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Performance evaluation of cement concrete incorporating cellulose coir fibre and nano-silica

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Original research paper

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Performance evaluation of cement concrete incorporating cellulose coir fibre and nano-silica

This paper employs experiments to examine the effects of cellulose coir fibre (CCF) and nano-silica (NS) on the fresh, mechanical, and durability properties of C20/25 grade cement concrete. A slump cone test is used to assess the fresh concrete properties, followed by compressive, split tensile, and flexural strength tests on the hardened concrete. Durability is evaluated through water penetration, water absorption, and acid resistance tests. The addition of 3 % nano-silica results in an approximate 14 % increase in compressive strength. With the incorporation of 0.9 % cellulose coir fibre, the strength increase rises from 14 % to 27 % compared to the control specimen. A compressive strength exceeding 40 N/mm^2 is achieved with the inclusion of 3 % nano-silica and 0.9 % cellulose fibre in C20/25 grade concrete. Similar trends are observed in other mechanical tests. For durability assessment, specimens cured for 28 days are exposed to an acidic environment by immersion in hydrochloric acid for 30, 60, and 90 days. The cement concrete blended with nano-silica and cellulose coir fibre is also subjected to scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis.

Key words:

nano silica, cellulose coir fiber, acid resistance, water penetration, water absorption

Izvorni znanstveni rad

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Analiza svojstava betona s dodatkom celuloznih kokosovih vlakana i nanosilike

U ovome radu ispitani su učinci celuloznih kokosovih vlakana (CCF) i nanosilike (NS) na mehanička svojstva i trajnost svježeg i očvrsnulog betona razreda C20/25. Svojstva svježeg betona procjenjuju se ispitivanjem slijeganja betona pomoću Abramsova stošca (engl. *slump cone test*), nakon čega slijede ispitivanja tlačne čvrstoće, vlačne čvrstoće cijepanjem i čvrstoće na savijanje na očvrsnulome betonu. Trajnost se procjenjuje ispitivanjem prodora vode, upijanja vode i otpornosti na kiseline. Rezultati pokazuju da dodatak 3 % nanosilike povećava tlačnu čvrstoću za približno 14 %, dok kombinacija 3 % nanosilike i 0,9 % celuloznih kokosovih vlakana povećava čvrstoću za 27 % u odnosu na kontrolni uzorak, pri čemu se postiže tlačna čvrstoća veća od 40 N/mm^2. Slični trendovi zabilježeni su i u ostalim mehaničkim ispitivanjima. Za ocjenu trajnosti uzorci njegovani 28 dana izlagani su agresivnoj sredini uranjanjem u otopinu klorovodične kiseline na 30, 60 i 90 dana. Beton s dodatkom nanosilike i celuloznih kokosovih vlakana analiziran je skenirajućim elektronskim mikroskopom (SEM) i energijsko-disperzijskom rendgenskom analizom (EDX).

Ključne riječi:

nanosilika, celulozna kokosova vlakna, otpornost na kiseline, prodor vode, upijanje vode

1. Introduction

In the construction sector, concrete is arguably the most widely used material [1]. Cement is a key component in concrete production due to its binding and adhesive properties [2]. However, the manufacture of ordinary Portland cement (OPC) releases significant amounts of CO_2 into the atmosphere, contributing substantially to greenhouse gas emissions [3, 4]. It is estimated that one tonne of CO_2 is emitted for every tonne of OPC produced [5]. In modern construction, alongside strength, the durability of concrete has also become a critical consideration [6]. Progress in the concrete industry focuses on enhancing concrete grades through the use of supplementary cementitious materials (SCMs) [7]. In this study, nano-silica is incorporated into the concrete mix as an additional cementitious material. Its inclusion aims to improve the strength and durability of concrete [8]. Cement serves as the binder that holds together the other components in concrete [9]; however, its major drawback lies in its high contribution to CO_2 emissions and environmental degradation [10]. To mitigate this environmental impact, the integration of nano-silica particles into concrete presents a promising solution [11, 12]. This involves replacing a portion of cement with varying proportions of nano-silica by weight, thereby enhancing the grade and performance of the concrete [13]. The grade of concrete increased from low to high, while the cement content decreased [14, 15]. The primary objective of this investigation is to achieve C30/37 grade concrete from C20/25 grade without increasing the cement content. Nano-silica is highly effective in enhancing various strength, physical, and mechanical properties of concrete compared to other nanomaterials [16, 17]. It is an extremely potent pozzolanic material [18, 19], with particles significantly smaller than those of ordinary cement [20, 21]. The addition of nano-silica improves the compressive strength of concrete, accelerates the formation of calcium silicate hydrate (C-S-H) gel, and shortens setting times [22-24]. Nano-silica particles fill nano-sized pores and air voids, increasing the density of concrete, reducing permeability, and lowering water absorption capacity [25-27]. As a result, durability performance improves. Sarita Rai et al. evaluated the effectiveness of nano-silica in cement paste [28]. When nano-silica reacts with calcium hydroxide, it forms additional C-S-H phases, further enhancing strength development [29, 30]. Moreover, nano-silica contributes to the reduction of cement setting time [17, 31].

