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PRACTICE-ORIENTED PAPER

# The effect of nano-silica powder on mechanical and non-mechanical characteristics of self-consolidating concrete (SCC) and its impact on environment protection

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**Abstract**

Self-consolidating concrete (SCC) is a type of concrete that solves the problem of unconsolidated concrete structures that have high consolidating bar, due to its high performance. This type of concrete is condensed under the effect of its own weight, and it needs no vibration. In recent years, different admixtures have been used in order to improve the mechanical and non-mechanical characteristics of different types of concretes. With regard to nano-science advancements, nano-silica powder is one of the most effective concrete admixtures. In this study, properties of concrete, such as compressive and tensile strength, permeability, initial setting time, abrasion percent, and concrete viscosity, were investigated by replacing nano-silica powder with cement of 3, 6, 9, 11, and 13 percent weight ratios. Results showed that the optimum replacement amount of nano-silica powder instead of cement is equivalent to 11%. This study exhibited a 45% increase in the compressive strength and an 11.5% increase in tensile strength after 28 days into the concrete life. This improvement of concrete mechanical properties reduces the size of concrete parts and thus reduces cement and aggregates consumption and environmental damages.

**Keywords** Self-consolidating concrete (SCC) · Nano-silica · Compressive strength · Tensile strength · Environment

## Introduction

Concrete is widely used in constructions, and due to its low price, it is easy to use, and its adaptability with every circumstance turns it into one of the most useful building materials. Since the time that Romans used concrete until 1824, when Portland cement was created by Joseph Aspdin [1], humans have been looking for enhancing mechanical and non-mechanical concrete properties through changing or adding stone and non-stone materials. In recent years, the disadvantage of cement production and its negative environmental impacts lead to extensive research works aimed to use various admixtures in concrete to enhance the mechanical and non-mechanical properties and to decrease the usage of cement around the world [2–4]. Accordingly, self-consolidating concrete has been taken into consideration in recent years and for the past two decades. Due to its high performance, this concrete solves the problem of unconsolidated concrete in places with a high consolidating bar, such as a beam–column joint. Self-consolidating concrete condenses under the effect of its own weight without any vibration. Besides increasing the quality, using this concrete leads to a reduction in the time of pouring the concrete and noise pollution, which are very important in urban areas. Self-consolidating concrete can be used for every type of structure. There is no difference in terms of compressive and tensile strength, elastic modulus, etc., between self-consolidating concrete and other conventional concretes. Furthermore, all the parameters and formulas are the same for both self-consolidating and conventional concretes [1].

In recent years, with respect to the importance and usage of self-consolidating concrete in the construction of specific structures, various admixtures have been used in order to improve physical properties. With due attention to advancements in nano-science and technologies, the use of nano-dimensional admixtures is recommended since it can be more effective than conventional admixtures. Nanotechnology is a general term that can refer to all the advanced technologies in the field of work at a nanoscale. The entrance of nanotechnology to different industries, including concrete

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manufacturing industry, leads to enormous changes in the properties of this useful material. One of the most effective and widely used nano-admixtures for concrete is nano-silica powder. Nano-silica is a pozzolan material used in making concrete with high strength, and due to its effect on the zone between the cement paste and stone materials it has always attracted the attention of researchers [5–8].

Nano-silica consists of spherical-shaped particles, the diameters of which are less than 100 nm. It can be used in the form of dry powder particles or soluble gel. In terms of physical properties, the special surface area of nano-silica is usually 60–600 square meters per gram and its density is 30–40 g per liter [9]. Using nano-silica in concrete has many advantages including increase viscosity, compressive and tensile strength, decrease permeability, improve the quality of concrete, and decrease the environment pollution. Nano-silica is an active material due to its high-specific surface area, and it can react rapidly to calcium hydroxide crystal and produce calcium silicate hydrate gel. This gel reduces the size and amount of calcium hydroxide crystal in concrete and decreases the amount of sediments and removes calcium hydroxide from concrete. As a result of this reaction, the formation of micropores in concrete is prevented, which reduces the concrete permeability. On the other hand, calcium hydroxide fills the pores of the concrete, and it reinforces the joint between the aggregate and cement paste, and improves the mechanical properties of concrete [10, 11].

