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BEHAVIOUR OF HIGH-PERFORMANCE CONCRETE BEAMS WITH SILICA AND PINEAPPLE LEAF FIBER FOR ENHANCED STRUCTURAL BEHAVIOUR

LASTNOSTI VISOKO ZMOGLJIVIH BETONSKIH STEBROV, ARMIRANIH S SILIKO IN VLAKNI IZ ANANASOVIH LISTOV ZA IZBOLJŠANJE NJIHOVE NOSILNOSTI

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This study explores the mechanical performance of high-performance concrete (HPC) beams incorporating silica fume (SF), and nano silica (NS) as cement replacements and pineapple leaf fibre (PALF) as a secondary reinforcement for enhancing the strength of the beams. The objective of this research is to examine the load-bearing capacity, deflection and failure mode of the beams. Various proportions of SF (5, 7.5, 10 and 12.5) % and NS (0.5, 1, 1.5, 2 and 2.5) % were incorporated into the concrete mix, with a constant addition of 2.5 % PALF. The beams were cast, cured for 28 days, and subjected to static loading tests, employing single-point loading methods to assess their load-carrying capacities and flexural behaviour. Experimental results demonstrated that beams with 10 % SF and 2 % NS exhibited superior structural performance, achieving the highest load-carrying capacity among all tested mixes. Crack patterns indicated flexural failure in all specimens, affirming their ductile behaviour under loading conditions. This investigation highlights the synergistic effects of SF, NS, and PALF in enhancing the strength and ductility of HPC beams, offering promising insights for advanced construction applications.

Keywords: high-performance concrete, silica fume, nano silica, pineapple leaf fibre

Avtorji v članku opisujejo študijo, v kateri so ugotavljali mehanske lastnosti in nosilnost stebrov iz visoko zmogljivega betona (HPC; angl: High Performance Concrete), v katerega so kot armaturo vgradili pepel silike (SF; angl.: Silica Fume), nano siliko (SiO_2, NS) in vlakna iz listov ananasa (PALF; angl.: Pineapple Leaf Fiber). Cilj te raziskave je bil ugotoviti nosilnost, upogib in poškodbe ter dokončno odpoved (porušitev) HPC nosilcev. Kot armaturo so v betonu uporabili različno vsebnost SF (5 %, 7,5 %, 10 % in 12,5 %), NS (0,5 %, 1 %, 1,5 %, 2 % in 2,5 %) ter konstanten dodatek 2,5 % PALF. Vzorci nosilcev so bili uliti v modele, utrjevani 28 dni in nato izpostavljeni statičnim obremenitvam z uporabo eno-točkovne metode. Na ta način so ocenili nosilnost in upogibno trdnost izdelanih HPC nosilcev. Eksperimentalni rezultati so pokazali, da imajo betonski nosilci armirani z 10 % SF in 2 % NS vrhunsko strukturno (konstrukcijsko) nosilnost v primerjavi z vsemi ostalimi izdelanimi vzorci HPC. Vzorci razpok so v vseh primerih pokazali, da je prišlo do duktilnega obnašanja betona in končno zaradi obremenjevanja do poškodb in porušitve zaradi upogiba. Ta raziskava je pokazala izboljšanje trdnosti in duktilnosti HPC nosilnosti zaradi kombiniranega sinergijskega učinka armature iz SF, NS in PALF, kar obeta njihovo uporabo za napredne gradbene in konstrukcijske aplikacije.

Ključne besede: visoko zmogljiv beton, pepel iz silike, nano silica, vlakna iz ananasovih listov

1 INTRODUCTION

Concrete is a composite substance primarily comprising cement, fine aggregates, coarse aggregates and water. It is meticulously designed to achieve specific strength parameters at various curing stages. The advancements in construction technology have significantly increased the use of concrete, making it the second most consumed material worldwide after water. However, this extensive usage depletes natural resources and raises environmental concerns, primarily due to the substantial CO_2 emissions associated with cement production. Cement manufacturing alone contributes approximately seven percent of global CO_2 emissions, highlighting the urgent need for sustainable practices.[1]

