



## Strength and Durability Assessment of Composite Road Pavements with Nano-Enhanced and Polypropylene Fiber-Reinforced Concretes

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### ABSTRACT

Due to Iran's abundant oil resources, asphalt concrete pavements have traditionally been favored in road construction, as well as sideling alternatives like Portland cement concrete, which is widely used globally. However, with increasing demands on transportation infrastructure and the limitations of traditional materials, there was a growing need for innovative solutions. This study aimed to explore the potential of advanced materials for road pavement construction, specifically focusing on nano-enhanced Fiber-Reinforced Concrete (FRC) as an alternative to conventional materials. The primary objective was to evaluate and compare the mechanical and durability properties of composite road pavements constructed with nano-enhanced FRC and polypropylene fiber-reinforced concrete. The research involved testing the compressive strength, flexural strength, crack resistance, and performance under acidic conditions of concrete samples containing varying percentages of polypropylene fibers (12 mm and 18 mm) and Nano-silica (ranging from 0.3% to 2.5% by weight of cement). The results revealed that while polypropylene fibers reduced compressive strength by 10% and 11% (for 12 mm and 18 mm fibers, respectively), they enhanced crack resistance and cohesion. On the other hand, nano-silica improved compressive strength by up to 7.3% at 1.5% by weight of cement, providing a more durable alternative for road pavements. The combination of polypropylene fibers and Nano-silica was recommended for optimal performance, offering a balanced enhancement of strength, flexibility, and durability.

**Keywords:** Polypropylene Fiber, Nano-Silica, Road Pavements, Strength, Durability.

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## 1. Introduction

The use of additives such as traditional materials, pozzolans (Eshghi et al., 2025), waste materials (Eshghi et al., 2022; Eshghi and Jafary, 2022), and nanomaterials (Eshghi et al., 2024, Eshghi et al., 2024) have attracted the attention of many engineers in recent years to improve the properties of materials used in construction project (Arabani et al., 2017). Reliance on bitumen has limited the exploration and adoption of alternative materials, such as Portland cement concrete, in infrastructure design. However, as the world's second most utilized material, concrete possesses unique properties and is composed of readily available constituents, highlighting its potential as a strategic choice for road construction.

In this context, the escalating demands on transportation networks and the inherent challenges posed by traditional road construction methods, especially in asphalt concrete pavements, have prompted a critical reassessment of materials and techniques. Concrete, with its diversified formulations such as High-Performance Concrete (HPC), Ultra-High-Performance Concrete (UHPC), fiber-reinforced, nano-enhanced, self-compacting, and roller-compacted concrete, emerges as a compelling alternative (Mosavinejad et al., 2020). This paradigm shift in material selection, prompted by the continuous evolution of technology, introduces the prospect of enhanced strength, durability, and longevity in road pavements.

The deterioration of asphalt concrete pavements due to factors like traffic loads, environmental conditions, and material aging underscores the urgency for innovative solutions. This study embarks on an exploration of advanced materials, specifically focusing on the integration of nano-enhanced Fiber-Reinforced Concrete (FRC) in road pavement construction. This exploration is motivated by the limitations inherent in traditional approaches and seeks to usher in a new era of materials science for sustainable infrastructure.

The primary objective of this research is to comprehensively evaluate and compare the performance of composite road pavements constructed with nano-enhanced FRC against those reinforced with polypropylene fiber. The study aims to quantify the mechanical and durability properties of these materials, providing insights into their potential advantages and limitations.

This study focuses on the practical application of nano-enhanced FRC in road pavements, addressing gaps in current knowledge regarding its feasibility and advantages over conventional methods. The findings hold significance for civil engineers, infrastructure planners, and policymakers involved in the design and maintenance of road networks.

To guide our investigation, we will address key inquiries focusing on the comparative analysis of nano-enhanced Fiber-Reinforced Concrete (FRC) and traditional polypropylene fiber-reinforced concrete in road pavement applications. We will explore the mechanical strength of nano-enhanced FRC in contrast to its polypropylene fiber counterpart, aiming to discern potential differences that could impact their performance. Additionally, our investigation will delve into the durability characteristics of nano-enhanced FRC under diverse environmental conditions. We will also scrutinize the microstructural aspects of both materials to identify any distinctive features that may contribute to their respective performances on road pavements.

In summary, this research aims to bridge the gap between the conventional preference for asphalt concrete pavements and the untapped potential of Portland cement concrete pavements containing innovative materials, particularly nano-enhanced FRC. The subsequent sections will delve into the methodology, experimental setup, results, and discussions, offering a comprehensive analysis of the proposed approach's efficacy in revolutionizing road infrastructure.

## 2. Literature Review

Concrete, a fundamental construction material celebrated for its versatility and extensive application, demands a profound comprehension of its strength and durability to optimize performance, especially in challenging contexts like road pavements. Neville (2011) provides a comprehensive exploration of concrete technology, offering insights into mechanical robustness and resilience to environmental degradation, crucial factors for ensuring the longevity of concrete structures. The American Concrete Institute's (ACI) Building Code Requirements for Structural Concrete (ACI 318) further provides standardized guidelines for designing concrete structures, underscoring the importance of durability considerations.

The incorporation of nano-materials into concrete structures has emerged as an innovative paradigm, introducing distinct properties with significant potential to enhance concrete strength and durability. A thorough investigation into nanotechnology in construction sheds light on the influence of the nanoscale dimension on material behavior. This encompasses an examination of nano-materials, with dimensions below 100 nanometers, contributing to improved mechanical properties and heightened resistance to environmental challenges. Studies scrutinizing various nanoparticles' effects on concrete characteristics underscore the potential of nano-materials in fortifying concrete against structural vulnerabilities and environmental factors, thereby paving the way for their exploration in road pavement applications.

Polypropylene fiber-reinforced concrete signifies a noteworthy advancement in concrete technology, specifically addressing tensile and flexural deficiencies. These fibers, when uniformly distributed, enhance toughness and crack resistance, mitigating the inherent brittleness of conventional concrete. The American Concrete Institute's Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (ACI 440.1R-15) provides

standardized directives for incorporating polypropylene fibers in concrete mixes, ensuring structural integrity and durability.

Recent years have witnessed a surge in research dedicated to unraveling the potential of nano-materials for enhancing concrete properties. Multiple studies have focused on investigating the influence of nano-silica on concrete compressive strength, revealing substantial improvements. Additional investigations delved into the durability of concrete modified with titanium dioxide (TiO<sub>2</sub>) nanoparticles, showcasing enhanced resistance to chemical attacks. Moreover, studies explored the self-healing properties of concrete through nano-capsules filled with healing agents, demonstrating promising results in autonomously healing microcracks. Furthermore, the application of graphene oxide (GO) to improve the fire resistance of concrete exhibited the potential to form a protective layer and delay spalling under high temperatures. This collective body of research contributes significantly to the understanding of nano-materials and their diverse applications in concrete technology.

The research conducted by Salemi and Behfarnia (2013) aimed to investigate the impact of nano-particles on the durability of fiber-reinforced concrete pavement. The primary goal was to assess frost resistance and mechanical properties, with nano-particles serving as a partial substitute for cement. The study involved three main experimental groups: plain concrete (control concrete), concrete containing nano-particles without fibers, and concrete containing polypropylene fibers. The specimens underwent cycles of freezing and thawing. The results revealed that the incorporation of 5% nano-silica improved compressive strength and frost resistance by approximately 30% and 83%, respectively. Substituting 3% of cement with nano-alumina particles enhanced compressive strength and frost durability by about 8% and 81%, respectively. The study also noted that polypropylene fibers had a minor influence on frost durability and compressive strength. In

conclusion, the use of nano-particles in conjunction with polypropylene fibers demonstrated enhanced frost resistance and compressive strength in Portland cement concrete pavement, attributed to the reduction in permeability and porosity due to nano-particle use and the improvement in tensile strength facilitated by polypropylene fibers.

Liu et al. (2018) investigated the use of brucite nano-fiber as reinforcement in road cement concrete material to enhance its toughness. The brucite nano-fiber was produced by immersing natural low-cost brucite short fibers in a superplasticizer solution, followed by agitation in a forced mixer to refine it to the nanometer level. The study delved into the mechanical properties, including elastic modulus, dry shrinkage, anti-frost capability, thermal expansion, and flexural fatigue performance of the nano-fiber concrete. The implementation of nano-fiber reinforced cement concrete on a highway was also explored. Results demonstrated that nano-fiber concrete exhibited superior toughness, with flexural strength of 7.4% and 17.7% higher than ordinary fiber concrete and plain concrete, respectively. Moreover, its ratio of compression to flexural strengths was 6.4% and 16.1% lower than the other two. Nano-fiber concrete displayed lower static modulus and higher dynamic modulus, with a 41.0% and 61.3% reduction in flexural elastic modulus compared to ordinary fiber concrete and plain concrete. Furthermore, nano-fiber concrete demonstrated enhanced resistance to dry shrinkage, freeze-thaw damage, thermal expansion, and bending fatigue stresses, outperforming ordinary fiber concrete and plain concrete in various aspects. The study also highlighted the comprehensive cost-performance superiority of nano-fiber concrete over ordinary fiber concrete and plain concrete. Remarkably, after more than 8 years of traffic practice, the nano-fiber concrete test road remained in excellent condition.

