Fig. 10. Tensile strength at various SF percentages and different ages.

Figure 11 illustrates the tensile strength of concrete based on the life index of the samples. This figure highlights the effect of concrete age on the tensile strength of mixtures with varying percentages of SFs. It is evident that the addition of SFs to the concrete mix results in a relative increase in tensile strength across samples of different ages.

Figure 12 illustrates the tensile strength as a function of the SF content added to the concrete. The figure demonstrates the influence of SF incorporation on the tensile strength of concrete at various ages. It has been observed that, as the concrete ages, its tensile strength increases. Additionally, an increase in the SF content in concrete results in higher tensile strength, with the highest tensile strength recorded in the 28-day samples.

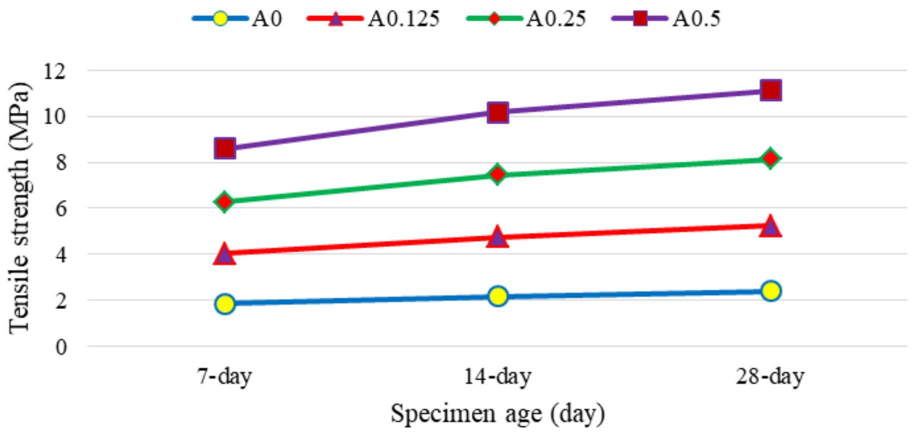


Fig. 11. VTS at different ages.

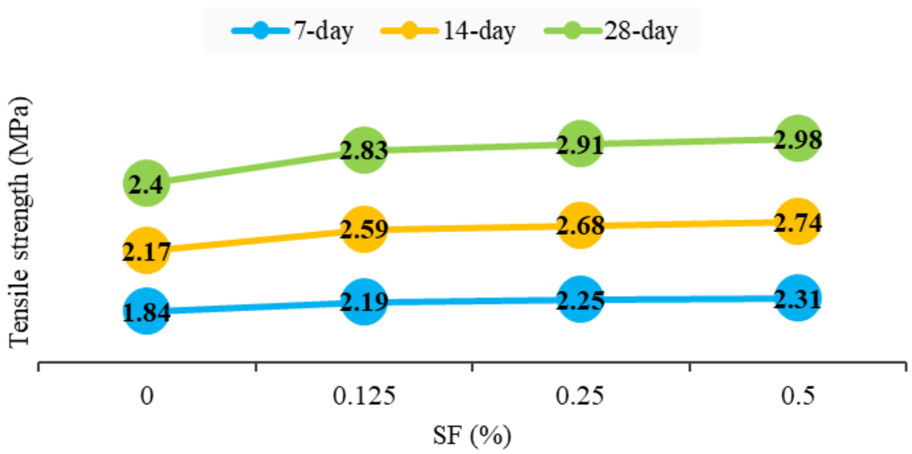


Fig. 12. VTS at various SF percentages.

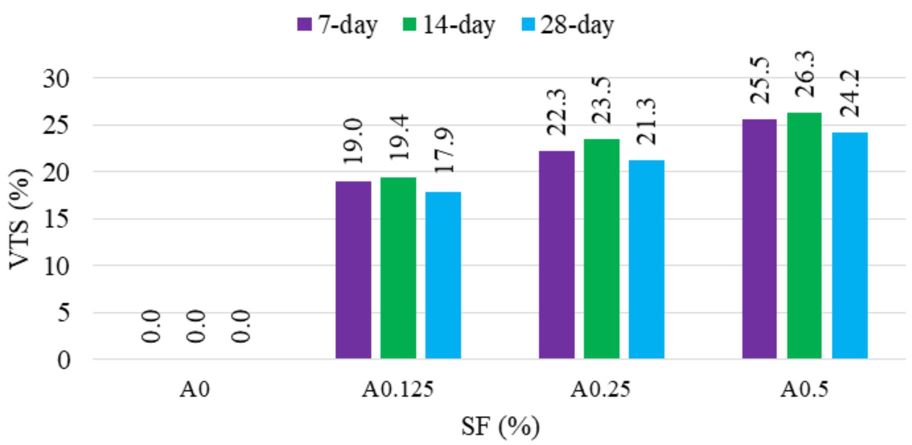


Fig. 13. Percent of VTS at various SF percentages.

Figure 13 shows the percent variations in tensile strength (VTS) at different ages. This figure evaluates the improvement in tensile strength of samples containing SFs compared to control samples without SFs, expressed as a percentage.