Numerous studies have been conducted to explore the potential use of industrial by-products in construction (Sakir et al., 2020). Integrating substances such as fly ash (FA) and silica fume (SF) has been demonstrated to improve the characteristics of concrete and cement, and their use has become commonplace in various applications. Proper utilization of other industrial by-products and waste materials could further mitigate disposal problems and contribute to more sustainable construction practices. Given the projected increase in the concrete use, the demand for cement is expected to rise correspondingly. Therefore, finding effective measures to reduce environmental impact while maintaining the benefits of concrete is crucial for achieving a sustainable construction industry.[2]

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One effective strategy to address these environmental concerns is the use of industrial by-products like FA and SF in concrete. These by-products, typically wastes from other industries, can partially replace cement. Fly ash and silica fume improve concrete strength, durability, and workability, making it more robust and sustainable. By reducing the raw cement demand, these by-products also lower the overall carbon footprint of concrete production. Building on this approach, our study explores using silica fumes and nano silica as cement replacements. These materials are known for their superior pozzolanic properties, which refine the concrete microstructure and enhance performance. This study investigates the potential of pineapple leaf fiber (PALF), an agricultural by-product, as a sustainable reinforcement material. Cesarino et al. (2020) showed that properly treated PALF can significantly improve concrete mechanical properties.[3]

Proper treatment of PALF before incorporation into the mortar is crucial for enhancing its bonding with the cement matrix. Our research is motivated by the need to develop high-performance concrete (HPC) that meets growing structural demands and aligns with sustainable development goals. This study aims to evaluate the workability, strength, and durability characteristics of concrete mixtures incorporating treated PALF and silica-based materials. To accomplish this, the study utilizes various mechanical testing methods, including one-point and two-point loading, as outlined by Shakir and Hannon (2024). These tests enable the assessment of the concrete performance under various conditions, ensuring that it meets the rigorous demands of modern construction. By exploring innovative materials and their potential to produce more eco-friendly concrete, this study addresses the environmental and waste management challenges faced by the construction industry.[4]

Particular attention is directed towards blends incorporating silica fumes, nano silica, and pineapple leaf fiber. The HPC mixtures underwent thorough testing for workability traits, and strength characteristics of M60-grade concrete. To produce HPC, it is crucial to considerably condense the w/c proportion. Enhancing the quality of the interfacial region can be effectively achieved by decreasing the w/c ratio while adding admixtures or pozzolanic materials. The effect of these admixtures on the concrete workability and strength depends on their physical, chemical, and reactive properties. In this research, NS, SF, and PALF were employed to explore the strength progression at different curing periods. The findings were compared to identify the most effective mix proportions.[5]

PALF, an agricultural byproduct, has demonstrated significant potential to improve concrete's mechanical behaviour and resistivity when properly treated and integrated. Previous studies showed that fibre additions, including polypropylene fibre (PPF), along with nano and micro silica additives, significantly increase compressive and tensile strengths as well as electrical resistivity.[5] The incorporation of nano silica (NS) up to 3 % into high-performance concrete (HPC) was shown to enhance the calcium-silicate-hydrate (C-S-H) gel formation, leading to a denser microstructure, improved water resistance, and accelerated cement hydration, which collectively boost concrete performance.[6–8]

Alongside NS, pineapple leaf fibre (PALF), an agricultural by-product, has demonstrated significant potential as a sustainable reinforcement. PALF treated at 0.2 % by weight improved compressive and tensile strengths to 30 and 2.7 MPa, respectively, after 28 days, outperforming traditional concrete formulations.[9] Similarly, a 2 % PALF addition to cement bricks increased compressive strength to 16.9 N/mm² compared to 14.15 N/mm² in the controls, confirming its effectiveness as a performance enhancer.[10]

Experimental studies indicate that PALF enhances tensile and flexural properties in normal-strength concrete at an optimal fibre content; improvements were observed at fibre dosages ranging from 0 % to 1 %.[11] Variations in the PALF content (0.04, 0.09, 0.15) % have also demonstrated positive correlations between fibre addition, workability, slump, and compressive strength in high-strength concrete.[12] Moreover, PALF additions of up to 1.5 % by cement weight have consistently improved compressive and split-tensile strengths after curing. Complementing fibre reinforcement, NS and SF accelerate hydration in high-content fly ash cement composites, reduce setting time, and enhance early strength and micropore structure.[13,14]

The mechanical, thermal, and morphological properties of PALF further endorse its viability for sustainable composite applications, supported by advancements in fibre extraction and processing.[15] However, strength gains from NS as a cement replacement peak at around 5 %, with declines beyond this threshold.[16]