In recent years, many research papers investigated the effect of admixtures and nano-powder in concrete. Qing et al. studied the effect of nano-SiO2 addition on properties of hardened cement paste as compared with the silica fume. They realized that the compressive strengths of hardened cement paste and bond strengths of paste–aggregate interface incorporating nano-silica were obviously higher than those incorporating silica fumes, especially at early ages. By increasing the nano-silica quantity, the increase in the bond strength rate was more than that of the compressive strength [12]. The mechanical properties of concrete and the corresponding cement paste at older and early ages that affected by nano-silica powders at 0%, 1.5%, 3%, 5%, and 7.5% and silica fumes at 0%, 5%, and 7.5%, by the weight of cement investigated by Nili and Ehsani. A microstructure research was also accomplished by SEM, XRD, and EDS to detect the reasons for the obtained results. The results showed that adding 3% or 5% nano-silica to samples free of silica fume can increase the strength of both cement paste and concrete compression [13]. Jankovic et al. studied the effect of the nano-silica replacement of cement (2% or 5%) and the aggregate type (quartz, barite or its combination 50:50 by volume) on the properties of ultra-high-performance concrete (UHPC). They found that UHPC with nano-silica and a mixture of quartz and barite aggregate is a composite with a finer pore-size distribution and improved flexural and compressive strength and in-radiation protection characteristics. It can be used as building material for hospitals and nuclear facilities [14]. Hendi et al. design a high strength self-compacting concrete that blended of microsilica and nano-silica to resist the sulfuric acid medium. They used of artificial intelligence to predict and compare the behavior of these two pozzolans in a sulfuric acid medium. The results demonstrated that further substitution of the pozzolans can lead to less mass loss, as nano-silica has a marginal effect on the residual compressive strength. The results also showed that replacement of microsilica by %7 indicated the same effects as the %2 nano-silica substitution [15]. Chen et al. investigated the use of superfine zeolite (SZ) in cohesion with silica fume (SF) in the cementitious paste. A number of cementitious paste samples with different contents of SZ and SF and varying ratios of water/cementitious materials were produced for testing the compressive strengths, cohesiveness, workability, packing density, and water film thickness (WFT) at 7 days, 28 days, and 70 days. The test results indicated that in the presence of SF, the addition of SZ as cement substitution can decrease the early-age strength, decrease the flow ability, increase the packing density, increase the cohesiveness, decrease the WFT, and increase the long-term strength. Furthermore, the cementing efficiency of the SZ for the 70-day strength was higher when added in conjunction with SF compared to once added alone, determining certain synergistic impact of the blended addition of SZ and SF on the long-term strength [16]. The effect of carbon nanotube (CNT), nano-silica (NS) and fly ash (FA) as solo, binary, or ternary mixtures on fresh and hardened properties of self-consolidating concretes (SCC) was studied by Aydın et al. The results indicated that NS decreased the fresh concrete properties due to its higher water demand, but in the presence of FA, NS improved these properties significantly and removed segregation and bleeding effects of the 40% FA. In addition, the CNT replacement in concrete provided a 20% increase in the toughness index of SCC. The results showed that the combination with the 2% NS, 0.02% CNT, and 40% FA could be considered as the best SCC mix due to the discussed properties [17]. Mehmet et al. studied the simultaneous impact of nano-silica and steel fiber on the fresh and hardened state performance of self-consolidating geopolymer concretes (SCGC). So self-consolidating geopolymer concretes with and without nano-silica (0, 1%, and 2%), and with and without steel fiber (0, 0.5%, and 1%) were produced. In addition, the impact of nano-silica was indicated to be dominant on the fresh state characteristics and the compressive strength, as the impact of steel fiber was indicated to be superior on flexural performance and bonding strength [18]. The effect of the nano-powder on concrete was studied by several researchers, Heidari and Tavakoli, Senhadji et al., Liu and Wang, Bashar et al., Ruan et al., Wang et al., Sun and Chen, Han and Zhang, Li et al., Hamed et al., Norhasri et al., and Tobbala [19–30].

