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Investigating the Mechanical Characteristics of Self-Compacting Light Transmitting Concrete Due to the Addition of Silica Fume

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Abstract

This study investigates the mechanical properties of Self-Consolidating Light-Transmitting Concrete (SCLTC) incorporating 4% optical fibers and varying Silica Fume (SF) contents (5%, 10%, and 15%) after 28 days of curing. While conventional concrete benefits from SF due to its pozzolanic reactivity and microstructural refinement, this research reveals a contrasting trend in SCLTC. The control sample (0% SF) exhibited the highest compressive strength (58.3 MPa), whereas SF incorporation led to significant reductions of 67.8% at 5% SF (18.8 MPa), 39.6% at 10% SF (35.2 MPa), and a further decline at 15% SF (18.9 MPa). The optimal SF content was identified as 10%, balancing limited strength recovery against the detrimental effects of higher dosages, likely due to disrupted particle packing, increased water demand, and impaired fiber-matrix bonding. Light transmittance remained consistent (~5%) across all mixes, indicating SF's negligible impact on optical performance. These findings highlight the need for more appropriate mix designs in SCLTC. Future research should explore lower SF dosages (<5%) and synergistic admixtures to enhance performance while preserving self-consolidation and translucency. This study advances the understanding of multifunctional concrete, bridging rheological efficiency with sustainable architectural applications.

Keywords: Self-compacting concrete, Light transmitting concrete (Litracon), Compressive strength, Silica fume, Optical fiber.

1 | Introduction

The construction industry relies heavily on concrete because it is affordable, readily available, and possesses significant compressive strength. Its ability to be molded into various shapes and have its strength modified

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by adjusting the ratios of cement, water, and aggregate makes it a highly adaptable material. The diversity of concrete types allows engineers to match materials precisely to a project's structural or environmental needs. Light-transmitting concrete (Litracon) is a type of concrete that uses optical fibers to transmit light [1–4]. This material serves primarily as an aesthetic element in architecture and is often employed for interior wall coverings [5], [6]. By channeling daylight through its structure, Lightracon concrete aims to replace traditional electric lighting with sunlight, lowering energy consumption and enhancing efficiency [4], [7–10]. Utilizing lightweight concrete can contribute to a decrease in the consumption of non-renewable energy resources. Beyond practical uses, this material serves artistic purposes, providing structures with a distinctive visual appeal. Litracon concrete has been incorporated into diverse projects, such as park benches, where it merges durability with light-emitting features for a striking effect. As technology advances and concrete structures become more complex, there is an increasing need for concrete with excellent workability to facilitate the easy consolidation of densely reinforced elements. This demand, along with the requirement for sufficient durability and strength, has driven the development of High-Performance Concretes (HPCs). A key advantage of Self-Consolidating Concrete (SCC) is its ability to consolidate under its weight without segregation of its components [11], [12].

In a laboratory study, Sreevani et al. [5] compared light-transmitting concrete made with optical fibers to conventional concrete in terms of environmental compatibility. They used 3% optical fiber in this concrete, which is also known as translucent concrete. Using this concrete allows light to pass through the opaque concrete, thus reducing energy consumption in enclosed environments. While this translucent concrete is used in architecture as a decorative material, it possesses all the properties that must be considered to maintain the concept of a green building. In a compressive strength test performed on the concrete samples, the results showed that the use of 3% optical fibers further increased the compressive strength. Also, the compressive strength of the concrete cube depends on the diameter of the holes in the mold and the diameter of the optical fibers. Swain et al. [6] studied the behavior of concrete and mortar with optical fibers. They found that the compressive strength of transparent concrete depends on the optical fiber content. Sahithi and Mouunica [7] analyzed the characteristics of light-transmitting concrete, focusing on its mechanical performance. Flexural strength was evaluated using beam specimens measuring 500mm × 100mm × 100mm, with results compared to traditional concrete samples cured for 7 and 28 days. Additionally, compressive strength was assessed via a compression testing apparatus following light-transmittance measurements on the same samples.

Ugale et al. [1] explored the potential of Litracon in terms of its applications, properties, and effect on energy consumption. They concluded that Litracon's efficiency can be enhanced through the strategic use of additives and material substitutions. Their study also showed that the incorporation of marble powder improves both light transmission and resistance. Many types of waste and chemical additives and waste aggregates could be used in concrete mixtures, asphalt mixtures [13], and soil stabilization, such as waste glass [11], [14], [15], fly ash [16], volcanic ash [17], SF [18], metakaolin [18], marble powder [19], sawdust [15], waste tiles [19], cold bitumen [20], PVC granules [21], crumb rubber [22], cement [23], and waste plastic [24–26]. Also, many types of fibers, like polypropylene fibers, natural fibers [27], basalt fibers [28], and glass fibers [28], could be employed to enhance the strength of these materials. SF is a highly reactive pozzolan consisting predominantly of amorphous Silicon Dioxide (SiO_2). Its ultrafine particle size, with a typical diameter of less than 1 μ m, provides an exceptionally high surface area that facilitates rapid reaction with Calcium Hydroxide ($Ca(OH)_2$) liberated during cement hydration. This pozzolanic reaction results in the formation of additional Calcium Silicate Hydrate (C-S-H) gel, filling voids within the cement matrix and significantly refining the microstructure [29–32]. The resulting denser and more homogeneous microstructure enhances durability and improves both early and long-term strength development.