The primary objective of this research is to investigate the potential of using NS and SF as partial substitutes for concrete binder to enhance the performance of high-performance concrete. The study aims to evaluate the effects of these substitutions on the workability, strength, and durability of HPC. Additionally, it seeks to assess the viability of integrating pineapple leaf fibre into a concrete mix as a step towards promoting environmental sustainability. Furthermore, the study aims to determine the ultimate load-carrying capacity of beams under single-point loading to evaluate their structural performance.[17,18] NS has gained attention as an effective additive to improve concrete's microstructure, strength, and durability. Its fine particles accelerate cement hydration and reduce porosity, resulting in enhanced mechanical properties and resistance to degradation.[19–21]

1.2 Research significance

While numerous studies explored the use of SF and NS as supplementary cementitious materials to improve the mechanical properties of HPC, limited research exists on their combined effect with natural fibres such as PALF. Most existing studies focus on compressive strength and durability, neglecting critical aspects like load-bearing capacity, stiffness, deflection behaviour, and crack propagation under static loading conditions. Additionally, the effect of varying proportions of SF and NS, along with a constant addition of PALF, on the flexural behaviour of reinforced concrete beams remains underexplored. This gap necessitates a comprehensive investigation into the mechanical performance and failure modes of HPC beams incorporating SF, NS, and PALF under single-point loading scenarios.

2 MATERIALS

2.1 Cement

Ordinary Portland cement (OPC), 53 grade, confirming to IS:12269 – 2013, is mainly used for preparing the specimens. The important properties of the cement are given in **Table 1**.

Table 1: Properties of cement

S. No	Tests performed	Experimental values	Requirements as per IS 12269-2013
1	Standard consistency	31 %	28-32
2	Initial setting time	115 min	Not less than 30
3	Final setting time	235 min	Not more than 600
4	Specific gravity	3.14	3.15
5	Fineness (<m^2/kg)	325	Not less than 225
6	3rd day compressive strength of cement	31.5 N/mm^2	Greater than 27.0 N/mm^2
7	7th day compressive strength of cement	42.5 N/mm^2	Greater than 37.0 N/mm^2
8	28th day compressive strength of cement	57.5 N/mm^2	Greater than 53.0 N/mm^2

2.2 Silica fume

Silica fume typically appears as a grey powder with spherical particles. It can demonstrate both pozzolanic and cementitious properties, significantly enhancing the compression capacity of a cementitious material, confirming to IS 15388 – 2003 standards. The properties of SF are presented in **Table 2**.

Table 2: Properties of SF

S. No	Attributes	Experimental values	Requirements as per ACI 234R – 96
1	Particle size	0.1–0.3 µm	
2	Specific gravity	2.21	2.2–2.3
3	Fineness	15,000	12,000–30,000 m^2/kg
4	Mass density	520 kg/m^3	475–720 kg/m

2.3 Nano silica

Nano silica is an engineered material characterized by spherical particles ranging from 1 to 100 nm. Due to its nanoscale size, it acts as a nanofiller, effectively filling the spaces between C-S-H binder gel particles, thus densifying the concrete matrix. The attributes of the nano silica used are specified in **Table 3**.

Table 3: Properties of NS

S. No	Attributes	Experimental values
1	Particle size	15–40 nm
2	Specific gravity	1.31
3	Active nanocontent	40.5 %
4	pH	9.4
5	Specific surface area	200 m^2/g

2.4 Aggregate

River sand confirming to IS: 383 – 1970 was used as the fine aggregate and crushed granite stone with a maximum size of 12.5 mm was used as the coarse aggregate. The properties of fine and coarse aggregates are presented in **Table 4**.

Table 4: Properties of fine and coarse aggregates

S. No	Property	Fine aggregate	Coarse aggregate
1	Specific gravity	2.65	2.75
2	Fineness modulus	2.85	5.01
3	Density	1750 kg/m^3	1630 kg/m^3
4	Water absorption	0.7 %	0.5 %

2.5 Chemical admixtures

Conplast SP430, a superplasticizer, conforming to IS: 9103 –1999, was used.

2.6 Steel

The size and diameter of reinforcement was selected with references to IS: 1786 –2008. 10-mm diameter rebars were tested for their tensile stress in a universal testing machine.

