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PRACTICE-ORIENTED PAPER

Synergistic effects of pozzolan and carbon fibers on the performance of self-consolidating concrete under plastic shrinkage and dynamic loading

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Abstract

Self-Consolidating Concrete (SCC) is widely used in infrastructure development, but challenges with cracking persist, largely due to its high cement content. While extensive research has been conducted on various types of concrete shrinkage, the phenomenon of plastic shrinkage in SCC remains insufficiently addressed. Additionally, concrete structures' susceptibility to transient dynamic loads, such as impacts, highlights the need for a deeper understanding of concrete behavior under such conditions. Concrete's response to short-term dynamic loads like impacts from projectiles, seismic activities, and strong winds significantly differs from its static condition response. This study aims to investigate SCC with the incorporation of various pozzolans as partial cement substitutes, along with carbon fibers to enhance concrete reinforcement. Specifically, zeolite was introduced with substitution ratios of 5% and 10%, nano-silica at 0.5% and 1%, and carbon fibers at 0.25% and 0.5%. The research objectives were pursued through a three-part testing methodology: (1) analysis of fresh concrete properties using slump flow, V-funnel, and L-box tests; (2) evaluation of hardened concrete performance through compressive, tensile, flexural, and impact assessments; and (3) examination of hardened concrete characteristics using non-destructive methods, including quantification of water absorption, electrical resistance, and plastic shrinkage. The results of the fresh concrete assessments for the various SCC mixtures met the EFNARC benchmarks. The inclusion of pozzolans led to increases in compressive strength by 2–8%, tensile strength by 5–29%, and flexural strength by 4.5–14.5%. Furthermore, the incorporation of carbon fibers was found to enhance compressive, tensile, and flexural strength by up to 3.5%, 20.5%, and 12%, respectively. Importantly, regarding impact resistance, the combined presence of pozzolans and carbon fibers had a positive effect. Carbon fibers, with their crack-bridging properties, effectively reduced crack propagation, resulting in a significant 50% improvement in peak impact strength and a remarkable 70.83% reduction in crack width. Although nano-silica showed promising effects on mechanical properties, it adversely affected plastic shrinkage, indicating increased susceptibility to initial cracking.

Keywords Self-consolidating concrete · Carbon fiber · Zeolite · Nano-silica · Plastic shrinkage · Impact strength · Mechanical properties

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Introduction

The United Nations report [1] predicts that the global population will exceed 9.772 billion by 2050, fueling a significant increase in construction activity. According to Statista [2], the construction industry, encompassing both residential and non-residential sectors, spent an estimated $10.5 trillion, $10.9 trillion, and $11.5 trillion in 2016, 2017, and 2018, respectively. Similarly, expenditures for 2020, 2021, and 2022 amounted to $12.5 trillion, $12.9 trillion, and $13.4 trillion. Projections indicate a further increase to $14.8 trillion by 2025 and $19.2 trillion by 2035 [2]. Consequently, this rapid surge in construction activity intensifies the demand for concrete, a crucial construction material. However, concrete production has negative environmental impacts, including pollution from cement, depletion of natural aggregates, and extensive water consumption [3]. Given the urgent need to reduce energy consumption and greenhouse gas emissions, designers are actively exploring methods to produce environmentally friendly concrete that maintains acceptable mechanical strength and optimal durability [4].

In recent years, there has been a concerted effort to produce greener and more sustainable concrete by replacing cement with industrial by-products and various pozzolans. Nanomaterials, zeolite, silica fume, fly ash, slag, and other types of pozzolanic materials are categorized as supplementary cementitious materials (SCMs) and can effectively substitute cement [5–7]. When incorporated into concrete in specified proportions alongside cement, SCMs reduce permeability and enhance concrete's resistance to acid attack, reinforcement corrosion, and sulfate exposure. Concrete containing SCMs has demonstrated improved durability, reduced environmental impacts, and lower production costs [8].

In recent years, the construction industry has been exploring new methods for concrete design. One remarkable outcome of these innovations is Self-Consolidating Concrete (SCC), which originated in Japan in the late 1990s. SCC is a cementitious material that has the ability to flow under its weight [9]. SCC offers a range of benefits, including ecological sustainability, reduction of noise pollution, faster construction speed, improved on-site safety, higher construction quality, reduced labor requirements, better economic feasibility, superior final product quality, enhanced freeze–thaw resistance, and longer mold lifetimes due to the elimination of vibration. However, concrete does have certain weaknesses, such as low tensile strength and limited strain capacity upon failure. Cracking is a particularly significant issue, and the inherent brittleness of concrete can lead to unexpected structural problems [10]. To address these challenges, fibers can be effectively incorporated into concrete to strengthen it and mitigate its weaknesses [3].

Fibers offer numerous advantages, including fatigue enhancement, improved impact resistance (both initial and failure strength), increased ductility, decreased creep, reduced shrinkage cracking, diminished permeability, and better post-crack performance [11]. Research indicates that fibers can enhance crucial structural properties of concrete, such as flexural strength, compressive strength, tensile strength, and shear strength [3]. Carbon fibers, which have been used for concrete reinforcement since the 1970s, are particularly noteworthy for their low density, excellent thermal conductivity, and high elastic modulus [12]. They effectively enhance the mechanical properties of concrete and have garnered attention as smart structural materials in contemporary research due to their favorable electrical conductivity [13]. Fibers also improve the resistance and crack-control capabilities of the matrix [14].

Plastic shrinkage cracks are the initial cracks that appear in concrete, typically emerging within six hours after casting and before the concrete fully sets. These cracks pose a threat to the durability of concrete structures by allowing water, chloride, and other corrosive substances to infiltrate the material. Volume changes occurring before the cementitious matrix hardens are the primary cause of plastic shrinkage cracks. Bleeding, aggregate distribution, and water evaporation are factors contributing to volume changes during the plastic stage of concrete. In this phase, denser components like solid particles tend to settle, while less dense ones such as air and water rise to the surface. As a result, air escapes rapidly, while water, known as bleeding water, drains more slowly. If the rate of water loss due to evaporation surpasses the water supply from bleeding, the concrete surface becomes dry, heightening the risk of plastic shrinkage cracks.

Extensive research has been conducted on concrete containing carbon fibers, exploring various aspects of its properties and performance. Xiong et al. studied the influence of carbon fibers on mechanical properties and microstructure, demonstrating that higher carbon fiber content enhances fracture toughness, ultimate strength, and Vickers hardness. Tabatabaei et al. investigated the impact of long carbon fibers on concrete and observed improved blast resistance, contributing to enhanced durability. Jeon et al. examined the mechanical and dynamic performance of carbon fiber-reinforced polymer concrete, finding that it effectively reduces noise and offers a solution for mitigating noise pollution from high-speed trains. Mastali et al. concluded that increasing carbon fiber length and quantity significantly enhances impact resistance and mechanical characteristics of concrete. Deng et al. demonstrated the substantial positive impact of carbon fibers on the flexural fatigue of concrete. Additionally, Ghosh et al. conducted research on high-early-strength fiber-reinforced self-compacting concrete (SCC) using various types of fibers, including steel, glass, and carbon fibers, confirming that the type of fibers significantly influenced factors such as slump flow diameter, flow time, and concrete workability.

Significance of the research

The occurrence of cracks in concrete undermines its strength and durability. Previous research on concrete cracking has primarily focused on cracks induced by autogenous shrinkage, drying shrinkage, and static loads. This study delves into the cracking of self-consolidating concrete (SCC), incorporating fibers and pozzolans, resulting from two less-noticed factors: (1) Cracking due to rapid drying occurring in the plastic phase before the final setting of concrete (referred to as a plastic shrinkage test), and (2) Cracking due to short-term dynamic loads such as impact loads from bullets, vehicles, and earthquakes (referred to as a drop-weight test). Besides evaluating the performance of zeolite and nano-silica as cementitious materials, this study also examines the effect of carbon fibers as concrete reinforcement alongside pozzolans. Figure 1 provides a schematic representation of the study methodology.

Materials and test methods

Materials

This study employed a range of materials including cement, aggregates, zeolite, nano-silica, carbon fibers, water, and superplasticizer. The cement utilized was Type II from the Hegmatan Cement factory, featuring an initial setting time of 90 min, a final setting time of 240 min, and a density of 3170 kg/m^3. Chemical characteristics of the cement are presented in Table 1. Two types of pozzolans, nano-silica and zeolite, as shown in Figs. 2a and b, were incorporated into the cementitious mixture to enhance the properties of hardened concrete. The zeolite, sourced from the Semnan mine and Afrazand Company, boasted a specific gravity of 2.3 and a fineness of 320 cm^2/g, with chemical attributes detailed in Table 1. Amorphous nano-silica from Isatis Yazd company, with a maximum size of 15 ± 2 nm and a purity of 98% (Table 1), was also part of the mixture. Ordinary

