Technobius, 2026, 6(3), 0106, DOI: https://doi.org/10.54355/tbus/27897338.6.3.2026.0106

Technobius

https://technobius.kz/

e-ISSN 2789-7338

Article

Effect of polypropylene fiber length on the mechanical properties, frost resistance, and microstructure of silica fume-modified self-compacting concrete

Assel Ospanova[1,*], Evgeniya Tkach[2], Tolebi Myrzaliyev[3]

[1]Department of Construction and Building Materials, Satbayev University, Almaty, Kazakhstan
[2]Department of Urban Planning, National Research Moscow State University of Civil Engineering, Moscow, Russia
[3]Department of Building Materials and Expertise in Construction, M. Auezov South Kazakhstan Research University, Shymkent, Kazakhstan
*Correspondence: ospanovakzz@mail.com

Abstract. This study investigates the influence of polypropylene fiber length (6–20 mm) on the mechanical properties, frost resistance, density, and microstructure of silica fume-modified self-compacting concrete (SCC). Microstructural analysis by scanning electron microscopy (SEM) was performed on the fiber-free reference mixture and the optimum fiber lengths of 12- and 15-mm. Polypropylene fibers affected the durability and strength performance of SCC: mixtures with 12 mm and 15 mm fibers performed best overall, reaching the highest 28-day compressive strengths (55.3 and 54.9 MPa), average density up to 2412 kg/m^3, and frost resistance up to F350. Water absorption decreased from 4.8% in the fiber-free reference mixture to 4.1-4.2% in these mixtures. SEM observations indicated a relatively dense cement matrix with fewer visible pores and apparent fiber–matrix contact in the 12 mm and 15 mm mixtures. Because all mixtures contained the same silica fume dosage, its individual effect could not be experimentally isolated; based on the literature, its pozzolanic and microfiller effects may have contributed to the observed matrix morphology, while differences among mixtures were primarily associated with fiber presence and length. Overall, 12 mm and 15 mm fibers provided the best combination of mechanical and durability-related properties among the lengths tested.
Keywords: self-compacting concrete; microsilica; polypropylene fiber; compressive strength; frost resistance; density; SEM; microstructure.

1. Introduction

Self-compacting concrete (SCC) is a highly flowable concrete that consolidates under its own weight without external vibration. Due to its high flowability and ability to fill formworks of complex geometry and pass through densely reinforced structures, this material significantly improves the quality of concrete placement, reducing labor intensity during construction work [1]. The use of SCC also improves working conditions at construction sites by eliminating vibration compaction and reducing noise levels [2]. Owing to its high filling ability and passing ability, SCC is particularly effective in the production of complex reinforced concrete structures and elements with dense reinforcement [3]. Despite its significant advantages, the design of self-compacting concrete mixtures remains challenging. The high flowability of SCC is typically achieved by increasing the content of fine particles and paste phase, which may lead to increased shrinkage and the formation of microcracks at early stages of hardening [4]. The development of microcracks is one of the key factors affecting the durability of concrete structures, since moisture and aggressive agents penetrate the material structure through these microcracks [3]. Moreover, concrete is a complex multiphase system consisting of cement paste, pores, and hydration products, and its microstructure largely determines its strength and durability characteristics [5].

One of the most effective approaches to improving the properties of self-compacting concrete is the use of active mineral admixtures. Among them, silica fume occupies a special place. Silica fume is a highly reactive amorphous silicon dioxide with an extremely high specific surface area. Its incorporation into concrete mixtures contributes to densification of the cement matrix, reduction in porosity, and formation of additional C–S–H gel, thereby improving the strength and durability of concrete [6]. In addition, silica fume enhances the microstructure of concrete by refining the pore structure and promoting a denser distribution of hydration products, thereby improving the material's mechanical properties and long-term durability [7]. Furthermore, the use of mineral admixtures such as silica fume and fly ash can reduce the clinker content in cement composites, thereby decreasing the carbon footprint of concrete production [8], [9]. Previous studies have also shown that an optimal dosage of silica fume significantly increases concrete strength through pozzolanic reactions and improved cement matrix structure [10]. Another approach to improving the performance of SCC is the use of dispersed fiber reinforcement. The incorporation of polypropylene fibers helps reduce crack initiation and propagation and enhance the mechanical and deformation properties of cement-based composites [11]. Experimental studies have demonstrated that the addition of polypropylene fibers improves compressive, tensile, and flexural strength and increases the durability of self-compacting concrete. However, a slight reduction in workability may occur [2].