This study presents a pioneering investigation into the mechanical and functional properties of Self-Consolidating Light-Transmitting Concrete (SCLTC) incorporating 4% optical fibers by volume, marking the first comprehensive analysis of this hybrid material. While prior research has explored SCC and light-transmitting concrete as distinct entities, their synergistic integration—particularly with the inclusion of SF as a Supplementary Cementitious Material (SCM) remains unexplored in the literature. The novelty of this work lies in its dual focus: 1) evaluating the feasibility of achieving self-consolidation in light-transmitting concrete, which traditionally faces workability challenges due to the presence of embedded optical fibers, and 2) systematically assessing the impact of SF substitution at varying ratios (5%, 10%, and 15%) on the compressive strength and light-transmittance efficiency of the mixtures. By bridging the gap between advanced rheological properties (e.g., flowability and passing ability) and functional aesthetics (e.g., light transmission), this study introduces sustainable construction mixtures.

2 | Material and Methods

2.1 | Materials

2.1.1 | Aggregates

Crushed river sand and gravel, locally sourced from mines near Mashhad City, Iran, were used in this research. The coarse aggregates exhibited angular shapes. The maximum size of the coarse aggregates was 12.5 mm, whereas the fine aggregates had a maximum size of 4.75 mm. The particle size distribution of the fine and coarse aggregates is depicted in *Fig. 1*.

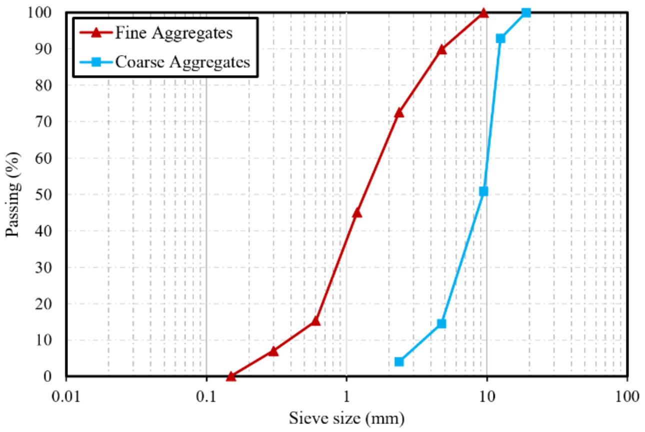

Fig. 1. Distribution of particle sizes in fine and coarse aggregates.

2.1.2 | Cement

All experiments in this study incorporated Portland cement, specifically type 325-1, exhibiting a specific gravity of 3150 kg/m3. This specific cement was manufactured in accordance with ASTM-C150 standards [33] by the Zaveh Cement Company. The chemical composition of the cement is presented in *Table 1*.

Table 1. Chemical composition of the cement.

Material	Chemical Composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	C_3S
Portland cement	20.9	4.5	3.8	63.5	2.7	2	0.5	0.5	1.15

2.1.3 | Superplasticizer and water

Superplasticizers are a category of chemical admixtures used in concrete to enhance its quality by significantly reducing the water content required for optimal workability. Superplasticizer (Type BS410) was sourced from Mashhad city, Iran. Tap water was used in the concrete mix preparation. Official standards for concrete mixing water categorize its suitability based on parameters such as pH levels, filtration requirements, chemical composition, presence of toxic substances, impurities, and other critical factors. Overlooking these seemingly straightforward criteria can lead to irreversible damage and structural failures. Water is the most influential element in the concrete curing process, directly impacting its final properties. For instance, if the pH of the water falls outside the 5.5–6.0 range, the resulting concrete will exhibit poor quality and a significantly reduced lifespan. Similarly, the presence of substances like sulfur compounds in the mixing water can drastically diminish the concrete's compressive strength. Therefore, adhering to the guidelines outlined in official standards is essential for ensuring the durability, performance, and safety of concrete structures.

2.1.4 | Silica fume

This study employed SF prepared specifically from the products of the Iran Ferrosilice Company. The physical properties of SF are comprehensively displayed in *Table 2*. ASTM C1240 standard [34] mandates a minimum amorphous silica content of 85%, a maximum moisture content of 3%, and a maximum L.O.I. of 6% for SF production. According to the standard, at least 90% of SF particles should be under 45 microns. Laser Particle Size Analysis (PSA) of SF produced by Iran Ferrosilice Company shows that nearly 98% of its particles are smaller than 45 microns, exceeding the standard requirement. All the materials used in this study are displayed in *Fig. 2*.