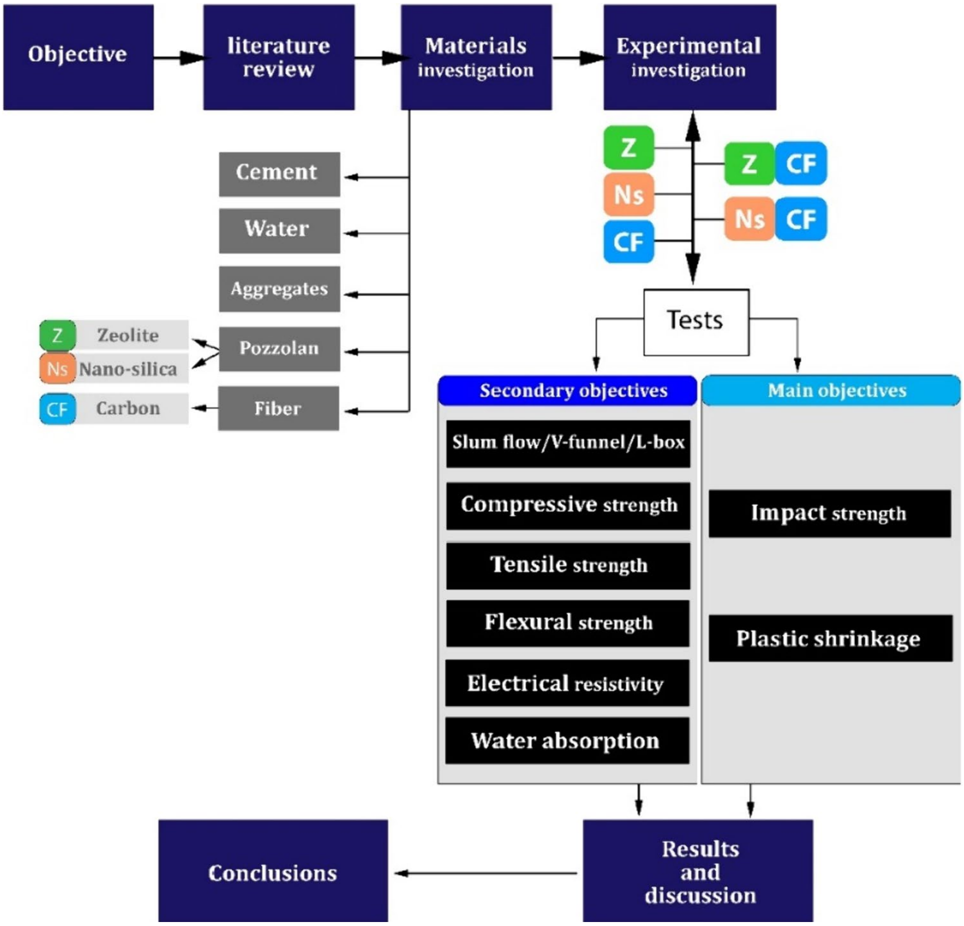


Fig. 1 The methodology utilized in this study

Table 1 Chemical properties of cement, zeolite, nano-silica, and limestone

Chemical analysis	Cement	Zeolite	Nano-silica	Limestone
SiO_2	21	68.5	98.6	0.22
Al_2O_3	5.26	11	0.07	0.18
Fe_2O_3	3	1.5	0.294	0.44
CaO	63	0.6	0.393	55.07
MgO	2.7	1.3	0.05	0.34
K_2O	0.65	4	0.08	0.11
SO_3	2.3	0.33	0.185	
Fineness-specific surface Blain (cm^2/g)	2910	320	202	6244

drinking water was used in the mixtures, along with the superplasticizer FARCO PLAST P10-3R, a product of Shimi Sakhteman company, with characteristics outlined in Table 2.

The study investigated the impact of carbon fibers on mix designs, utilizing 6 mm long and 7-micron diameter carbon fibers from Toray company. The carbon fibers used are depicted in Fig. 2c, and their mechanical properties are summarized in Table 3. River gravel and sand served as the aggregates, with the gravel having a maximum size of 12.5 mm, an apparent specific gravity of 2.64, a fineness modulus of 6.37, and a water absorption rate of 1.5%. The sand exhibited an apparent specific gravity of 2.5, a fineness modulus of 2.46, and a water absorption of 2.5%. Aggregate grading, following ASTM C33 standards, is provided in Table 4. Limestone powder, sourced from the Qom factory, featured a density of 2.7 g/cm^3, with chemical characteristics and granulation detailed in Tables 1 and 4, respectively.

Table 3 Mechanical properties of carbon fiber

	Diameter (µm)	Density (g/cm^3)	Tensile strength (GPa)	Young's modulus (GPa)	Electrical resistivity (Ωcm)
Carbon fiber	7 ± 0.1	1.78	≥ 3	235	2.8×10^{-3}

Mixing and sample preparation

This study examined several Self-Consolidating Concrete (SCC) mixes with unique characteristics, detailed in Table 5. The research objectives necessitated nine distinct mix designs, each comprising 25 specimens. Cement was partially substituted with zeolite and nano-silica, with replacement rates of 5% and 10% for zeolite, and 0.5% and 1% for nano-silica. Additionally, the mixtures incorporated carbon fibers for reinforcement, at volumes of 0.25% and 0.5%.

The SCC mixes adhered to ASTM C 192 [25] standards for material blending. Initially, gravel and a small quantity of mixing water were introduced into the mixer. The mixer operated for 30 s to distribute the gravel uniformly. Subsequently, sand, limestone powder, and pozzolanic materials were added to the mixer and blended for 1 min. Water and

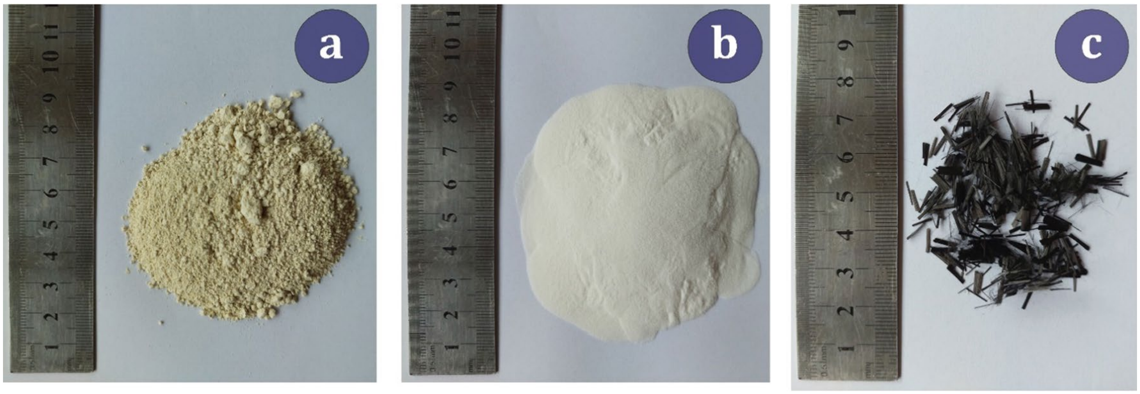


Fig. 2 Concrete additives: **a** zeolite, **b** nano-silica, **c** carbon fibers

Table 2 Specifications of superplasticizer

Technical features					
Physical State	Color	Specific weight	Chemical Base	PH	Chloride
Liquid	Dark green	1.1 ± 0.02 gr/cm^3	Modified polycarboxylic acid copolymers	7 ± 1	500 PPM Max

Table 4 Aggregate grading

Sieve size	Passing percentage		
	Gravel	Sand	Limestone
19 mm	100	100	
12.5 mm	91.1	100	
9.5 mm	67.12	100	
4.75 mm	4.361	99.97	
2.36 mm	0.43	92.96	100
1.18 mm		77.35	95
600 µm		58	80
300 µm		22.32	61
150 µm		3.44	40

superplasticizer were then introduced into the mixer and mixed for 2 min. Carbon fibers were incorporated into the mix for an additional 2 min. Following a 1-min pause, the mixer resumed operation for an additional 3 min, totaling a mixing duration of 9.5 min. Subsequently, the concrete samples were left in molds for 24 h, in accordance with concrete production standards. Afterward, they were removed from the molds and placed in a water tank at 23 ± 2 °C until testing commenced.

Tests

This investigation examined Self-Consolidating Concrete (SCC) through three distinct phases: (1) Fresh Concrete Tests, (2) Hardened-Destructive Concrete Tests, and (3) Hardened-Non-Destructive Concrete Tests. The initial phase involved assessing the fresh concrete using slump flow, V-funnel, and L-box tests to gauge the efficiency and workability of SCC. Subsequently, the hardened concrete underwent various examinations, which were either destructive or non-destructive. The destructive assessments included evaluations of compressive strength, tensile strength (Brazilian), flexural strength, and impact resistance. Non-destructive investigations focused on plastic shrinkage, electrical resistivity, and water absorption.

- Compressive strength was tested on three cubic samples (100 × 100 × 100 mm) per mixture at 28 and 42 days, following the BS 1881 [26] standard.
- Tensile strength (Brazilian) was assessed on three cylindrical samples (300 × 150 mm) per mixture according to the ASTM C496 [27] standard.
- The flexural strength test applied a load at the center of the beam span at 28 days, adhering to the ASTM C293 [28] standard. Three prism samples (70 × 70 × 280 mm) per mixture were utilized, with rupture occurring when the stress below the load point exceeded the concrete's tensile strength.
- Impact resistance was measured through a drop-weight test, based on ACI544 [29] recommendations. The test involved a concrete disc (64 mm thick, 150 mm diameter) extracted from the cylindrical samples (300 × 150 mm) and impacted by a 4.54 kg hammer released from a height of 457 mm. The first crack strength (number of blows causing the first surface crack) and the failure strength (number of blows causing the concrete disc to touch three of four metal lugs) were recorded by the test supervisor [6].
- Concrete water absorption was assessed on 28-day samples following the ASTM C642 [30] standard, using three cubic samples (100 × 100 × 100 mm) per mixture.
- Electrical resistivity evaluation was conducted on cylindrical samples (100 × 200 mm) at 28 days in accordance with AASHTO TP 119 [31] standard, using three samples per mixture.
- Plastic shrinkage testing for early-age concrete cracking assessment was performed following the ASTM C1579 [32] standard. The plastic shrinkage test is schematically shown in Fig. 3. Table 6 outlines the suitable laboratory

Table 5 Proportions of the investigated SCC mixtures

N.O	Mix code	Cement (Kg/m3)	Zeolite (Kg/m3)	Nano-silica (Kg/m3)	W/C	SP/C	Carbon fiber (Kg/m3)	Fine (Kg/m3)	Course (Kg/m3)
1	Ctrl	500	0	0	0.35	0.008	0	1325	1415
2	Z25	475	25	0	0.35	0.008	0	1325	1415
3	Z50	450	50	0	0.35	0.008	0	1325	1415
4	NS2.5	500	0	2.5	0.35	0.008	0	1325	1415
5	NS5	500	0	5	0.35	0.008	0	1325	1415
6	CF4.4	500	0	0	0.35	0.008	4.4	1325	1415
7	CF8.8	500	0	0	0.35	0.008	8.8	1325	1415
8	Z50CF8.8	450	50	0	0.35	0.008	8.8	1325	1415
9	NS5CF8.8	500	0	5	0.35	0.008	8.8	1325	1415