In this study, the effect of adding different nano-silica weight percentages relative to the cement weight on compressive and tensile strength, initial setting time of cement, permeability, abrasion percent, and concrete viscosity was investigated. Moreover, the optimum percentage of using nano-silica powder in self-consolidating concrete will be determined.

## Materials and methods

The purpose of this research was to produce self-consolidating concrete by using the nano-silica admixture in order to investigate mechanical and non-mechanical properties of concrete. To achieve this purpose, different types of concretes with fixed aggregate gradation have been made. Nano-silica is the only variable added to the used materials. In this research, concrete laboratory mixing design is based on the ACI-211 standard [31] with the strength category of C30. It means that concrete will be produced with a compressive strength (fc) equal to 30 MPa. By replacing different amounts of nano-silica from 3 to 13% of the cement weight, compressive and tensile strength, curing time, permeability, abrasion percent, and viscosity of ready-made samples and controlled samples (the sample without nano-silica) in a completely similar situation will be measured. Then, by comparing the results of nano-silica samples and controlled samples, the effect of the added nano-silica percent to concrete on the increase and decrease in the examined characteristics and the optimum percentage of this additive material was investigated. One of the most important parameters that should be considered in concrete production is the type and percentage of the aggregates used in the concrete mixing design. To achieve this, aggregate gradations were determined based on ASTM-C33 and ACI-304-2R standards [32, 33]. The specific weight of aggregates and water absorption of coarse grains will be determined based on the ASTM-C127-15 standard [34]. Additionally, the sand equivalent of the sand used will be determined based on the ASTM D2419-14 standard [35]. The size of the aggregates used in this research is 19 mm for gravel, 12.5 mm for sand, 2.6% for the water absorption of sand, and 0.5% for water the absorption of gravel. The relative density of aggregates and the sand equivalent of materials were 2.61 and 87%, respectively. Moreover, the cement content and the water-cement ratio were equal to 350 kg/m3 (W/C) and 0.4, respectively. Figure 1 shows the aggregate gradation curve, which is used to produce self-consolidating concrete.

Also, the physical and chemical properties of cement and nano-silica used in this research were given in Tables 1, 2 and 3.

One of the most important factors that should be considered when producing concrete with nano-silica is the way of adding nano-silica to aggregates. If nano-silica does not distribute homogenously to all of the mixture of aggregates, results are not valid and reliable. In this research, in order to produce concrete samples, outside and inside of the mixer should be moist in order to control the water of