The investigations reveal the following:

- For samples with 0.125% SFs, the tensile strength at 7 days increased by 19.0% compared to the control samples. At 14 days, the tensile strength increased by 19.4%, and at 28 days, it rose by 17.9%.
- For samples with 0.25% SFs, the tensile strength at 7 days increased by 22.3%, and at 14 days, it improved by 23.5%. After 28 days, the tensile strength increased by 21.3% compared to the control samples.
- For samples with 0.5% SFs, the tensile strength at 7 days was 25.5% higher, at 14 days it increased by 26.3%, and after 28 days, it was 24.2% higher than the control samples.

4.3. Flexural strength experiment outcomes

The outcomes of the flexural strength experiments on SCLC containing pumice are presented in Figures 14 to 17. Hardened concrete samples with SF contents of 0%, 0.125%, 0.25%, and 0.5% were tested at ages of 7, 14, and 28 days.

Figure 14 shows the values obtained from the flexural strength test. As observed, with increasing SF percentage and concrete age, the flexural strength also increased.

Figure 15 illustrates the flexural strength of concrete based on the life index of the samples. This figure demonstrates the effect of concrete age on the flexural strength of concrete containing different percentages of SFs. As seen, adding SFs to the concrete mix results in a relative increase in the flexural strength of concrete across samples of varying ages.

Figure 16 depicts the flexural strength as a function of the SF content added to the concrete. This figure demonstrates the influence of SF incorporation on the flexural strength of concrete at different ages. It has been observed that as the concrete ages, its flexural strength increases. Furthermore, increasing the SF content in concrete leads to higher flexural strength, with the highest flexural strength observed in the 28-day samples.

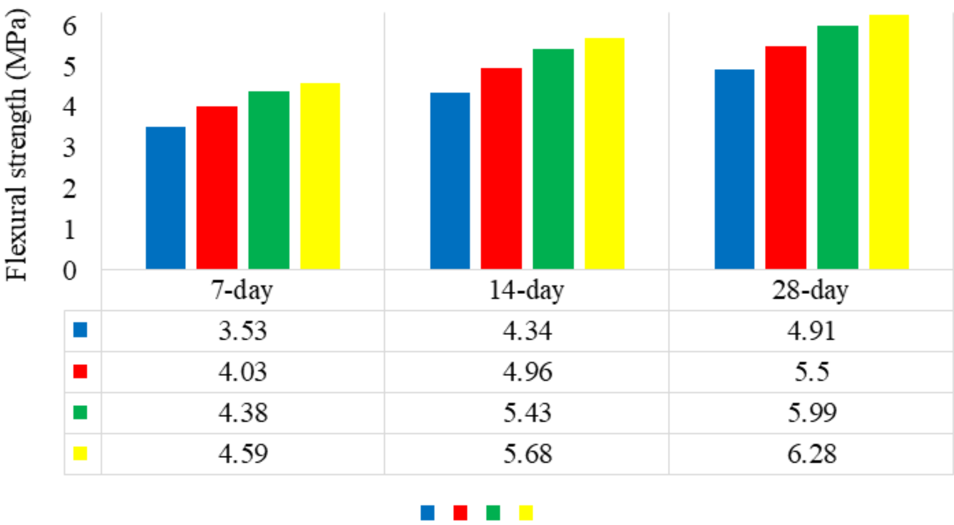


Fig. 14. Flexural strength at various SF percentages and different ages.

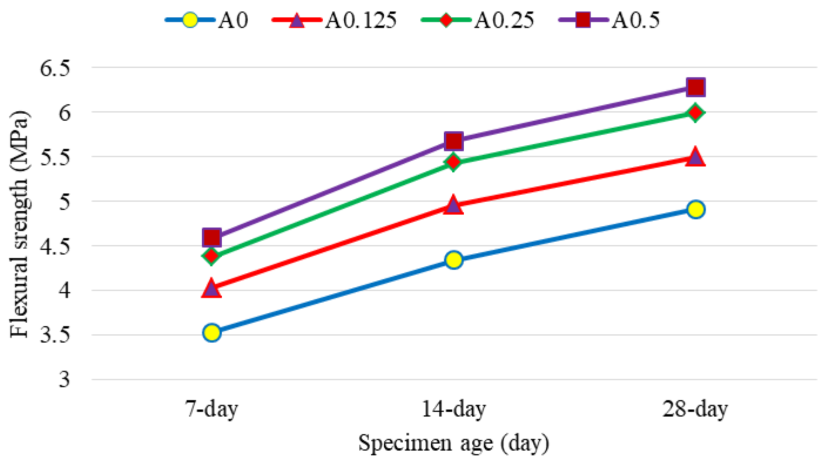


Fig. 15. VFS at different ages.

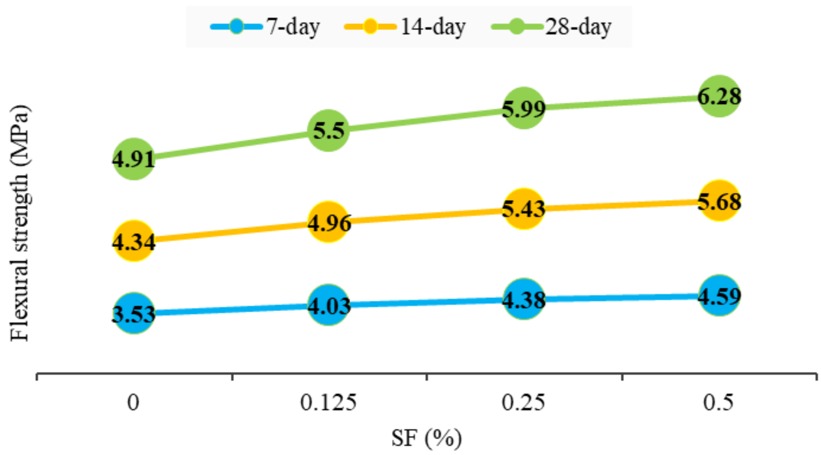


Fig. 16. VFS at various SF percentages.