Z Zeolite, *NS* Nano-silica, *CF* Carbon fiber

Fig. 3 The plastic shrinkage test chamber

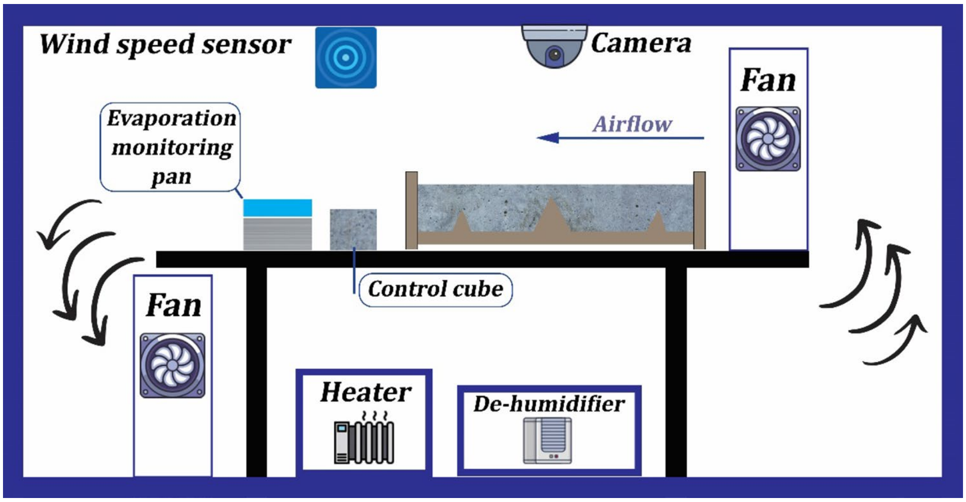


Table 6 Suitable laboratory conditions based on ASTM C1579 / Plastic shrinkage

Temperature	36 ± 3°C
Relative humidity	30 ± 10%
Wind speed	> 4.7 m/s

conditions according to ASTM C1579 [32]. The test utilized a controlled chamber with two slabs: a reference slab and a target slab, allowing simultaneous evaluation. After a 6-h test period, crack width was measured using a millimeter steel ruler at over 25 locations along each crack 24 h post-experiment. The crack reduction ratio (CRR) was calculated using Eq. 1, as recommended by ASTM C1579 [32]. A sample with visible cracks under plastic shrinkage conditions is depicted in Fig. 4.

Discussion and results

Fresh concrete results

Slump flow (SF)

The results of the slump flow (SF) test for various SCC mixtures are illustrated in Fig. 5. The Ctrl mix exhibited an SF value of 69 cm. The SF decreased by 1.45% and 2.9%, respectively, when the mix replaced 5% and 10% of cement with zeolite. This reduction in SF was primarily attributed to the water absorption and porosity of zeolite particles. When

$$\mathrm{CRR} = \left[1 - \frac{\text{Average Crack Width of Fibre Reinforced Concrete Mixture}}{\text{Average Crack Width of Fibre Control Concrete Mixture}}\right] \times 100\% \tag{1}$$

Fig. 4 the cracked sample under plastic shrinkage conditions

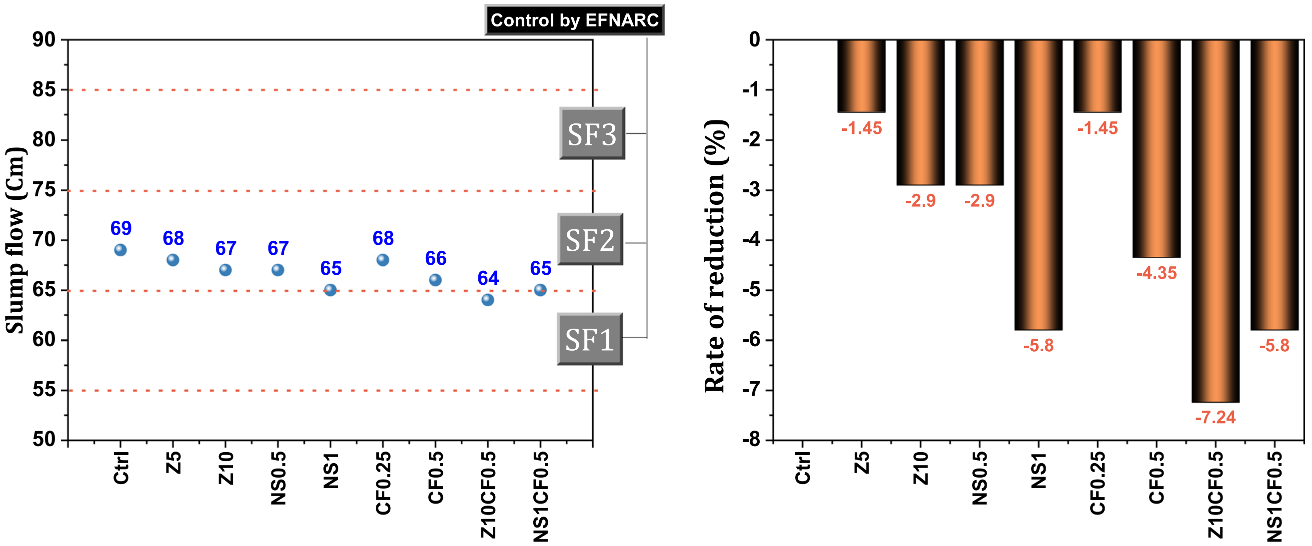


Fig. 5 Results of slum flow test

the mix incorporated 0.5% and 1% of nano-silica into the cement, the SF reductions were 2.9% and 5.8%, respectively. The greater reduction in SF compared to zeolite mixes was mainly due to the smaller particle size of nano-silica and the resulting increase in thixotropy. Additionally, the mixtures contained 0.25% and 0.5% carbon fibers, which reduced the SF by 1.45% and 4.35%, respectively, impacting the movement of aggregates in the mixes. SF values were also lower for the combined mixtures, which included both carbon fibers and pozzolans. The SF reduction was 7.24% for the Z10CF0.5 mixture (carbon fiber and zeolite) and 5.8% for the NS1CF0.5 mixture (carbon fiber and nano-silica).

V-funnel (Vf)

The findings of the V-funnel (Vf) test for various SCC mixes are depicted in Fig. 6. The Ctrl mixture exhibited a Vf value of 14 s. The addition of zeolite led to an increase in the Vf value. Specifically, the Vf increased by 7.14% and 21.42%, respectively, when the mix replaced 5% and 10% of cement with zeolite. Similarly, the Vf values were higher when the mix replaced cement with nano-silica, with increases of 14.29% and 28.58% observed for mixtures containing 0.5% and 1% nano-silica, respectively. Nano-silica demonstrated greater effectiveness than zeolite in

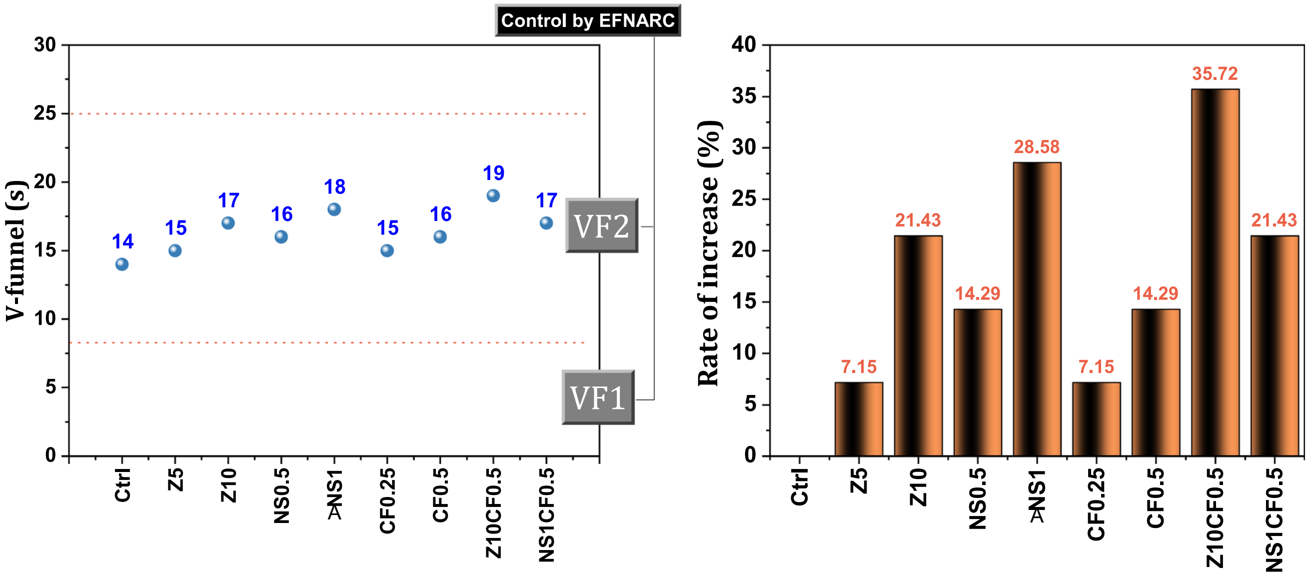


Fig. 6 Result of V-funnel test

increasing Vf, as evidenced by the comparison of the two pozzolans. Moreover, the inclusion of carbon fibers in the concrete mixes resulted in Vf increases ranging from 7.15 to 14.29%. The combined mixtures containing both carbon fiber and pozzolan also exhibited enhanced Vf values, with increases of 35.72% and 21.43%, respectively, observed for the Z10CF0.5 and NS1CF0.5 mixtures, as indicated by the investigation.