In their investigation of dispersed reinforcement in Fibre Reinforced Concrete

(FRC), Signorini et al. (2019) delved into the effects of a swift, acid-catalyzed sol-gel silica nano-coating on the mechanical performance of draw-wire Polypropylene (PP) fibers. The study aimed to unravel the intricacies of the failure mechanism, specifically exploring the influence of curing time on the mechanical behavior. The research involved comprehensive assessments through pull-out and three-point bending tests on un-notched beams. The findings uncovered a significant impact of the coating on the post-cracking behavior of FRC, transitioning from brittleness in plain concrete to softening in uncoated fibers and ultimately to plastic-softening in coated fibers. Notably, a 28-day curing period exhibited enhanced energy dissipation capability for coated fibers compared to an 8-day curing period. This enhancement indicated a shift in the failure mechanism, attributing it to improved fiber-to-matrix bond strength, from delamination at the interface to failure in the interphase zone. In the former case, failure was inconsistent and independent of curing time, while in the latter, it relied on the quality of the matrix.

Kim et al. (2019) conducted a comprehensive assessment of styrene-butadiene latex-modified polyvinyl alcohol (PVA) fiber-reinforced rapid-set cement concrete (LMFRRSC) with the primary goal of evaluating its suitability for emergency repair of Portland cement concrete pavements. The study focused on analyzing various strength properties, chloride ion permeability, and abrasion resistance. Experimental investigations involved measuring compressive strength, flexural strength, splitting tensile strength, bond strength, chloride ion penetration, and abrasion resistance for LMFRRSC with varying PVA fiber content (0%, 0.05%, and 0.10%). The results indicated a direct correlation between the volume fraction of PVA fiber and the enhancement of these key parameters. Importantly, the findings demonstrated that the addition of PVA fiber effectively mitigated crack formation attributed to high

hydration heat in the early stages of material development and curtailed the development of fiber balls. Consequently, the incorporation of PVA fiber exhibited a positive impact on the performance of LMFRRSC, meeting the necessary criteria for emergency repair of Portland cement concrete pavements.

Blazy and Blazy (2021) conducted a study exploring the application of polypropylene fiber-reinforced concrete (PFRC) in creating architectural forms for public spaces. The research aimed to provide an overview of selected polypropylene fibers available on the market and assess their influence on the physical and mechanical properties of concrete. PFRC, a cementitious composite with dispersed fiber reinforcement, features both microfibers and macrofibers, each contributing differently based on their length and function within the concrete matrix. The study delved into the impact of polypropylene fibers on various concrete properties, including workability, elasticity modulus, compressive, flexural, and tensile strength, toughness, impact resistance, spalling resistance, freeze-thaw durability, abrasion resistance, water absorption, porosity, permeability, and overall durability. The research also discussed certain constraints to consider during the design of fiber-reinforced concrete mixtures. The findings highlighted the potential of PFRC in public spaces, showcasing its benefits in mitigating unfavorable environmental conditions, resisting impact damages, enduring surface abrasion, and deterring vandalism. The study demonstrated that utilizing concrete with enhanced properties in public spaces is undeniably advantageous.

In the comprehensive review conducted by Liu et al. (2021), the primary objective was to assess the impact of polypropylene fiber (PPF) on the durability of concrete. Leveraging the advantageous properties of PPF such as its lightweight nature, high strength, and corrosion resistance the study focused on enhancing crack resistance and optimizing the pore size distribution of concrete. The incorporation of PPF

demonstrated significant improvements in concrete durability by impeding the penetration of water or harmful ions. Various durability aspects were considered, including drying shrinkage, creep, water absorption, permeability resistance, chloride ion penetration resistance, sulfate corrosion resistance, freeze-thaw cycle resistance, carbonation resistance, and fire resistance. The authors systematically analyzed the influence of factors such as fiber content, fiber diameter, and fiber hybrid ratio on these durability indexes. Furthermore, the study explored the synergistic effects of combining PPFs with steel fibers to further enhance concrete durability. The drawbacks associated with PPF application, such as imperfect dispersion and weak bonding with the cement matrix, were addressed through proposed solutions, including the use of Nano-active powder or chemical treatment on the fibers. The paper concludes by outlining future research prospects for concrete incorporating PPFs.

Kos et al. (2022) conducted a comprehensive comparative analysis to assess the impact of steel and polypropylene fibers on the strength, frost resistance, abrasion, and corrosion resistance of fiber-reinforced concrete designed for industrial floors and road pavements. Employing steel fibers with dimensions of 50 mm length and 1 mm diameter, and polypropylene fibers with dimensions of 36 mm length and 0.68 mm diameter, the study varied the quantity of steel fibers from 15 to 25 kg/m<sup>3</sup> and polypropylene fibers from 2 to 3 kg/m<sup>3</sup>. The findings indicated that steel fibers had a more pronounced effect on increasing compressive strength, while both types of dispersed reinforcement equally enhanced flexural strength by 27–34%. Dispersed reinforcement, however, resulted in a reduction of concrete abrasion resistance by 15–35%, coupled with an increase in frost resistance by 50 cycles, contributing to the overall durability of industrial floors and road pavements. Notably, the combination of 20 kg/m<sup>3</sup> steel fiber and 2.5 kg/m<sup>3</sup>

polypropylene fiber improved concrete corrosion resistance in an acidic environment. Despite similar technological impacts on the specified applications, the economic feasibility favored polypropylene fibers, with the cost increase for steel fiber reinforcement ranging from \$22.5 to \$37.5 per cubic meter, compared to \$10 to \$15 for polypropylene fiber.

In the study conducted by Song et al. (2022), the goal was to enhance the toughness of concrete by incorporating polypropylene fibers while considering environmental impact and cost-effectiveness through the use of manufactured sand and high-content fly ash. The research employed the response surface method (RSM) to design and conduct tests, focusing on the mechanical and bending properties of polypropylene-fiber-reinforced high-performance concrete (PPFHPC). Three key process variables—polypropylene fiber content (1%, 1.5%, and 2%), fly ash content (45%, 60%, and 75%), and water-binder (W/B) ratio (0.27, 0.3, and 0.33)—were investigated. The evaluation covered compressive strength, flexural strength, flexural-compressive ratio, splitting tensile strength, and first-crack strength, along with the bending strength of thin plates. The RSM-established prediction model demonstrated a strong correlation and predictability between the factors and the response, providing a relationship equation. Multi-objective optimization revealed that the optimal combination of factors (PPF content, FA content, and W/B ratio) was 2%, 62%, and 0.27, respectively. The developed model proved effective in predicting the fundamental mechanical and bending properties of PPFHPC materials, laying a theoretical foundation for their further development.

Guler and Akbulut (2023) conducted a comprehensive study to evaluate the impact of micro- and macro-polypropylene (PP) fibers on the workability and residual strength properties of concrete road pavements subjected to freeze-thaw (F-T) cycles. The research encompassed key parameters such as

slump, mass loss (ML), abrasion loss (AL), residual compressive strength (RCS), and residual splitting tensile strength (RSTS) of concrete blends with varying volumes (0.3%, 0.6%, and 1%) of micro- and macro-PP fibers. All specimens underwent 25, 50, 100, and 150 F-T cycles. The findings revealed a negative influence of micro- and macro-PP fibers on slump values, while these fibers did not contribute significantly to reducing ML values post F-T exposure. Interestingly, up to 0.3% volumetric fiber content, PP fibers effectively prevented a decline in RCS capacities after the F-T process. Furthermore, PP fibers demonstrated increased efficacy in hindering reductions in AL and RSTS capacities. The study also observed that the hybrid form of macro-PP fibers with micro-PP fibers yielded better results in terms of reduced AL and improved RCS and RSTS capacities compared to single macro-PP fibers. After 150 F-T cycles, the control concrete (C0) exhibited a 9.41% reduction in AL, whereas C1-C6 samples displayed declines ranging from 7.56% to 8.92%. Additionally, after 150 F-T cycles, the reduction in RCS and RSTS loss for C0 was 25.09% and 28.30%, respectively, while C1-C6 samples exhibited variations between 22.94–32.97% and 20.10–25.75%, respectively.