2.7 Water

The water employed in this mixing process should be fresh and devoid of any organic or harmful solutions that might compromise the properties of the mortar. The use of saltwater is prohibited. Potable water is suitable for both mixing and beam curing.

2.8 Pineapple leaf fibre (PALF)

PALF is an innovative and sustainable reinforcement material used in concrete. Derived from the leaves of the pineapple plant, they are typically considered agricultural waste.

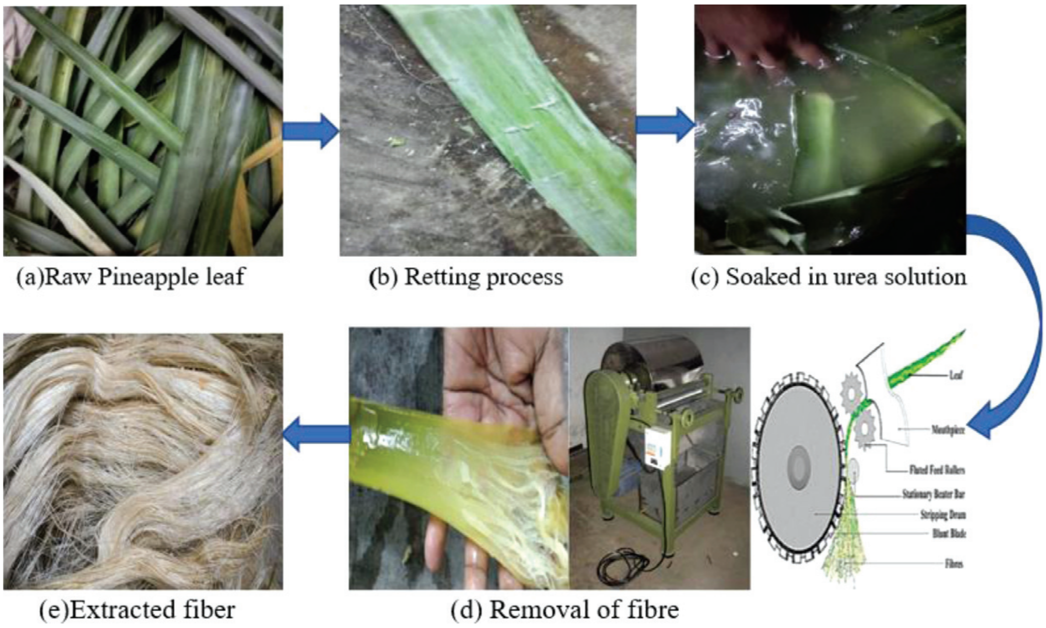

Figure 1: Procedure of PALF extraction

2.8.1 Processing and extraction of PALF

The extraction of PALF involves mechanical scrapping and microbial retting to ensure high-quality fibres suitable for concrete (Rafiqah et al., 2020). Pineapple leaves are fed into a scrapping machine with three rollers: intake, abrasion, and toothed roller, to remove the waxy coating and initiate breaks for retting. The leaves are then immersed in water with urea or ammonium phosphate to accelerate retting, with the process monitored to loosen fibres, and free them from lignin, waxes, and other compounds. Finally, the fibers are mechanically separated, rinsed, and air-dried. **Figure 1** illustrates the extraction of PALF.

2.8.2 Treatment of PALF

Post-extraction, PALF undergoes treatments to enhance its performance in concrete. Alkaline treatment with sodium hydroxide (NaOH) at concentrations of (2, 4, 6 and 8) % removes impurities like lignin and improves surface roughness, enhancing bonding with the concrete matrix. Silane treatment follows, using a 5 % silane solution to improve hydrophobic acid and mechanical bonding. Fibres are soaked in a methanol solution with 1 % silane, adjusted to pH of 3.5 using acetic acid, and agitated for 6 h before being air-dried. These treatments improve the compatibility of PALF with the concrete matrix.

2.8.3 Strength testing of PALF

The mechanical properties of PALF are assessed through tensile strength, Young's modulus, and strain at break tests. Both untreated fibres and those treated with NaOH and silane are evaluated to observe improvements in performance. The findings indicated that PALF treated with 6 *w*/% NaOH and 5 % silane solution shows optimal mechanical properties. The treated fibres exhibit significantly higher tensile strength and modulus compared to untreated fibres, making them suitable for reinforcing concrete. The physical properties of PALF are given in **Table 5**.