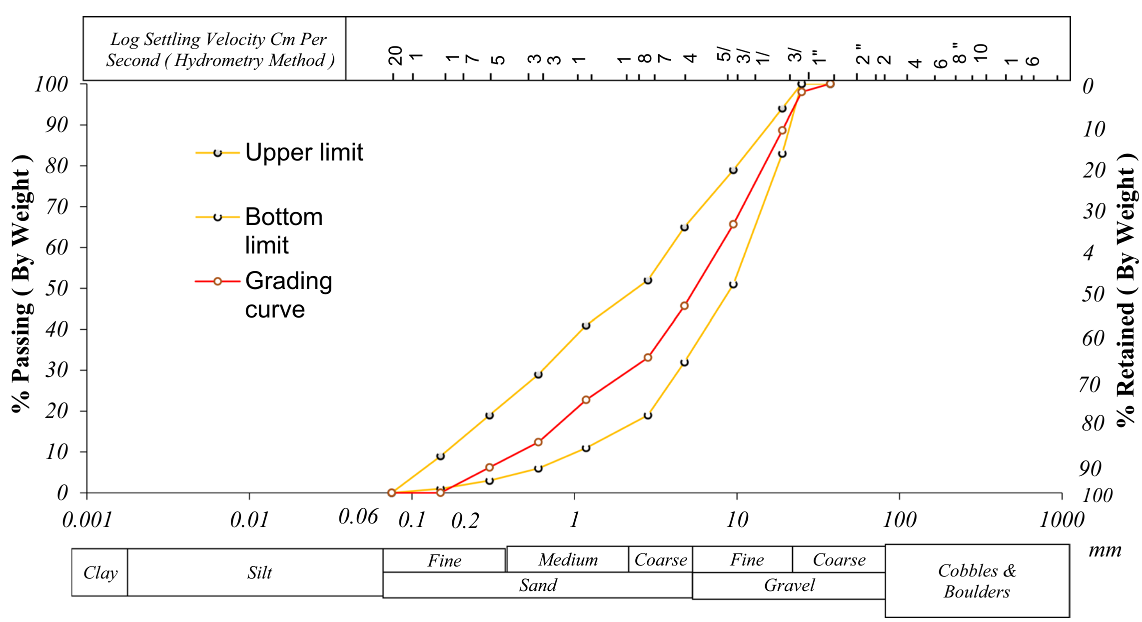



**Fig. 1** Aggregates gradation curve of self-consolidating concrete

**Table 1** Physical properties of silicon dioxide SiO2 nano-powder

| | |
|---|---|
| Nanoparticles $SiO_2$ purity | 99.5% |
| Nanoparticles $SiO_2$ APS | 20–30 nm |
| Nanoparticles $SiO_2$ SSA | 180–600m2/g (particles size: 100% < 40 nm) |
| Nanoparticles $SiO_2$ color | White |
| Nanoparticles $SiO_2$ bulk density | < 0.10 g/cm3 |
| Nanoparticles $SiO_2$ true density | 2.4 g/cm3 |
| Nanoparticles $SiO_2$ making method | High-temperature combustion method |

**Table 2** Chemical composition of nano-silica

| Fe | Na | Ca | Ti | $SiO_2$ |
|---|---|---|---|---|
| 20 ppm | 30 ppm | 70 ppm | 120 ppm | 99.5% |

mixing design. Then the saturated aggregates, which were weighed with 0.1-g accuracy, were poured into the mixer carefully from larger to smaller sizes, respectively. Finally, the cement is poured into the mixer. It should be considered that when the aggregate materials are being poured into the mixer, mixing the materials should be done simultaneously. Subsequently, after the reduction of the saturated water absorption of aggregates and surface moisture of mixer walls, 60% of the water from the mixing design is added to the mixer and mixing process done for 60 s. Next, the nano-silica gel is added to mixer. This gel is made by compounding nano-silica powder with 20% of water from the mixing design and mixed using a magnetic stirrer for 3 min (Fig. 2). Since nano-silica is water reducing, it should be used by a super plasticizer, otherwise concrete will get cracked, its performance will reduce, and it will not be consolidated. In this research, the type of used super plasticizer is super viscose1, its weight is 1.08 kg/liter, and the used dose is 0.5% of cement weight according to the PREN 934–2 standard [36]. The super plasticizer used in this research is mixed in the 20% remaining water of mixing design and added to concrete. This will mix for 2 min in the mixer.

After mixing materials together, concrete is poured into 15×15×15 cm cube molds and 30×15 cm (height×diameter) cylindrical molds, which were ready and lubricated before. According to the ASTM C31 standard [37], prepared concrete samples are kept in the temperatures around 20 to 30 °C and 50–55 percent relative humidity. After 24±8 h, samples are transferred to laboratory and after taking them out from molds, they are kept in standard curing tanks at 23±1/7 °C, which had been saturated with lime. They were kept until the day of the experiment. The compressive strength experiment will be done according to the ASTM C39/ C39M standard [38] at the age of 7, 14, and 28 days (Fig. 3).