In summary, the literature review provides a comprehensive exploration of key aspects related to the proposed study on "Composite Road Pavements: Nano-Enhanced Fiber-Reinforced Concrete (FRC) vs. Polypropylene Fiber - An Exploration of Strength and Durability." The overview of concrete strength and durability underscores the fundamental importance of robust materials for sustainable road pavement applications. The role of nano-materials in concrete, as discussed in the literature, highlights the potential advancements in enhancing mechanical and durability properties. The examination of polypropylene fiber in reinforced concrete reveals insights into the influence of fiber types on various

performance parameters, further informing our investigation. Previous studies on nano-materials in concrete showcase evolving methodologies and research goals, emphasizing the dynamic nature of material science in the field of reinforced concrete. Lastly, the literature on advancements in reinforced concrete technology provides a forward-looking perspective, indicating a continuous quest for innovative solutions and technologies that contribute to the development of more resilient and durable road pavements.

### 3. Materials and Methods

To construct durable and high-performance composite road pavements, the selection of materials plays a pivotal role in influencing the structural integrity, longevity, and overall effectiveness of the infrastructure. In this section, we delve into a detailed examination of the materials employed in our study, focusing on the critical components that constitute the Nano-Enhanced Fiber-Reinforced Concrete (FRC) and Polypropylene Fiber. The rationale behind the choice of these materials stems from their unique properties, which are anticipated to synergistically contribute to the enhanced strength and durability of the road pavements. A comprehensive understanding of the materials used lays the groundwork for subsequent discussions on the manufacturing processes, testing methodologies, and the ultimate performance of the composite pavements under consideration. Through meticulous material selection and thoughtful engineering, our aim is to advance the current standards in road pavement construction, offering a sustainable and resilient solution for future transportation infrastructure.

In crafting a pavement that withstands the rigors of diverse environmental conditions and heavy traffic loads, the integration of Nano-Enhanced Fiber-Reinforced Concrete (FRC) stands as a promising innovation. Nano-materials, introduced into the concrete

matrix, exhibit unique mechanical and chemical properties that hold the potential to enhance the overall strength and durability of the road surface. Concurrently, Polypropylene Fiber, a well-established reinforcement material, contributes to the composite's toughness and crack resistance. The synergy between these materials is anticipated to create a robust and resilient composite capable of withstanding the challenges posed by modern road pavements.

This section will provide an in-depth exploration of the characteristics, properties, and manufacturing considerations associated with Nano-Enhanced FRC and Polypropylene Fiber. Subsequent discussions will extend to the blending of these materials, shedding light on the methodologies employed to achieve an optimal composite mix for road pavement applications. Through a meticulous examination of the materials used, we aim to elucidate the scientific underpinnings that guide our study and contribute to the advancement of composite road pavement technology.

#### 3.1. Research Materials

##### 3.1.1. Cement

Cement is an adhesive material with the ability to bind particles together, creating a cohesive and robust body of interconnected particles. It is produced by combining lime, clay, silica, and mineral oxides at temperatures ranging from 1400 to 1500 degrees Celsius. Given that the study is conducted in Guilan province, the use of cement produced in this region takes precedence. The cement employed in this research is "Deylman" Type 2 cement (Green Guilan Industries), conforming to ISIRI 389 standards. Chemical and physical analyses of this cement are presented in [Table \(1\)](#), and its image is depicted in [Figure \(1\)](#).

**Table 1.** Chemical and physical properties of cement

Chemical properties		Physical properties		
SiO <sub>2</sub>	20.79	Compressive strength (Kgf/cm <sup>2</sup> )	2 Days	160
Al <sub>2</sub> O <sub>3</sub>	4.76		3 Days	208
Fe <sub>2</sub> O <sub>3</sub>	3.86		7 Days	333
CaO	62.28		28 Days	492
MgO	3.22	Setting time	Initial	153
SO <sub>3</sub>	1.89		Final	212
Na <sub>2</sub> O	0.37			
K <sub>2</sub> O	0.68	Percentage of water		23
f. Cao	0.82			
CL	0	Longitudinal expansion		
LOI	1.88			0.21
I.R	0.51			
C3S	52.67	Remaining on a 90-µm sieve		5.7
C2S	19.89			
C3A	6.09	Special surface (Blaine) (cm <sup>2</sup> /gr)		3081
C4AF	11.74			



**Figure 1.** The cement used in this research

### 3.1.2. Nano-Silica

Nano SiO<sub>2</sub> is an advanced additive based on nanotechnology designed for specialized and high-performance concretes. Its unique properties, such as improving mechanical strength and increasing concrete durability, have garnered significant attention, especially

in coastal concrete applications. Nano-Silica, purchased from Iranian Nano Materials “Pishgaman” and produced by US Research Nanomaterials, is featured in Tables (2) and (3) for physical specifications and chemical analysis, respectively. The image of Nano-Silica is also presented in Figure (2).

**Table 2.** Physical properties of nano-silica

Purity	Color	PH	Density (gr/cm <sup>3</sup> )
99.99	White	7	2.65

**Table 3.** Chemical composition of nano-silica

Material	Content (%)
SiO <sub>2</sub>	99.5
Fe <sub>2</sub> O <sub>3</sub>	0.016
Al <sub>2</sub> O <sub>3</sub>	0.03
MgO	0.02
K <sub>2</sub> O	0.064



**Figure 2.** The nano-silica used in this research

### 3.1.3. Polypropylene Fibers

Polypropylene fibers serve as additives for reinforcing and strengthening concrete and cementitious mixtures, enhancing flexural, tensile, shear, and abrasion resistance. These fibers, when mixed, do not settle or increase the weight of concrete, maintaining the alkalinity of the environment. Advantages of incorporating polypropylene fibers include

reduced cracking, increased impact resistance, fire resistance, wear resistance, and decreased permeability to water and corrosive substances. Mason Company's polypropylene fibers, with lengths of 12 mm and 18mm, were used in this study. Physical specifications of polypropylene fibers are presented in [Table \(4\)](#), and their image is displayed in [Figure \(3\)](#).

**Table 4.** Physical properties of polypropylene fibers

Appearance	filamentous
Length (mm)	12 and 18
Tensile strength (MPa)	400
Water absorption (%)	<0.01
Diameter ( $\mu\text{m}$ )	18
Color	White
Unit weight ( $\text{gr}/\text{cm}^3$ )	0.91
Modulus of elasticity (Mpa)	18



**Figure 3.** The polypropylene fibers used in this research

### 3.1.4. Aggregate Materials

The aggregate materials used consist of washed and completely clean sand and gravel, free from clay and silt. The maximum particle

size is approximately 19 mm, classified as well-graded sandy gravel (GW) according to the Unified Soil Classification System.

### 3.1.5. Water

Water plays a fundamental role in concrete; therefore, the use of suitable water must

always be a priority. Inappropriate water can lead to issues such as delayed concrete setting, reduced final strength, corrosion of reinforcement, and discoloration of the dried concrete surface. Generally, the water used in concrete construction should be clean and free from any impurities. The PH of the water should ideally range from 5 to 5.8. The water used in this study is drinking water from the Bandar Anzali city.

### 3.1.6. Superplasticizer

The use of superplasticizers results in cement savings, denser concrete, and prevents water bleeding. With increased surface tension due to surfactant properties, cement particles repel each other, preventing their agglomeration and enhancing concrete efficiency. BCS 404 superplasticizer from Concrete Chemistry Structure Company was used in this research.

### 3.1.7. Calcium Chloride

Various factors contribute to concrete deterioration, with exposure to acidic and alkaline environments being crucial. In this research, calcium chloride is employed to

assess the durability of concrete specimens. The specimens were immersed in a solution containing this substance for 28 days, and the effects on durability were examined.

## 3.2. Mixing Design and Procedure

The mixing design of this research comprises three sections:

**3.2.1. Control Group (F121 to F128 and F181 to F188):** This section includes a reference concrete without any additives.

**3.2.2. Nano-Silica Group (NS1 to NS8):** This section involves concrete containing nano-silica, where a superplasticizer is also used.