When a crack forms in reinforced concrete, it gradually propagates under applied loads until it reaches the rebar [32, 33]. Owing to such limitations, extensive research has been undertaken to develop new strategies for improving the brittle nature of concrete [34, 35]. Consequently, there is a need for reinforcement in concrete that is multidirectional and closely spaced [36]. To address this, researchers have developed methods to incorporate fibres into concrete [37-39]. The inclusion of fibres enhances both the strength and ductility of concrete [40]. Fibre-reinforced concrete refers to concrete that contains various types of fibres [41]. The present study focuses on cellulose fibre-reinforced concrete (CFRC) using cellulose coir fibre. Recent studies have utilised natural fibres to improve mechanical strength [42, 43]. Natural fibres such as coir fibre, palmyra fruit fibre, oil palm fibre, coir pith fibre, jute fibre, and banana fibre have been investigated for their potential in concrete reinforcement [44-46]. However, limited research has been conducted on the use of treated natural fibres or cellulose-based natural fibres embedded in concrete for strength enhancement. Therefore, this study incorporates cellulose coir fibre into cement concrete to improve its mechanical properties. The coconut fibre used in this research was sourced from coconut gardens in nearby villages, where large quantities of coconut shells are readily available [47, 48]. Coconut fibre is extracted from coconut shells [49]. Two types of coconut fibre are commonly found in coconut gardens: brown coconut fibre and white coconut fibre. Brown coconut fibre is obtained from mature coconuts, while white coconut fibre is derived from immature coconuts. Brown coconut fibre is stronger and thicker than its white counterpart [50, 51]. This study utilises brown coconut fibres. Globally, approximately 500,000 tonnes of coconut fibre are produced annually [52], with India ranking third in coconut production [53]. Key advantages of coconut fibres include resistance to moths, fungi, and rot; thermal and acoustic insulation properties; flame retardancy; resistance to moisture and dampness; high strength and durability; and the ability to regain shape after prolonged use [54-56]. Coconut fibre also exhibits a stain absorption capacity 4 to 6 times greater than that of other fibres [57-59], along with superior elongation and stretchability [60-62]. The fibres are extracted from the coconut shell, washed with normal water to remove dirt, and then cleaned further to eliminate gum-like substances [63]. Following washing, drying, and chemical treatment, the surface of the cellulose coir fibre becomes significantly rougher than that of other fibres [64, 65]. The average diameter of the cellulose coir fibre is reported to be between 1.08 and 5.80 μm [66]. Finally, the treated fibres are ready for use in cement concrete. The cellulose fibre is added to the concrete mix in proportions of 0.3 %, 0.6 %, 0.9 %, 1.2 %, and 1.5 % by weight of the binder [67].

The addition of cellulose coir fibre (CCF) to conventional concrete disperses millions of fibres per cubic metre, thereby enhancing the structural integrity [68, 69]. While fibres exist in various forms, cellulose fibres in hardened concrete exhibit a high modulus of elasticity [70]. Unlike steel fibres, cellulose coir fibres provide durable reinforcement without the risk of corrosion [56]. They are also safe and easy to handle, distributing uniformly throughout the concrete mix [71]. Although cellulose coir fibres have minimal influence on compressive strength, they significantly improve toughness and impact resistance [72, 73]. Advancements in the production of cellulose coir fibres have led to high-quality fibres with excellent alkali resistance and dispersion characteristics, greatly improving their long-term durability [74, 75]. This study investigates the effect of incorporating the optimum amount of cellulose coir fibre along with 3 % nano-silica on C20/25 grade cement concrete. The experimental work examines the influence of CCF and nano-silica (NS) on the fresh, mechanical, and durability properties of C20/25 grade concrete. A slump cone test is conducted to assess fresh concrete characteristics, followed by compressive, split tensile, and flexural strength tests on hardened concrete. Durability is evaluated through water penetration, water absorption, and acid resistance tests. Nano-silica is added at a constant rate of 3 % by weight of cement. Cellulose coir fibre is added in varying proportions (0.3 %, 0.6 %, 0.9 %, 1.2 %, and 1.5 % by weight of cement) in combination with nano-silica. The primary aim of this study is to determine the optimal cellulose coir fibre content that maximises mechanical properties and durability.

2. Materials and methods

The raw materials used for the concrete were locally sourced and selected for their superior quality and purity. The performance and behaviour of these materials were initially assessed through physical inspection. Further testing was conducted to evaluate their suitability in accordance with the recommendations of IS 456, IS 650, IS 1498, IS 8112, IS 10086, IS 383, IS 2386: Parts I–VIII, IS 2430, IS 516, IS 1786, IS 3025, IS 4031, IS 8142, and IS 1607. Ordinary Portland cement was procured from Chettinad Cement, Madurai, while M-sand and coarse aggregate were obtained from Vignesh Blue Metals, Madurai. Nano-silica was sourced from Trimex Ltd, Hyderabad. Cement, the primary component of mortar and concrete, was represented in this study by 53 Grade Ordinary Portland Cement, used as the binding material. The properties of the cement were determined based on IS 8112:1989 and IS 4031 (Parts 1, 3, 5, and 11) – 1988 and 1999. Laboratory tests were conducted on the 53 Grade OPC, including fineness (sieve test), initial setting time, final setting time, specific gravity, and standard consistency. The test results revealed the following properties: specific gravity of 3.18, fineness of 6.95 %, initial setting time of 45 min, final setting time of 585 min, and a standard consistency of 30 %. Naturally hard aggregates were selected as concrete ingredients due to their essential role in the mix. Aggregates form the bulk of the concrete, providing shape, a rigid skeletal framework, and contributing to reduced shrinkage, enhanced strength, and overall cost efficiency. They account for approximately 75 to 80 % of the concrete volume and significantly influence its properties [76-79]. Concrete typically comprises two material phases: the paste phase and the aggregate phase. In the aggregate phase, the filler materials form a covalent bond with the cement matrix [80]. Aggregates are categorised into two main types based on particle size: fine aggregate (less than 4.75 mm) and coarse aggregate (greater than 4.75 mm). In this study, M-sand conforming to grading Zone II, as per IS: 383-1970, was used as the fine aggregate and sourced locally [81]. The laboratory test results for fine aggregate were: specific gravity of 2.69, fineness modulus of 2.79, water absorption of 0.24 %, and bulk density of 1670 kg/m^3. The coarse aggregate used was natural crushed granite that complied with the grading requirements of IS: 383-1970. It was retained on a 4.75 mm IS sieve after passing through a 20 mm sieve. The test results for the coarse aggregate were: specific gravity of 2.71, fineness modulus of 7.55, water absorption of 0.24 %, impact value of 14.88 %, crushing value of 14.55 %, and an angular particle shape.