Several studies have investigated the combined use of mineral admixtures and fiber reinforcement. It has been reported that incorporating silica fume improves crack resistance and increases the fracture energy of concrete [11]. Other studies confirm that the use of fibers in SCC mixtures helps limit microcrack propagation and improve material strength through crack-bridging [3]. However, the influence of polypropylene fiber length on the structure of the cement matrix and the formation of SCC microstructure remains insufficiently studied.

[12] established that the use of polypropylene fibers of a certain length can significantly improve the physical and mechanical properties of self-compacting concrete. However, the microstructural mechanisms responsible for improving the performance characteristics of such compositions have not yet been sufficiently investigated. Based on this, it can be hypothesized that incorporating polypropylene fibers of optimal length into silica fume-modified self-compacting concrete contributes to the formation of a denser, more stable microstructure of the cement matrix through fiber reinforcement mechanisms and the restriction of microcrack propagation.

This study aims to conduct a comparative analysis of the microstructure, compressive strength, density, and frost resistance of self-compacting concrete modified with silica fume and containing polypropylene fibers of different lengths. The comprehensive evaluation of these parameters is intended to establish the relationships among the structural features of the cement matrix, the material's physical and mechanical properties, and its durability under cyclic freezing and thawing conditions.

2. Methods

Portland cement CEM II 42.5 produced by Alacem LLP (Almaty region, Kazakhstan), complying with [13] requirements, was used as the binder. The results of laboratory tests showed that the cement met the regulatory requirements for its main physical and mechanical characteristics. The residue on the sieve was 0.5%, indicating a high degree of cement fineness. The normal consistency of the cement paste was 28%. The initial and final setting times were within the limits specified by the standards. The compressive strength at 7 days reached 63 MPa, while the flexural strength was 6.6 MPa. No violation of volumetric stability was detected [13].

Microsilica of grade MC-95 produced by Tau-Ken Temir LLP (Karaganda, Kazakhstan) was used in the study. The mass fraction of active SiO_2 in the material is 95.9%, with a recommended dosage of up to 50 kg/m^3. Microsilica particles have a spherical shape with an approximate size of 0.1 μm, and the bulk density ranges from 150 to 250 kg/m^3. The main physicochemical characteristics of the material comply with the requirements, confirming its suitability for use in concrete mixtures [14], [15].

Quartz sand obtained from the Giada LLP (Almaty region, Kazakhstan) quarry was used as fine aggregate. Laboratory tests showed that it fully complies with the requirements of [16]. The fineness modulus of the sand was 2.3, corresponding to medium-grained sand. The moisture content of the sand was 2.5%, while the dust and clay content was 0.15%. The mass loss during washing did not exceed 0.15%. The bulk density of the sand was 1140 g/l [16].

Crushed stone produced by Ozentas LLP (Almaty region, Kazakhstan) with fractions of 5-10 mm and 10-20 mm was used as coarse aggregate. The tests conducted per [17] showed that it fully complies with the requirements of [18]. The content of needle-shaped and lamellar grains did not exceed 10%. The mass loss during crushing was 1.28%. The bulk density of the crushed stone was approximately 1240 g/l, confirming the material's high quality and stability [17].

The dosage of the polycarboxylate-ether-based superplasticizer CHRYSO®Fluid Optima 203 (Chryso, Inc., Dallas, TX, USA) was fixed at 6.5 kg/m^3 based on the previously optimized self-compacting concrete composition reported by [12]. However, fresh-state properties were not measured in the present study; therefore, compliance of the investigated mixtures with the EFNARC workability classes could not be independently verified.

