UDC 691.78
IRSTI 67.09.33
RESEARCH ARTICLE

3D PRINTING OF FINE-GRAINED CONCRETE WITH NANO-BLEND

K. Akmalaiuly, A.U. Kanarbay*, D.M. Rakhimdzhanov, N.I. Berdikul

Kazakh National Technical University after K.I. Satbayev, 050013, Almaty, Kazakhstan

Abstract. *The integration of modern computer technologies into the construction industry is transforming design and building processes, offering professionals numerous advantages. One of the most significant advancements is the adoption of virtual modeling tools, which enhance design accuracy, improve project quality, and reduce implementation time. These technologies also optimize material costs, making construction more efficient and cost-effective. A major milestone in this digital transformation is the widespread use of Building Information Modeling (BIM) technologies, such as Revit and Archicad. These programs create a unified software environment that streamlines project management across all stages, from initial design to construction and operation. Additionally, they enable the development of complex architectural forms through 3D printing, further expanding the potential of modern construction methods. The success of 3D printing in construction depends heavily on advanced materials, particularly fine-grained concrete with inorganic binders. While these materials enhance durability and structural integrity, their development remains a challenge due to strict technical requirements. Overcoming these challenges requires a scientifically grounded approach to optimizing material composition and ensuring seamless integration into additive manufacturing processes. In conclusion, the fusion of digital tools with construction methodologies significantly improves efficiency, precision, and sustainability. These innovations not only advance the design and building processes but also pave the way for the successful realization of complex and economically viable projects, shaping the future of the construction industry.*

Keywords: *nano silicon, fine-grained concrete, 3D printer, strength, modified additives, hydro silicates, water-cement ratio.*

***Corresponding author**
Assel Kanarbay, e-mail: asel.kanarbay@mail.ru

https://doi.org/10.51488/1680-080X/2025.2-05
Received 09 January 2025; Revised 11 February 2025; Accepted 03 March 2025

ӘОЖ 691.78
ҒТАМР 67.09.33
ҒЫЛЫМИ МАҚАЛА

НАНО ҚОСПАСЫ БАР ҰСАҚ ТҮЙІРШІКТІ БЕТОНДЫ 3D-да БАСЫП ШЫҒАРУ

К. Ақмалайұлы , Ә.Ү. Қанарбай* , Д.М. Рахимджанов, Н.И. Бердіқұл

Қ.И.Сәтбаев атындағы ҚазҰТЗУ, Алматы, 050013, Қазақстан

Аңдатпа. *Қазіргі заманғы компьютерлік технологиялардың құрылыс саласына енгізілуі жобалау және құрылыс үдерістерін түбегейлі өзгертіп, мамандарға көптеген артықшылықтар ұсынып отыр. Ең маңызды жаңалықтардың бірі – жобалау дәлдігін арттырып, жоба сапасын жақсартатын және іске асыру уақыты мен шығындарын азайтатын виртуалды модельдеу құралдарын пайдалану. Бұл технологиялар сондай-ақ материалдық шығындарды оңтайландырып, құрылысты анағұрлым тиімді әрі үнемді етеді. Цифрлық трансформациядағы маңызды кезеңдердің бірі – Building Information Modeling (BIM) технологияларының, атап айтқанда Revit пен Archicad секілді бағдарламалардың кеңінен қолданылуы. Бұл бағдарламалар жобалаудан бастап құрылыс пен пайдалануға беру кезеңдеріне дейінгі барлық үдерісті біріктіретін біртұтас бағдарламалық орта қалыптастырады. Сонымен қатар, олар 3D басып шығару арқылы күрделі сәулеттік формаларды әзірлеуге мүмкіндік беріп, қазіргі құрылыс әдістерінің мүмкіндіктерін кеңейтеді. Құрылыста 3D басып шығарудың табысты болуы негізінен бейорганикалық байланыстырғыштары бар ұсақ түйіршікті бетон секілді жетілдірілген материалдарға байланысты. Бұл материалдар беріктік пен құрылымдық тұтастықты арттырады, алайда олардың дамуы қатаң техникалық талаптарға байланысты күрделі міндет болып қала береді. Бұл мәселелерді шешу үшін материал құрамын ғылыми негізде оңтайландырып, оларды аддитивті өндіріс үдерістеріне үйлесімді енгізу қажет. Қорытындылай келе, цифрлық құралдар мен құрылыс әдістерінің үйлесімі тиімділік, дәлдік және тұрақтылық деңгейін айтарлықтай арттырады. Бұл жаңалықтар жобалау мен құрылыс үдерістерін жетілдіріп қана қоймай, сонымен қатар күрделі әрі экономикалық тұрғыдан тиімді жобаларды табысты жүзеге асыруға жол ашып, құрылыс саласының болашағын қалыптастырады.*