L-box (Lb)

The results of the L-box (Lb) test for various SCC mixes are depicted in Fig. 7. The control (Ctrl) mixture exhibited an Lb value of 0.86%. The Lb value decreased with the addition of zeolite to the mix. This reduction was attributed to the heightened cohesion of the cement matrix resulting from the friction generated by the zeolite particles. The interaction of this thixotropic behavior with the Lb walls led to a decrease in the Lb ratio. Specifically, the Lb reductions were 4.66% and 5.82%, respectively, when the mix replaced 5% and 10% of cement with zeolite. For mixtures containing 0.5% and 1% nano-silica, the Lb reductions were 1.17% and 6.98%, respectively. Similarly, the Lb decreased when carbon fibers were included in the concrete mixes. The Lb reductions were 2.33% and 5.82%, respectively, for mixtures with 0.25% and 0.5% carbon fibers. Unlike the behavior of zeolite and nano-silica, carbon fibers primarily affected the flow of concrete by impeding the movement of aggregates. The rate of Lb reduction was higher for combined mixtures containing both carbon fiber and pozzolan. Specifically, the Lb reductions were 8.14% and 5.82%, respectively, for the Z10CF0.5 and NS1CF0.5 mixtures, as indicated by the assessment.

EFNARC

The EFNARC classification [33] was utilized to analyze the outcomes of the fresh concrete tests for various mixtures. Figures 5, 6, 7 illustrate the correlation between the results of the slump flow, V-funnel, and L-box tests and the EFNARC classification. These results demonstrate that the formulations examined in this study adhere to the EFNARC criteria, confirming their compliance with industry standards.

Hardened concrete results / destructive

Compressive strength (28 days and 42 days)

Figure 8 depicts the compressive strength results for different SCC mixtures at 28 and 42 days. The Ctrl mixture exhibited a 28-day compressive strength of 58.9 MPa. The compressive strength at 28 days increased by 2.03% and 6.45% for the mixtures containing 5% and 10% zeolite (Z5 and Z10 mixtures), respectively. Similarly, the 28-day compressive strength improved by 4.07% and 8.99% for the mixtures with 0.5% and 1% nano-silica (NS0.5 and NS1 mixtures), respectively. Two key factors contributed to the enhancement in compressive strength for the mixtures with SCM: the efficient packing and pozzolanic potential of the SCM, and the lower water-to-binder ratio. The hydration process of cementitious materials contributed to the improvement in compressive strength, with positive effects from both pozzolans.

Zeolite was found to increase compressive strength when the water-to-cement ratio was below 0.45 but decreased it when the ratio exceeded 0.45, as demonstrated by Chan and

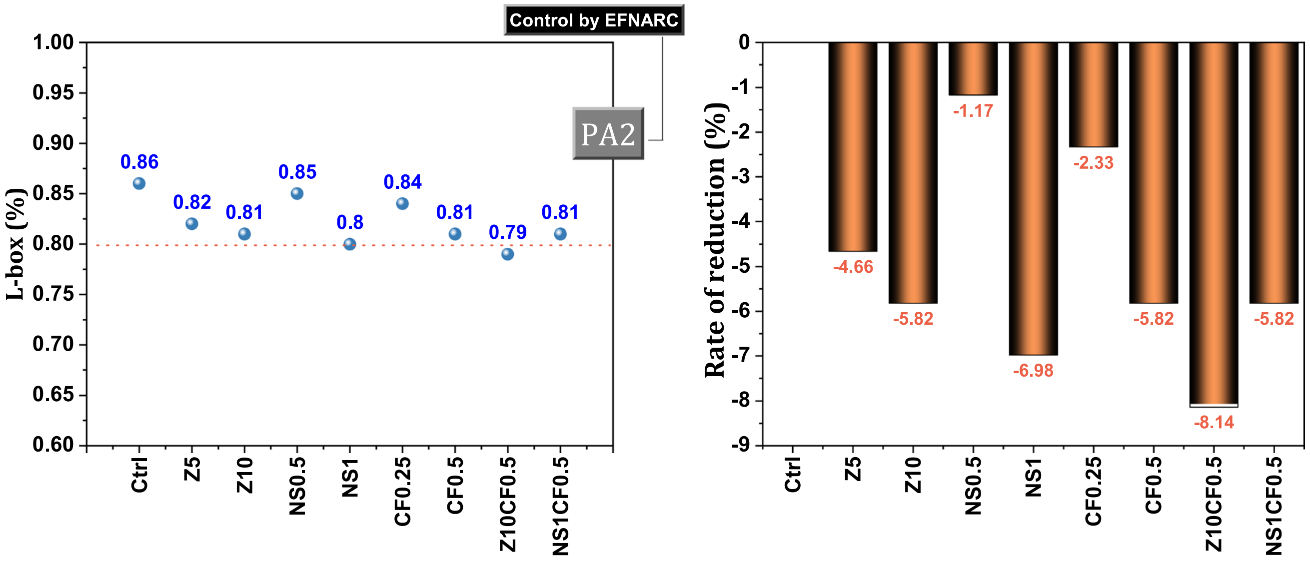
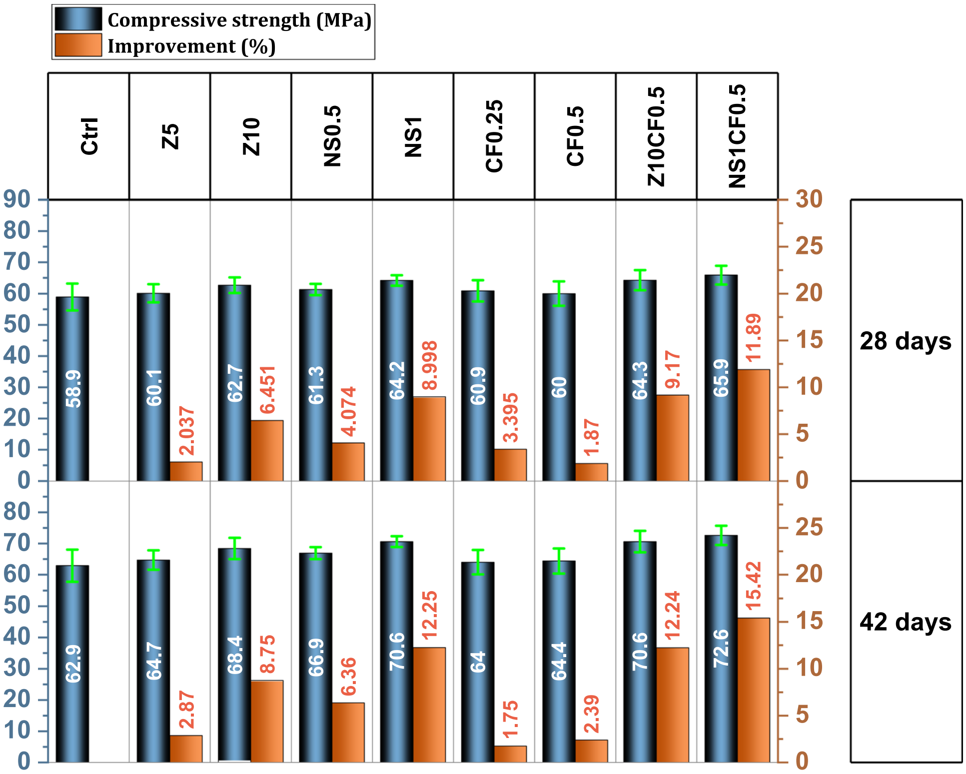


Fig. 7 Result of L-box test

Fig. 8 Results of compressive strength of mixtures at at 28 and 42 days



Ji [34]. A review by Mohtsham Moein et al. [35] indicated that nano-silica in small amounts significantly enhances the compressive strength of concrete at early ages. According to Mukharjee and Bara [36], the rapid increase in compressive strength in concrete with nano-silica is attributed to its high pozzolanic activity, resulting in densification of the Concrete-Substrate Hydrate (CSH) gel that fills the voids. Nano-silica accelerates the hydration process and increases the packing density of CSH from low to high, as highlighted by Singh et al. [37]. The results suggest that nano-silica-based formulations enhance compressive strength more than zeolite-based ones when comparing mixtures without fibers, owing to the superior pozzolanic activity of nano-silica.

The 28-day compressive strength increased by 3.39% and 1.86%, respectively, for SCC reinforced with carbon fibers at consumption rates of 0.25% and 0.5%. Carbon fibers, known for their high tensile strength, act as bridges during concrete compression, effectively improving concrete compressive behavior. Mixtures with both cement additives and carbon fibers exhibited the highest 28-day compressive strength. Specifically, the Z10CF0.5 mixture (zeolite and carbon fibers) demonstrated an increase of about 9.16%, while the NS1CF0.5 mixture (nano-silica and carbon fibers) exhibited an increase of 11.88% in compressive strength. Moreover, the compressive strength was higher for the combination of carbon fibers and nano-silica compared to carbon fibers and zeolite.

The Ctrl mixture had a 42-day compressive strength of 62.9 MPa, as illustrated in Fig. 8. The compressive strength of the mixtures increased with time, following a similar trend. The 42-day compressive strength improved by 2.86% and 8.74% for the Z5 and Z10 mixtures, respectively, due to the addition of zeolite. Similarly, the 42-day compressive strength increased by 6.35% and 12.24% for the NS0.5 and NS1 mixtures, respectively, with the incorporation of nano-silica. Consistent with the 28-day compressive strength, the 42-day compressive strength was higher for formulations with nano-silica (NS0.5 and NS1) compared to those with zeolite (Z5 and Z10), owing to superior pozzolanic activity.

The 42-day compressive strength increased by 1.74% and 2.38%, respectively, for SCC formulations containing 0.25% and 0.5% carbon fibers (CF0.25 and CF0.5). Mixtures with both cement additives and carbon fibers exhibited the most substantial enhancement in 42-day compressive strength. Specifically, the Z10CF0.5 mixture (zeolite and carbon fibers) demonstrated an increase of about 12.24%, while the NS1CF0.5 mixture (nano-silica and carbon fibers) exhibited an increase of 15.42% in compressive strength. Moreover, the compressive strength was higher for the combination of carbon fibers and nano-silica compared to the combination of carbon fibers and zeolite.