Table 1 – Characteristics of CHRYSO®Fluid Optima 203 superplasticizer

State	Density	Color	pH	Solid content	Chloride content
Liquid	1.040 ± 0.02 g/cm^3	Brown	6.0 ± 1	21.5 ± 5 %	< 0.10 %

Polypropylene fiber from Fibralux LLC (St. Petersburg, Russian Federation) was used as a dispersed reinforcing material. The fiber has a circular cross-section and is produced in the form of monofilaments with a length of 6-20 mm and a diameter of approximately 34 µm. The fiber surface is treated with Silastol CUT 70, which ensures uniform distribution in the concrete mixture and improves adhesion with the cement matrix. The fiber density is 0.91 g/cm^3, the tensile strength ranges from 320 to 600 MPa, the modulus of elasticity is 3500-3900 MPa, and the elongation at break reaches up to 200%. In addition, the fiber does not absorb water and remains stable up to temperatures of 160-170 °C [19].

Table 2 – Composition of Concrete Mixtures

Mixture designation	Fiber length, mm	Cement, kg/m^3	Sand, kg/m^3	Crushed stone 5-10 mm, kg/m^3	Crushed stone 10-20 mm, kg/m^3	Silica fume, kg/m^3	Fiber, kg/m^3	Superplasticizer, kg/m^3	Water, kg/m^3
Fiber-free reference mixture	-	540	944	625	75	54	-	6.5	260
F-6	6	540	944	625	75	54	1.0	6.5	260
F-12	12	540	944	625	75	54	1.0	6.5	260
F-15	15	540	944	625	75	54	1.0	6.5	260
F-18	18	540	944	625	75	54	1.0	6.5	260
F-20	20	540	944	625	75	54	1.0	6.5	260

The frost resistance of the self-compacting concrete mixtures was determined in accordance with [20] using the first basic freeze-thaw method. Cube specimens measuring 100 × 100 × 100 mm were tested after water saturation in accordance with the standard procedure. Three specimens were tested for each mixture ($n = 3$). Freeze-thaw cycles were performed by freezing the specimens in air at a temperature of −18 ± 2 °C for at least 2.5 h, followed by thawing in water at 20 ± 2 °C for 2.0 ± 0.5 h. Frost resistance was evaluated based on residual compressive strength, mass loss after freeze-thaw exposure, and the absence of visible damage. The frost resistance grade (F250-F350) was assigned according to the requirements of [20].

Water absorption was determined in accordance with [21]. Cube specimens measuring 100 × 100 × 100 mm were oven-dried to constant mass, cooled to room temperature, and then immersed in water until full saturation. Three specimens were tested for each mixture (n = 3). Water absorption was calculated as the percentage increase in mass after saturation relative to the oven-dry mass, and the reported values represent the mean of three specimens.

Compressive strength was determined in accordance with [22] using cube specimens measuring 100×100×100 mm after 7 and 28 days of curing. Three specimens were tested for each mixture (n = 3), and the reported values represent the mean of three measurements. The average density of the concrete specimens was determined before the compressive strength test based on the specimen mass and dimensions in accordance with [22].

The composition of the self-compacting concrete used in this study was adopted from the experimentally validated mixture proposed by [12]. In that study, this composition was used as the base mixture, and subsequent tests evaluated its rheological properties, frost resistance, and microstructural characteristics. The water-to-binder (w/b) ratio of the mixtures was 0.42, where the binder consisted of Portland cement and silica fume used as a partial cement replacement.

Microstructural investigations were performed using scanning electron microscopy (SEM) to analyze the morphology of fracture surfaces of the self-compacting concrete specimens. Samples for SEM analysis were collected after mechanical testing. The size of the examined fragments was approximately 1-2 cm.