Түйін сөздер: *нано кремний, түйіршікті бетон, 3D принтер, беріктілік, модификациялық қоспалар, гидросиликаттар, су-цемент қатынасы*.

***Автор-корреспондент**
Әсел Үсенқызы Қанарбай, e-mail: asel.kanarbay@mail.ru

https://doi.org/10.51488/1680-080X/2025.2-05
Алынды 09 қаңтар 2025; Қайта қаралды 11 ақпан 2025; Қабылданды 03 наурыз 2025

УДК 691.78
МРНТИ 67.09.33
НАУЧНАЯ СТАТЬЯ

3D-ПЕЧАТЬ МЕЛКОЗЕРНИСТОГО БЕТОНА С НАНО-СМЕСЬЮ

К. Ақмалайұлы , Ә.Ү. Қанарбай* , Д.М. Рахимджанов, Н.И. Бердіқұл

КазНИТУ имени К.И.Сатпаева, Алматы, 050013, Казахстан

Аннотация. *Внедрение современных компьютерных технологий в строительную отрасль трансформирует процессы проектирования и строительства, предоставляя специалистам многочисленные преимущества. Одним из наиболее значимых достижений является применение инструментов виртуального моделирования, которые повышают точность проектирования, улучшают качество проектов и сокращают время их реализации. Эти технологии также оптимизируют затраты на материалы, делая строительство более эффективным и экономичным. Важным этапом цифровой трансформации стало широкое использование технологий информационного моделирования зданий (BIM), таких как Revit и Archicad. Эти программы создают единую программную среду, которая упрощает управление проектом на всех этапах – от первоначального проектирования до строительства и эксплуатации. Кроме того, они позволяют разрабатывать сложные архитектурные формы с помощью 3D-печати, расширяя возможности современных строительных методов. Успех 3D-печати в строительстве во многом зависит от передовых материалов, особенно от мелкозернистого бетона с неорганическими вяжущими. Несмотря на то, что эти материалы повышают долговечность и структурную целостность, их разработка остается сложной задачей из-за строгих технических требований. Для преодоления этих трудностей необходим научно обоснованный подход к оптимизации состава материалов и обеспечению их бесшовной интеграции в аддитивные производственные процессы. В заключение, интеграция цифровых инструментов с методами строительства значительно повышает эффективность, точность и устойчивость. Эти инновации не только способствуют развитию процессов проектирования и строительства, но и прокладывают путь для успешной реализации сложных и экономически выгодных проектов, формируя будущее строительной отрасли.*

Ключевые слова: *нано кремний, мелкозернистый бетон, 3D принтер, прочность, модифицированные добавки, гидросиликаты, водоцементное отношение.*

***Автор-корреспондент**
Әсел Үсенқызы Қанарбай, e-mail: asel.kanarbay@mail.ru

https://doi.org/10.51488/1680-080X/2025.2-05
Поступило 09 января 2025; Пересмотрено 11 февраля 2025; Принято 03 марта 2025

ACKNOWLEDGEMENTS/SOURCE OF FUNDING

The research was conducted using private sources of funding.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The construction industry is actively adopting BIM technologies and software like Revit and Archicad, enabling the design and construction of buildings through 3D printing. For creating materials for construction objects, a variety of materials based on inorganic binders with specific properties are used, depending on the product's purpose and the chosen 3D printing method.