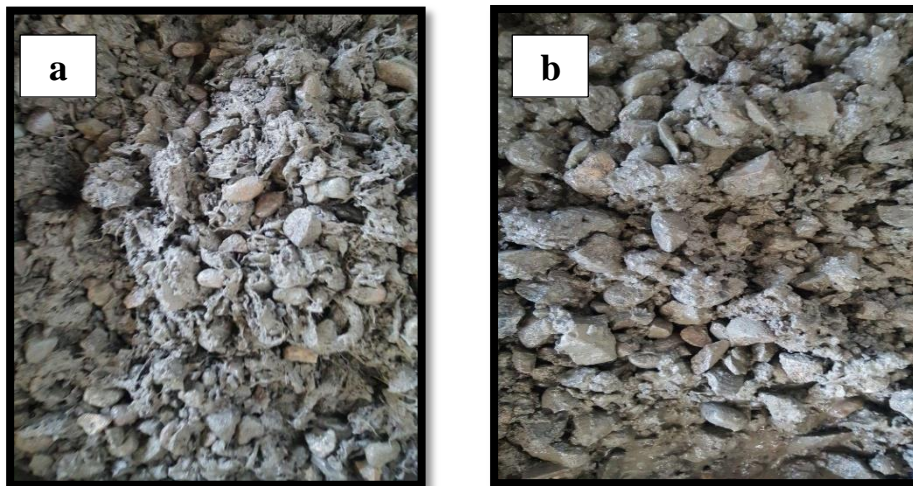
**3.2.3. Polypropylene Fiber Group (F121 to F128 and F181 to F188):** This section includes concrete reinforced with polypropylene fibers of lengths 12 and 18 millimeters, similar to the nano-silica group, and also incorporates a superplasticizer. The mixing design in this study follows a weight-based method. The details of the mixing design used in this research are presented in [Table \(5\)](#).

**Table 5.** Concrete mixing plan used in this article

Sample	Cement (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	Gravel (kg/m <sup>3</sup> )	PP Fiber (%)	Nano-Silica (%)
Control	400	180	758	1051	0	0
F121	398.8	180	758	1051	0.3	0
F122	398	180	758	1051	0.5	0
F123	397.2	180	758	1051	0.7	0
F124	396	180	758	1051	1	0
F125	395.2	180	758	1051	1.2	0
F126	394	180	758	1051	1.5	0
F127	392	180	758	1051	2	0
F128	390	180	758	1051	2.5	0
F181	398.8	180	758	1051	0.3	0
F182	398	180	758	1051	0.5	0
F183	397.2	180	758	1051	0.7	0
F184	396	180	758	1051	1	0
F185	395.2	180	758	1051	1.2	0
F186	394	180	758	1051	1.5	0
F187	392	180	758	1051	2	0
F188	390	180	758	1051	2.5	0
NS1	398.8	180	758	1051	0	0.3
NS2	398	180	758	1051	0	0.5
NS3	397.2	180	758	1051	0	0.7
NS4	396	180	758	1051	0	1
NS5	395.2	180	758	1051	0	1.2
NS6	394	180	758	1051	0	1.5
NS7	392	180	758	1051	0	2
NS8	390	180	758	1051	0	2.5

Various methods can be employed for concrete mixing in civil engineering projects. In this study, a predetermined amount of water and superplasticizer is added to nano-silica and mixed for 15 to 20 minutes at high-speed using a mixer. The aim is to achieve uniform dispersion of nano-silica particles, preventing agglomeration. After the nano-silica mixing, the aggregate materials are added to the mixer. The pouring of aggregate materials must be done in a way that prevents spillage and the dispersion of fine particles in the air. In the control group, some water is added to achieve the saturated surface-dry (SSD) state for the aggregate materials, while in other groups, a prepared homogeneous solution is added to the aggregate materials. The mixing process continues, and then cement, along with the remaining nano-silica chloride solution, is gradually added to the

mixture. The mixing time is approximately 5 minutes. After mixing, the slump test is performed on the prepared samples. Images of concrete with and without polypropylene fibers are shown in Figure (4). After concrete production, the next step is molding, where standard cylindrical samples of dimensions 15×30 centimeters for compressive strength tests and 7×7×28 centimeters for flexural strength tests are prepared. The cylindrical samples are preferred over cubic ones due to their larger surface area and higher compressive strength. The molding procedure follows ASTM C293 standards. After one day, the samples are demolded and cured in a moist environment for 7, 14, 28, and 90 days. Additionally, to examine the durability of the concrete samples, some are cured in a calcium chloride solution until the day of the testing.



**Figure 4.** Concrete containing (a) polypropylene fibers and (b) without fibers

### 3.3. Laboratory Testing Procedure

The laboratory testing program in this research includes conducting tests for workability, compressive strength, flexural strength, and durability.

#### 3.3.1. workability Test (Slump Test)

The slump test for concrete is conducted to assess the workability or flowability of concrete, either in the laboratory or on-site in a project. This test is exclusively performed on a fresh concrete sample to ensure the

compatibility of the delivered concrete with the required workability for the project. The results of the slump test are expressed as the length measurement of the fresh concrete mixture undergoing dimensional changes. The concrete slump test standard in our country is nearly similar to both the European and American standards, with minor differences in cone dimensions and the method of lifting, following both European and American standards. In this study, the slump test, following ASTM C143 standards, will be

carried out on samples containing polypropylene fibers and Nano-silica. The obtained results will be compared with the concrete standard procedures outlined in Publication 101 of the National Management and Planning Organization.

The formula for calculating the slump is:

$$S = H_i - H_f \quad (1)$$

Where:

$S$  = Slump of Concrete in millimeters

$H_i$  = The initial height is the height of the cone before the concrete is slumped

$H_f$  = The final height is the height of the concrete mass after the slump

**3.3.2. Compressive Strength Test:** The compressive strength test is performed on cured samples

after 7, 14, 28, and 90 days. Following the construction of samples according to the provided method and curing at the specified ages, the ASTM C39 standard is employed for testing 30×15-centimeter samples. This method is applicable to concrete with a specific gravity exceeding 800 kilograms per cubic meter. Vertical axial loads are applied to cubic samples until failure. The samples are prepared and cured according to laboratory standards, and they are tested in an environment with a temperature of 20 to 30 degrees Celsius within 3 hours of being removed from the moist storage. Before loading, the surfaces of the samples are cleaned and dried, and loose particles on the surfaces are removed. Loading is applied to the smooth faces of the samples, and they are carefully placed under the testing machine. The deviation from perpendicularity up to 1.5 degrees is acceptable. The loading rate, according to the standard, should be between 900 to 1800 Newton per second, with 1300 Newton per second adopted for this experiment. Hydraulic jacks in a concrete breaker device are used for loading. The compressive strength is calculated by dividing

the maximum load applied to the sample by its loaded area.

The mathematical formula to calculate the compressive strength is:

$$\sigma = \frac{F}{A} \quad (2)$$

Where:

$\sigma$  = The compressive strength is reported in units of pressure: Megapascals (MPa)

$F$  = The maximum compressive load applied to the specimen during the test

$A$  = The cross-sectional area of the concrete specimen

**3.3.3. Flexural Strength Test (Three-Point Flexural Test):** After undergoing the curing process, 7×7×28-centimeter beams are subjected to a three-point flexural test using a flexural strength testing machine (initial, middle, and endpoints). This test is conducted following ASTM C293 standards. Before the flexural strength test, samples are dried, and particles adhered to the surfaces in contact with the loading point are cleaned. After placing the samples on the support, loading is applied through a loading blade perpendicular to the length of the sample, at the center of the span, with a loading rate of 50 Newton per second.

The flexural strength test results were determined using the following formula:

$$R = (pl/bh^2) \quad (3)$$

Where:

$R$  = Modulus of rupture in megapascals

$p$  = Applied force at the center of the specimen in Newton

$b$  = Width of the specimen in millimeters

$h$  = Height of the specimen in millimeters

$l$  = Span length between two supports in millimeters

**3.3.4. Durability Test:** The durability of concrete encompasses resistance to various factors, including physical elements (fire, freezing and thawing cycles, salt

crystallization), chemical attacks (sulfates, carbonation, alkaline reactions with aggregates), mechanical factors (abrasion, erosion, impact), and corrosion of reinforcement due to rust. Durability tests are conducted on 30×15-centimeter cylindrical samples that have been subjected to a 4% calcium chloride solution for 7, 14, 28, and 90 days. Following the completion of the curing period, the samples will be evaluated through a concrete compressive strength test. After verifying the material characteristics and executing the proposed mixing design, the concrete is mixed and prepared in alignment with the project objectives. Through slump tests, compressive strength tests, flexural tests, and durability assessments, we will analyze and scrutinize the produced concrete specimens.