Before analysis, the specimen surfaces were cleaned of dust particles. During sample preparation, concrete fragments were mounted on Ø12/25 mm aluminum stubs using conductive carbon double-sided tape. Impregnation with epoxy resin and conductive coating (Au, C, or Pd) was not applied.

SEM observations were performed in high-vacuum mode using a JEOL JSM-7000 scanning electron microscope (JEOL Ltd., Tokyo, Japan) with secondary electron detection. The accelerating voltage was varied between 5 and 15 kV depending on the specimen and the imaging conditions, while the working distance ranged approximately from 13.6 to 15.5 mm. Microstructural observations were carried out at magnifications of ×2000 and ×4000. The analysis focused on fracture-surface morphology, visible pores and cracks, and the apparent contact between the polypropylene fibers and the cement matrix.

3. Results and Discussion

3.1 Frost Resistance and Water Absorption of SCC Mixtures

To evaluate the durability of the developed self-compacting concrete mixtures, water absorption and freeze-thaw resistance tests were conducted. These parameters are among the key indicators of concrete durability under cyclic freezing and thawing conditions. Water absorption, mass loss after freeze-thaw exposure, residual compressive strength, and the corresponding frost resistance grade were determined for each mixture. The results presented in Table 3 show that water absorption, mass loss after freeze-thaw exposure, residual compressive strength, and frost resistance varied with polypropylene fiber length in the investigated silica-fume-modified SCC mixtures.

Table 3 – Effect of fiber length on water absorption and frost resistance of SCC

Parameter	Fiber-free reference mixture	F-6	F-12	F-15	F-18	F-20
Water absorption, %	4.8	4.5	4.1	4.2	4.3	5.2
Mass loss after freeze-thaw, %	2.6	2.1	1.4	1.6	1.9	2.3
Residual compressive strength, %	87.2	89.1	93.4	92.6	90.3	85.6
Frost resistance grade	F300	F300	F350	F350	F300	F250

Table 3 presents the water absorption, mass loss after freeze-thaw exposure, residual compressive strength, and the corresponding frost resistance grade for all investigated SCC mixtures. The reported values represent the mean values of three specimens (n = 3).

The fiber-free reference mixture exhibited a water absorption of 4.8%, a mass loss of 2.6%, a residual compressive strength of 87.2%, and a frost-resistance grade of F300. Because all investigated mixtures contained 54 kg/m³ of silica fume, the individual contribution of silica fume to these properties could not be determined from the present experimental design.

Among the tested mixtures, those containing 12 mm and 15 mm fibers exhibited the lowest water absorption values (4.1% and 4.2%), the lowest mass losses (1.4% and 1.6%), the highest residual compressive strengths (93.4% and 92.6%), and the highest frost-resistance grade (F350). These results indicate that the addition of fibers with these tested lengths was associated with improved durability-related properties compared with the fiber-free reference mixture.

The observed trends may be associated with differences in fiber distribution and crack-bridging behavior. Previous studies have reported that polypropylene fibers can restrict crack development in cement-based composites [2], [11]. However, because no silica-fume-free mixture was investigated, the present results should not be interpreted as direct experimental evidence of the pore-refining or pozzolanic effects of silica fume. Furthermore, microcrack development during freeze-thaw exposure was not directly monitored in this study; therefore, the proposed crack-bridging mechanism should be regarded as a literature-supported explanation rather than an experimentally verified mechanism.

For the mixtures containing 18 mm and 20 mm fibers, the frost-resistance grade decreased to F300 and F250, respectively. At the same time, water absorption increased to 4.3% and 5.2%, mass loss increased to 1.9% and 2.3%, and residual compressive strength decreased to 90.3% and 85.6%, respectively. Longer fibers may adversely affect the flow of SCC and the uniformity of fiber distribution, as reported in previous studies [2], [12]. However, because fresh-state properties, fiber distribution, and porosity were not directly measured in the present study, reduced workability, fiber agglomeration, and increased porosity should be considered possible explanations rather than experimentally verified mechanisms. Overall, among the fiber lengths investigated in this study, the mixtures containing 12 mm and 15 mm fibers exhibited the best combined frost resistance, lowest water absorption, lowest mass loss, and highest residual compressive strength. Nevertheless, the mechanisms underlying these trends require further investigation through fresh-state testing and quantitative assessment of fiber distribution, pore characteristics, and freeze-thaw-induced damage.