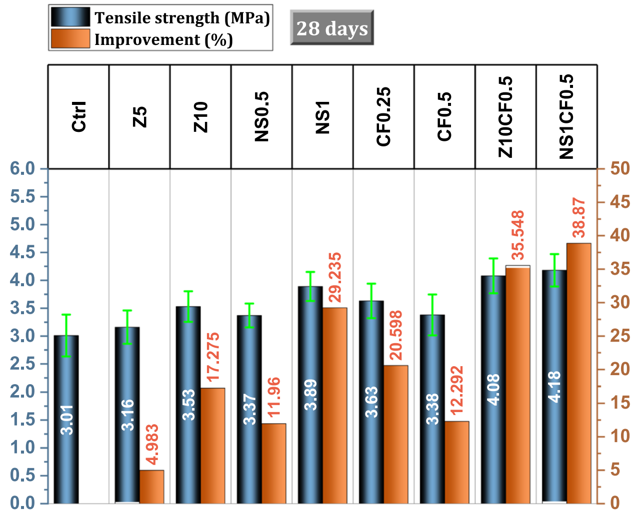


Fig. 9 The 28-day tensile strength results

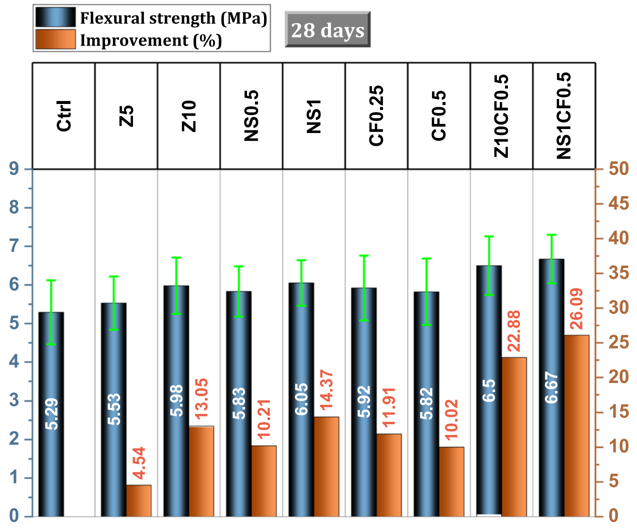


Fig. 10 The 28-day flexural strength results

Tensile strength

The 28-day tensile strength results for various SCC mixtures are depicted in Fig. 9. The Ctrl mixture exhibited a 28-day tensile strength of 3.01 MPa. When 5% and 10% zeolite (Z5 and Z10 mixtures) were added to the mix, the tensile strength increased by 17.27% and 11.96%, respectively. This increase can be attributed to the porous nature of zeolite, which has a strong water-absorbing capacity, effectively reducing the effective water-to-cement ratio and engaging in internal curing [38]. As a result, zeolite released trapped water, thereby enhancing the tensile strength by potentially improving the binding of the CSH structure. For the NS0.5 and NS1 mixtures, where 0.5% and 1% of cement were replaced by nano-silica, respectively, the tensile strength increased by 11.96% and 29.23%. The inclusion of nano-silica particles enhanced the density of CSH and improved the bond between the hardened paste and aggregates, consequently leading to improved tensile strength [35]. Comparison between the performance of zeolite and nano-silica mixtures (without fibers) revealed that nano-silica-based mixtures yielded higher tensile strength outcomes for SCC, which can be attributed to the greater pozzolanic activity of nano-silica compared to zeolite. The tensile strength of the mixture containing 0.25% carbon fibers (CF0.25) increased by 20.59%, whereas the tensile strength of the mixture containing 0.5% carbon fibers (CF0.5) only increased by 12.29%, which was about 8% lower than that of the CF0.25 mixture. This discrepancy may be due to the challenge of evenly distributing these fine fibers in concentrations above 0.25%. Mixtures incorporating both cement additives and carbon fibers exhibited the greatest improvement in tensile strength. The tensile strength of the Z10CF0.5 mixture (with zeolite and carbon fibers) increased by about 35.54%, while the tensile strength of the NS1CF0.5 mixture (with nano-silica and carbon fibers) increased by 38.87%. The synergy between carbon fibers and nano-silica resulted in higher tensile strength compared to the synergy between carbon fibers and zeolite.

Flexural strength

The 28-day flexural strength results of different SCC mixtures are depicted in Fig. 10. The Ctrl mixture exhibited a flexural strength of 5.29 MPa. The substitution of cement with zeolite resulted in an enhancement of the flexural strength of SCC. Specifically, the flexural strength of the Z5 and Z10 mixtures increased by 4.53% and 13.04%, respectively. Similarly, SCC mixtures with 0.5% and 1% cement replacement by nano-silica experienced increases in flexural strength by 10.20% and 14.36%, respectively. Behzadian and Shahrajabian [39] reported that nano-silica enhances flexural strength by improving the bond between the cement paste and the aggregates. Comparison of the performance of the two pozzolans (zeolite and nano-silica) in fiber-free mixtures indicates that nano-silica outperforms zeolite in terms of flexural strength, as well as compressive strength and tensile strength. The flexural strength of SCC mixtures with 0.25% and 0.5% carbon fiber content increased by 11.90% and 10.01%, respectively. The lower improvement in flexural strength at higher carbon fiber dosages was attributed to the challenge of uniformly dispersing these fibers in the concrete matrix. Comparison of mixtures with both pozzolans and carbon fibers revealed that the mixture with carbon fibers and nano-silica (NS1CF0.5) exhibited approximately 2.61%

Table 7 The impact strength results of different SCC mixtures

N.O	Mix code	Additives (%)			First crack strength (blows)	Failure strength (blows)	INPB	Impact energy (J)	IDI
		Zeolite	Nano-silica	Carbon fiber	N1	N2	N2-N1	(N2-N1)/N2	N2 × mgh
1	Ctrl	–	–	–	23	24	1	488.4	0.043
2	Z5	5	–	–	25	27	2	549.45	0.080
3	Z10	10	–	–	30	32	2	651.2	0.067
4	NS0.5	–	0.5	–	28	30	2	610.5	0.071
5	NS1	–	1	–	33	36	3	732.6	0.091
6	CF0.25	–	–	0.25	31	36	5	732.6	0.161
7	CF0.5	–	–	0.5	29	35	6	712.25	0.207
8	Z10CF0.5	10	–	0.5	36	43	7	875.05	0.194
9	NS1CF0.5	–	1	0.5	41	50	9	1017.5	0.220

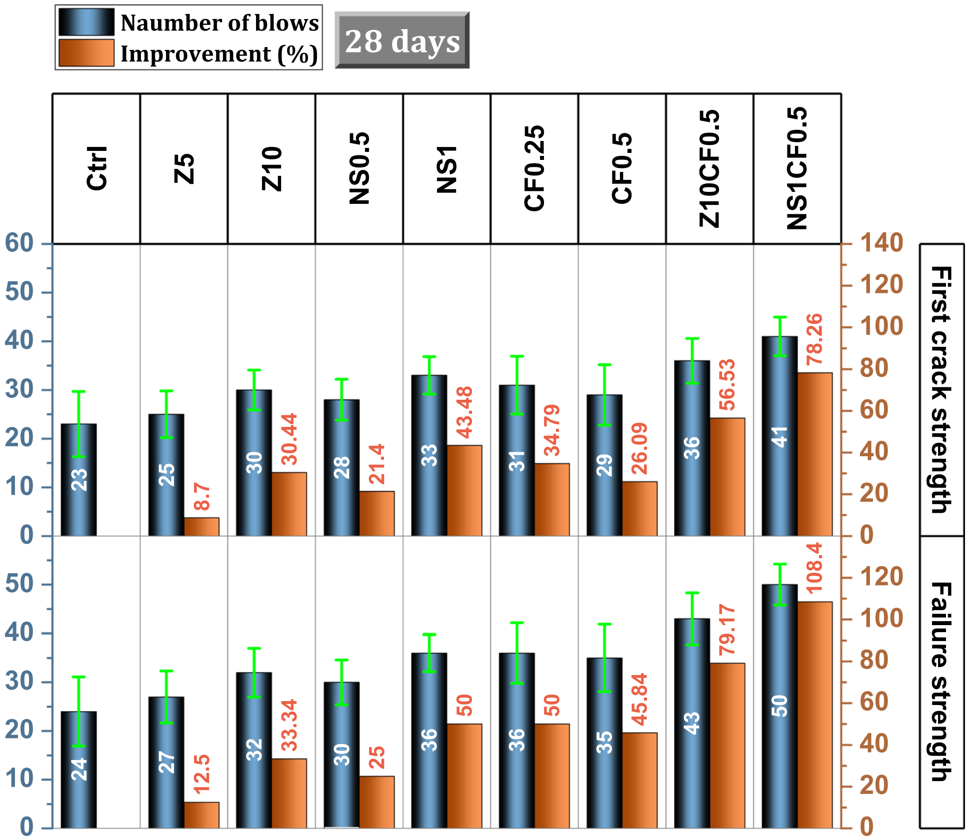


Fig. 11 Results of impact strength of mixtures (first crack strength and failure strength)

higher flexural strength than the mixture with carbon fibers and zeolite (Z10CF0.5).