#### 4. Results and Discussion

In this chapter, we delve into the analysis and interpretation of the results obtained from the performance tests conducted on the samples. As outlined in the first chapter, the primary objective of this research is to assess and evaluate the technical comparison between fiber-reinforced concrete and concrete made with nanotechnology. The study involves conducting compressive strength, flexural strength, and durability tests at ages 7, 14, 28, and 90 days. Through a comprehensive examination of the outcomes of these functional tests, this chapter aims to establish criteria for drawing conclusions. The research experiments encompassed slump tests to evaluate the efficiency of samples containing polypropylene fibers and Nano-silica. Furthermore, concrete slump tests were conducted to assess the workability of the concrete. Compressive strength tests were performed on cylindrical samples, while flexural strength tests focused on the resistance of constructed beams. Additionally, durability tests were carried out to examine the resistance of the samples to acidic environments. This analytical discussion will provide insights into the performance characteristics of the concrete samples,

shedding light on how the incorporation of polypropylene fibers and Nano-silica technology impacts their compressive strength, flexural strength, and durability. The examination of these results will serve as a basis for drawing informed conclusions and implications for the practical application of fiber-reinforced and nanotechnology-enhanced concrete in construction projects.

##### 4.1. Discussion of Workability Test (Slump Test)

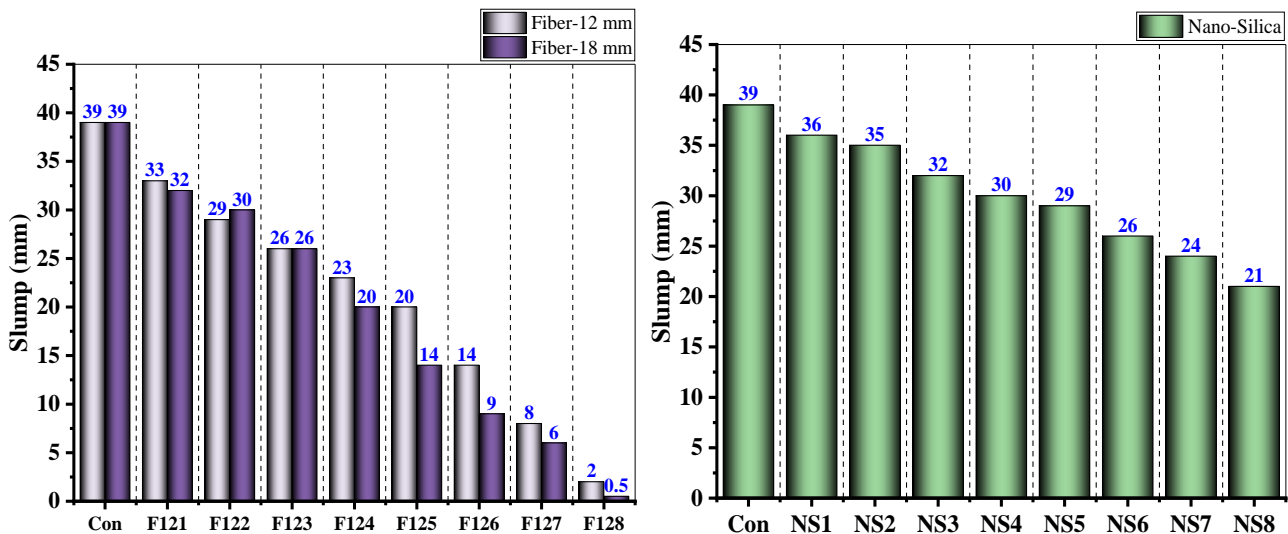
The slump test, conducted in accordance with ASTM C143 on samples containing polypropylene fibers and Nano-silica, reveals results presented in Figures 4-1. As observed from the disclosed outcomes, the addition of polypropylene fibers leads to a reduction in the concrete slump, indicating a direct relationship between fiber content and slump decrease. Therefore, it is recommended to use a superplasticizer or a high-range water reducer when employing fiber-reinforced concrete in civil engineering projects. Furthermore, the decrease in slump in samples containing Nano-silica suggests that Nano-silica accelerates the hydration process, reducing the water content in concrete due to its cementitious properties. According to the analysis in Table (6), the slump values align with the concrete mix design standards outlined in Road Design Code 101 by the National Management and Planning Organization. The investigation, in compliance with the guidelines, categorizes the control sample within the slump range suitable for roller-compacted concrete using manual rolling or vibrating metal rollers. With the gradual addition of 12 and 18-mm fibers, the slump of concrete decreases progressively, placing it in the firm slump range for concrete overlays subjected to manual roller compaction. This indicates the suitability of these fiber-reinforced concretes for roller-compacted applications. In samples containing Nano-silica, a reduction in slump is observed. However, the slump reduction trend is dissimilar to that of adding polypropylene fibers. Adding Nano-silica to

concrete does not significantly reduce its slump, meaning the mix remains workable. However, at Nano-silica levels of 2% and 5.2%, the concrete becomes firmer, moving from a soft, moldable state to a denser, more compact one. At this firmer consistency, the

concrete can be compacted effectively using vibrating rollers. This shows that Nano-silica can help create concrete mixes that are both workable and compactable for specific construction needs.

**Table 6.** Concretes containing aggregates with a maximum size of 19 to 37.5 mm

Workability	Slump test results (mm)	Suitable application of concrete
Very low (hard)	0-25	The concrete surface is shaken by a roller. In some cases, the concretes of the higher performance level of this group can be compacted with manual machines.
Low (paste)	25-50	The concrete surface is shaken by hand rollers or metal bars with a vibrator. The higher performance concretes of this group can also be compacted by hand to make a concrete surface in cases where irregular or irregular stone materials are used.
Medium (loose)	50-100	Foundations with massive concrete without shaking or reinforced concrete parts with little steel and with slight shaking.
High (Workable)	100-175	At the lower level of efficiency of this group, reinforced slabs are made with concrete containing crushed stone and compacted by hand. Ordinary reinforced concrete that is compacted by hand or parts that have a lot of steel and vibrate. It is not suitable for parts that have a lot of reinforcement close to each other and is usually not suitable for shaking.



**Figure 5.** Slump test results on concrete samples

#### 4.2. Compressive Strength Test

One of the primary characteristics defining concrete for the design of various civil structures is its compressive strength parameter. Achieving optimal and stable design is possible by increasing this characteristic. For this purpose, samples are extracted from the molds after one day, and the desired age is attained for the compressive strength test in a lime and water solution.

Prior to conducting the compressive strength test, the following actions were taken: a) Drying the concrete surface and removing any excess pieces, b) Weighing and c) Measuring sample dimensions using calipers or any other suitable tool.

To validate the obtained results for each mix design, three samples were created, evaluated, and the average values served as the basis for graph plotting and the analysis in this study.

In general, polypropylene fibers with a length of 12 mm were added to the concrete matrix in percentages of 0.3, 0.5, 0.7, 1, 1.2, 1.5, 2, and 2.5. Following the completion of the curing period, evaluations were conducted. In accordance with Figure (6), which depicts the compressive strength of samples with 12 mm polypropylene fibers at various percentages on days 7, 14, 28, and 90, it is evident that the compressive strength of these samples decreased at all ages compared to the control sample. Examining the results in Figure (6) indicates that adding polypropylene fibers results in a reduction in compressive strength, and as the percentage of these fibers in the concrete matrix increases, the compressive strength decreases. This decrease can be attributed to the creation of voids between the components in the concrete.

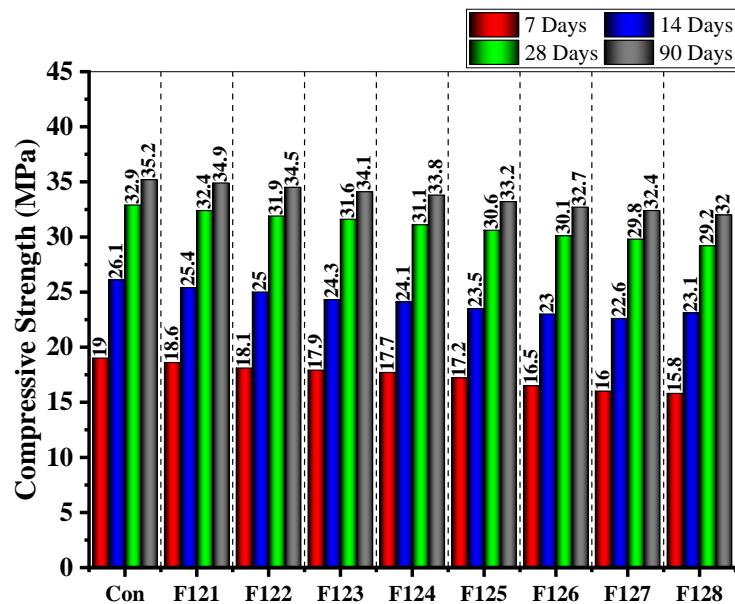


Figure 6. Compressive strength of samples containing 12 mm PP fibers at the ages of 7, 14, 28 and 90 days

Figure (7) presents the compressive strength of samples containing 18 mm polypropylene fibers at ages 7, 14, 28, and 90 days. The results can be summarized as follows:

1. Similar to 12 mm polypropylene fibers, samples containing 18 mm polypropylene fibers also experience a reduction in compressive strength. This reduction is attributed to the voids formed between the concrete's components.
2. Adding fibers reduces the compressive strength of concrete, and this reduction becomes more pronounced with an increase in the percentage of polypropylene fibers. Additionally, an

increase in fiber length exacerbates this reduction.