2.1. Nano silica (SiO_2)

Nano-silica can be obtained through direct silica synthesis or by the crystallisation of quartz crystals into nanoscale particles [82]. This material consists of extremely fine vitreous particles, approximately 1,000 times smaller than typical cement particles [83]. Nano-silica is widely recognised as a highly efficient pozzolanic material [8, 11, 84]. It has proven to be an effective additive in cement, enhancing durability and reducing permeability. The nano-silica used in this study has a particle size of 17 nm. Its physical and chemical properties are presented in Table 1. The chemical composition was determined in the laboratory of M/S Trimex Mineral Industries Ltd, Hyderabad. As shown in Table 1, the primary constituent of nano-silica is SiO_2, comprising approximately 99.54 %. A visual representation of the nano-silica is provided in Figure 1c.

2.2. Cellulose fiber

The raw coconut fibre was sourced from the rural village of Kumarapuram Thoppur in Kanyakumari district, Tamil Nadu. The chemicals used for the extraction process—sodium hydroxide pellets for alkali treatment, hydrochloric acid for acid hydrolysis, and sodium hypochlorite for bleaching—were procured from Suja Chemicals, Nagercoil.

Coconut fibre offers significant advantages across various industries. However, it tends to lose strength within a few months due to its high content of lignin, hemicellulose, and cellulose. The cellulose was extracted using an acid hydrolysis method. Lignin, which contributes to the fibre's biodegradability, causes it to degrade and weaken over time—typically within one to two years, or up to a maximum of five years depending on its content. Lignin was removed by treating the fibre with sodium hydroxide (alkalisation) [85]. For this process, 200 g of fibre was heated with a 50 % sodium hydroxide solution (500 g NaOH in 1 litre of water) for 3 h at a temperature between 80 °C and 100 °C. The mixture was then cooled and rinsed with water until the brown colour, indicating the presence of lignin, faded. To remove any remaining lignin, a second alkali treatment was carried out using 25 % sodium hydroxide. Subsequently, the fibre was acid-hydrolysed using 50 % hydrochloric acid (500 ml in 1 litre of water) and soaked for 12 h to eliminate excess non-cellulosic components. The resulting residue was then bleached

Table 1. Chemical and physical properties of Nano Silica

Series code	Physical properties	Value	Chemical	Proportions [%]
1	Specific surface area (m^2/g)	200 ± 20	Silica (SiO_2)	99.54
2	pH value	3.7 – 4.5	Aluminium (Al_2O_3)	0.056
3	Specific gravity	2.2 – 2.4	Iron (Fe_2O_3)	0.016
4	Particle size	17 nm	Potassium (K_2O)	0.007
5	Loss on drying 105 °C	≤ 1.5	Sodium (Na_2O)	0.005
6	Loss in ignition 1000 °C	≤ 2.0		
7	Sieve residue	≤ 0.04		
8	Tamped density (g/L)	40 – 60		
9	Color	White		

Figure 1. Natural fibre and nano-silica: a) Raw coconut fiber; b) Cellulose coconut fiber; c) Nano silica

with sodium hypochlorite by heating the mixture at 60°C for 1 h. This bleaching process marked the final stage of cellulose extraction. The extracted cellulose fibre was thoroughly washed with distilled water and dried in a hot air oven at 110°C for 2 h. Finally, the fibre was cooled using a desiccator [86]. Figures 1a and 1b show the raw and extracted cellulose coconut fibres, respectively.

2.3. Mix design

The objective was to determine the concrete mix design for C20/25 grade based on the test results of individual components. The mix design was guided by the properties of the selected materials. The water–cement ratio plays a critical role in producing high-quality concrete. The mix design was carried out in accordance with IS 10262:2019 [87]. For this study, C20/25 grade concrete was designed for casting specimens including cubes, cylinders, and prisms. One cubic metre of concrete comprised 425.73 kg of cement, 640.34 kg of fine aggregate, 1150 kg of coarse aggregate, and 191.60 kg of water. The mix proportion of the design mix was 1:1.5:2.7, with a water–cement ratio of 0.45.