Table 5: Physical properties of PALF

Property	Experimental values
Density (g/cm^3)	1.3
Young's modulus (GPa)	14.4
Elongation at break (%)	1.4
Tensile strength (MPa)	132
Micro-fibril angle (°)	8
Length (mm)	21.5
Diameter (mm)	0.215

2.9 HPC mix design

The mix design for this research is meticulously formulated to achieve M60 grade concrete, adhering to the guidelines prescribed by ACI 211 for high-performance concrete. The inclusion of PALF is optimized to enhance both the mechanical properties and the environmental profile of the concrete. The concrete mix was modified by incorporating SF in proportions of (5 7.5, 10 and 12.5) %, along with NS in varying percentages of (0.5, 1, 1.5, 2 and 2.5) %. The mix proportions for different replacements of cement with SF and NS are detailed in **Table 6**.

Each sample ID corresponds to a specific proportion of cement replacement with SF or NS. The proportions are balanced to maintain a consistent water-binder ratio and workability. PALF, treated with NaOH and silane solution, is added at an optimal amount of 2.5 % by mass of cement. The superplasticizer quantity is adjusted to

Table 6: Final mix proportioning

Sample ID	OPC (kg/m^3)	SF (kg/m^3)	NS (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Super plasticizer (kg/m^3)	PALF (%)
Control	516	–	–	601	1174	160	5.16	–
SF5	490.2	25.8	–	601	1174	160	5.16	2.5
SF7.5	477.9	38.7	–	601	1174	160	5.16	2.5
SF10	464.4	51.6	–	601	1174	160	5.16	2.5
SF12.5	451	64.5	–	601	1174	160	5.16	2.5
NS0.5	513.42	–	2.58	601	1174	160	5.16	2.5
NS1	510.84	–	5.16	601	1174	160	5.16	2.5
NS1.5	508.26	–	7.74	601	1174	160	5.16	2.5
NS2	505.68	–	10.32	601	1174	160	5.16	2.5
NS2.5	503.1	–	12.9	601	1174	160	5.16	2.5

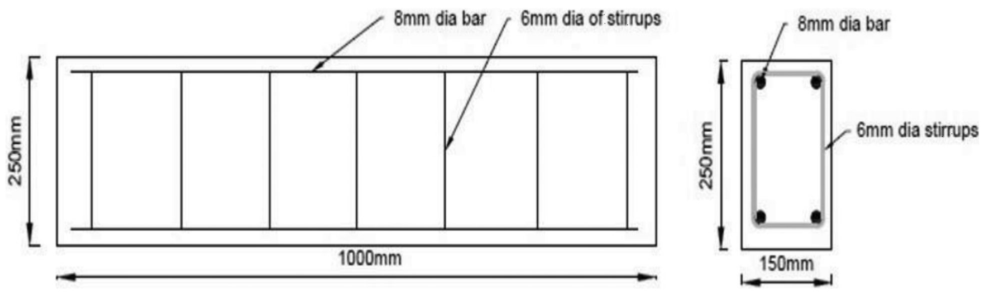

Figure 2: Reinforcement details of a beam

achieve the desired slump while ensuring that the mix remains homogeneous and workable.

3 CASTING AND TESTING OF HIGH-PERFORMANCE CONCRETE BEAMS

3.1 Design

The beams were designed in accordance with the Indian design code IS456-2000, with cross-sectional dimensions of 150 × 250 mm and a total length of 1 m. A clear cover of 25 mm was provided on each side of the beams. **Figure 2** illustrates the reinforcement details of the beam.

Two 10-mm diameter longitudinal bars were placed in the tension zone, and two 8-mm diameter hanger bars were positioned in the compression zone. Additionally, 6-mm diameter two-legged vertical stirrups were provided at 100-mm centre-to-centre spacing.

3.2 Casting of HPC beams

Steel moulds measuring (1000 × 150 × 250) mm were fabricated for the casting process. Once the reinforcements were properly positioned, the casting was performed. Cover blocks were used, and the mould sides were greased to facilitate smooth demoulding. Concrete was cast, and the specimen surface was finished. The specimens were demoulded after 24 h and cured for 28 d. **Figure 3a** illustrates the reinforcement of a beam, **Figure 3b** depicts the casting process with the concrete being poured and levelled.