Impact strength

The impact strength results of different SCC mixtures are presented in Table 7, while the first crack strength and failure strength of various mixtures are depicted in Fig. 11. The Ctrl mixture exhibited a first crack strength of 23 blows. Mixtures with zeolite (Z5 and Z10) showed first crack strengths of 25 and 30 blows, respectively, representing strength increases of 8% to 30%. Similarly, the mixtures with nano-silica (NS0.5 and NS1) displayed first crack strengths of 28 and 33 blows, respectively, indicating strength increases of 21% to 43% due to the addition of nano-silica to the SCC mixture. The first crack resistance of the mixture with 0.25% carbon fibers (CF0.25) increased by 34.78%, while the mixture with 0.5% carbon fibers (CF0.5) had a 26.09% higher first crack resistance. The greatest improvement in first crack strength was observed in mixtures containing both carbon fibers and pozzolan. Specifically, the Z10CF0.5 and NS1CF0.5 mixtures exhibited 36 and 41 blows, respectively. Therefore, the combination of carbon fibers and nano-silica resulted in the most significant enhancement in first crack strength, increasing it by 78.26% in the concrete.

The Ctrl mixture had a failure strength of 24 blows. Mixtures with zeolite (Z5 and Z10) showed increased failure strengths of 27 and 32 blows, respectively, representing a 12% to 33% improvement in resistance. Similarly, the NS0.5 and NS1 mixtures had failure strengths of 30 and 36 blows, corresponding to enhancements of about 25% to 50% attributed to the nano-silica content. The mixture with 0.25% carbon fibers (CF0.25) exhibited a 50% increase in failure strength, whereas the mixture with 0.5% carbon fibers (CF0.5) displayed a 45.83% enhancement in failure resistance. Similar to the first crack strength, the highest improvements in failure strength were found in mixtures containing both carbon fibers and pozzolan. In this case, the failure strength of Z10CF0.5 and NS1CF0.5 mixtures increased by 79.17% and 108%, respectively.

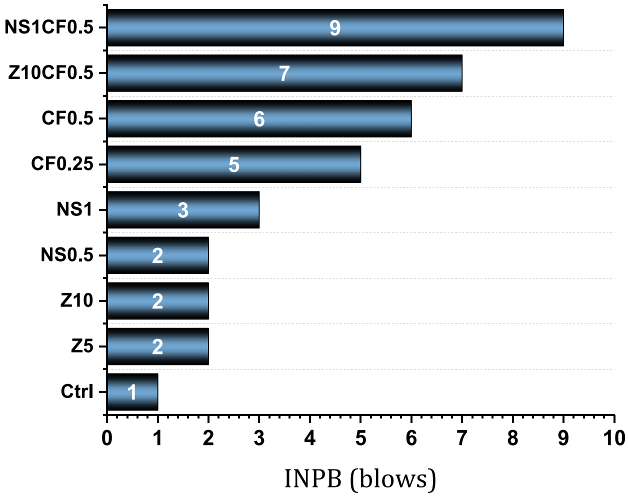
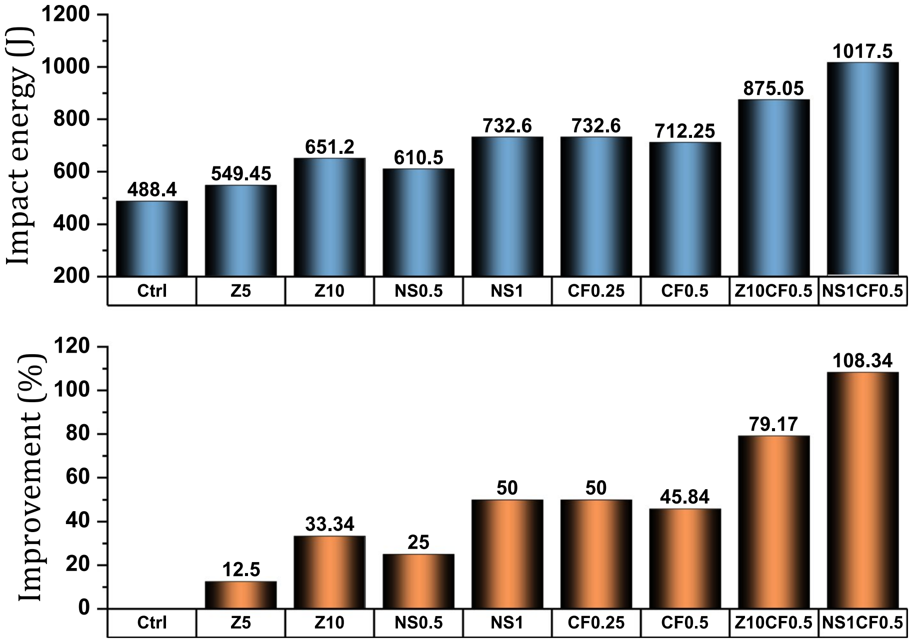


Fig. 12 The INPB results

The results of the INPB (Initial Notch Position Before failure) for different SCC formulations are presented in Fig. 12. The INPB is the distance from the first crack initiation to the failure point, indicating the number of blows that occur after the first crack until the complete failure of the concrete disc. The control concrete without pozzolan and carbon fibers had the lowest performance, with an INPB value of 1 blow. Mixtures with only pozzolans (Z5, Z10, NS0.5, and NS1) performed better than the control mixture, with INPB values between 2 and 3 blows. The fibers significantly increased the INPB due to their bridging properties, preventing crack propagation and further crack development. The mixtures with 0.25% and 0.5% fibers (without pozzolan) had INPB values of 5 and 6 blows, respectively. Although the CF0.5 mixture had lower impact strength than the CF0.25 mixture in compressive and flexural strength, the higher fiber concentration enhanced the INPB, indicating its complex role. The CF0.5 mixture had more cracks due to the higher fiber content, which increased the INPB. The mixtures with both carbon fibers and pozzolan had the highest INPB value in this study, with the INPB values of Z10CF0.5 and NS1CF0.5 mixtures being 7 and 9 blows, respectively.

Fig. 13 Impact energy results



Impact energy The impact energy results of different SCC compositions are illustrated in Fig. 13. The Ctrl mixture recorded an impact energy of 488.4 J. Mixtures incorporating pozzolan exhibited impact energy values ranging from 550 to 730 J. Interestingly, mixtures containing nano-silica demonstrated higher impact energy values compared to those with zeolite. Additionally, mixtures reinforced with carbon fibers (CF0.25 and CF0.5) displayed a 50% and 45.83% increase in impact energy, respectively. Notably, the highest impact energy value was observed in mixtures featuring both carbon fibers and pozzolan. Among these, the NS1CF0.5 mixture delivered the best performance in terms of impact energy, showcasing a remarkable 108% improvement.

Impact ductility index (IDI) The Impact Damage Index (IDI) results for various SCC mixtures are depicted in Fig. 14. The Ctrl mixture yielded an IDI value of 0.043. Notably, the IDI values increased for mixtures incorporating pozzolan, ranging from 0.71 to 0.91 within this group. Mixtures containing carbon fibers exhibited higher IDI values, attributed to the bridging capabilities of fibers, as documented by previous studies [3]. Specifically, the mixtures with carbon fibers (CF0.25 and CF0.5) recorded IDI values of 0.161 and 0.207, respectively, indicating a 275% and 381% improvement in IDI, respectively. It's worth noting that higher concentrations of carbon fibers led to more significant enhancements in IDI. Remarkably, the highest IDI value was observed in mixtures featuring both carbon fibers and nano-silica. Particularly, the NS1CF0.5 mixture displayed an IDI value of 0.220, representing a remarkable 410% improvement.

Correlations

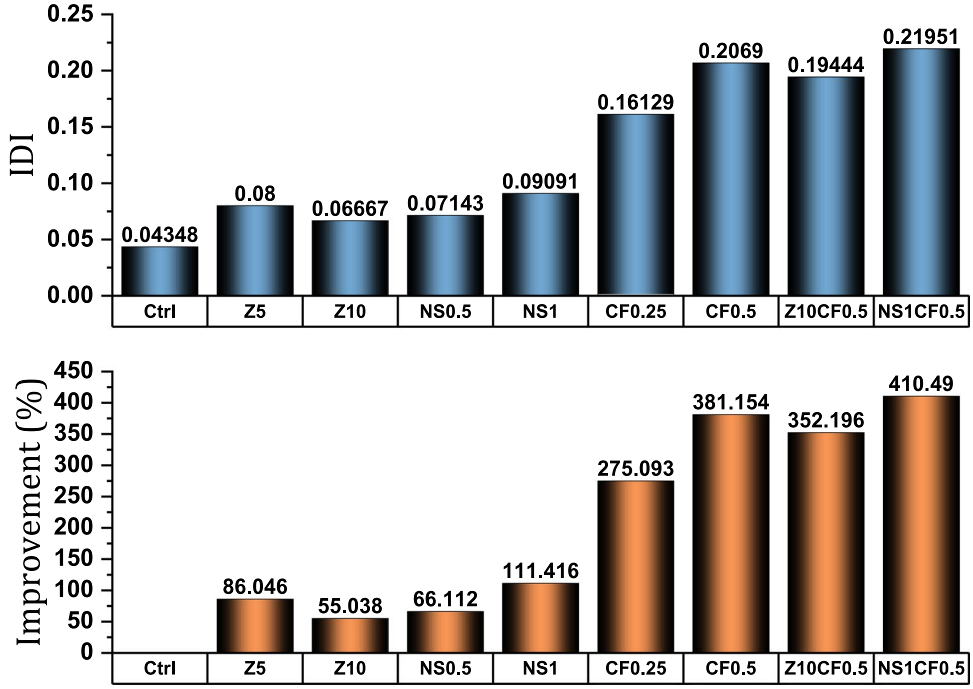
As depicted in Fig. 15a, the compressive strength and tensile strength of SCC mixtures display a robust exponential correlation. This relationship is substantiated by the high coefficient of determination (R^2) value, which stands at 0.889. Similarly, Fig. 15b showcases the exponential correlation between compressive strength and tensile strength results, with an R^2 value of 0.858, signifying a substantial degree of correlation. In Fig. 15c, the exponential correlation between electrical resistivity and water absorption results is presented. The R^2 value for this association is 0.934, indicating an exceptionally high level of correlation. It's worth noting that a model is generally deemed acceptable when the R^2 value exceeds 0.7, according to established statistical criteria [3, 14].