Figure 17 shows the percent variations in flexural strength (VFS) at different ages. This figure evaluates the improvement in flexural strength of samples containing SFs compared to control samples without SFs, expressed as a percentage.

The investigations reveal the following:

- The 7-day flexural strength of samples containing 0.125% SFs increased by 14.2% compared to the control samples.
- The 14-day flexural strength of samples with 0.125% SFs increased by 14.3% compared to the control samples.
- The 28-day flexural strength of samples with 0.125% SFs increased by 12.0% compared to the control samples.

The 7-day flexural strength of samples containing 0.25% SFs increased by 24.1% compared to the control samples. The 14-day flexural strength of samples with 0.25% SFs rose by 25.1% compared to the samples without SFs. After 28 days, the flexural strength of samples containing 0.25% SFs was 22.0% higher than that of the control samples.

For samples with 0.5% SFs, the 7-day flexural strength improved by 30.0% compared to the control samples. At 14 days, the flexural strength of the samples with 0.5% SFs increased by 30.9%.

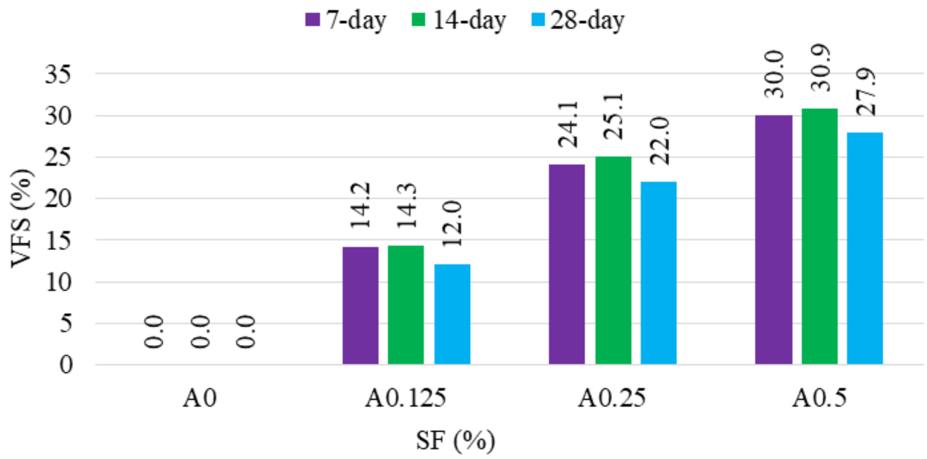


Fig. 17. Percent of VFS at various SF percentages.

The 28-day flexural strength of these samples was 27.9% higher than that of the control samples.

As observed, the addition of SFs to SCLC containing pumice resulted in a significant increase in its flexural strength.

5. The suggested equation

This section presents the proposed equations for estimating the compressive, flexural, and tensile strengths of SCLC containing pumice and SFs at 28 days of age. The formulas for compressive, tensile, and flexural strengths related to steel fiber content are derived by fitting experimental data using regression analysis. Mechanical strength values are measured for different SF percentages, and a suitable regression model (typically quadratic or polynomial) is selected to represent the observed nonlinear trends. Statistical software such as Excel or MATLAB is used to calculate the coefficients by minimizing errors between predicted and actual values. The model's accuracy is assessed using the coefficient of determination (R^2), and validation is performed by comparing the predictions with additional experimental results. This approach ensures reliable equations for capturing the influence of SF on mechanical properties. Figures 18 to 20 and Equations 1 to 3 illustrate the proposed formulas for SCLC with varying SF percentages. As observed, the suggested formulas exhibit high accuracy, as evidenced by their high R-squared values.

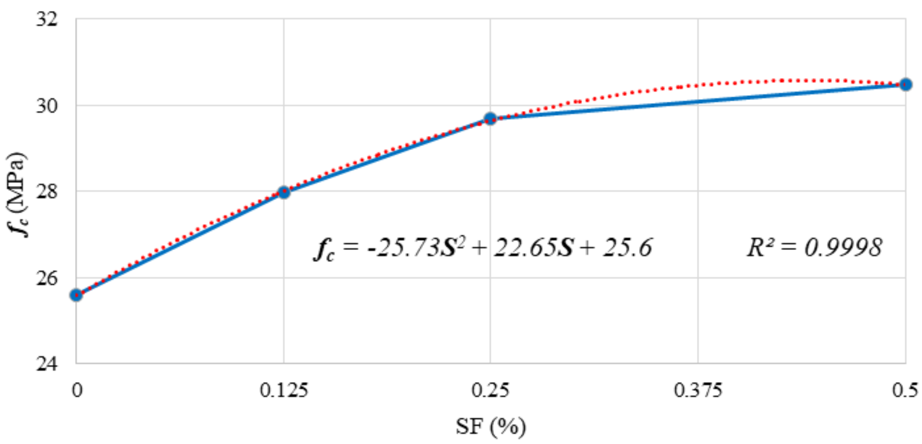


Fig. 18. Compressive strength related to SF rate (28 days).