This study focuses on modifying fine-grained concrete using nano-silica. The introduction of chemical additives makes it possible to produce high-strength concrete with rapid hardening properties. To enhance and accelerate strength development, the optimal dosage of the additive was determined. Adding nano-silica resulted in a strength increase of 1.4 times (or 76.3%) within one day, 76.3% within three days, 66.2% within seven days, and 44.0% within 28 days. The results also demonstrated a significantly accelerated strength gain.

The key characteristic of concrete is its compressive strength. To ensure rapid and high-quality construction, it is recommended to use high-strength concrete that gains substantial strength during the initial curing period. This can be achieved by incorporating nano-silica additives **(Zolotaryeva, S. V., 2016)**.

Despite the globally proven efficiency of active mineral additives, their usage in Kazakhstan remains limited. The main reasons include their dusty, hygroscopic, and lightweight nature, making them less suitable for some applications. Such materials tend to clog technological equipment and cement delivery systems. In specific cases, the consumption of such fillers can reach 200–250 kg per cubic meter of concrete, requiring additional cement silos at concrete plants for storage. Moreover, the low bulk density of mineral fillers, often as low as 150 kg/m³, further increases costs **(Baigarina, A., Shehab, E., & Ali, M. H., 2023).**

The effectiveness of active fillers is often assessed by their impact on strength properties. When a specific amount of cement is replaced by an equivalent amount of active filler, the resulting increase in concrete strength serves as a performance indicator. However, the benefits of nano-silica extend beyond strength improvement. Nano-silica acts as a critical component in high-strength, corrosion-resistant, and frost-resistant concrete.

Nano-silica particles are up to 100 times smaller than cement particles and exhibit high pozzolanic reactivity due to their large surface area and high silicon dioxide content. A standard dose of 40 kg of nano-silica provides a surface area sufficient to react with calcium hydroxide released during cement hydration. This early pozzolanic activity sets nano-silica apart from other additives. In concrete containing nano-silica, the porous structure shows a marked reduction in capillary pores and an increase in fine gel pores. The amount of chemically bound water and the degree of Portland cement hydration indicate that nano-silica accelerates hydration significantly during the initial seven days. At a constant water-cement ratio, concrete with nano-silica achieves a hydration level at seven days comparable to that of ordinary cement at 28 days. This acceleration results in a twofold increase in concrete strength under both normal humidity and elevated temperatures of 60°C **(Mustafin, N. Sh., & Baryshnikov, A. A., 2015), (Rudyak, K. A., & Chernychev, Y. O.2016).**

The improved hydration of calcium silicates and the reduction of capillary pores provide two key benefits for nano-silica-modified concrete: high strength and low permeability. These enhancements make the concrete highly resistant to physical (wear, erosion, and impact) and chemical (water, sulfates, chlorides, organic substances, and acids) effects.

Studies of concrete structures containing nano-silica have shown that such materials maintain durability for up to 10 years. High-quality concretes with nano-silica additives demonstrate superior resistance to carbonation and chloride penetration from seawater compared to ordinary Portland cement concretes with equivalent strength. Under proper conditions, nano-silica-modified concrete offers excellent protection for steel reinforcement, comparable to that provided by ordinary Portland cement concretes of the same strength class **(Ilyina, L. V., & Zavadskaya, L. V.,2018), (Inozemtsev, A. S., Korolev, E. V., & Zhyong, Thanh Kui. 2018).**

2 LITERATURE REVIEW

Considering the results of various experiments by different researchers, it can be noted that the specific surface area of SiO_2 nanoparticles (S = 50 to 450–900 m²/g) is a critical factor in improving the mechanical performance of concrete. This improvement is achieved by activating the hydration reaction of calcium silicates, forming C-S-H hydrates, and modifying the nanostructure of the C-S-H gel.

The use of nano-silica provides several benefits, including:

- Enhancing resistance to abrasion;
- Reducing cement consumption;
- Increasing the strength of concrete, particularly in fine-grained mixtures;
- Improving early strength under normal curing conditions (25–40 MPa within the first 24 hours);
- Producing highly workable, non-segregating concrete mixtures with a slump of 20–24 cm;
- Increasing corrosion resistance.

The addition of nano-silica reduces water permeability by 50%, doubles sulfate resistance, and increases frost resistance to F500. As research indicates (**Ibragimov, R. A., & Izotov, V. S. 2014**), the objective of this study is to analyze the effect of nano-silica on the strength characteristics of fine-grained concrete and to determine its optimal dosage.