Table 2. Physical properties of SF.

Material	SF
Particle sizes (μm)	98% of particles less than 45 μm
Bulk density	200-300 kg/m^3
Specific weight	2200 kg/m^3
Melting point	1550-1570 ^{o}C

Fig. 2. All materials used in this study.

2.1.5 | Optical fiber

Optical fibers are slender strands of transparent material, typically glass or plastic, designed to transmit light from one end to the other. Decorative optical fibers are commercially available in various diameters, including 0.5 mm, 1 mm, 1.5 mm, and 3 mm. They are also classified based on their light transmission characteristics, falling into two main categories: end-emitting fibers and side-emitting fibers. End-emitting fibers, as the name suggests, transmit light primarily from one end to the other. Conversely, side-emitting fibers transmit light along the entire length of the fiber in addition to the end. In this study, end-emitting optical fibers with a diameter of 1.5 mm were employed.

2.2 | Cast and Curing

The molds were designed from 6 mm thick polycarbonate sheets with dimensions of 15 cm x 15 cm and prepared by laser cutting. In *Fig. 3*, two molds are shown (Pay attention to the arrangement of optical fibers before concreting). During mold fabrication, a grid of 49 holes (Arranged in a 7x7 array) with a diameter of 5 mm is precisely drilled into the mold faces. This hole configuration is designed to achieve a 4% optical fiber volume fraction within the final concrete composite. The mold components are then assembled using adhesive and further secured with wire ties to prevent deformation or separation during the concrete casting process. With the mold assembled, the optical fibers are carefully positioned. The fibers are pre-cut to a length of 20 cm, exceeding the mold's 15 cm dimension to allow for secure anchoring. Six optical fibers are then inserted into each hole, and both ends are affixed to the mold surface using adhesive. *Fig. 4* shows the design of light-transmitting concrete molds.

Fig. 3. Two molds with optical fibers.

Fig. 4. Design of light transmitting concrete molds.

Following fabrication, the concrete specimens comprising three control samples, three samples with 5% microsilica gel, three samples with 10% microsilica gel, and three samples with 15% microsilica gel were initially cured for 24 hours in a controlled environment maintained at 90% relative humidity and 21°C. Subsequently, the specimens were demolded and submerged in water for a 28-day curing period, consistent with the procedure illustrated in *Fig 5*. Three samples were prepared for each proposed mixture to provide reliable results.

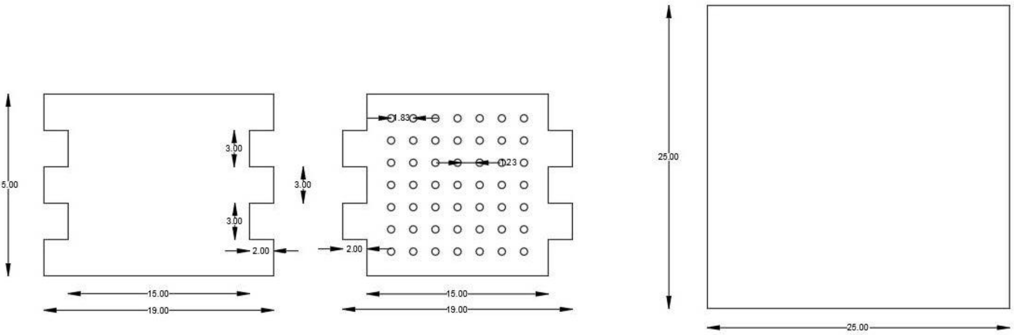

Fig. 5. Curing of samples.

2.3 | Testing

Light transmittance through the concrete specimens was quantified using a spectrometer. This analysis revealed that, on average, the specimens transmitted approximately 5% of incident light. Subsequently, the

28-day compressive strength was determined by testing three specimens from each mix design to failure using a compression testing machine.

3 | Discussions

The compressive strength of Self-Compacting Light-Transmitting Concrete (SCLTC) and its variations with different SF contents (5%, 10%, and 15%) were evaluated and shown in *Table 3*. Three samples were prepared for each mixture, and the average values were assessed as depicted in *Fig. 6*. The control sample (SCLTC) exhibited the highest compressive strength of 58.3 MPa. The incorporation of 5% SF (SF5SCLTC) resulted in a drastic reduction to 18.8 MPa, representing a 67.8% decrease compared to the control. Increasing the SF content to 10% (SF10SCLTC) improved the strength to 35.2 MPa, though this remained 39.6% lower than the control. Further increasing the SF to 15% (SF15SCLTC) led to a decline in strength (18.9 MPa), mirroring the 5% SF sample and indicating a saturation threshold beyond which additional SF becomes detrimental.