3.2 Strength and Average Density of SCC

Following the evaluation of durability-related properties, the average density and strength characteristics of the developed self-compacting concrete mixtures were analyzed. These parameters enable assessment of cement matrix densification, dispersed reinforcement efficiency, and the influence of polypropylene fiber length on the material's load-bearing capacity. The obtained results are presented in Table 4.

Table 4 – Effect of polypropylene fiber length on compressive strength and density of self-compacting concrete

No.	Fiber length, mm	Compressive strength, MPa		Density, kg/m³
		7-day	28-day	
1	Fiber-free reference mixture	39	51	2390
2	6	40.5	52.4	2398
3	12	42	55.3	2412
4	15	41.9	54.9	2408
5	18	40.9	53.2	2399
6	20	38.7	49.5	2378

The average density and compressive strength at 7 and 28 days varied with the length of the incorporated polypropylene fibers.

The fiber-free reference mixture exhibited compressive strengths of 39.0 MPa at 7 days and 51.0 MPa at 28 days, with an average density of 2390 kg/m³. The mixture containing 6 mm fibers exhibited corresponding compressive strengths of 40.5 and 52.4 MPa and an average density of 2398 kg/m^3. This moderate increase may be associated with the reinforcing and crack-bridging functions of polypropylene fibers reported in previous studies [2], [11]. However, microcrack development was not directly evaluated in the present study.

Among the tested mixtures, those containing 12- and 15-mm fibers exhibited the highest compressive strength and average density values. The mixture containing 12 mm fibers reached compressive strengths of 42.0 MPa at 7 days and 55.3 MPa at 28 days, with an average density of 2412 kg/m^3. For the mixture containing 15 mm fibers, the corresponding values were 41.9 MPa, 54.9 MPa, and 2408 kg/m^3, respectively. Because no statistical analysis or direct measurements of compaction and porosity were performed, the small differences between these two mixtures should be interpreted descriptively and cannot be attributed conclusively to more efficient fiber distribution or matrix densification.

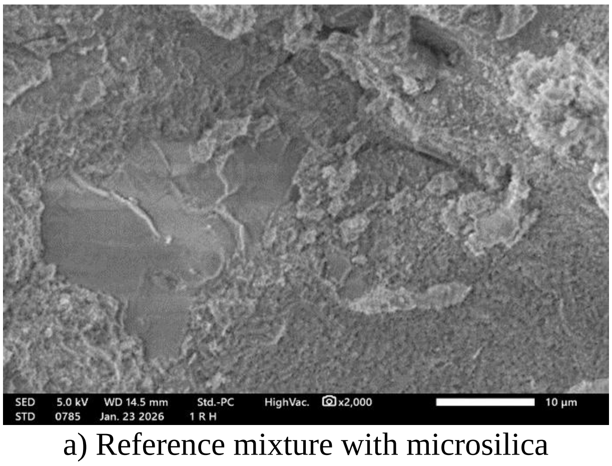
For the mixture containing 18 mm fibers, the compressive strength and average density decreased slightly compared with the mixtures containing 12- and 15-mm fibers. Nevertheless, its compressive strength and average density remained higher than those of the fiber-free reference mixture. Fiber distribution was not quantitatively assessed; therefore, the observed changes cannot be conclusively attributed to differences in distribution efficiency.

When the fiber length was increased to 20 mm, the compressive strength decreased to 38.7 MPa at 7 days and 49.5 MPa at 28 days, while the average density decreased to 2378 kg/m^3. This trend may be associated with changes in fresh-state behavior or fiber distribution caused by the use of longer fibers. However, because workability, fiber distribution, air content, and porosity were not directly measured, these factors should be regarded as possible explanations rather than experimentally verified mechanisms.