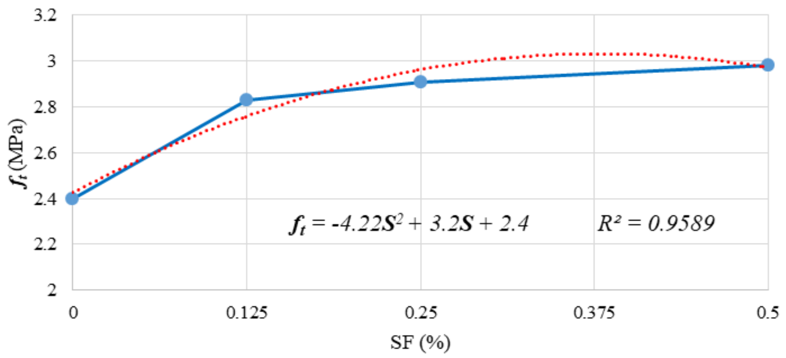


Fig. 19. Tensile strength related to SF rate (28 days).

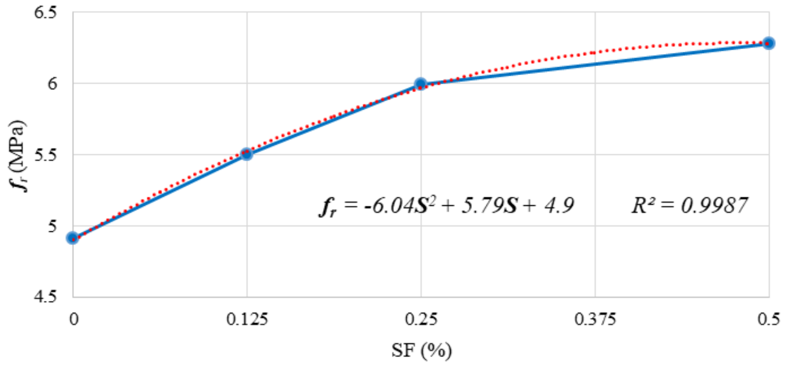


Fig. 20. Flexural strength related to SF rate (28 days).

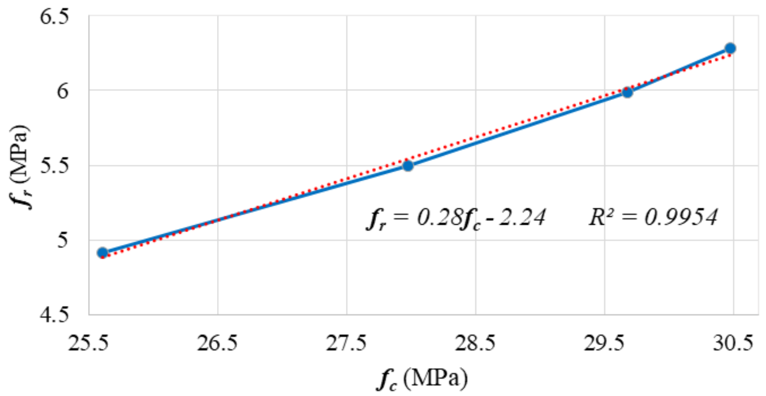


Fig. 21. Flexural strength dependent on Compressive strength (28 days).

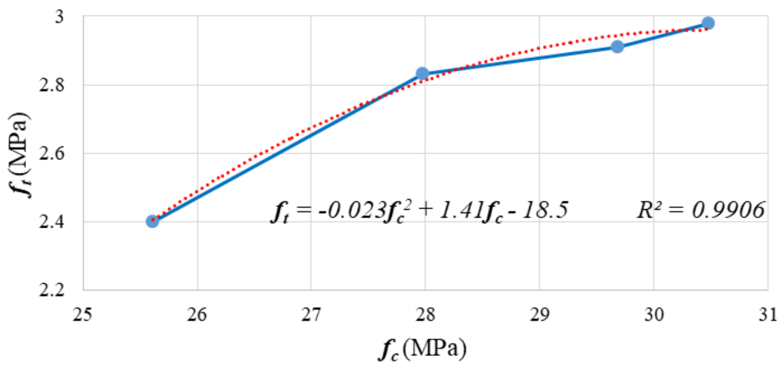


Fig. 22. Tensile strength dependent on Compressive strength (28 days).

$$\mathrm{f_r} = -6.04\mathrm{S}^2 + 5.79\mathrm{S} + 4.9 \qquad \mathrm{R}^2 = 0.9987 \tag{1}$$

$$\mathrm{f_t} = -4.22\mathrm{S}^2 + 3.2\mathrm{S} + 2.4 \qquad \mathrm{R}^2 = 0.9589 \tag{2}$$

$$\mathrm{f_c} = -25.73\mathrm{S}^2 + 22.65\mathrm{S} + 25.6 \qquad \mathrm{R}^2 = 0.9998 \tag{3}$$

Where f_r, f_t, f_c, and S represent the flexural strength, tensile strength, compressive strength, and SFs content, respectively. Finally, based on Figures 21 and 22, Equations 4 and 5 (with acceptable R-squared values) have been proposed to estimate the tensile and flexural strengths of 28-day SCLC containing pumice and SF, respectively.