Hardened concrete results/non-destructive

Water absorption

The 28-day water absorption test results for various SCC mixtures are depicted in Fig. 16. These results reveal an inverse correlation with the mechanical test outcomes, consistent with prior research suggesting that lower water absorption indicates reduced porosity and, consequently, better concrete quality. The water absorption rate for the

Fig. 14 Impact ductility index (IDI) results



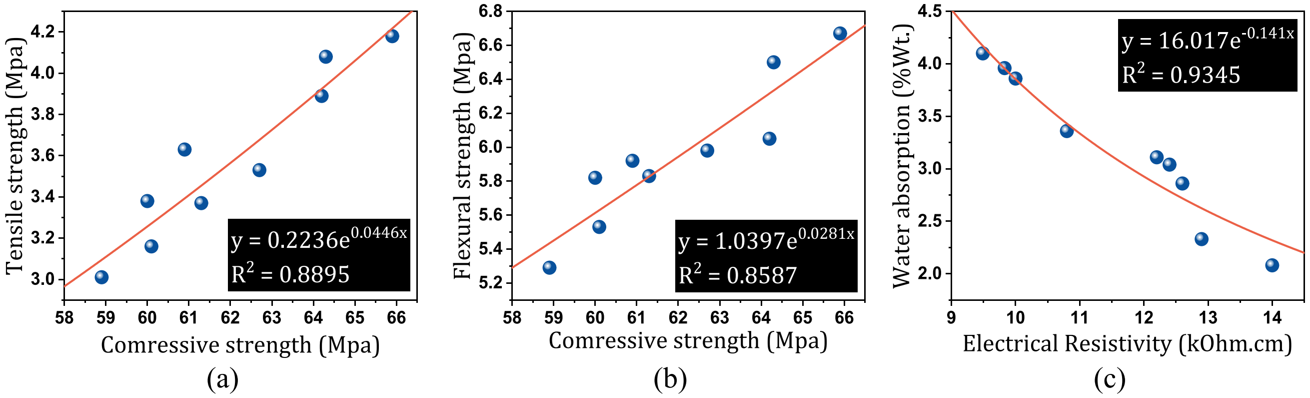


Fig. 15 Correlation between different tests: **a** compressive strength and tensile strength, **b** compressive strength and flexural strength, and **c** electrical resistivity and water absorption

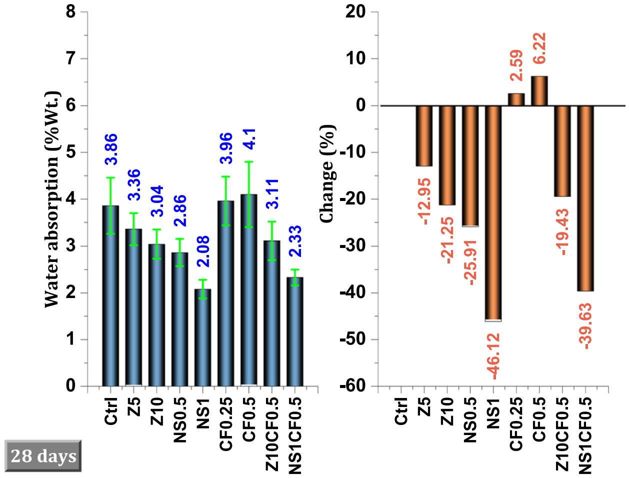


Fig. 16 Water absorption test results (28 days)

control mixture (Ctrl) stood at 3.86%. Mixtures containing zeolite (Z5 and Z10) exhibited decreased water absorption rates, showcasing reductions of 12.95% and 21.24%, respectively, compared to the control mixture. This can be attributed to the formation of secondary gels resulting from the interaction between Ca(OH)2 and SiO2 in zeolite, which enhances the concrete microstructure and diminishes capillary porosity. For mixtures incorporating nano-silica (NS0.5 and NS1), water absorption rates were 25.90% and 46.11% lower, respectively, than the control mixture, upon replacing 0.5% and 1% of cement with nano-silica. Nano-silica reduces inter-pore connectivity, promotes CSH gel formation, and fills voids, thereby lowering water absorption [35]. A comparison between zeolite and nano-silica reveals that nano-silica outperforms zeolite in reducing SCC water absorption, owing to its superior pozzolanic activity. The addition of fibers, which impacts capillary porosity and concrete structure, led to increased water absorption, as anticipated. The water absorption rate for the mixture with 0.25% carbon fibers (CF0.25) was 2.59% higher than that of the control mixture, while the mixture with 0.5% carbon fibers (CF0.5) exhibited a 6.21% higher water absorption rate, attributed to the presence of carbon fibers. Mixtures containing both carbon fibers and pozzolan (Z10CF0.5 and NS1CF0.5) demonstrated lower water absorption rates than the control mixture, as depicted in Fig. 16. Specifically, the water absorption rates for the Z10CF0.5 and NS1CF0.5 mixtures were 19.43% and 39.63% lower, respectively, than the control mixture. The introduction of fibers to the Z10 and NS1 mixtures increased water absorption rates by 2.03% and 12.01%, respectively, compared to mixtures lacking fibers. The pozzolanic activity of the cement additives reduced water absorption in the combined mixtures (fiber and pozzolan) by fostering a more cohesive structure and diminishing concrete porosity and pore size.

Electrical resistivity

The electrical resistivity findings for various SCC compositions are depicted in Fig. 17. Electrical resistivity serves as a gauge of the internal porosity and density of the concrete microstructure. Previous research has demonstrated that higher electrical resistivity correlates with lower concrete permeability. The electrical resistivity value for the control mixture (Ctrl) measured at 10 kOhm.cm. Mixtures containing 5% and 10% zeolite (Z5 and Z10) exhibited 8% and 24% greater electrical resistance, respectively, compared to the control mixture. Likewise, mixtures incorporating 0.5% and 1% nano-silica (NS0.5 and NS1) displayed 26% and 40% higher electrical resistivity, respectively, than the control mixture. Nano-silica demonstrated superior performance over zeolite in enhancing the electrical resistivity and density of concrete. The introduction of pozzolan into concrete augments electrical resistance due to the pozzolanic activity

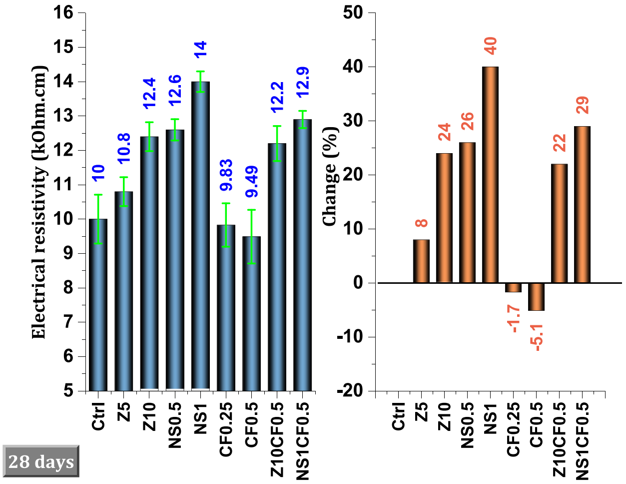


Fig. 17 Electrical resistivity test results (28 days)

occurring within the concrete matrix. This activity yields secondary silicate gel, reducing pore size and disrupting pore connectivity.

Carbon fibers influence concrete electrical resistivity in two distinct ways. Firstly, they elevate concrete water absorption, altering its porosity and facilitating more ion exchange, thereby reducing electrical resistivity. Secondly, carbon fibers possess electrical conductivity, independently lowering electrical resistivity regardless of their impact on density. Mixtures containing 0.25% and 0.5% carbon fibers (CF0.25 and CF0.5) demonstrated 1.7% and 5.1% lower electrical resistivity, respectively, than the control mixture. The mixture featuring both fibers and zeolite (Z10CF0.5) exhibited a 22% higher electrical resistivity than the control mixture, while the mixture containing both fibers and nano-silica (NS1CF0.5) displayed a 29% higher electrical resistivity than the control mixture. The inclusion of fibers in Z10 and NS1 mixtures reduced electrical resistance by 1.61% and 7.85%, respectively, compared to mixtures devoid of fibers. The pozzolanic activity of the cement additives heightened electrical resistivity in the combined mixtures (fiber and pozzolan) by fostering a denser concrete structure.

Plastic shrinkage

Cracks in concrete pose a persistent challenge and can stem from various factors. Table 8 offers insights into the classification of concrete cracks. Figure 18 presents the results of plastic shrinkage for different SCC compositions. The shrinkage crack width for the control mixture (Ctrl) measured 0.48 mm. The mixture containing 5% zeolite (Z5) exhibited a crack width of 0.4 mm, marking a 16.66% decrease compared to the control mixture, signifying a notable reduction in shrinkage cracking. Similarly, the mixture incorporating 10% zeolite (Z10) displayed a 25% lower crack width than the control mixture, indicating the beneficial impact of this pozzolan in curbing concrete shrinkage. However, the mixtures containing 0.5% and 1%

Table 8 Classification of intrinsic cracks of concrete [40]

N.O	Type of cracking	Subdivision	Most common location	Primary cause (Excluding restraint)	Secondary cause/ factor	Time of appearance
1	Plastic settlement	● Over reinforcement ● Arching ● Change of depth	● Deep sections ● Top of columns ● Trough and waffle slabs	● Excess bleeding	● Rapid early drying	Ten min. to three hours
2	Plastic shrinkage	● Diagonal ● Random ● Over reinforcement	● Roads and slabs ● Reinforced slabs ● Reinforced slabs	● Rapid early drying ●Ditto plus steel near surface	● Low rate of bleeding	30 min. to six hours
3	Early thermal contraction	● External restraint ● Internal restraint	● Thick walls ● Thick slabs	● Excess heat generation ● Excess temp gradients	● Rapid cooling	One day to two or three weeks
4	Long-term drying shrinkage	● Thin slabs and walls	● Inefficient joints	● Excess shrinkage; inefficient curing	● Excess shrinkage; inefficient curing	Several weeks or months
5	Crazing	● Against formwork ● Floated concrete	● `Fair faced' concrete Slabs	●Impermeable formwork ●Over-trowelling	● Richmixes; poor curing	One to seven days, or even later
6	Corrosion of steel reinforcement	● Natural ● Calcium chloride	● Columns and beams ● Precast concrete	● Lack of cover ● Excess calcium chloride	● Poor quality concrete	More than two years
7	Alkali-silica reaction		● Damp locations	● Reactive aggregate plus high alkali cement		More than two years