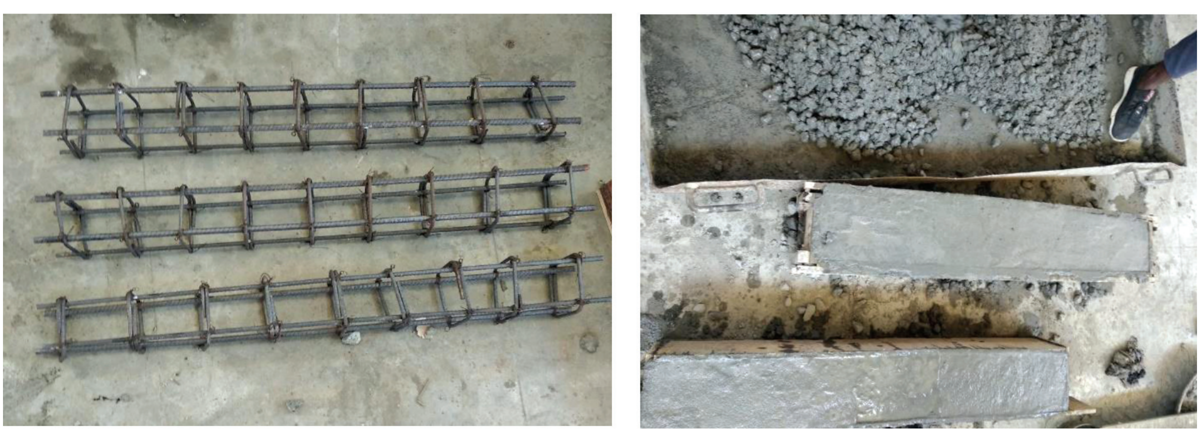

Figure 3: Reinforcement details and casting of a beam

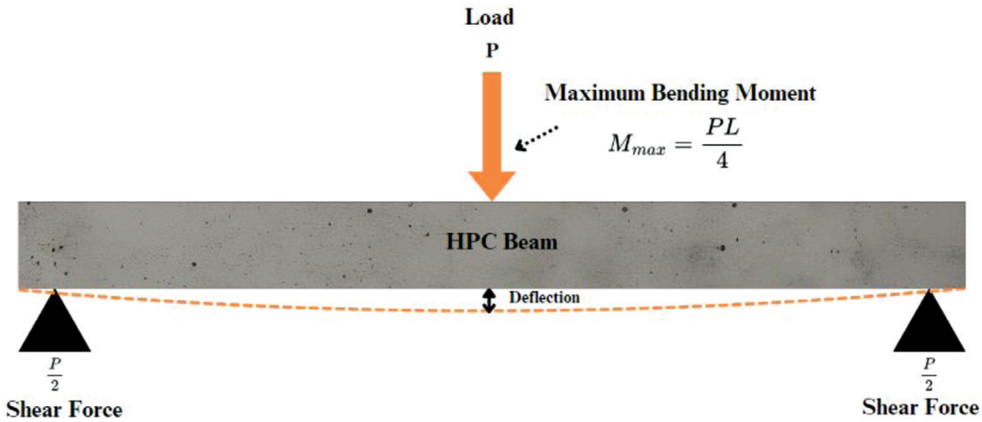

Figure 4: Schematic representation of the single-point loading test

3.3 Testing of the specimens

Single-point loading tests were conducted on HPC beams to evaluate their performance under concentrated loads. The tests aimed to assess the load-bearing capacity and structural integrity of these beams. A beam was simply supported at both ends. **Figure 4** includes a schematic diagram depicting the loading set up for single-point testing. The experimental setup for this test is shown in **Figure 5**.

Table 7: Single-point loading test results

Mix designation	PALF (%)	Ultimate load (kN)	Mid-span deflection (mm)
Control	-	67.4	12.3
SF5	2.5	70.2	11.8
SF7.5	2.5	75.0	11.5
SF10	2.5	85.6	12.2
SF12.5	2.5	80.8	9.0
NS0.5	2.5	71.0	10.5
NS1	2.5	76.3	9.3
NS1.5	2.5	83.2	8.0
NS2	2.5	91.2	7.4
NS2.5	2.5	85.5	8.6

Figure 5: Testing of beams

The single-point loading test on HPC beams with dimensions of (150 × 250 × 1000) mm was conducted to evaluate their performance under concentrated loads, focusing on the applied load, and mid-span deflection. The findings are summarized in **Table 7**.