$$\mathrm{f_r} = 0.28\mathrm{f_c} - 2.24 \qquad \mathrm{R}^2 = 0.9954 \tag{4}$$

$$\mathrm{f_t} = -0.023\mathrm{f}_c^2 + 1.41\mathrm{f_c} - 18.5 \qquad \mathrm{R}^2 = 0.9906 \tag{5}$$

To illustrate the application of the proposed equations, an example calculation is provided. Assuming a steel fiber content (S) of 0.5%, the compressive strength (f_c), flexural strength (f_r), and tensile strength (f_t) of the 28-day SCLC can be estimated using Equations 3, 1, and 2, respectively. Accordingly, in Equations 6, 7, and 8, the values of f_c, f_r, and f_t have been obtained:

$$\mathrm{f_c} = -25.73(0.5)^2 + 22.65(0.5) + 25.6 = 30.49\ \mathrm{MPa} \tag{6}$$

$$\mathrm{f_r} = -6.04(0.5)^2 + 5.79(0.5) + 4.9 = 6.28\ \mathrm{MPa} \tag{7}$$

$$\mathrm{f_t} = -4.22(0.5)^2 + 3.2(0.5) + 2.4 = 2.94\ \mathrm{MPa} \tag{8}$$

These results highlight the capability of the proposed equations to effectively estimate the mechanical properties of 28-day SCLC containing pumice and steel fibers.

To demonstrate the application of Equations 4 and 5 in estimating the tensile and flexural strengths of 28-day SCLC containing pumice and SF, a sample calculation is presented below.

In Equations 9 and 10, assuming f_c =30.49 MPa, the values of compressive and tensile strength of the SCLC specimen have been obtained based on Equations 4 and 5 as follows:

$$f_r = 0.28(30.49) - 2.24 = 6.29\ \mathrm{MPa} \tag{9}$$

$$f_t = -0.023(30.49)^2 + 1.41(30.49) - 18.5 = 3.1\ \mathrm{MPa} \tag{10}$$

Therefore, for an SCLC sample with a compressive strength of 30.49 MPa, the estimated tensile strength is 3.1 MPa and the flexural strength is 6.29 MPa, which are very close to the results obtained from Equations 1 and 2. These results confirm the effectiveness of the proposed equations in predicting the mechanical properties of SCLC.

6. Discussion

In this section, a method for estimating the strength growth of hardened samples at different percentages of SFs is presented. Figures 23 to 26 illustrate the increase in compressive, tensile, and flexural strengths in relation to changes in SF percentages. For this purpose, the results from the 28-day tests were used. In each test, the strengths were normalized relative to the lowest value, and the slope of the line connecting the points at different SF percentages was calculated. These slopes represent the strength growth rate. A larger slope indicates a more favorable trend with the addition of SFs, while a smaller slope suggests that the impact of SFs on strength improvement is less significant.

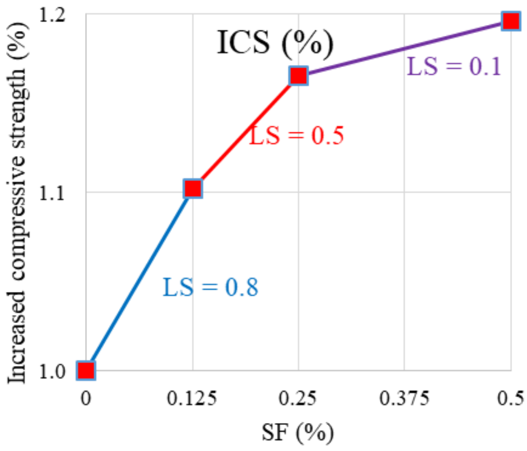


Fig. 23. ICS (%).

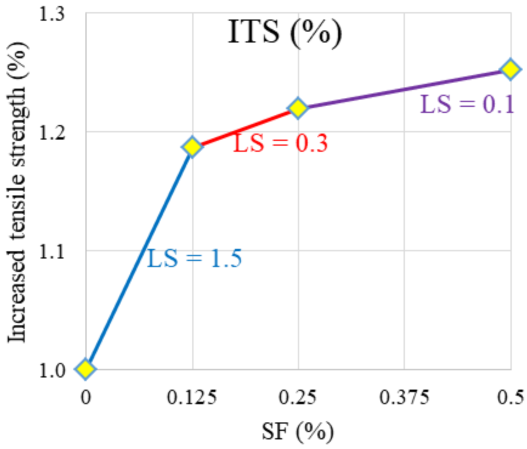


Fig. 24. ITS (%).

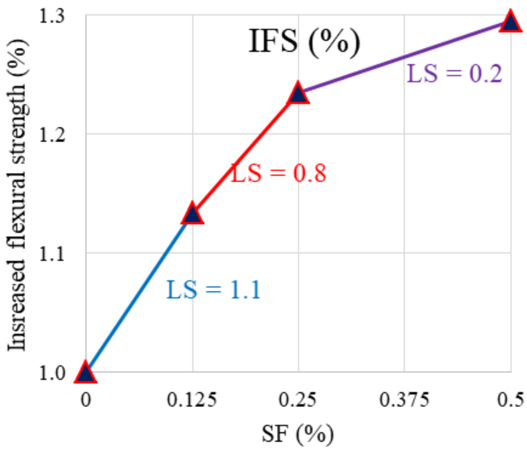


Fig. 25. IFS (%).