3. Comparing the results of concrete containing 18 mm and 12 mm polypropylene fibers indicates an inverse relationship between fiber length and compressive strength. Therefore, as fiber length increases, the compressive strength of the samples decreases.
4. During the sample fabrication, it was observed that compacting samples containing 1.5, 2, and 2.5 percent polypropylene fibers was challenging. The likely causes of the reduced compressive strength include inadequate air release, low sample density, and the presence of voids between the materials.

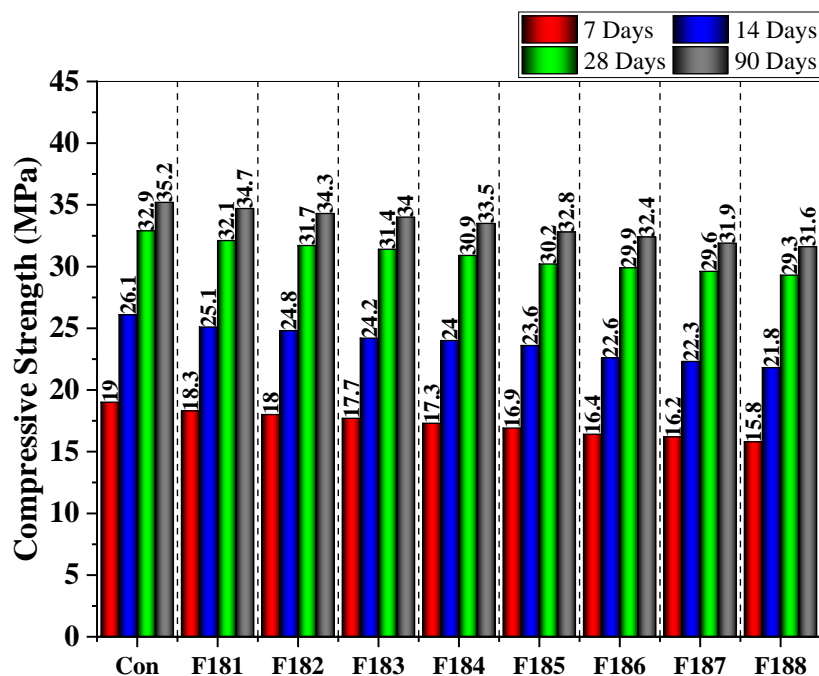


Figure 7. Compressive strength of samples containing 18 mm PP fibers at the ages of 7, 14, 28 and 90 days

As depicted in Figure (8), the addition of Nano-silica increases the compressive strength of concrete. This enhancement is attributed to the filling properties of Nano-silica, reducing defects and increasing compressive strength at all ages (7, 14, 28, and 90 days). Among all samples, NS5, composed of approximately 1.2% Nano-silica, exhibits the highest compressive

strength. The evidence suggests that adding 0.7 to 1.2% Nano-silica to concrete significantly enhances its compressive strength. However, percentages lower than 0.7% and higher than 1.2% also increase compressive strength compared to the control sample at 7, 14, 28, and 90 days, but the increase is not substantial. Adding Nano-silica at percentages of 1.2, 1.5, 2 and 2.5% is

not economically justified due to the non-indigenous production of Nano-silica and its very low purity (around 25%) in Iran. According to American standards, the minimum compressive strength for Portland cement concrete pavement is generally specified to be over 25 MPa to 35 MPa after 28 days. The concrete produced (control, with

12-mm and 18-mm polypropylene fibers, and with Nano-silica) exhibits 28 days of compressive strength values that exceed the minimum specified value. Therefore, the compressive strength of this concrete meets or exceeds the required standards, making it acceptable in terms of the cement used.

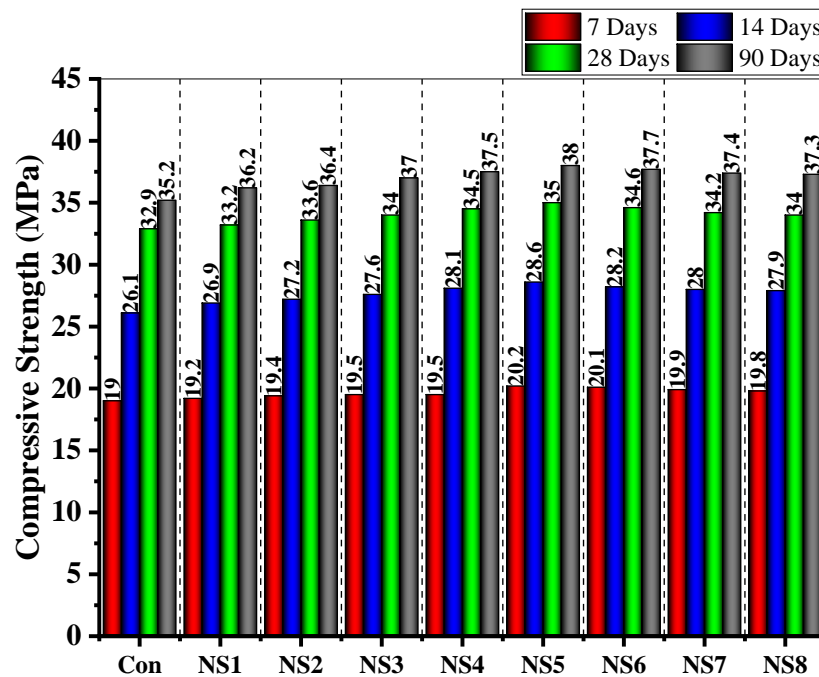


Figure 8. Compressive strength of samples containing Nano-silica at the ages of 7, 14, 28 and 90 days

### 4.3. Flexural Strength Test (Three-Point Flexural Test)

The flexural strength test was conducted on 7×7×28 cm samples according to ASTM C293 standards, incorporating polypropylene fibers (12 and 18 mm in length) and Nano-silica after 28 and 90 days of curing.

Results for the flexural strength of samples containing 12 mm and 18 mm polypropylene fibers after 28 and 90 days of curing are presented in Figures (9) and (10). Unlike compressive strength, the addition of fibers to the concrete matrix increased flexural strength at all different percentages compared to the control sample.

Sample F126, containing 1.5% polypropylene fibers, exhibited the highest flexural strength

among all mix designs at ages 28 and 90 days. It appears that polypropylene fibers create a chain-like structure among the aggregates, enhancing cohesion and increasing the flexural strength of the samples.

Samples F127 and F128, containing 2% and 2.5% polypropylene fibers, respectively, achieved flexural strengths of 7.4 and 2.4 MPa. This suggests that an increase in fiber percentage beyond 1.5% leads to a reduction in flexural strength.

Samples with 18 mm polypropylene fibers showed increased flexural strength at various percentages at ages 28 and 90 days compared to the control sample. This increase indicates effective bonding between the polypropylene

fibers and the aggregates, contributing to the observed strength enhancement.

In mix design F186, which used 1.5% polypropylene fibers, flexural strength reached its maximum, similar to mix design F126. This suggests that the optimal percentage of polypropylene fibers in concrete is around 1.5%.

Mix designs F187 and F188 exhibited a slight decrease in flexural strength after reaching

their maximum values, recording 8.5 and 6.5 MPa, respectively.

Analyzing Figures (9) and (10), it can be concluded that increasing fiber length leads to an increase in flexural strength. This enhancement may be attributed to the improved cohesion and adhesion between the fibers and the aggregates in the concrete.