Table 3. Compressive strength of different samples.

Sample Name	SF (%)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
SCLTC No. 1	0	52.9	58.3
SCLTC No. 2	0	61.6	
SCLTC No. 3	0	60.4	
SF5SCLTC No. 1	5	14.3	18.8
SF5SCLTC No. 2	5	13.1	
SF5SCLTC No. 3	5	29.0	
SF10SCLTC No. 1	10	48.1	35.2
SF10SCLTC No. 2	10	28.5	
SF10SCLTC No. 3	10	29.0	
SF15SCLTC No. 1	15	19.7	18.9
SF15SCLTC No. 2	15	21.6	
SF15SCLTC No. 3	15	15.3	

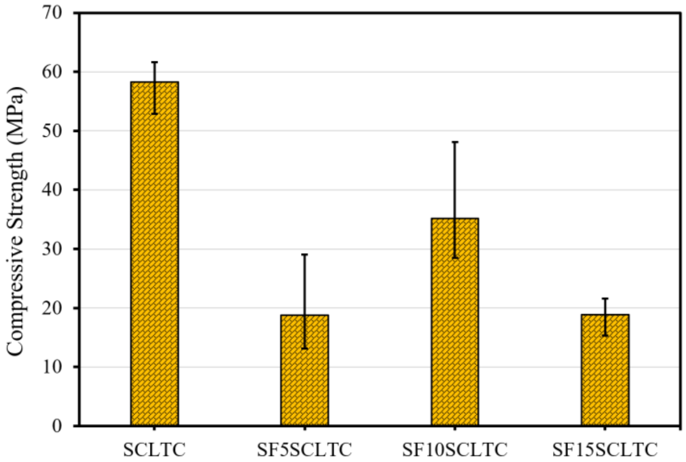

Fig. 6. The average values compressive strength of 3 samples for each mixture.

The optimal SF content for compressive strength was identified as 10%, as it yielded the highest strength among the modified samples. However, none of the SF-modified samples surpassed the control, suggesting that SF negatively impacts the compressive strength of SCLTC under the tested conditions. This trend contrasts with conventional concrete, where SF typically enhances strength via pozzolanic reactions and pore refinement. The observed reduction may stem from incompatibility between SF and the specialized components of SCLTC (e.g., optical fibers, lightweight aggregates). Excessive SF likely disrupted the particle packing density, increased water demand due to its high surface area, and potentially hindered fiber-matrix bonding, leading to stress concentration points. The rebound in strength at 10% SF may reflect a balance between limited pozzolanic activity and manageable rheological disruption, while higher percentages exacerbated agglomeration and microstructural defects. These findings underscore the need for tailored mix design optimization when incorporating SF into SCLTC, as its behavior diverges from conventional concrete. Future studies should explore lower SF dosages (<5%) and synergistic use with superplasticizers to mitigate adverse effects while leveraging its potential benefits.

4 | Conclusion

This study presents a comprehensive investigation into the mechanical and functional properties of SCLTC incorporating 4% optical fibers by volume and varying ratios of SF (5%, 10%, and 15%). The results show that the incorporation of SF negatively impacts the compressive strength of SCLTC, with an optimal content of 10% yielding the highest strength among the modified samples. However, none of the SF-modified samples surpassed the control, highlighting the need for mix design optimization when incorporating SF into SCLTC.

The findings of this research can be summarized as follows:

I. The control sample (SCLTC) exhibited the highest compressive strength of 58.3 MPa.

II. The incorporation of 5% SF (SF5SCLTC) resulted in a 67.8% decrease in compressive strength compared to the control.

III. Increasing the SF content to 10% (SF10SCLTC) improved the strength to 35.2 MPa, though this remained 39.6% lower than the control.

IV. Further increasing the SF to 15% (SF15SCLTC) led to a decline in strength (18.9 MPa), mirroring the 5% SF sample.

V. The optimal SF content for compressive strength was identified as 10%.

While this study provides valuable insights into the behavior of SCLTC with SF, further investigation is needed to fully understand the effects of SF on the mechanical and functional properties of SCLTC. Future studies should explore lower SF dosages (<5%) and synergistic use with superplasticizers to mitigate adverse effects while leveraging its potential benefits. Additionally, the study of other SCMs and their interactions with optical fibers and lightweight aggregates could provide new avenues for improving the performance of SCLTC. Furthermore, durability tests like freeze-thaw cycles should be done on the proposed mixtures. The development of optimized mix designs and tailored construction techniques will be crucial for the widespread adoption of SCLTC in building applications.

Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data generated or analyzed during this study are included in this published article. The raw data is also available from the corresponding author upon reasonable request.

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