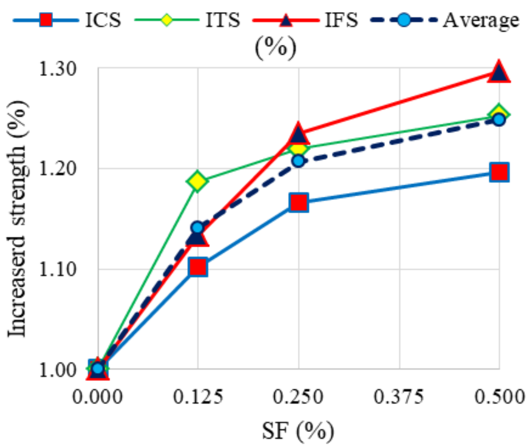


Fig. 26. ICS, ITS, IFS (%).

Figure 23 illustrates the rate of increase in compressive strength (ICS). As observed, the line slope (LS) for 0.125% SFs is 0.8, indicating a significant impact of SFs on compressive strength improvement. For 0.25% SFs, the LS is 0.5, showing a high influence of SFs on compressive strength. However, for 0.5% SFs, the LS reduces to 0.1, suggesting a diminished effect of SFs on further increasing compressive strength. Up to the addition of 0.25% SFs, the compressive strength increases substantially due to enhanced ductility of the concrete. Beyond this point, additional SFs do not significantly affect the concrete's ductility.

Figure 24 shows the rate of increase in tensile strength (ITS). The LS for 0.125% SFs is 1.5, reflecting a strong influence of SFs on tensile strength improvement. The LS for 0.25% SFs is 0.3, indicating a lower impact of SFs on tensile strength, and the LS for 0.5% SFs is 0.1, showing a reduced effect of SFs in increasing tensile strength. Up to 0.125% SFs, the tensile strength improves significantly, correcting the inherent weakness of the concrete in tension. However, higher percentages of SFs reduce the tensile strength due to air entrapment in the concrete.

Figure 25 presents the rate of increase in flexural strength (IFS). The LS for 0.125% SFs is 1.1, demonstrating a strong influence of SFs on flexural strength enhancement. The LS for 0.25% SFs is 0.8, showing a high impact, and the LS for 0.5% SFs is 0.2, indicating a reduced influence. Up to the addition of 0.25% SFs, the flexural strength increases substantially, attributed to the improvement in the concrete’s ductility. Beyond this point, additional SFs do not significantly affect ductility.

Figure 26 displays the growth of compressive, tensile, and flexural strengths and their averages. As seen, up to 0.25% SFs, the average strength increases significantly due to the enhancement in concrete ductility.

The diminishing returns observed in the enhancement of mechanical properties with increasing SF percentages can be attributed to several factors. At lower percentages, SF particles are well-dispersed within the base material, effectively filling voids and improving load transfer, which significantly enhances the mechanical properties. However, as the percentage increases, particle agglomeration becomes prominent due to the limited dispersion capability of the base material. This agglomeration not only reduces the surface area available for interaction but also creates weak zones within the composite material.

Additionally, the excessive addition of SFs disrupts the continuity of the base material, leading to stress concentration points and a decrease in overall ductility. The saturation effect indicates that beyond an optimal percentage, the reinforcing benefits of SFs plateau, and further additions may even result in negative impacts on the mechanical properties. These findings align with previous studies that highlight the importance of maintaining a balance between filler content and base material integrity to achieve optimal performance.

Additionally, the use of pumice and SFs in concrete offers notable environmental and economic benefits. The incorporation of pumice reduces the density of concrete, lowering its ecological footprint by replacing traditional aggregates. SFs enhance not only the mechanical properties but also the durability of concrete, reducing maintenance costs and extending its service life. This combination provides a more sustainable and cost-effective approach to concrete production, decreasing reliance on conventional materials and lowering long-term expenses.

7. Conclusion

In this research, SCLC containing SFs was produced using pumice aggregate. The effect of incorporating SFs on the mechanical properties of SCLC was then assessed. A method for estimating the strength growth of hardened samples at various SF percentages was proposed. The enhanced mechanical properties and durability of SF-SCLC suggest its suitability for lightweight structural elements, especially in applications requiring improved crack resistance and durability under harsh environmental conditions, such as marine or acidic environments.

Based on the results and observations from the tests, the following conclusions are drawn:

- The highest compressive strength was achieved by adding up to 0.5% SFs, with the addition of 0.25% SFs showing the most significant effect on compressive strength growth.
- The highest tensile strength was achieved by adding up to 0.5% SFs, with the addition of 0.125% SFs showing the most significant effect on tensile strength growth.
- The highest flexural strength was achieved by adding up to 0.5% SFs, with the addition of 0.25% SFs showing the most significant effect on flexural strength growth.

The use of pumice and SFs in concrete offers significant environmental and economic benefits. Pumice reduces concrete density and its environmental impact, while SFs improve durability and mechanical properties, lowering maintenance costs and extending service life. This combination promotes more sustainable and cost-effective concrete production.

Finally, linear Equation 4 is proposed to estimate the modulus of rupture of SCLC containing pumice and SFs based on compressive strength.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. No funding was received for this project.

Conflicts of interest

The authors confirm that they hold no financial interests or personal relationships that could be perceived as influencing the findings presented in this paper.

Authors contribution statement

Masoud Dadkhah: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Software, Resources.