Load-deflection curves for all beams were constructed by plotting the applied loads against the resulting deflections. **Figures 6** and **7** show the load-deflection curves for SF- and NS-modified HPC beams, respectively.

Figures 8 and **9** depict the performance of concrete beams under static loading, highlighting the comparison between conventional beams and HPC beams integrated with SF and NS. The ultimate load-carrying capacity of SF-incorporated HPC beams under static loading exhibits significant variations depending on the percentage of SF added. Control beams achieved an ultimate strength

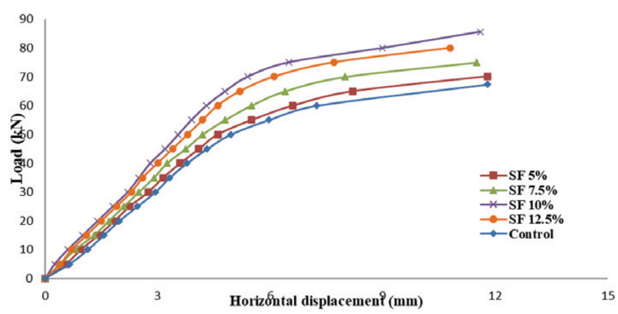

Figure 6: Load-deflection curves of SF-modified HPC beams

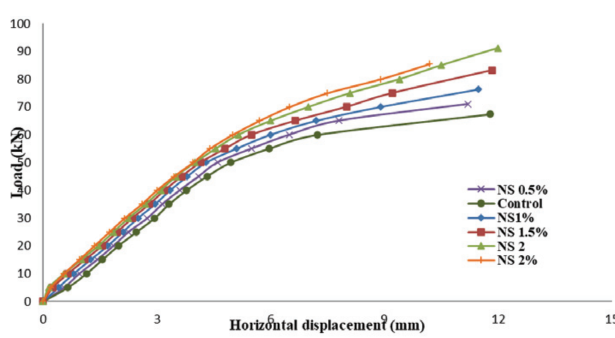

Figure 7: Load-deflection curves of NS-modified HPC beams

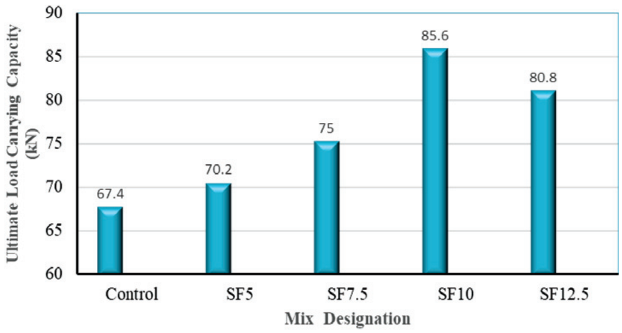

Figure 8: Ultimate load-carrying capacity of SF-modified HPC beams

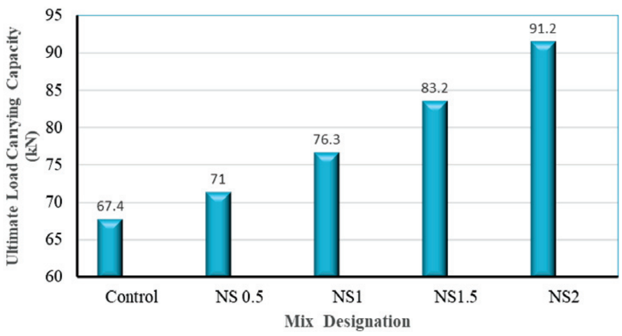

Figure 9: Ultimate load-carrying capacity of NS-modified HPC beams

of 67.4 kN, while SF-incorporated beams demonstrated a significant enhancement, attaining higher ultimate strength. HPC beams with 10 % SF achieved an ultimate load of 85.6 kN, reflecting a moderate improvement and an increase of nearly 27 % compared to the control beam. The additions of (5, 7.5, and 10) % SF to HPC resulted in an increase in the ultimate load capacity, while a further increase to 12.5 % SF led to a decline in ultimate load performance. This decline observed with 12.5 % SF incorporation can be attributed to the excessive SF content, which may disrupt the optimal binder-to-aggregate ratio and result in increased brittleness. High SF percentages can lead to reduced workability, inadequate compaction, and potential micro-cracking during hydration, negatively impacting the overall structural performance of the concrete. These findings highlight the effectiveness of incorporating SF in improving the load-bearing capacity.