M25 grade concrete mix was designed for this experiment. The constituent materials included cement, fine aggregate (FA), coarse aggregate (CA), and water. The concrete was prepared using the specified mix proportion of 1 : 1.5 : 2.7 (one part cement, 1.5 parts FA, and 2.7 parts CA) with a water–cement ratio of 0.45. Mixing was carried out using a mechanical mixer. Great care was taken during placing, compaction, de-moulding, and testing. The concrete was placed and compacted within the initial setting time. The standard mould dimensions were as follows: cubes – 150 × 150 × 150 mm; cylinders – 150 mm in diameter and 300 mm in height; and prisms – 100 × 100 × 500 mm. Separate cast-iron moulds were used for casting cubes, cylinders, and prisms. To ensure easy de-moulding, a single coat of shuttering oil was applied to the inner surfaces of each mould. A pan mixer with a capacity of 100 kg was used for mixing the concrete. NS and CCF were added after thoroughly mixing the dry ingredients. For mix designs with a layer thickness of five centimetres, the concrete was carefully prepared and placed in layers into the moulds. Each layer was compacted manually using a bullet-tipped tamping rod. The top surface was finished and levelled evenly using a trowel. The moulds were de-moulded 24 h after casting. A trial mix was prepared with varying nano-silica content: 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight of cement. The mix containing 3 % nano-silica achieved the optimum strength. Cellulose coir fibre was then added in varying amounts 0.3 %, 0.6 %, 0.9 %, 1.2 %, and 1.5 % by weight of cement while maintaining a constant 3 % nano-silica content. The mix containing 0 % NS and 0 % CCF was designated as the control mix (CM). The mix with 3 % nano-silica and 0 % CCF was designated as F0. Mixes containing 3 % nano-silica and varying CCF contents were labelled as follows: F0.3 (0.3 % CCF), F0.6 (0.6 % CCF), F0.9 (0.9 % CCF), F1.2 (1.2 % CCF), and F1.5 (1.5 % CCF).

2.4. Fresh and hardened concrete test

The slump test is the most commonly used method for determining the consistency of concrete. It is suitable for both on-site and laboratory applications and is widely adopted due to its simplicity. The test is conducted using a mould shaped like the frustum of a cone, with internal dimensions conforming to IS 1199:1959.

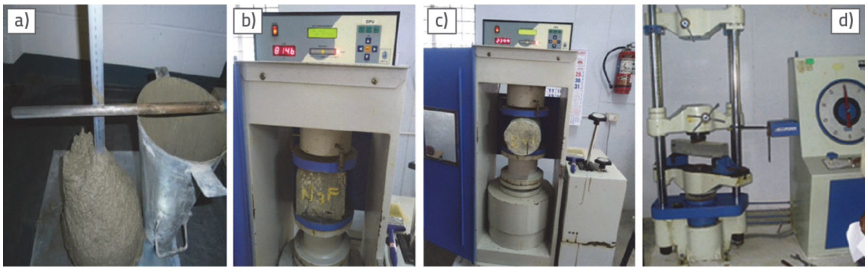

Figure 2. Fresh and hardened concrete tests: a) Slump test; b) Compressive strength test; c) Split tensile strength test; d) Flexural strength test

In this test, a clean, non-absorbent tray was used to hold the slump cone. The cone was filled with four layers of freshly mixed concrete, each compacted with 25 strokes of a standard tamping rod, evenly distributed across the cross-section. After the fourth layer was filled, the top surface was levelled using a trowel. The slump cone mould was then carefully removed by lifting it vertically in a steady motion, allowing the concrete to subside. This downward movement is referred to as the "slump of concrete." The slump is measured in millimetres as the vertical distance between the top of the slumped concrete and the original height of the mould. This value, known as the concrete slump, is illustrated in Figure 2(a), and the results are presented in Table 2. The mechanical properties of the specimens were tested in accordance with IS 5816:1999 and IS 516:1959 [88]. Compressive strength tests were carried out using an electro-hydraulic compression testing machine (CTM) with a capacity of 2000 kN. Figure 2(b) illustrates the application of axial compressive load, applied gradually at a rate of 5.4 kN/sec in increments of 50 kN. The average compressive strength values for each cube specimen are presented in Table 2. Figure 2(c) shows the setup of the split tensile strength test apparatus, with loading applied at a rate of 2.9 kN/sec to determine the split tensile strength of the cylinders. The experimental results, summarised in Table 2, were used to calculate the split tensile strengths. Figure 2(d) depicts the flexural strength testing of prisms using a universal testing machine (UTM). The flexural strengths were calculated based on the experimental data tabulated in Table 2.

2.5. Durability test

Durability refers to concrete's ability to withstand weathering, chemical attack, and abrasion while retaining its intended engineering properties. The required level of durability varies depending on the specific performance requirements and exposure conditions. In this experiment, durability was assessed using cube specimens prepared with both the standard and optimal dosages of micro-silica.

2.5.1. Acid resistance test

The specimens were submerged in a 2 % HCl solution for 30, 60, and 90 days at room temperature. The pH and total dissolved solids (TDS) of the solution were 1.54 and 54.5 ppm, respectively. After removal from the HCl solution, the specimens were tested to assess any loss in strength or weight, and the results were compared accordingly. To evaluate the durability of concrete cubes and their resistance to acid attack, an experimental investigation was conducted using NS. A total of 21 concrete cube specimens comprising conventional, NS-modified, and


Figure 3. Cube specimens immersed in HCl solution

Table 2. Fresh and hardened concrete properties

Series code	Mixture	Nanosilica [%]	Cellulose coconut fibers [%]	Slump [mm]	Compressive strength [N/mm^2]			Split tensile strength [N/mm^2]			Flexural strength [N/mm^2]		
					Trajanje njege [dani]			**Trajanje njege** [dani]			**Trajanje njege** [dani]		
					7	**14**	**28**	**7**	**14**	**28**	**7**	**14**	**28**
1	CM	0	0	76	19.83	27.93	31.74	2.13	3.01	3.42	3.12	3.70	3.94
2	F0	3	0	73	22.01	31.14	37.29	2.37	3.35	4.01	3.28	3.91	4.27
3	F0.3	3	0.3	71	22.85	32.36	38.79	2.46	3.48	4.18	3.35	3.98	4.36
4	F0.6	3	0.6	70	23.72	33.63	40.46	2.55	3.62	4.36	3.41	4.06	4.45
5	F0.9	3	0.9	68	24.43	34.72	41.77	2.63	3.74	4.50	3.46	4.12	4.52
6	F1.2	3	1.2	67	23.88	34.08	41.02	2.57	3.67	4.42	3.42	4.09	4.48
7	F1.5	3	1.5	65	23.26	32.76	39.07	2.50	3.53	4.21	3.38	4.01	4.38