Reza Rahgozar: Conceptualization, Methodology, Data curation, Validation, Project administration, Supervision, Visualization, Resources.

Ehsan Barahouei Pasandi: Conceptualization, Data curation, Validation, Formal analysis, Writing – original draft, Project administration.

Peyman Rahgozar: Methodology, Validation, Writing – review & editing, Project administration, Supervision.

References

[1] Okamura H, Ozawa K, Ouchi M. Self-compacting concrete. Struct Concr 2000;1:3–17.

[2] Ouchi M. Development , Applications and Investigations of Self-Compacting Concrete. Int Work 2000;23:2–4.

[3] Ramezanianpour AA, Bahrami Jovein H. Influence of metakaolin as supplementary cementing material on strength and durability of concretes. Constr Build Mater 2012;30:470–9. https://doi.org/10.1016/j.conbuildmat.2011.12.050.

[4] De Schutter G, Bartos PJM, Domone P, Gibbs J. Self-compacting concrete. vol. 288. Whittles Publishing Scotland, UK; 2008.

[5] Masoud Dadkhah 1 Ali Bandani 2 Reza Rahgozar 3 Peyman Rahgozar 4. Mechanical properties of self-compacting lightweight concrete containing pumice and metakaolin. J Rehabil Civ Eng 2024;12:97–118. https://doi.org/10.22075/jrce.2023.29150.1762.

[6] Bharathi KPP, Adari SK, Pallepamula U. Mechanical properties of self-compacting concrete using steel slag and glass powder. J Build Pathol Rehabil 2022;7:46. https://doi.org/10.1007/s41024-022-00184-z.

[7] Askari Dolatabad Y, Kamgar R, Gouhari Nezad I. Rheological and Mechanical Properties, Acid Resistance and Water Penetrability of Lightweight Self-Compacting Concrete Containing Nano-SiO2, Nano-TiO2 and Nano-Al2O3. Iran J Sci Technol - Trans Civ Eng 2020;44:603–18. https://doi.org/10.1007/s40996-019-00328-1.

[8] Dolatabad YA, Kamgar R, Jamali Tazangi MA. Effects of perlite, leca, and scoria as lightweight aggregates on properties of fresh and hard self-Compacting concretes. J Adv Concr Technol 2020;18:633–47. https://doi.org/10.3151/JACT.18.633.

[9] Alireza Rashno 1 Mohamadreza Adlparvar 1 2 Mohsen Izadinia. Study on Rheology Properties, Durability and Microstructure of UHPSCC Contains Garnet, Basalt, and Pozzolan. J Rehabil Civ Eng 2023;11:96–110. https://doi.org/https://doi.org/10.22075/JRCE.2022.25651.1584.

[10] Beigi MH, Berenjian J, Lotfi Omran O, Sadeghi Nik A, Nikbin IM. An experimental survey on combined effects of fibers and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete. Mater Des 2013;50:1019–29. https://doi.org/10.1016/j.matdes.2013.03.046.

[11] Vakhshouri B, Nejadi S. Compressive strength and mixture proportions of self-compacting light weight concrete. Comput Concr 2017;19:555–66. https://doi.org/10.12989/cac.2017.19.5.555.

[12] Sivakumar VR, Kavitha OR, Prince Arulraj G, Srisanthi VG. An experimental study on combined effects of glass fiber and Metakaolin on the rheological, mechanical, and durability properties of self-compacting concrete. Appl Clay Sci 2017;147:123–7. https://doi.org/10.1016/j.clay.2017.07.015.

[13] Samimi K, Kamali-Bernard S, Akbar Maghsoudi A, Maghsoudi M, Siad H. Influence of pumice and zeolite on compressive strength, transport properties and resistance to chloride penetration of high strength self-compacting concretes. Constr Build Mater 2017;151:292–311. https://doi.org/10.1016/j.conbuildmat.2017.06.071.

[14] Samimi K, Kamali-Bernard S, Maghsoudi AA. Durability of self-compacting concrete containing pumice and zeolite against acid attack, carbonation and marine environment. Constr Build Mater 2018;165:247–63. https://doi.org/10.1016/j.conbuildmat.2017.12.235.

[15] Hedayatinia F, Delnavaz M, Emamzadeh SS. Rheological properties, compressive strength and life cycle assessment of self-compacting concrete containing natural pumice pozzolan. Constr Build Mater 2019;206:122–9. https://doi.org/10.1016/j.conbuildmat.2019.02.059.

[16] Ghasemi M, Rasekh H, Berenjian J, AzariJafari H. Dealing with workability loss challenge in SCC mixtures incorporating natural pozzolans: A study of natural zeolite and pumice. Constr Build Mater 2019;222:424–36. https://doi.org/10.1016/j.conbuildmat.2019.06.174.

[17] Azad A, Saeedian A, Mousavi SF, Karami H, Farzin S, Singh VP. Effect of zeolite and pumice powders on the environmental and physical characteristics of green concrete filters. Constr Build Mater 2020;240:117931. https://doi.org/10.1016/j.conbuildmat.2019.117931.

[18] Ghafor K, Mahmood W, Qadir W, Mohammed A. Effect of particle size distribution of sand on mechanical properties of cement mortar modified with microsilica. ACI Mater J 2020;117:47–60. https://doi.org/10.14359/51719070.