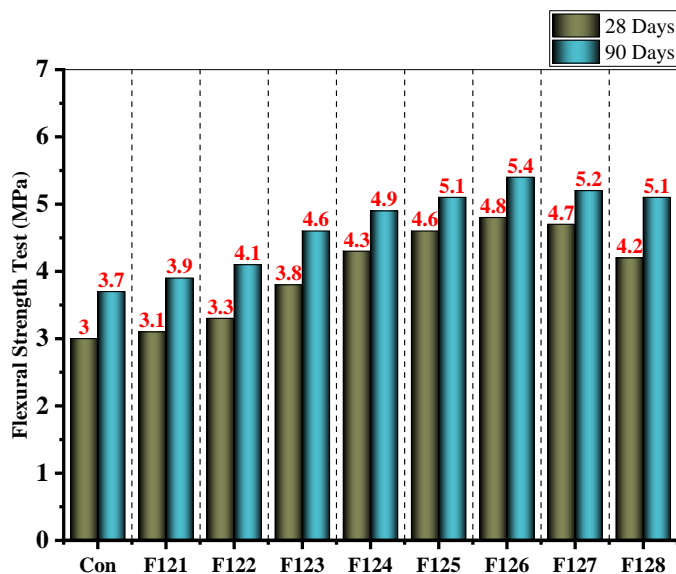


Figure 9. Flexural strength of concrete containing 12 mm polypropylene fibers at the ages of 28 and 90 days

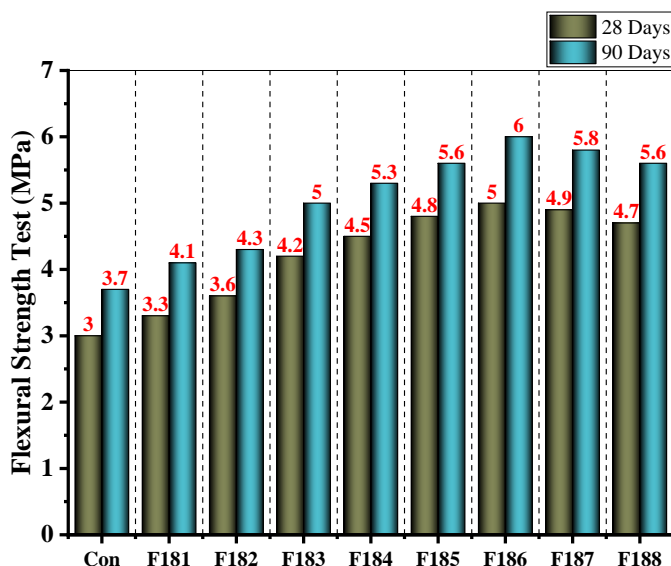
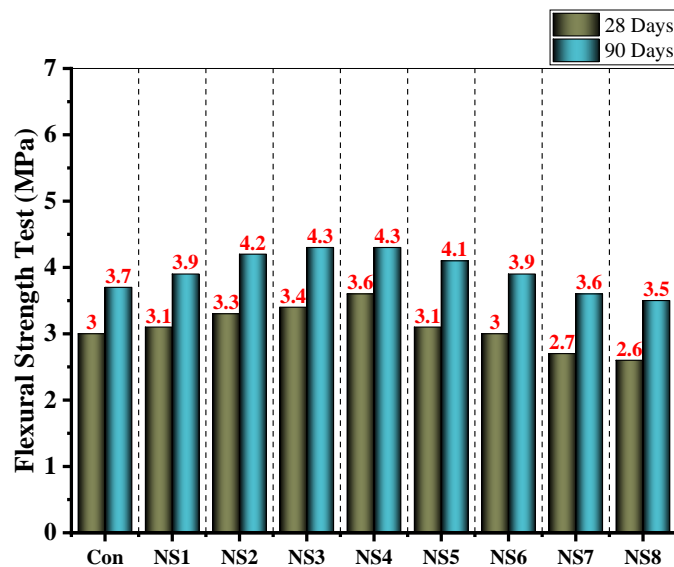


Figure 10. Flexural strength of concrete containing 18 mm polypropylene fibers at the ages of 28 and 90 days

Considering Figure (11), the following observations can be made:

1. The flexural strength results for samples containing Nano-silica at ages 28 and 90 days indicate an initial increase followed by a descending trend.
2. Mix design NS4, incorporating 1% Nano-silica, achieved the highest flexural strength of 6.3 MPa.
3. Mix designs NS7 and NS8, containing 2% and 2.5% Nano-silica, respectively, exhibited lower flexural strength than the control mix, suggesting a decrease in flexural strength beyond 1% Nano-silica.



**Figure 11.** Flexural strength of concrete containing Nano-Silica at the ages of 28 and 90 days

Although flexural strength of roller-compacted concrete is a crucial parameter in pavement design, obtaining flexural samples in the laboratory or cutting in-place specimens from concrete can be challenging. Upon analysis, it can be inferred that the use of polypropylene fibers with lengths of 12 and 18 mm contributes to a significant and acceptable growth in flexural strength, aiding in reducing surface cracking. In comparison, the addition of Nano-silica generally increases flexural strength, although the magnitude is lower than that achieved with polypropylene fibers.

#### 4.4. Durability Test

As previously discussed in Chapter 3, concrete durability encompasses the material's ability to maintain structural integrity, provide protective capabilities, and exhibit aesthetic appeal over an extended period. It is crucial to

ensure that the benefits of concrete in its plastic and early hardened states are not compromised in the long-term durability by the addition of water-reducing agents. The durability of concrete encompasses resistance to various factors such as physical (fire, freezing and thawing cycles, salt crystallization), chemical (sulfates, carbonation, alkaline-aggregate reaction), and mechanical (abrasion, abrasion, impact) stresses. Additionally, susceptibility to corrosion of reinforcement due to environmental factors needs consideration.

**Durability Testing in the Study:** In this research, durability tests were conducted to investigate the impact of various parameters on concrete durability. Samples were prepared using concrete mixes cured for 7, 14, 28, and 90 days in water and calcium chloride solution. Subsequently, compressive strength tests were performed to evaluate the influence

of acidic environments on the long-term durability parameters.

**Observations from Durability Tests:** A comparison of results between the control sample cured in lime water and calcium chloride solution indicates a substantial role of acidic environments in reducing compressive strength.

Figure (12) shows a reduction in compressive strength for all samples containing polypropylene fibers during the 7, 14, 28, and 90-day curing periods in a calcium chloride solution compared to the control sample.

Furthermore, a comparison between Figures (12) and (6) reveals that polypropylene fibers contribute to reduced compressive strength by creating voids within the concrete matrix, and calcium chloride solution also leads to decreased strength in these samples.

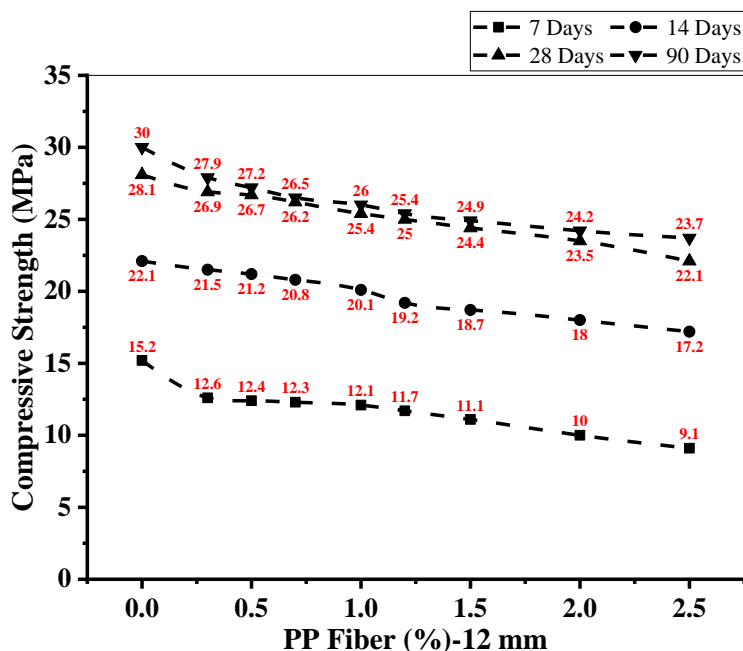


Figure 12. Durability of samples containing 12 mm polypropylene fibers at the ages of 7, 14, 28 and 90 days

It seems that the age at which the samples are placed in the calcium chloride solution has an inverse relationship with compressive strength. That is, as the age of sample placement increases, the compressive strength decreases, a trend further evident in the analysis of Figure (12). Sample F128, with 2.5% 12mm fibers, exhibited the lowest compressive strength during the 7, 14, 28, and 90-day periods. This suggests that the use of polypropylene fibers with high percentages and exposure to acidic environments significantly contribute to reducing the

compressive strength of cylindrical specimens.