The ultimate load-carrying capacity of NS-incorporated HPC beams under static loading exhibited significant variations with different NS percentages. Notably, beams with 2 % NS achieved an ultimate load of 91.2 kN, which is nearly 35 % higher than the control beam. This indicates a substantial improvement compared to the control beam and beams with (0.5, 1, and 1.5) % NS. However, while the addition of up to 2 % NS enhanced the load-carrying capacity, further increase to 2.5 % led to a decline in the ultimate load. This decline beyond a 2 % NS addition can be attributed to the excessive inclusion of NS, which may lead to particle agglomeration. This agglomeration reduces the uniform dispersion of NS within the concrete matrix, negatively impacting its microstructure and weakening the interfacial transition zone (ITZ). Consequently, the strength of the concrete and load-carrying capacity are diminished.

3.4 Mode of failure

The cracking patterns and failure modes observed during the load testing of HPC beams provide critical insights into their structural behaviour. The failure modes of different types of beams are as follows: conventional shear deficient RC beams typically fail in shear because their flexural strength is high. Due to insufficient shear reinforcement, these beams fail primarily by shear, with visible cracks forming and propagating in the critical shear regions at the beam ends, ultimately leading to shear failure. On the other hand, conventional flexure-deficient RC beams fail in flexure since they are designed

Figure 10: Cracking patterns of beam specimens

with adequate shear reinforcement. These beams fail in flexure due to insufficient flexural reinforcement, with cracks primarily developing in the flexure zone near the centre.

Figure 10 shows the cracking patterns observed in the HPC beams, subjected to single-point loading.

Observations of crack patterns revealed that all the beams failed in flexure when subjected to single-point loading. Initially, microcracks appeared at the point of maximum stress, typically at the mid-span of the beams. As the load increased, these microcracks propagated along the tension face, leading to visible cracks that spread towards the supports. The beams ultimately failed when the cracks reached a critical size, causing the tension zone to rupture. The presence of different materials, such as SF and NS, influenced the cracking behaviour, with beams incorporating these additives showing more controlled and slower crack propagation, thus delaying the onset of failure compared to the control beams.

4 CONCLUSION

The control mix exhibited moderate load-bearing capacity with significant mid-span deflection, indicating lower toughness compared to the beams enhanced with SF and NS. The SF5, SF7.5, and SF12.5 mixes showed improvements in load-bearing capacity and reduced deflection, with more ductile failure modes, reflecting better energy absorption. Among the SF mixes, SF10 demonstrated the highest load-bearing capacity with a ductile failure mode and superior bending moment capacity.

The NS0.5 and NS1 mixes offered moderate improvements with mixed failure modes, combining ductility and brittleness. The NS1.5 and NS2 mixes exhibited the best overall performance, with the NS2 mix achieving the highest load-bearing capacity and minimal deflection, indicating superior structural integrity and toughness. However, the NS2.5 mix, while performing well, displayed a slightly lower load-bearing capacity and increased deflection compared to NS2, suggesting an optimal NS content around of 2 %.

The control mix exhibited widespread cracking, with cracks forming early and propagating rapidly. In contrast, the beams incorporating SF and NS showed improved resistance to cracking, with fewer and narrower cracks, and a more ductile failure mode. Among these, the SF10 and NS2 mixes demonstrated the best performance, characterized by minimal cracking and a delayed failure mode, indicating enhanced toughness and durability.

The load-testing results for the HPC beams validate the substantial benefits of incorporating SF and NS into the mix design. Beams with 10 % SF and 2 % NS showed superior load-bearing capacity, stiffness, and ductility, making them well-suited for applications demanding high structural performance. All the beams exhibited flexural failure when subjected to single-point loading, as clearly evidenced by the observed crack patterns. The HPC beams with 10 % SF showed a 27 % increase in ultimate load carrying capacity compared to the control beam, whereas those with 2 % NS demonstrated an even greater enhancement, achieving a 35 % higher load-carrying capacity than the control beam. These findings underscore the importance of optimizing the mix design to achieve optimal performance in real-world structural applications.

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