CCF-modified mixes were prepared, each measuring 150 mm × 150 mm × 150 mm. These specimens were subjected to acid attack testing at specified intervals, as shown in Figure 3. After 28 days of water curing, the specimens were removed from the curing tank, their surfaces wiped to remove residual moisture, and then air-dried for one day at room temperature. The dried specimens were weighed precisely to record their initial weights. One set of specimens (three cubes each) from the conventional and NS-modified mixes was tested for compressive strength using a CTM, in accordance with IS 516:1959. The applied load was divided by the cross-sectional area to determine the compressive strength, and the mean values were recorded.

2.5.2. Water absorption test

Concrete cube specimens measuring 150 × 150 × 150 mm were used to evaluate water absorption. After 28 days of water curing, the specimens were oven-dried for 48 h. Once dried, each specimen was weighed and then submerged in water for 24 h. After immersion, the specimens were removed, and their surfaces wiped clean with a dry cloth. The final weights were recorded. Water absorption was calculated as the percentage increase in weight after 24 h of immersion. Figure 4 shows the cube specimens submerged in water.

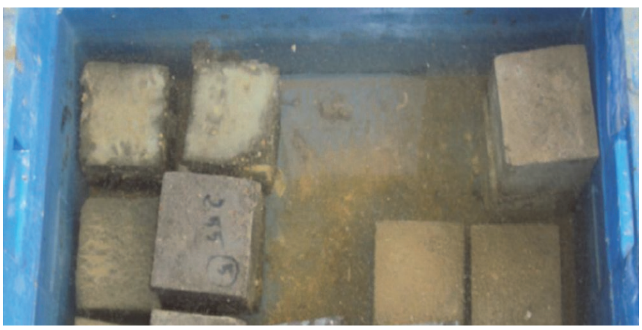

Figure 4. Cube specimens immersed in water

2.5.3. Water permeability test

The purpose of the water permeability test was to assess and analyse the porosity of conventional, NS, and CCF concrete. Prior to testing, the density of each specimen was determined. During the test, the concrete cover was positioned in contact with the pressure chamber to prevent water seepage through the cover. A water pressure of 2 to 3 pascals was applied to both standard and fibre-reinforced concrete specimens. The calibration test duration was not less than one hour. If water permeability was observed, the coefficient of permeability was calculated using the steady flow method. In the absence of measurable water flow, the depth of penetration method was used to determine the coefficient of permeability (K). This involved splitting the cubes and measuring the depth of water penetration. Water permeability tests were conducted in accordance with IS 3085:1965 [89]. The test apparatus is shown in Figure 5.

Figure 5. Water permeability test apparatus

2.6. Microscopy studies

This study employed two types of microscopy investigations: scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). Both are highly accurate and powerful analytical techniques.

2.6.1. Scanning Electron Microscopy (SEM)

SEM analysis produces high-resolution images [90]. An electron gun generates a highly focused electron beam, which is directed onto a small area of the sample. The sample reflects high-energy electrons, which are then detected by the scanning electron microscope. The specific area of the sample is targeted using an SEM objective lens. The distance between the electron gun and the sample is referred to as the working distance, which significantly influences the quality of the SEM image [91]. SEM detects two types of electrons: backscattered electrons and secondary electrons. Backscattered electrons provide contrast that varies with the chemical composition of the sample, while secondary electrons, emitted near the surface, are used to determine the surface topography.

2.6.2. Energy-Dispersive X-Ray Spectroscopy (EDX)

EDX spectroscopy devices, also known as EDS, are integrated into each of our SEM systems [92]. When an atom is exposed to an electron beam, it emits characteristic X-rays specific to its atomic number. This enables elemental mapping, line scanning, and the analysis of elemental composition, either locally or across a wider area. Semi-quantitative analysis can also be used to assess the chemical composition of a sample. In addition, TWI offers wavelength-dispersive X-ray (WDX) spectroscopy for the analysis of light elements such as nitrogen and oxygen. When combined with conventional SEM analysis, EDX provides a more comprehensive understanding of a material's local composition [93].

3. Results and discussion

3.1. Impact on the concrete's slump

The inclusion of CCF and nano-silica reduced the workability of concrete. As shown in Table 1, increasing the proportion of

CCF led to a corresponding decrease in slump. The control mix exhibited the highest slump. The mix containing 3 % nano-silica showed a 4 % reduction in slump. The addition of CCF resulted in a stiffer concrete surface. In mix F1.5, which contained the highest CCF content, workability was reduced by 17 %. The incorporation of nano-silica helped fill nano-voids in the concrete matrix, which also contributed to reduced workability [94, 95]. Furthermore, fibre clustering and agglomeration were found to negatively affect workability [96]. The slump variations of all mixes are illustrated in Figure 6.