[19] Adai Al-Farttoosi HK, Abdulrazzaq OA, Hussain HK. Mechanical Properties of Light Weight Aggregate Concrete Using Pumice as a Coarse Aggregate. IOP Conf. Ser. Mater. Sci. Eng., vol. 1090, IOP Publishing; 2021, p. 012106. https://doi.org/10.1088/1757-899x/1090/1/012106.

[20] Hubertová M. Self compacting light concrete with liapor aggregates. Proc. Int. Conf. Young Res. Forum, Thomas Telford Publishing; 2005, p. 103–12.

[21] EFNARC. Specification and Guidelines for Self-Compacting Concrete. vol. 44. 2002.

[22] Ambroise J, Murat M, Péra J. Hydration reaction and hardening of calcined clays and related minerals V. Extension of the research and general conclusions. Cem Concr Res 1985;15:261–8. https://doi.org/10.1016/0008-8846(85)90037-7.

[23] Okamura H, Ouchi M. Self-compacting concrete. J Adv Concr Technol 2003;1:5–15.

[24] Poon CS, Ho DWS. A feasibility study on the utilization of r-FA in SCC. Cem Concr Res 2004;34:2337–9. https://doi.org/10.1016/j.cemconres.2004.02.013.

[25] Alahverdi A, Mehrpour K, Najafikani E. Taftan pozzolan-based geopolymer cement 2008;19:1–5.

[26] Yahia A, Tanimura M, Shimoyama Y. Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and W/C ratio. Cem Concr Res 2005;35:532–9. https://doi.org/10.1016/j.cemconres.2004.05.008.

[27] Zhu W, Gibbs JC, Bartos PJM. Uniformity of in situ properties of self-compacting concrete in full-scale structural elements. Cem Concr Compos 2001;23:57–64. https://doi.org/10.1016/S0958-9465(00)00053-6.

[28] Altun F, Haktanir T, Ari K. Effects of steel fiber addition on mechanical properties of concrete and RC beams. Constr Build Mater 2007;21:654–61. https://doi.org/10.1016/j.conbuildmat.2005.12.006.

[29] Nejati F, Edalatpanah SA. Experimental investigation for the effect of fiber on the mechanical properties of light-weight concrete under dry and wet conditions. Int J Struct Integr 2020;11:216–38. https://doi.org/10.1108/IJSI-04-2019-0036.

[30] Hassanpour M, Shafigh P, Mahmud H Bin. Lightweight aggregate concrete fiber reinforcement - A review. Constr Build Mater 2012;37:452–61. https://doi.org/10.1016/j.conbuildmat.2012.07.071.

[31] Pathan MG, Swarup A. A Review on Steel Fiber Reinforced Concrete. Ijarse 2017;1:822–8.

[32] Ramadoss P, Li L, Fatima S, Sofi M. Mechanical performance and numerical simulation of high-performance steel fiber reinforced concrete. J Build Eng 2023;64:105424. https://doi.org/10.1016/j.jobe.2022.105424.

[33] Zhao Y, Wu B, Peng S, Yu Z, Du X. Research and mechanism analysis on dynamic compressive behavior of steel fiber reinforced concrete. Constr Build Mater 2023;368:130358. https://doi.org/10.1016/j.conbuildmat.2023.130358.

[34] Doost Mohamadi A, Vatani Oskouei A, Kheyroddin A. An experimental study on effect of concrete type on bond strength of GFRP bars. J Rehabil Civ Eng 2021;9:52–70. https://doi.org/10.22075/JRCE.2020.19922.1392.

[35] Bezerra ACS, Maciel PS, Corrêa ECS, Soares Junior PRR, Aguilar MTP, Cetlin PR. Effect of high temperature on the mechanical properties of steel fiber-reinforced concrete. Fibers 2019;7:82–8. https://doi.org/10.3390/?b7120100.

[36] Razzaghi H, Madandoust R, Aghabarati H. Strength Assessment of Steel Fibre Reinforced Recycled Aggregate Concrete by Means of Correlation between Ultrasonic and Point Load Tests. J Rehabil Civ Eng 2022;10:79–92. https://doi.org/10.22075/JRCE.2021.21898.1456.

[37] Chaitanya BK, Sai Madupu LNK, Satyanarayana S V. Experimental study on fresh and mechanical properties of crimpled steel fibers in self compacting concrete. J Polym Compos 2023;11:S65–75.

[38] Nagaraj A, Girish S. Rheology of Fresh Concrete-a Review. J Rehabil Civ Eng 2021;9:118–31. https://doi.org/10.22075/jrce.2021.20557.1425.

[39] Wang H, Wei M, Wu Y, Huang J, Chen H, Cheng B. Mechanical behavior of steel fiber-reinforced lightweight concrete exposed to high temperatures. Appl Sci 2021;11:1–20. https://doi.org/10.3390/app11010116.

[40] Zhao M, Zhang B, Shang P, Fu Y, Zhang X, Zhao S. Complete stress-strain curves of self-compacting steel fiber reinforced expanded-shale lightweight concrete under uniaxial compression. Materials (Basel) 2019;12:2979. https://doi.org/10.3390/ma12182979.

[41] Iqbal S, Ali A, Holschemacher K, Bier TA. Mechanical properties of steel fiber reinforced high strength lightweight self-compacting concrete (SHLSCC). Constr Build Mater 2015;98:325–33. https://doi.org/10.1016/j.conbuildmat.2015.08.112.