In research on improving concrete strength through nano-silica modification, Portland cement of the CEM I 42.5 H grade, produced by the Shymkent Cement Plant, was used as the binder. As reported in previous studies (**Krasinikova & Ilyina, 2011,2016**), the mineralogical composition of the cement (by mass, %) was as follows: C_3S – 60.0; C_2S – 15.5; C_3A – 8.4; C_4AF – 11.3; free CaO – 0.50. The study used washed quartz sand from the Kapshagay quarry. According to research findings (**Krasinikova et al., 2016**), the sand complied with GOST 8736-2014 for construction sands, with a natural moisture content of 6–7%, a bulk density of 1450 kg/m³, a true density of 2600 kg/m³, a fineness modulus of 2.9, and impurity content of 0.5%.

Nano-silica was used as a modifying additive and met the requirements of technical specifications. As specified by the manufacturer **(Krasinikova, 2016),** the average particle size of the initial nano-silica particles was 12 nm, with a pH of 3.6–4.3. Nano-silica is a bluish-white material with a specific surface area of 200 m²/g. Its chemical composition (by mass, %) is as follows: SiO_2 – 99.5; Al_2O_3 – 0.05; Fe_2O_3 – 0.001; TiO_2 – 0.01.

Master Rheobuild 1000 superplasticizer was used as a plasticizing agent, with a density of 1095 kg/m³ and a solid content of 20% by mass. As noted in studies **(Ilyina et al., 2011),** the superplasticizer was added at a dosage of 0.5% by cement weight.

3 MATERIALS AND METHODS

To determine the characteristics of a fine-grained concrete mixture and fine-grained concrete, a mixture was prepared consisting of Portland cement, including 60 kg of cement, 1340 kg of sand, and 260 liters of water. Nano-silica powder was added to the water solution, and its uniform distribution was achieved through ultrasonic treatment. The resulting solution was added to the dry sand and cement mixture. The cement-sand solution was prepared using mechanical mixing for 60–90 seconds. From the obtained mixture, 40x40x160 mm column specimens were formed, which were cured under normal conditions for 3, 7, and 29 days.

Micro-silica, reacting a second time with calcium hydroxide, helps reduce the capillary porosity of cement paste by densifying the structure and sealing the pores of low-base calcium hydrosilicates. Detailed studies on the kinetics of strength development and the porosity characteristics of cement paste show that the introduction of micro-silica and superplasticizers into concrete significantly reduces the number of all types of pores compared to unmodified cement paste. The effectiveness of micro-silica is associated with the rate of pH reduction in the hardening system environment, which accelerates the main hydration reactions of cement **(Potapov, V. V., & Gorev, D. S. 2018**). As shown in **Figure 1**, the microstructure of the cement paste becomes denser after the addition of microsilica.