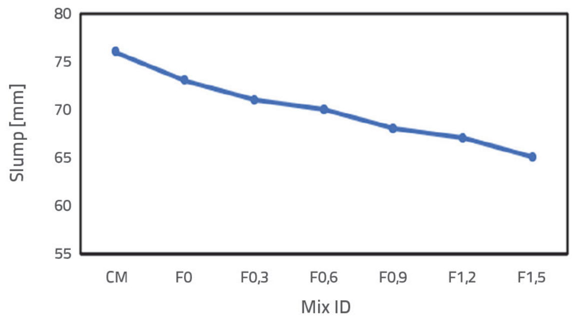

Figure 6. Slump variation for all mixes

3.2. Impact on the concrete's mechanical properties

Figure 7 presents the compressive strength of all mixes at 7, 14, and 28 days. The mix containing 0.9 % cellulose coir fibre and 3 % nano-silica achieved the highest compressive strength, with a value of 41.77 N/mm². The inclusion of nano-silica increased the density of the concrete by filling most of the porous regions. Nano-silica not only enhanced compressive strength but also improved split tensile and flexural strengths. The mix with 3 % nano-silica showed increases of 15 % in compressive strength, 14 % in split tensile strength, and 8 % in flexural strength compared to the control mix. This improvement is attributed to the high silica content of nano-silica, which rapidly forms calcium silicate hydrate (C-S-H) gel, thereby enhancing concrete strength [97–101]. However, excessive nano-silica can reduce the amount of calcium hydroxide (C-H) in the mix, and the surplus silica may lead to agglomeration, resulting in decreased strength [102]. In this study, 3 % nano-silica was selected as the optimal dosage, as it yielded the highest compressive strength. The addition of cellulose coir fibre increased compressive strength up to 0.9 %; beyond this point, compressive strength decreased due to fibre agglomeration. The mix containing 3 % nano-silica and 0.6 % cellulose fibre achieved a 32 % increase in compressive strength, a 31 % increase in split tensile strength, and a 15 % increase in flexural strength. Figure 8 illustrates the split tensile strength of each mix at 7, 14, and 28 days. Although cellulose coir fibre is relatively weak in tension and strong in compression, its inclusion in concrete improved both split tensile and flexural strengths, particularly at the 0.9 % dosage [103, 104]. Figure 9 shows the flexural strength of each mix at 7, 14, and 28 days.

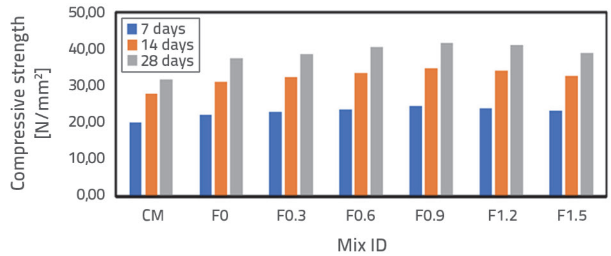

Figure 7. Compressive strength variation for all mixes

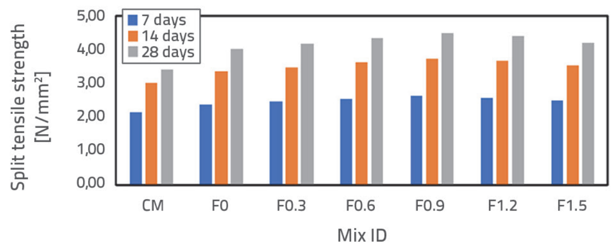

Figure 8. Split tensile strength variation for all mixes

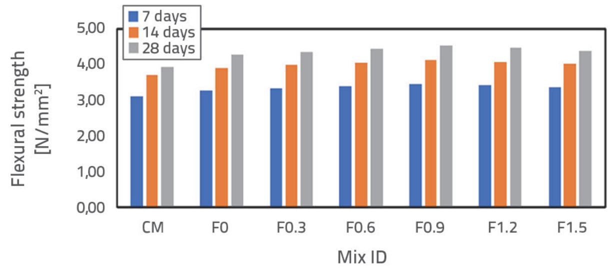

Figure 9. Flexural strength variation for all mixes

Table 3. Durability test results

Series code	Mixture	Absorption [%]	Weight loss [g]			Compressive strength loss [N/mm²]			Depth of water penetration [mm]
			30 days	60 days	90 days	30 days	60 days	90 days	
1	CM	7.00	27	33	51	29.84	28.22	27.45	18
2	F0	3.68	24	29	46	35.4	35.12	35.02	15
3	F0.3	3.17	22	28	44	37.68	37.54	37.48	12
4	F0.6	2.49	20	26	43	39.82	39.36	39.01	10
5	F0.9	1.39	19	25	42	40.66	40.38	40.17	8
6	F1.2	2.98	21	28	44	39.12	38.67	38.48	11
7	F1.5	3.29	23	29	45	38.47	37.88	37.24	12

3.3. Impact on the Concrete's durability properties

Three types of tests were conducted to assess the durability of cement concrete: water absorption, acid resistance, and water penetration, all performed at room temperature. Figure 10 shows the water absorption results for the seven mixes. The control cement concrete, composed only of fine aggregate, coarse aggregate, and cement, exhibited the highest water absorption at 7 %. The mix with 3 % nano-silica showed a 3.33 % reduction in water absorption compared to the control. The blend containing 3 % nano-silica and 0.9 % cellulose coir fibre recorded the lowest water absorption among all mixes. However, mixes containing 1.2 % and 1.5 % cellulose coir fibre showed increased water absorption. This was attributed to fibre agglomeration in certain areas and the presence of excessive fibres, which led to the formation of air voids.