The tensile strength test and other experiments will be done at the age of 28 days. Tensile strength cab be determined by an indirect method (Brazilian test). In this method, 30*15 cm (height*diameter) cylinder samples are cut into two parts, according to the ASTM C293/ C293M-16 standard [39]. Permeability test will be done based on the DIN1048 standard [40]. The concrete's abrasion percentage will be determined by the sand blasting method, according to the ASTM C418 standard [41], and the initial setting time of

**Table 3** Chemical composition of ordinary Portland cement type II

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O$ | $K_2O$ | L.O.I(loss on ignition) | Surface area (m2/g) |
|---|---|---|---|---|---|---|---|---|---|
| 21.11 | 4.48 | 3.91 | 63.36 | 1.48 | 2.58 | 0.43 | 0.48 | 2.25 | 0.315 |

**Fig. 2** Nano-silica powder and gel

cement will be determined according to the ASTM C191-82 standard [42].

## Results and discussion

Based on the performed experiments on concrete that had various percentages of nano-silica, results show that adding nano-silica to concrete will lead to significant impacts on the concrete, including compressive and tensile strength, initial setting time of cement, permeability, viscosity, and abrasion. According to Fig. 4, increasing the age of concrete, will lead to an increase in the compressive strength, and the process of increasing and decreasing concrete strength is identical at 7, 14, and 28 days, based on the amount of added nano-silica. Based on the compressive strength of the controlled sample (the concrete without nano-silica) at the age of 28 days, due to the concrete mixing design that was produced based on the 30 MPa compressive strength, a 40% increase in the compressive strength has been observed. This is due to adding super plasticizer to the water used in mixing design. Additionally, at different ages, by increasing the amount of nano-silica to 11%, the compressive strength of concrete increased, as well. Consequently, by increasing the amount of nano-silica in concrete, the compressive strength will decrease. With due attention to filling concrete pores with nano-silica particles and its chemical reaction with cement, the compressive strength will increase. By increasing the percentage of nano-silica to more than 11%, the amount of cement decreases as an adhesive material. This will lead to the decline of the compressive strength of concrete. If 11% nano-silica is added, the compressive strength of concrete increases 103% and 45%, respectively, in relation to the design strength and the controlled sample compressive strength at the age of 28 days, which is a noteworthy result.

The trend of changing tensile strength (Fig. 5) is similar to the compressive strength. This similarity is due to its fixed ratio between the compressive and tensile strength of concrete. Tensile strength ratio compared to compressive strength in concrete is almost 6 to 12 percent [43]. In this research, tensile strength ratio to compressive strength is %10, on average. By adding 11% nano-silica to the