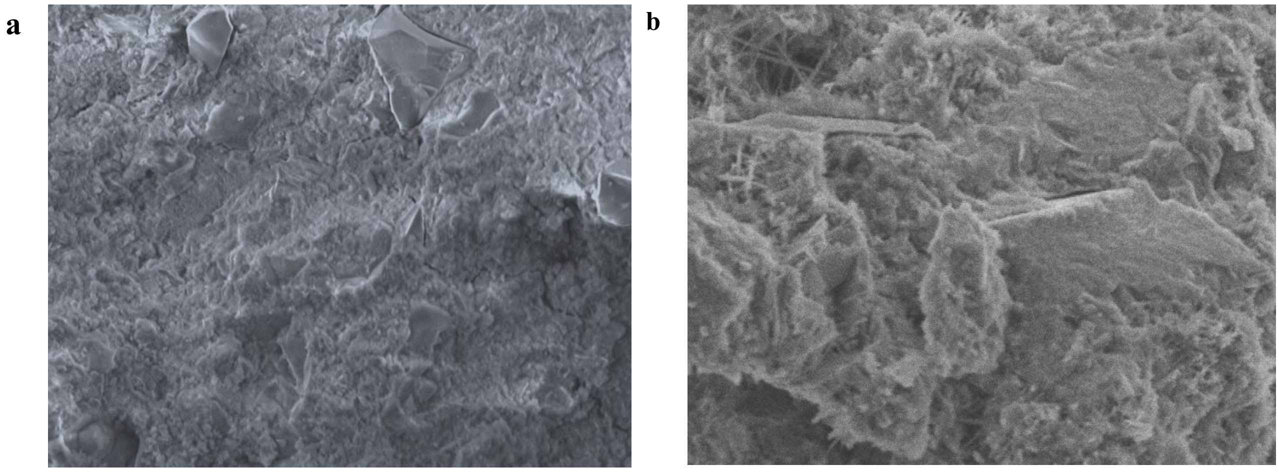

Figure 1 – SEM images of the cement paste microstructure:**a** – control sample without microsilica; **b** – sample with microsilica additive.

By reducing the concentration of calcium ions in the liquid phase of the cement paste, micro-silica in the mixture contributes to the formation of gel-like low-base calcium hydrosilicates in hydrated phases. This results in a simultaneous increase in gel pores and a decrease in the capillary porosity of the cement paste. It has been determined that micro-silica additives allow for obtaining high-strength dense cement paste. Furthermore, the correspondence between the phase composition and structure of the cement paste after heat-moisture treatment and normal curing enables the production of high-quality concrete with an accelerated strength gain rate under normal conditions. Micro-silica significantly increases the hydration degree of alite in the early stages.

Concrete modified with micro-silica is characterized by reduced water permeability, increased resistance to alkali, sulfate, and frost aggression. In studies of concrete degradation mechanisms, the primary durability factor is often considered to be the presence of open capillary pores that are easily filled with liquid phases during freezing, leading to hydraulic and crystallization pressure buildup. This causes stress in the concrete, with stress concentration occurring at structural defect sites, leading to local damage—crack formation and propagation accompanied by residual strain growth. To minimize frost damage, it is recommended to reduce open porosity (by densifying the concrete mixture and optimizing curing conditions with a lower water-to-cement ratio (W/C)) and to ensure reserve porosity for compressible pore water by using air-entraining additives, which reduce hydraulic pressure.

Experience shows that air entrainment reliably enhances concrete frost resistance. However, some researchers believe that the role of air entrainment diminishes sharply at low W/C ratios. To improve concrete strength, the introduction of damping additives capable of relaxing induced stresses is recommended. Studies have shown that gel-like products of cement hydration can serve as damping additives, and their stability can be enhanced by binding portlandite in cement paste with active mineral additives, among which micro-silica is one of the most active representatives **(Matyukhina, A. A., et al. 2017).**

Reducing the W/C ratio and increasing the micro-silica content decreases air volume and increases compressive strength. Furthermore, concrete frost resistance improves, reaching a maximum when the micro-silica content is 20%. For concrete specimens of this composition, minimal strength variation was observed during testing, indicating the highest stability of the cement paste structure.

Thus, at low air content, the matrix's relaxation properties, determined by the permeability of cement paste, pore size, and the number of crystalline and gel-like cement hydration products, play a critical role in ensuring concrete strength under frost impact without air-entraining additives. The introduction of micro-silica leads to an increase in low-base calcium hydrosilicates of the C-S-H type. Compared to high-base hydrosilicates, these hydrates exhibit greater stability and strength due to an increase in strong Si-O-Si siloxane bonds and a decrease in weak Ca-O ionic bonds. A reduction in portlandite crystals decreases the crystalline hydrate component and the number of stress concentrators, thereby enhancing crack resistance in cement paste. In the contact zone between cement paste and aggregates, the reduction of $Ca(OH)_2$ crystals contributes to increased strength, and the porosity and size of crystalline phases in cement paste also decrease **(Duballet, R., Baverel, O., & Dirrenberger, J. 2017).**

High frost resistance is also ensured by the stability of hydrated phases resulting from the effect of micro-silica additives. Therefore, the key factors in ensuring the durability of road concrete are:

- Low initial W/C ratios that ensure reduced capillary porosity and water saturation;
- Structural characteristics of cement paste, including increased cement gel content and a free $Ca(OH)_2$ content not exceeding 1.0%, which slows down gel phase aging and facilitates stress relaxation;
- Recommendations for road concrete with frost resistance grades of F500–F600 without air-entraining additives include W/C ratios of 0.25–0.30 and mandatory introduction of hydrogen-releasing components along with micro-silica additives up to 15–20% of the cement mass;
- Capillary porosity of concrete and the amount of free calcium hydroxide in cement paste can serve as predictive criteria for the durability of road concrete used under cyclic freezing conditions in de-icing solutions.