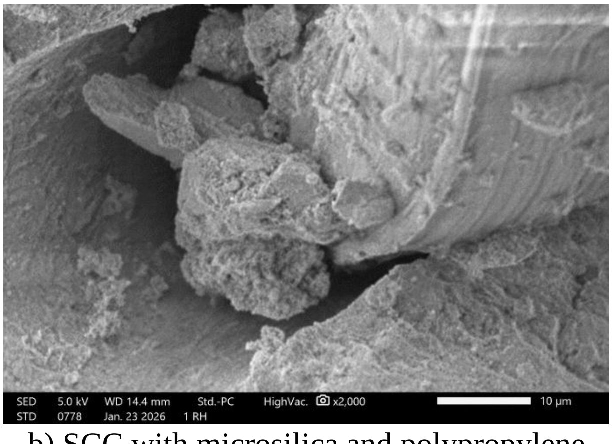
Overall, among the fiber lengths investigated in this study, the mixtures containing 12- and 15-mm fibers exhibited the highest compressive strength and average density values. These findings are consistent with their comparatively favorable frost-resistance and water-absorption results. Further research incorporating replicate-based statistical analysis, fresh-state testing, and quantitative assessment of fiber distribution and porosity is required to explain the mechanisms underlying these trends.

3.3 Microstructural Analysis of Selected SCC Mixtures

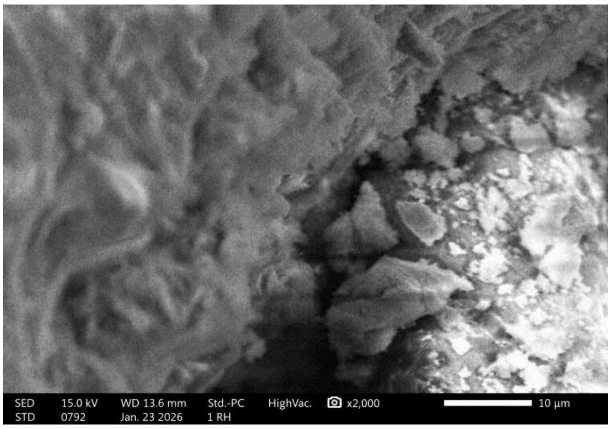
Considering that the mixtures containing 12 mm and 15 mm fibers showed the highest frost resistance grade (F350), the highest maximum compressive strength, and the highest average density, these compositions were identified as the optimum mixes. Therefore, together with the reference composition, they were selected for detailed SEM analysis to establish the relationship between microstructure and macroscopic performance.



a) Reference mixture with microsilica



b) SCC with microsilica and polypropylene fiber (12 mm)



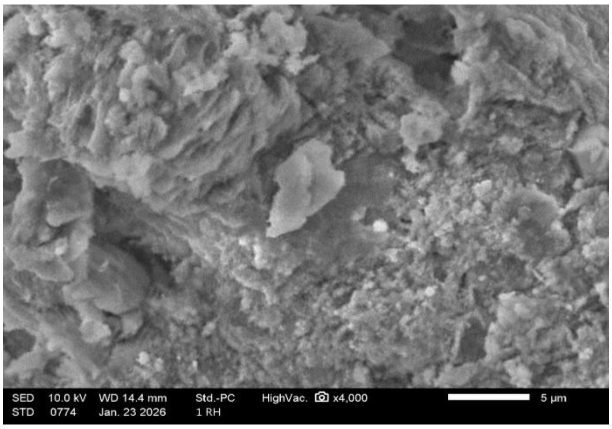
c) SCC with microsilica and polypropylene fiber (15 mm)

Figure 1 – Microstructure of modified self-compacting concrete at ×2000 magnification