**Effect of Fiber Length on Compressive Strength:**

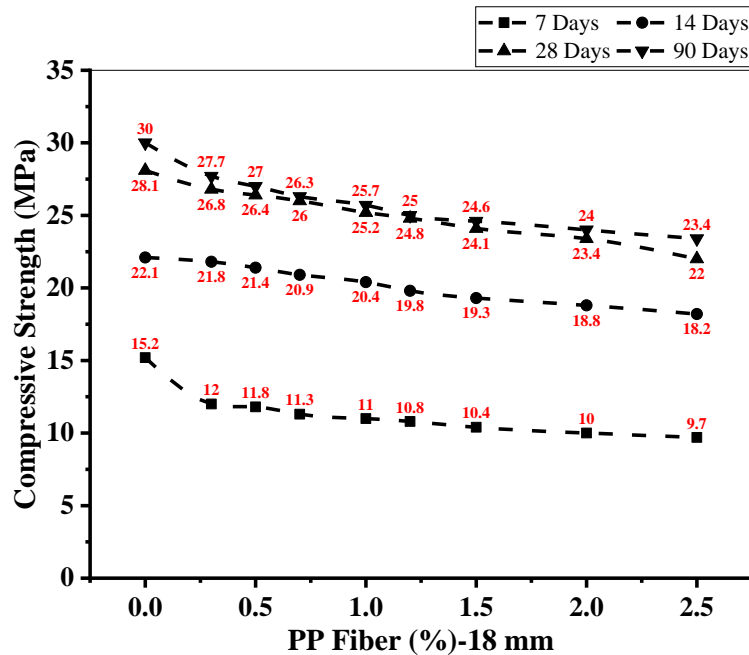
Analyzing Figure (13) and the results of adding different percentages of 18mm polypropylene fibers and curing with calcium chloride solution for 7, 14, 28, and 90 days, the following observations can be made:

1. Similar to 12mm fibers, the addition of 18mm fibers and acid curing resulted in decreased compressive strength, indicating

a negative impact of polypropylene fibers on concrete compressive strength.

2. Increasing fiber length significantly decreases compressive strength.
3. Sample F184 at 14 days showed an unexpected increase in compressive

strength, suggesting a potential error in construction or testing procedures.



**Figure 13.** Durability of samples containing 18 mm polypropylene fibers at the ages of 7, 14, 28 and 90 days

**Effect of Nano-silica on Compressive Strength:** Examining Figure (14) and analyzing the results of adding various percentages of Nano-silica (0.3, 0.5, 0.7, 1, 1.5, 2 and 2.5) in the 7, 14, 28, and 90-day periods, the following findings can be highlighted:

1. Compressive strength results confirm that, similar to samples containing Nano-silica cured in lime water, the optimum level of Nano-silica addition in concrete is around 1%.
2. Adding Nano-silica to concrete and curing it in saturated lime water or calcium chloride solution leads to increased compressive strength in the samples at 7, 14, 28, and 90 days.

3. Samples cured in lime water exhibit higher compressive strength compared to those cured in calcium chloride solution.
4. Compressive strength of the control sample cured in calcium chloride solution is lower than the control sample cured in lime water, highlighting the effect of an acidic environment on concrete compressive strength.
5. Samples containing Nano-silica and cured in calcium chloride solution show growth in compressive strength compared to the control sample, indicating Nano-silica's ability to counteract acidic and alkaline conditions.

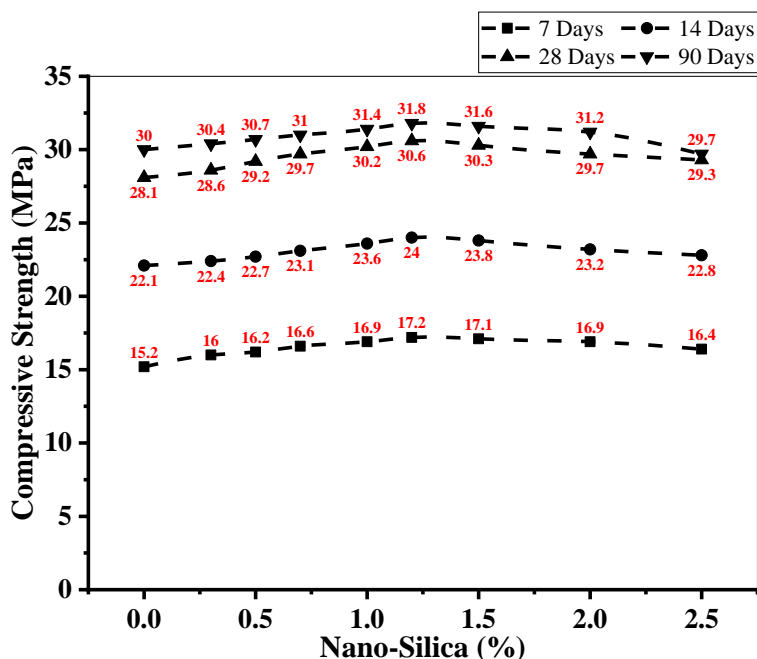


Figure 14. Durability of samples containing Nano-silica at the ages of 7, 14, 28 and 90 days

#### 4.5. Summary of Results

The summary of the results of the experiments in this study is shown in Table (7). The best percentage of using fibers is

about 1% of the weight of cement and the range of using Nano-silica is 0.7 to 1.2% of the weight of cement.

Table 7. Summary of test results on concrete samples

admixture	Workability	Compressive Strength	Flexural Strength	Durability
18 mm PP Fiber	Decrease	Decrease	Increase	Decrease
12 mm PP Fiber	Decrease	Decrease	Increase	Decrease
Nano-Silica	Decrease	Increase	Increase	Increase

### 5. Conclusion

#### 5.1 Summary of Findings

This study aimed to investigate and evaluate fiber-reinforced concrete and compare it with concrete made with nanomaterials (Nano-silica) for use in road pavements. Compressive strength, flexural strength, and durability tests were conducted on 15×30 cm cylindrical specimens and 7×7×28 cm beams at ages 7, 14, 28, and 90 days. The addition percentages of polypropylene fibers (with lengths of 12 and 18 mm) and Nano-silica were 0.3, 0.5, 0.7, 1, 1.5, 2, and 2.5% by weight of cement. Durability tests were performed on samples treated in a calcium chloride solution at 7, 14, 28, and 90 days.

#### 5.2 Implications for Practical Applications

The threefold test results lead to the following conclusions:

1. Polypropylene fibers, with a 2.5% addition, induce a noteworthy 10% and 11% decrease in compressive strength for 12 mm and 18 mm fibers, attributed to the voids they create. This finding necessitates caution when incorporating polypropylene fibers into road pavement concrete mixes, especially in load-bearing areas where compressive strength is pivotal.
2. On the contrary, Nano-silica exhibits a commendable enhancement in compressive strength across all age categories, achieving a maximum growth of 7.3%, with optimal performance at 1.5% by weight of cement. This signifies Nano-

silica's potential contribution to improving the load-bearing capacity of road pavements, making the specified optimal percentage a crucial parameter in mix design for road construction projects.

3. The combined use of polypropylene fibers and Nano-silica is suggested for enhanced concrete performance. This recommendation implies a synergistic effect that could harness the positive attributes of both materials. This combination warrants exploration in road pavement applications to achieve a balanced enhancement between polypropylene fibers and Nano-silica.
4. The incorporation of longer polypropylene fibers (12 and 18 mm) results in a substantial growth of 31% and 38% in flexural strength, showcasing their potential to enhance the pavement's resistance to bending and cracking. This is particularly crucial in areas prone to tensile stresses, such as pavements subjected to heavy traffic or thermal cycling.
5. Visual and structural comparisons highlight that polypropylene fibers significantly improve crack resistance and enhance concrete cohesion. This improvement in crack resistance is vital for the durability of road pavements, suggesting a positive role for polypropylene fibers in minimizing and controlling crack formation.
6. Nano-silica, when compared to polypropylene fibers, demonstrates superior performance in acidic environments. Given that road pavements may be exposed to acidic conditions, such as acid rain, Nano-silica's robust performance in such environments positions it as a valuable additive for enhancing the durability of concrete in road pavements.
7. Both polypropylene fibers and Nano-silica offer economic and environmental advantages, presenting potential applications in reducing road deterioration, surface irregularities, and greenhouse gas emissions. Their utilization aligns with

modern construction principles, contributing to sustainable road pavement practices through cost savings and environmental benefits.

### 5.3 Limitations and Future Research Directions

The project's limitations include its non-native nature and expensive import of nano-silica to Iran, which affects the examination of higher percentages. The absence of a specialized road laboratory in Guilan province led to the use of ordinary devices, impacting the research's quality. Future research suggestions include combining polypropylene fibers and Nano-silica, testing chloride ion permeability, investigating tensile strength in fiber-reinforced concrete, using higher percentages of Nano-silica, employing larger-sized aggregates, conducting ultrasonic tests, dynamic loading, and assessing electrical resistance in fiber-reinforced and Nano-silica-enhanced concrete.

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