4 RESULTS AND DISCUSSION

As **Figure 2** illustrates, nano-silica was added to fine-grained concrete in proportions of 0.05%, 0.10%, 0.25%, and 0.5% of the cement mass, and the workability of the prepared mixture was determined by measuring the slump of the cone.

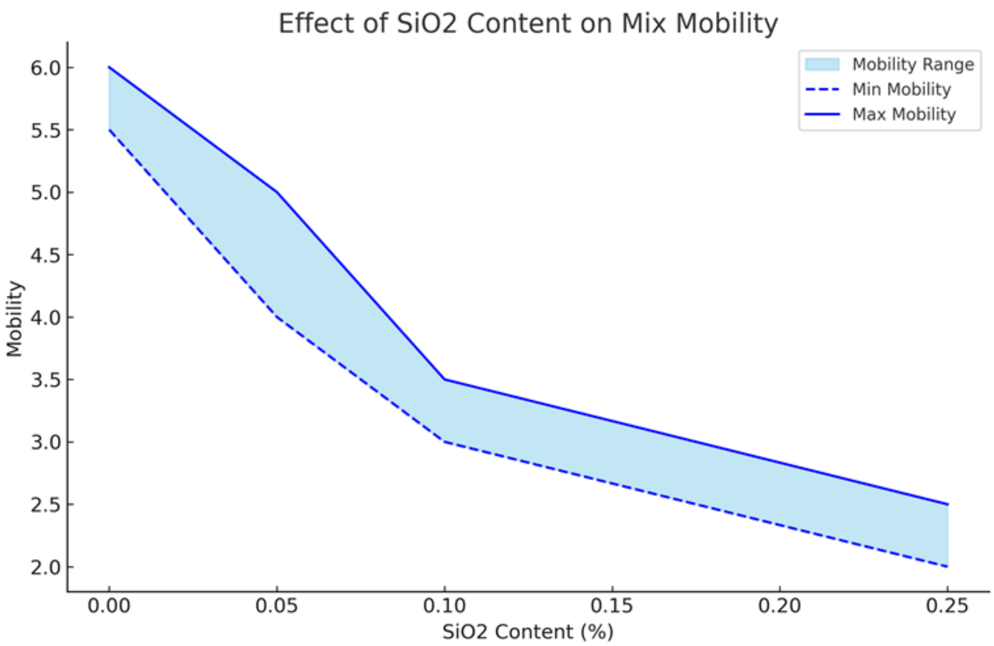

Figure 2 - Effect of Nano-Silica Content on the Workability of the Mixture

The analysis of the results revealed that in mixtures with nano-silica, the cement-to-water ratio remained consistent, but the workability of the mixture decreased. This indicates that within the studied range, the addition of nano-silica reduces the mobility of the mixture.