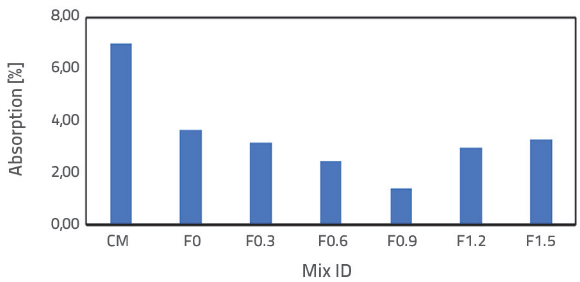

Figure 10. Water absorption percentage for all mixes

All mixes exhibited weight and strength loss due to the exposure to acidic environment, as shown in Figures 11 and 12. The control cement concrete showed the highest loss, while the F0.9 and F0.6 mixes recorded the least weight and strength loss, respectively. The inclusion of 3 % nano-silica acted as a nano-filler, effectively reducing overall porosity. Specimens containing nano-silica demonstrated significantly lower weight and strength loss compared to the control mix.

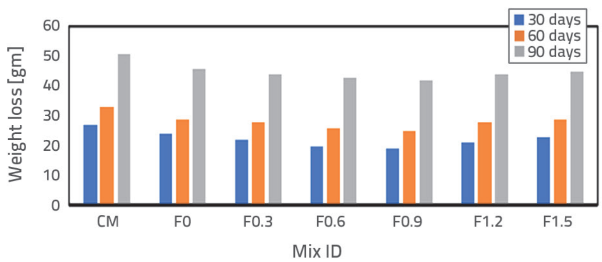

Figure 11. Weight loss due to acidic exposure for all mixes

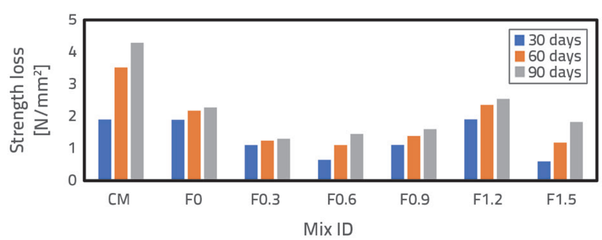

Figure 12. Strength loss due to acidic exposure for all mixes

Figure 13 illustrates the water penetration depth for all mixes. The control mix showed the highest depth of penetration, with a recorded value of 18 mm. The addition of 3 % nano-silica resulted in a denser mix, reducing water penetration. The mix containing 3 % nano-silica and 0.9 % cellulose coir fibre (F0.9) achieved the lowest water penetration depth, indicating a more compact structure than the other mixes. The F0.9 mix exhibited a 1.25-fold reduction in penetration depth compared to the control. Overall, the F0.9 mix demonstrated superior durability performance, with 3 % nano-silica significantly enhancing durability characteristics.

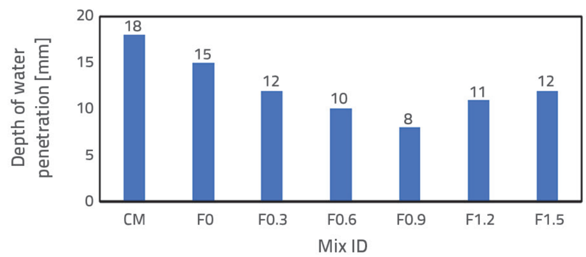

Figure 13. Water penetration depth for all mixes

3.4. Concrete surface and composition analysis

Nano-silica possesses a large surface area and exhibits strong pozzolanic properties. The silica content reacts rapidly with calcium hydroxide to form C-S-H gel. This reaction increases the amount of C-S-H gel, reduces air voids, and enhances concrete density, resulting in lower permeability. Quercia et al. observed a dense, uniform microstructure with C-S-H formation in the transition zone of SCC. andalibi et al. reported that nano-silica-blended concrete exhibited a homogeneous structure, with nano-silica effectively reducing micro air voids. According to Du et al., nano-silica displays a strong pozzolanic reaction, forming additional C-S-H gel that fills microcracks and voids, thereby producing a denser and more uniform microstructure. However, Huang et al. found that concrete blended with 6 % nano-silica developed numerous microcracks. Excessive nano-silica causes flocculation, which increases air voids and permeability. Figure 14.a shows the SEM image of the control specimen, revealing numerous calcium hydroxide crystals and large voids, indicating high permeability compared to the silica blended specimens. In contrast, Figure 14.b presents the SEM image of a specimen blended with 3 % nano-silica and 0.6 % cellulose coir fibre, showing a denser microstructure with significantly fewer voids. Calcium hydroxide crystals are visible in the SEM image in Figure 14(b). Figure 14(c) depicts a cement concrete specimen blended with 3 % nano-silica and 0.9 % coconut cellulose fibre. The SEM image reveals fewer pores and voids. However, increasing the cellulose coir fibre content beyond 1.2 % leads to fibre agglomeration, resulting in increased void formation. The permeability of the F0.9 mix is lower than that of the F0.6 specimen. Figure 14(d) shows a specimen blended with 3 % nano-silica, where the presence of SiO_2 is evident.