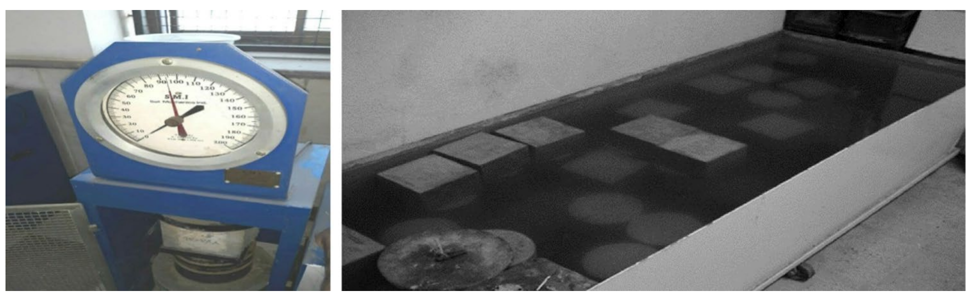


**Fig. 3** Concrete curing tank and concrete compression testing machine

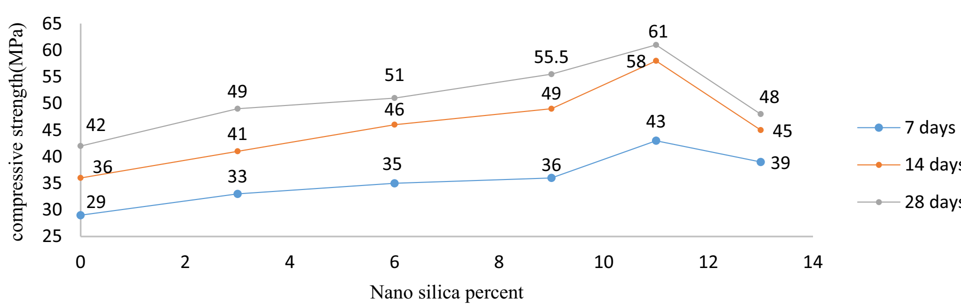



**Fig. 4** Concrete compressive strength with different percentage of nano-silica at the age of 7, 14, and 28 days

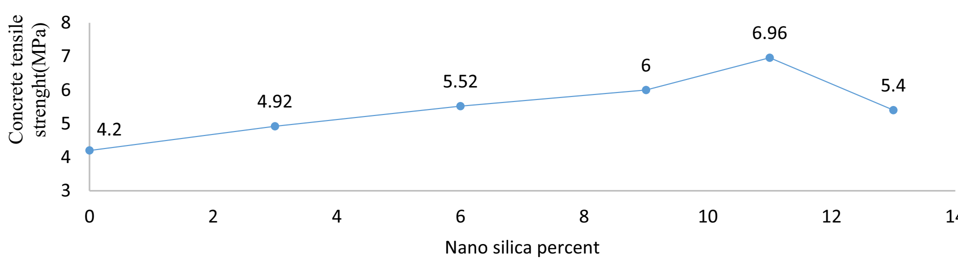



**Fig. 5** Tensile strength of self-consolidating concrete with different amount of nano-silica in the age of 28 days

self-consolidating concrete, the tensile strength ratio to compressive strength will increase by 11.4% and by adding 13%, this ratio decrease to 11.25%. So, if the amount of nano-silica in the concrete increases, the tensile strength ratio to compressive strength will decrease slightly. Therefore, with an increase in more than 11% of nano-silica in concrete, the percentage of reduction in tensile strength will be greater than the percentage of reduction in compressive strength. By adding 11% nano-silica to concrete, maximum tensile strength was obtained that it was increased 66% in comparison to the controlled sample.

According to Fig. 6, adding nano-silica to concrete leads to an increase in concrete viscosity and decrease in concrete performance. The trend of increasing viscosity is completely ascending due to the increasing percentage of nano-silica. This is due to the mixture of water with nano-silica particles and water reducing the property of nano-silica. The unit of measurement for viscosity is centipoise, and it can be measured by the rotational viscometer testing machine.

Permeability is one of the concrete properties that are affected by nano-silica. Permeability shows the porousness in concrete. According to Fig. 7, increasing the percentage of nano-silica in concrete will lead to the decrease in concrete permeability. Moreover, it will lead to an increase in the concrete lifetime and durability and improve its strength against rapid freezing and melting. The reason for the descending trend of concrete permeability with the increasing nano-silica percentage is filling small pores that are full of air with nano-silica particles. Considering the limitation of porousness, due to filling parts of the pores, concrete permeability will decrease slowly by increasing the percentage of nano-silica to more than 11%.

According to Fig. 8, by increasing the percentage of the nano-silica-to-cement ratio from zero to 11%, this will lead to a decrease in the initial setting time of cement from 90 to 40 min. This is due to the nano-silica high reactivity in combination with cement. In this case, the speed of chemical reactions of cement and its initial setting time increase. Based on the conducted experiments, by increasing the amount of nano-silica to 13%, the initial setting time of cement is fixed compared to samples with 11%. Therefore, the optimum percentage of nano-silica is equal to 11% of

**Fig. 6** The effect of nano-silica on mortar viscosity of self-consolidating concrete with different amount of nano-silica