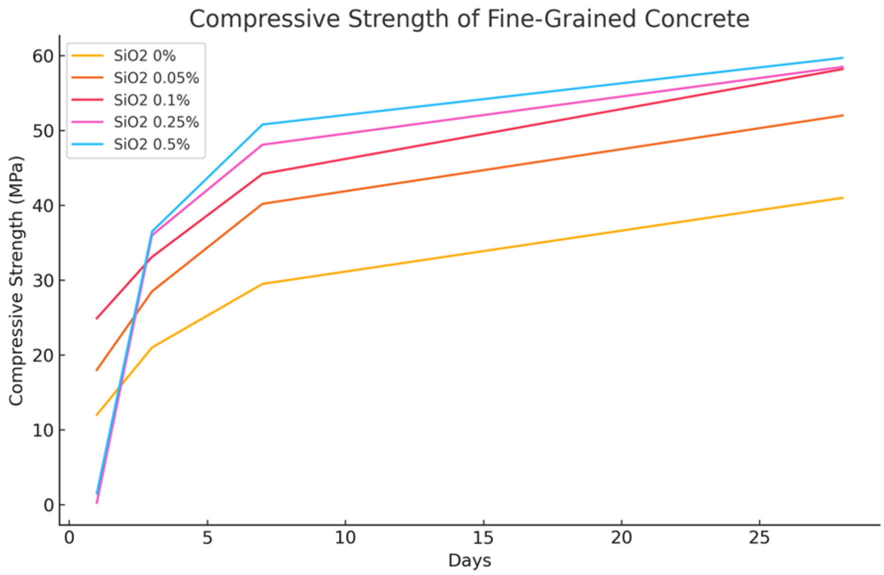

Figure 3 - Variation in Compressive Strength (MPa) of Fine-Grained Concrete with the Addition of Nano-Silica

As **Figure 3** demonstrates, the results of the experimental studies reveal the effect of nano-silica content on the compressive strength of fine-grained concrete. Meanwhile, **Figure 4** illustrates the strength gain over 3, 7, and 28 days at various nano-silica contents with a water-to-cement ratio of 0.45.

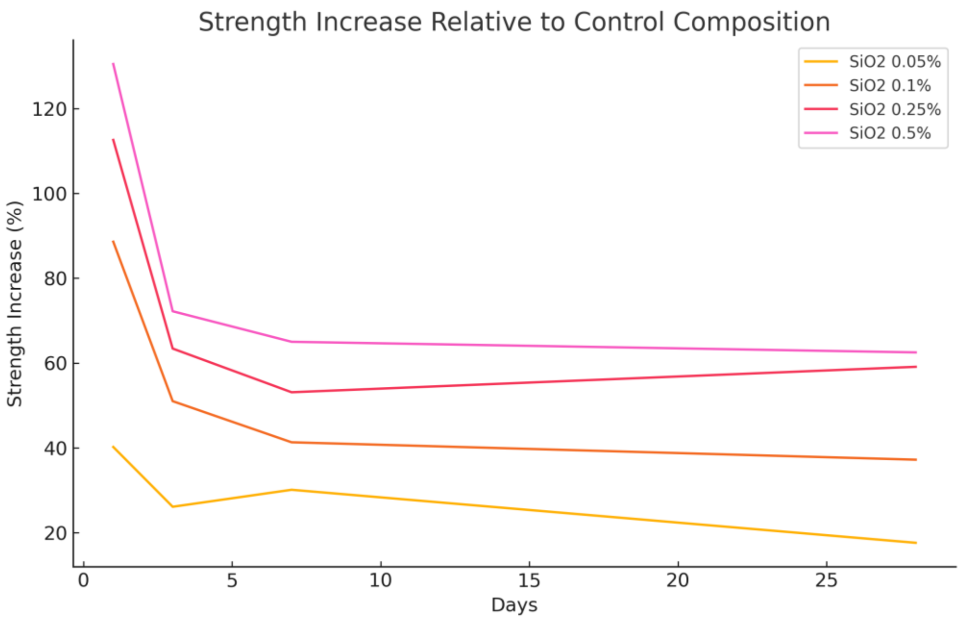

Figure 4 - Strength improvement of fine-grained concrete in comparison with the control mix.

As **Figure 5** illustrates, the rate of strength development of fine-grained concrete with the addition of nano-silicon dioxide is presented.