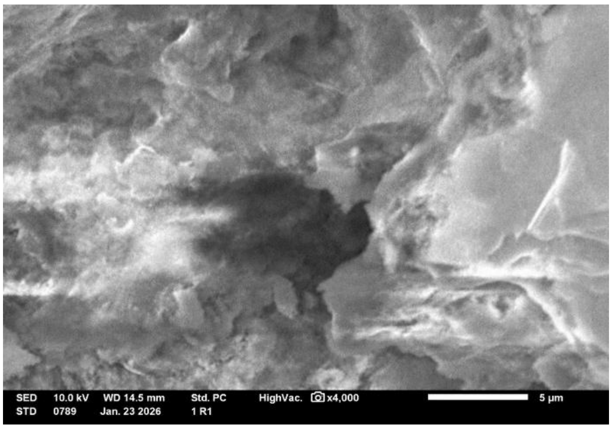
Figure 1a shows the microstructure of the fracture surface of self-compacting concrete containing microsilica without polypropylene fibers. SEM observations indicate that the cement matrix has a relatively dense and homogeneous structure. Fine hydration products and small pores were observed within the cement matrix. Based on the literature, the observed morphology may be associated with the microfiller and pozzolanic effects of microsilica. However, because all investigated mixtures contained the same silica-fume dosage, the independent contribution of microsilica could not be experimentally verified in the present study.

Figure 1b shows the microstructure of self-compacting concrete containing polypropylene fibers with a length of 12 mm. SEM observations indicate that the cement matrix remained relatively dense and that hydration products were observed around the polypropylene fibers. The interaction zone between the fiber and the cement matrix is clearly visible. The observed morphology may indicate good mechanical contact between the fiber and the cement matrix. A crack-bridging effect has been reported in previous studies [2], [11]; however, crack propagation was not directly evaluated in the present study.

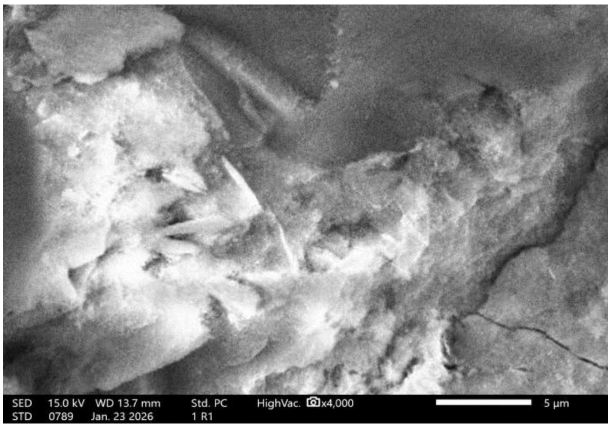
Figure 1c shows the microstructure of the composition containing polypropylene fibers with a length of 15 mm. SEM observations indicate that the cement matrix remained relatively dense and that hydration products were observed in the vicinity of the fibers. In the contact zone between the fiber and the cement matrix, the cement paste appears to be closely attached to the fiber surface. Although micropores were observed near the fiber in some areas, no major morphological differences were identified compared with the 12 mm mixture. These observations suggest that polypropylene fibers primarily act as dispersed reinforcing elements within the cement matrix.



a) Fiber-free reference mixture with microsilica



b) SCC with microsilica and polypropylene fiber (12 mm)



c) SCC with microsilica and polypropylene fiber (15 mm)

Figure 2 – Microstructure of modified self-compacting concrete at ×4000 magnification

Figure 2a presents the microstructure of the fiber-free reference mixture containing microsilica at a magnification of ×4000. SEM observations indicate a relatively dense cement matrix with fine hydration products distributed throughout the microstructure. Individual pores and microcracks were also observed. Based on the literature, the observed morphology may be associated with the microfiller and pozzolanic effects of microsilica. However, because all investigated mixtures contained the same silica-fume dosage, the independent contribution of microsilica could not be experimentally verified in the present study.

Figure 2b shows the microstructure of the mixture containing polypropylene fibers with a length of 12 mm. At higher magnification, the cement matrix appeared relatively dense and uniform. Hydration products were observed around the polypropylene fiber, and the interface between the matrix and the fiber was clearly visible. The observed morphology may indicate good mechanical contact between the fiber and the cement matrix. A crack-bridging effect has been reported in previous studies [2], [11]; however, crack propagation was not directly evaluated in the present study.