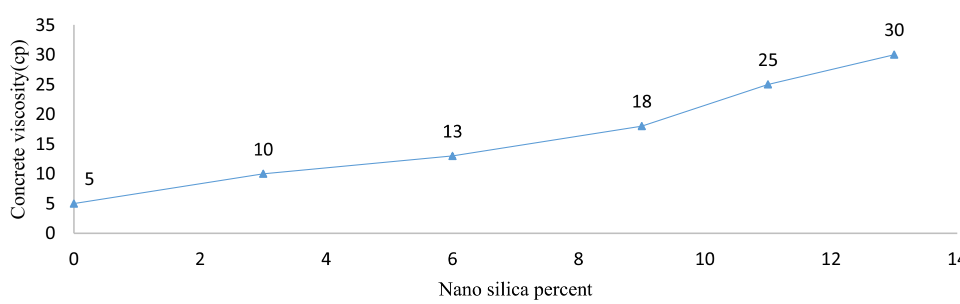



**Fig. 7** the effect of nano-silica on decreasing permeability of self-consolidating concrete with different percentages of nano-silica

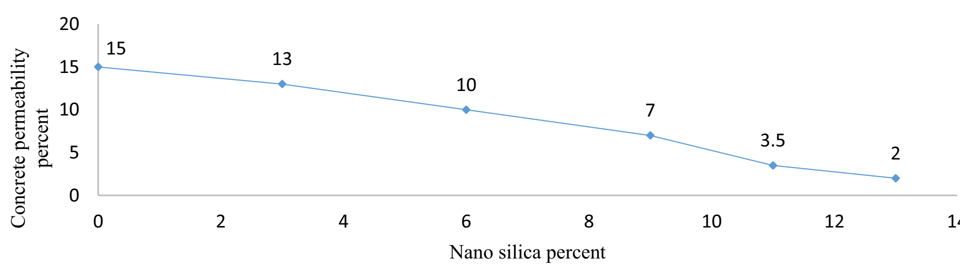
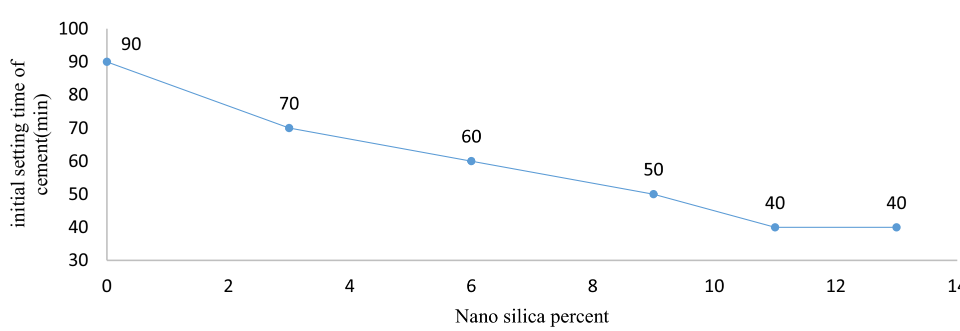



**Fig. 8** The effect of nano-silica on initial setting time of cement with different percentages of nano-silica



the cement weight, in order to reduce the initial setting time of cement.

Increasing the nano-silica percentage leads to an increase in the compressive strength and decrease in the concrete porosity. This leads to a decrease in concrete abrasion, which is affected by concrete mechanical characteristics. According to Fig. 9, by increasing the nano-silica percentage from 11 to 13%, in spite of the decrease in the compressive strength, concrete abrasion percent decrease, as well. This is due to the decrease in concrete porosity.

In general, the process of changes in mechanical properties of concrete obtained from this research was similar to the results obtained from other papers. According to Sattawat's studies, the optimal percentage of nano-silica added to concrete was equal to 9%, and with the increase in nano-silica to concrete, more than 9%, the compressive strength of concrete was decreased, which was similar to the results of this research [44].

In the Table. 4, the trend of percentage changes in compressive strength of the current research and Sattawat was compared.

Also, the process of changes in the viscosity of mortar had a direct relationship with the increase in the amount of nano-silica added to concrete but, the initial setting time had an inverse relationship with the increase in the amount of nano-silica added to concrete, which results were similar to the results of other researchers' research [45].