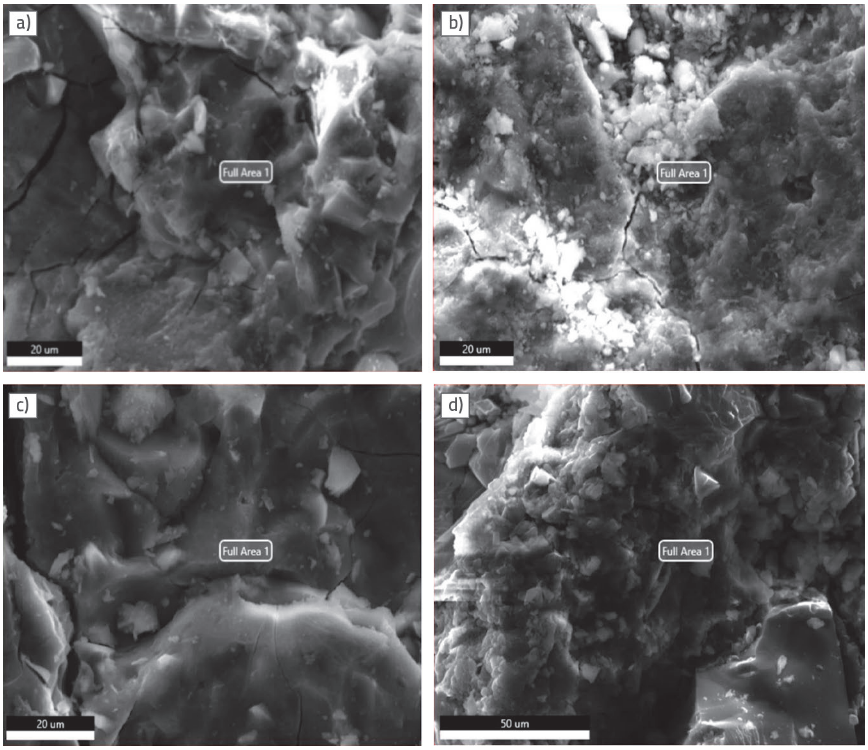

Figure. 14. SEM images: (a) CM specimen, (b) F0.6 specimen, (c) F0.9 specimen, (d) F0 specimen

The addition of nano-silica effectively fills the pores within the concrete's internal structure [105, 106]. The inclusion of 3 % nano-silica helps prevent microcracks and mitigates volume changes during drying, resulting in a uniform microstructure and reduced permeability [107]. As the permeability decreases, the strength of the concrete correspondingly increases [25].

The specimens were subjected to EDX analysis, and the corresponding images are shown in Figures 15 and 16. The incorporation of nano-silica into the concrete resulted in variations in chemical composition, particularly an increase in silica content. As the percentage of nano-silica increased, the Si content in the concrete also rose. An optimised dosage of nano-silica helps maintain a balanced Si-to-Ca ratio. However, excessive addition of nano-silica may lead to an elevated Si content relative to Ca [16, 108]. Figures also reveal partially hydrated nano-silica particles and signs of agglomeration. Calcium hydroxide reacts with these partially hydrated nano-silica particles to form C–S–H gel [109], indicating a pozzolanic reaction. The EDX analysis confirms that nano-silica is a highly pozzolanic material, significantly enhancing the concrete's strength and durability [22, 110].

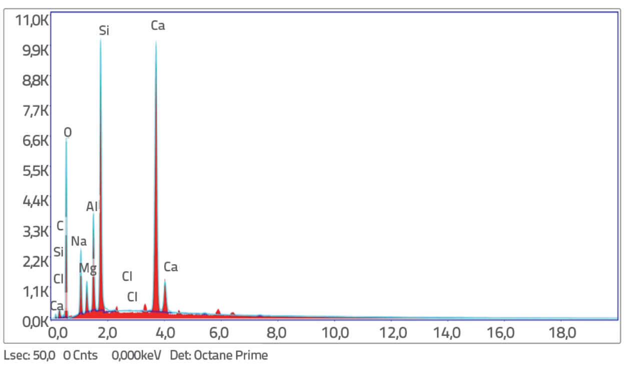

Figure 15. EDX spectrum for CM mix

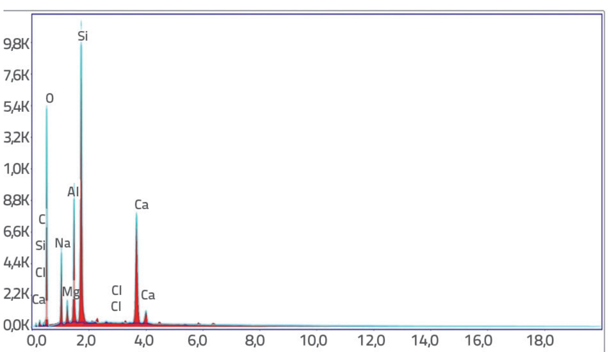

Figure 16. EDX spectrum for F0 mix

4. Conclusion

The present study investigated the effect of CCF and NS on the mechanical strength and durability properties of concrete. Based on the experimental results, the following conclusions can be drawn:

- The findings indicate that incorporating 0.9 % cellulose coir fibre and 3 % nano-silica significantly improves the mechanical strength of concrete. Specimens containing CCF and NS such as cubes, cylinders, and prisms exhibited superior strength compared to conventional concrete specimens. The mechanical performance of NS-based specimens was consistently better than that of conventional mixes. Additionally, the use of NS contributes to improved cost-effectiveness in concrete production. Future research should include detailed SEM analysis to further explore the microstructural effects of nano-silica in concrete.
- Based on the experimental results, specimens containing 0.9 % cellulose coir fibre and 3 % nano-silica exhibited higher characteristic strengths. Compared to standard specimens, only a slight loss in weight and compressive strength was observed after acid immersion.

- The results of acid resistance, water penetration, and water absorption tests confirm that the inclusion of nano-silica enhances the durability of concrete.
- The combined addition of nano-silica and cellulose coir fibre improves the flexural, tensile, and compressive strength of concrete.

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