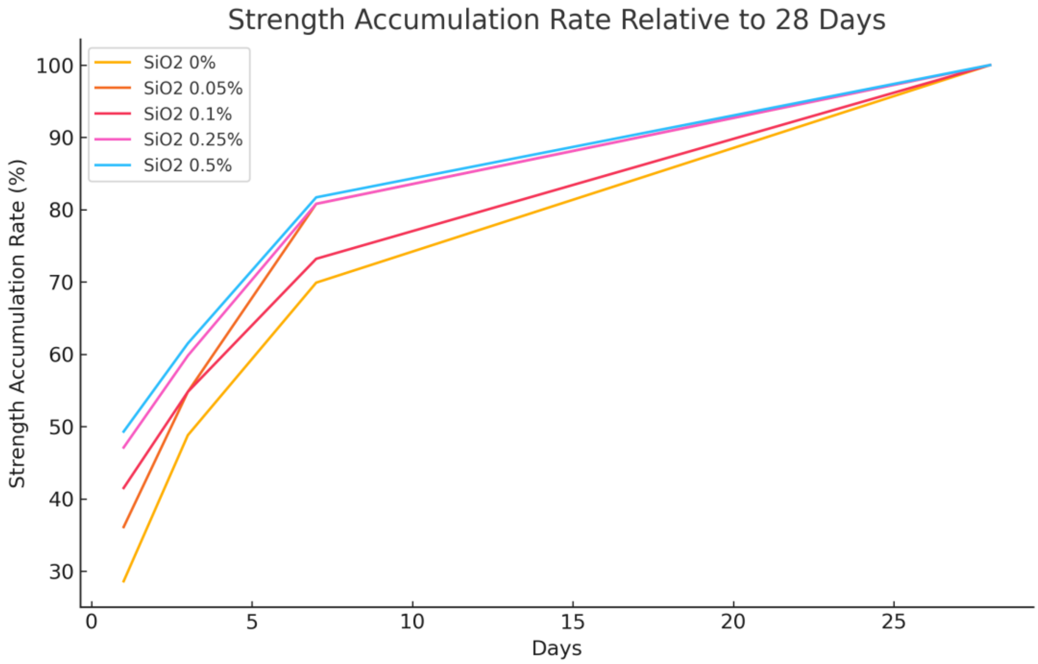

Figure 5 - The rate of strength development of fine-grained concrete (relative to 28 days).

The analysis of experimental data determined the effect of the nano-additive on the strength and rate of strength growth. When the nano-additive was introduced, the strength increased by 1.4 times on the first day, by 74.6% on the third day, by 65.7% on the seventh day, and by 42.0% on the 28th day. The maximum hardening was achieved with the addition of 0.5% nano-silica. The rate of increase in compressive strength rises with the addition of nano-silica, especially affecting the concrete during the first and third days of hardening. This suggests that the use of nano-additives can produce fast-hardening concrete.

As several scientists **(Nematollahi et al., 2017; Verian et al., 2020)** have noted, the obtained results regarding the increase in the solution's strength can be attributed to the nanostructure formed by the addition of nano-silica particles. These particles, characterized by a large specific surface area and high physicochemical activity, accelerate the hydration rate of cement. Consequently, the directed formation of calcium silicate hydrates occurs, which structures the cement matrix and enhances its strengthIn addition, the positive effect of nano-silica in cement compositions is explained by the pozzolanic reaction, as a result of which nano-silica binds free calcium hydroxide to form high-strength, low-basic calcium hydroxysilicates.

$$SiO_2 + Ca(OH)_2 + H_2O = mCaO \cdot nSiO_2 \cdot qH_2O$$

The use of nano-silica additives leads to increased strength, along with additional possible effects, such as improved sulfate resistance, frost resistance, and chloride migration resistance, etc. Thus, the analysis of the effect of nano-silica revealed that when nano-silica was added, the compressive strength increased by 1.4 times on the first day, by 74.8% on the third day, by 64.8% on the seventh day, and by 42.8% on the 28th day. The addition of nano-silica allows for the production of fast-hardening concrete with high strength.

5 CONCLUSIONS

This study demonstrates that the incorporation of nano-silica ash in fine-grained concrete significantly enhances its efficiency compared to micro-silica. By requiring 50 times less material to achieve comparable improvements in compressive and flexural strength, nano-silica presents a highly effective alternative. Additionally, its compatibility with standard technological regulations makes it a practical choice for the production of ready-mix and precast concrete. Beyond strength enhancement, nano-silica also contributes to increased sulfate resistance, improved frost durability, and greater resistance to chloride ion migration. However, to maximize its effectiveness, it is crucial to prevent particle agglomeration during production. This can be achieved by optimizing vacuum sublimation processes or refining incorporation techniques in concrete mixtures. Future research should focus on further improving the dispersion methods of nano-silica and evaluating its long-term performance in various environmental conditions.

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