**Table 4** Validation of changes in concrete compressive strength

| Nano-silica percentage | Percentage changes in concrete strength compared to the control sample | |
|---|---|---|
| | Experimented | Sattawat study |
| 3 | 116.6667 | 125.2551 |
| 6 | 121.4286 | 133.2908 |
| 9 | 132.1429 | 152.9337 |
| 11 | 145.2381 | – |
| 12 | – | 133.1633 |
| 13 | 114.2857 | – |

## Conclusion

In this research, mechanical properties of self-consolidating concrete with nano-silica were investigated. Based on the conducted experiments, the following results can be presented:

- The concrete used in this research belongs to the strength category of C30. Due to using super plasticizer in mixing design, the compressive strength of the 28-day samples without nano-silica increased to 42 MPa, which it was increased by 40% in strength.
- When the nano-silica increased up to 11%, the compressive strength of concrete was ascended, and after that due to decreasing the amount of cement as an adhesive material in concrete, the compressive strength was decreased. In this research, the maximum increase in the concrete compressive strength-to-controlled sample ratio was 45%, and its ratio to design strength was 103%.
- The changing trend of tensile strength is completely similar to compressive strength changes. Maximum increasing percentage of tensile strength compared to the controlled sample was %66. This amount has been seen when nano-silica increased by 11%. In the case that 11% nano-silica was added to concrete, tensile strength-to-compressive strength ratio was %11.5.
- By adding nano-silica to concrete, concrete viscosity increased, and its performance deteriorates. As a result of increasing the percentage of nano-silica, the trend of increasing the viscosity was completely ascending. This was due to the mixing water used in concrete manufacturing with nano-silica particles and nano-silica's water reducing property.
- When the percentage of nano-silica added to concrete increased, both small concrete pores and pores that were full of air are filled with nano-silica particles. Therefore, concrete permeability decreased, and this leaded to an increase in concrete's lifetime and durability and improves its strength against rapid freezing and melting.

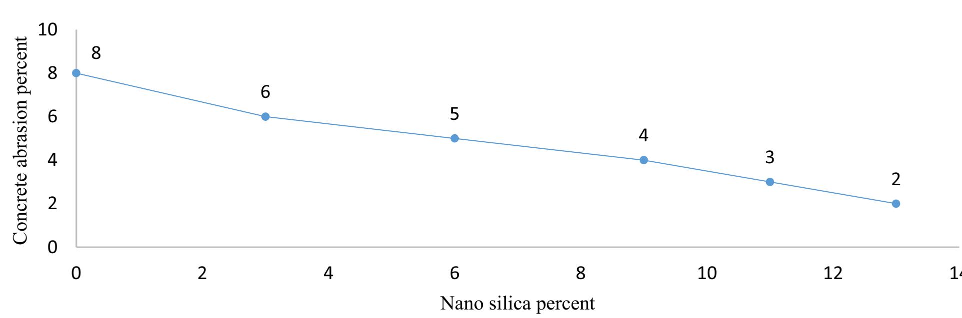



**Fig. 9** The effect of nano-silica on the abrasion of self-consolidating concrete with different percentages of nano-silica

- By increasing the nano-silica percentage in cement from zero to 11%, the initial setting time of cement decreased from 90 to 40 min. Based on the conducted experiments, when the nano-silica percentage increased to 13%, the initial setting time of cement is fixed compared to samples with 11%.
- By increasing the percentage of the existing nano-silica, the compressive strength increased and permeability decreased. This leaded to a decrease in the abrasion percentage of concrete, which was affected by mechanical characteristics of concrete. Furthermore, in case nano-silica increased from 11 to 13%, not only compressive strength decreased, but also abrasion percent decreased. This was due to the concrete porosity decline.
- Using nano-silica instead of silica reduced size of concrete samples that it reduced cement and aggregates consumption and damage to the environment.

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## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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

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

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