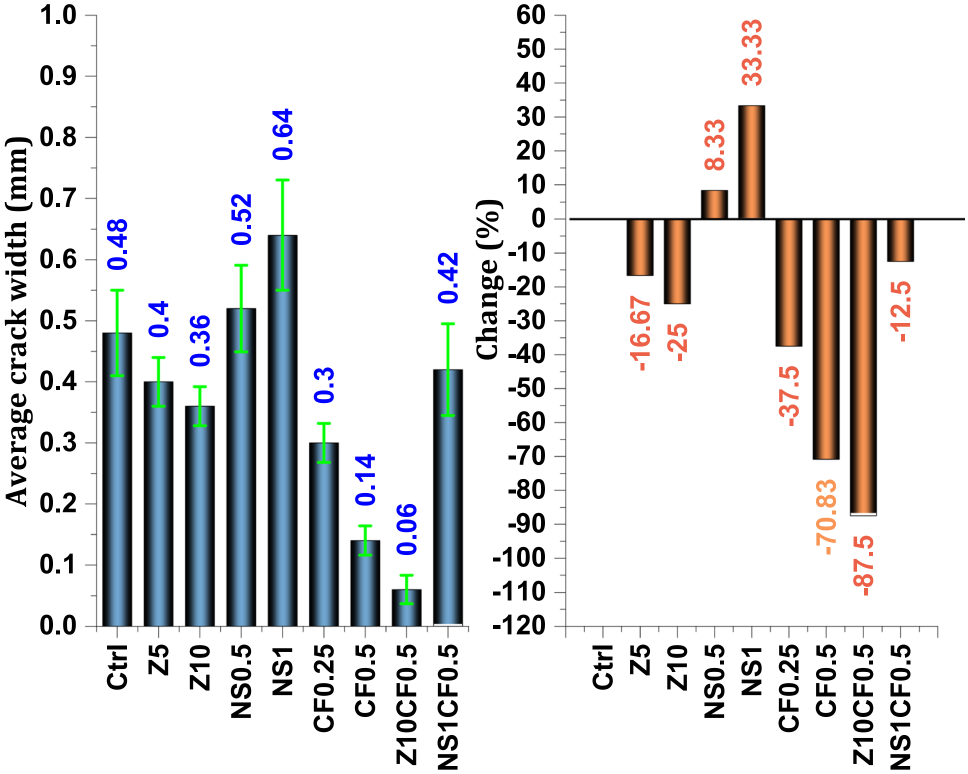


Fig. 18 Plastic shrinkage test results

nano-silica (NS0.5 and NS1) did not demonstrate a reduction in crack width due to shrinkage; instead, crack width increased by 8.3% and 33.33%, respectively. Comparative analysis of the two pozzolans (zeolite and nano-silica) in mitigating plastic shrinkage revealed that zeolite significantly outperformed nano-silica in terms of reducing crack width.

The incorporation of carbon fibers (CF0.25 and CF0.5) exerted a remarkable effect on diminishing crack width. Specifically, employing 0.25% and 0.5% carbon fibers led to shrinkage-induced crack width reductions of 37.5% and 70.83%, respectively. The synergistic effect of carbon fibers and zeolite resulted in the most substantial shrinkage-induced crack width reduction. The Z10CF0.5 mixture exhibited an impressive 87.5% decrease in crack width. The individual effects of zeolite and carbon fibers (as observed in the Z10 and CF0.5 mixtures) underscored the beneficial roles of these components in reducing crack width attributable to shrinkage. The integration of carbon fibers and zeolite in the Z10CF0.5 mixture bolstered the ability of the SCC composition to minimize crack width, yielding an optimal outcome. Nevertheless, the addition of nano-silica and carbon fibers (NS1CF0.5) led to a relatively minor decrease in crack width, around 12.5%. Intriguingly, despite the enhanced mechanical properties of designs incorporating nano-silica, these designs remained susceptible to shrinkage-related cracks. Moreover, the inclusion of fibers did not yield a significant reduction in crack width compared to the control design. Hence, exercising caution is recommended when employing nano-silica on expansive surfaces exposed to uncontrolled airflow, unless supplemented with special treatment measures.

Conclusions

The following summarized results were obtained from the investigation into Self-Consolidating Concrete (SCC) incorporating zeolite, nano-silica, and carbon fiber across various tests:

Workability

- Zeolite and nano-silica in SCC mixtures reduced slump flow, raised V-funnel, and lowered L-box. Carbon fibers exhibited a similar trend as pozzolans in influencing SCC workability parameters.

Compressive strength

- Adding zeolite and nano-silica as SCM improved SCC compressive strength by enhancing packing efficiency and pozzolanic activity. The compressive strength increased with pozzolan dosage, reaching peak values of

6.45% and 8.74% for 10% zeolite, and 8.99% and 12.24% for 1% nano-silica, at 28 and 42 days, respectively.
- Nano-silica was more effective than zeolite in enhancing compressive strength, especially in fiberless mixtures, due to its higher pozzolanic reactivity and gel densification.
- Carbon fibers improved compressive strength by reducing microcracking and compression damage. The highest improvement was observed in SCC mixtures with both carbon fibers and SCM, particularly 1% nano-silica and 0.5% carbon fibers, which increased compressive strength by 11.88% and 15.42% at 28 and 42 days, respectively.

Tensile strength

- Zeolite and nano-silica enhanced tensile strength by improving packing efficiency, pozzolanic activity, microstructure, and CSH binding. Nano-silica-based mixtures showed higher tensile strength than zeolite-based mixtures, recommending nano-silica for optimizing SCC tensile strength.
- Carbon fibers increased tensile strength, but higher dosages were challenging to distribute and resulted in less improvement. The synergy between carbon fibers and cement additives demonstrated the highest tensile strength improvement, with nano-silica being more effective than zeolite.

Flexural strength

- Zeolite and nano-silica improved flexural strength by enhancing packing efficiency, pozzolanic activity, microstructure, and CSH binding. Nano-silica-based mixtures exhibited higher flexural strength than zeolite-based mixtures, favoring nano-silica for optimizing SCC flexural behavior.
- Carbon fibers increased flexural strength, but higher dosages were challenging to distribute and resulted in less improvement. The highest flexural strength improvement was observed in SCC mixtures with carbon fibers and nano-silica, showing a synergistic effect and the advantages of nano-silica as an additive.

Impact strength

- Zeolite and nano-silica enhanced impact resistance, increasing first crack strength by 8.7%-30.44% and 21.4%-43.48%, and failure strength by 12.5%-33.34% and 25%-50%, respectively.
- Carbon fibers increased impact strength, raising first crack strength by 34.78% and 26.09%, and failure strength by 50% and 45.83%, for 0.25% and 0.5% carbon fiber content, respectively.
- The impact strength of SCC mixtures was amplified by the combination of carbon fibers and pozzolanic additives (zeolite or nano-silica). The first crack strength and the failure strength increased by 78.26% and 108.4%, respectively, for the mixture with carbon fibers and nano-silica, showcasing a synergistic effect.
- The impact energy and the IDI of SCC mixtures were augmented by zeolite and nano-silica, as well as by carbon fibers, underscoring the potential and positive impact of pozzolanic additives and carbon fibers on the impact strength of SCC.
- The INPB values were higher for mixtures with pozzolans compared to the control mixture, which had the lowest INPB value. By preventing crack propagation and development with their bridging properties, carbon fibers increased INPB and enhanced the impact resistance of blends with pozzolans, which exhibited the highest INPB values.

Water absorption

- Zeolite and nano-silica reduced water absorption rates by 12.95%-21.24% and 25.90%-46.11%, respectively, compared to the control mixture. Nano-silica showed higher pozzolanic activity.
- Carbon fibers increased water absorption rates, depending on fiber content, and affected capillary porosity. The combination of carbon fibers and pozzolanic additives reduced water absorption rates.

Electrical resistivity

- Zeolite and nano-silica improved electrical resistivity, with nano-silica being more effective due to its smaller size and better void-filling. Carbon fibers reduced electrical resistance through two contradictory ways.
- Carbon with zeolite or nano-silica increased electrical resistance, but slightly weakened the performance of these pozzolans in mono-component mixtures.

Plastic shrinkage

- Zeolite mixtures showed a significant reduction in crack width, indicating the beneficial effect of this additive. Nano-silica did not reduce crack width and raised it in SCC mixtures.
- Carbon fibers significantly reduced crack width caused by plastic shrinkage. Their combination with zeolite further reduced crack width, achieving optimal results.
- Nano-silica designs enhanced mechanical properties but were still prone to shrinkage-related cracks. Adding fibers to nano-silica mixtures did not significantly reduce

crack width, requiring special care on large surfaces exposed to unregulated airflow.

These results provide comprehensive insights into the performance of Self-Consolidating Concrete (SCC) under various conditions, highlighting the valuable contributions of zeolite, nano-silica, and carbon fibers in enhancing different mechanical and durability aspects.

Author contributions All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Journal of Innovative Infrastructure Solutions. MB: Validation, Investigation, Resources, Software. BA: Software, Validation, Formal analysis. KR: Writing—review & editing, Software. MMM: Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing -original draft, Writing—review & editing, Visualization, Supervision. AS: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing—original draft, Writing—review & editing, Visualization. MK: Writing—review & editing, Visualization.

Declarations

Conflict of interest All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript. The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

Ethical approval This article does not contain any studies with human participants performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

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