Figure 2c shows the microstructure of the composition containing polypropylene fibers with a length of 15 mm. SEM observations indicate that the cement matrix remained relatively dense and that hydration products were observed in the vicinity of the fibers. In the interface zone between the fiber and the cement matrix, the cement paste appeared to be closely attached to the fiber surface. Micropores and microcracks were observed in some areas. These observations suggest that polypropylene fibers primarily act as dispersed reinforcing elements within the cement matrix.

4. Conclusions

Based on the experimental investigation of silica-fume-modified self-compacting concrete containing polypropylene fibers of different lengths, the following conclusions were drawn:

The measured durability and mechanical properties varied depending on polypropylene fiber length. Among the tested mixtures, those containing 12- and 15-mm fibers exhibited the best combined performance. Their frost-resistance grade reached F350, their water absorption values were 4.1% and 4.2%, and their 28-day compressive strengths were 55.3 and 54.9 MPa, respectively.

The mixture containing 12 mm fibers exhibited the highest average density of 2412 kg/m^3. However, because no statistical analysis or direct measurement of compaction and porosity was performed, this result alone cannot confirm improved compaction or the formation of a denser cement matrix.

SEM examination of the selected fiber-free reference, 12 mm, and 15 mm mixtures revealed differences in fracture-surface morphology and apparent fiber-matrix contact. Local pores, gaps, and cracks were also observed. Because secondary-electron SEM does not provide chemical or phase identification, the observed features were interpreted only in terms of morphology. Furthermore, as all mixtures contained the same silica-fume dosage of 54 kg/m^3, the independent contribution of silica fume to pore refinement and matrix densification could not be experimentally determined.

The mixture containing 20 mm fibers exhibited the lowest 7- and 28-day compressive strengths of 38.7 and 49.5 MPa, respectively, the lowest average density of 2378 kg/m^3, the lowest frost-resistance grade of F250, and the highest water absorption of 5.2%. Reduced workability, nonuniform fiber distribution, and increased porosity may be possible explanations for this trend. However, these mechanisms were not experimentally verified because fresh-state properties, fiber distribution, and porosity were not directly measured.

Overall, among the fiber lengths investigated in this study, 12 and 15 mm produced the most favorable combined strength, density, frost-resistance, and water-absorption results at a fixed fiber dosage of 1.0 kg/m^3. Further research should include replicate-based statistical analysis, fresh-state testing, quantitative evaluation of fiber distribution and porosity, and microstructural examination of all investigated mixtures.

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Information about authors:

Assel Ospanova – MSc, PhD Student, Department of Construction and Building Materials, Satbayev University, Almaty, Kazakhstan, ospanovakzz@mail.com

Evgenia Tkach – Doctor of Technical Sciences, Professor, Department of Urban Planning, National Research Moscow State University of Civil Engineering, Moscow, Russia, ev_tkach@mail.ru

Tolebi Myrzaliyev – PhD Student, Department of Building Materials and Expertise in Construction, M. Auezov South Kazakhstan Research University, Shymkent, Kazakhstan, toleshadil.91@gmail.com

Author Contributions:

Assel Ospanova – conceptualization, methodology, experimental investigation, testing, analysis, visualization, writing – original draft.

Evgenia Tkach – supervision, validation, scientific guidance, writing – review & editing.

Tolebi Myrzaliyev – conceptualization, supervision, scientific consultation, writing – review & editing.

Conflict of Interest: The authors declare no conflict of interest.

Use of Artificial Intelligence (AI): AI tools were used to assist in literature screening and language refinement. All content was critically reviewed, verified, and edited by the authors to ensure accuracy and scientific integrity.

Received: 07.04.2026
Revised: 03.08.2026
Accepted: 16.08.2026
Published: 22.08.2026