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Development and Evaluation of Nano-Silica Sustainable Concrete

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Abstract: In the last decade, nanomaterials made a major breakthrough in the concrete industry by providing the concrete with unique properties. Earlier studies have shown improvement in the early strength of concrete that can accelerate the construction process. In this study, 1% and 2% of nano-silica were added to concrete mixtures that contain 30% and 70% ground granulated blast-furnace slag (GGBS). Adding 1% of nano-silica to the 30% GGBS mixture showed an increase in the compressive strength by 13.5%, 7.8%, 8.1%, and 2.2% at one day, three days, seven days, and twenty-eight days, respectively. The 2% of nano-silica increased the 30% GGBS mixture's compressive strength less effectively by 4.3%, 7.6%, and 4.9% at three days, seven days, and 28 days, respectively, when compared to the 1%. On the other hand, adding 1% and 2% of nano-silica reduced the 70% GGBS mixtures' compressive strength. Moreover, nano-silica reduced the deformability of the mixtures significantly, which caused the increase in the Young's modulus. The flexural strength of the 30% GGBS mixtures had similar behavior as the 28-day compressive strength. On the other hand, the flexural strength of the 70% GGBS mixtures increased as the nano-silica increased. Nano-silica addition improved the microstructure and the interface structure of the mixtures due to its high pozzolanic activity and the nano-filler effect, which is confirmed by RCPT results and SEM images.

Keywords: nano-silica; GGBS; nano-filler effect; pozzolanic activity; nucleation site; agglomeration effect

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1. Introduction

The concrete industry is one of the largest contributors of carbon dioxide [1]. The use of cement in concrete has raised concerns about its sustainability due to the fact that the production of one ton of OPC releases approximately one ton of carbon dioxide to the atmosphere [1]. In the past few decades, scientists and engineers have been able to partially replace the cement with supplementary cementitious materials, to reduce the extensive emission of CO_2 associated with the production of Portland cement and create more sustainable concrete. These materials are byproducts of other industries, such as fly ash, ground granulated blast furnace slag, silica fume, and other natural pozzolans. Not only have these supplementary cementitious materials have contributed in reducing the emission of CO_2, but they also provided the concrete with high-performance abilities in terms of strength and durability. The applications of nano-technology have been gaining popularity in different fields of science and technology, especially in concrete industries [2]. The development of new materials with new functions or improvements in the properties of existing materials using nano-technology are new areas of interest in civil engineering. Nanoparticles (NPs) exhibit unique chemical and physical properties at the nano-scale. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, ZnO_2, and carbon nanotubes are considered the most commonly used NPs in concrete production. The role of the NPs can be summarized as follows: (1) NPs not only act as fillers to improve the microstructure, but also as an activator to promote pozzolanic reactions; (2) NPs act as a nucleation site for C-S-H seeds, which then accelerate the cement hydration; (3) NPs (nano-silica [NS]) accelerate the consumption of C3S and the formation of portlandite (small-sized CH) crystals and homogeneous clusters of CSH composition; and (4) NPs improve the microstructure of the interfacial transition zone between aggregates and cement pastes [3].

S. Abd.El.Aleem et al. [3] carried out an experiment studying the hydration characteristic, thermal expansion, and microstructure of cement containing nano-silica. Seven different mixtures were used in this experiment that incorporated nano-silica at different dosages up to 6% partial replacement of OPC. The presence of nano-silica had remarkably increased the water demand, which, in consequence, retarded the setting time. This seemed to be controlled by the particle size distribution and the high specific surface area of NS in the presence of polycarboxylate superplasticizer [3]. Furthermore, the values of pH and free portlandite decreased as the dosage of nano-silica increased. Due to the pozzolanic reaction of nano-silica, the chemically combined water contents increased with increasing nano-silica percentage dosage. The microstructure, and consequently the mechanical properties, of the investigated cement mortars are improved sharply with NS up to 3.0% and then slightly up to 5% [3]. Additionally, using nano-silica as a partial replacement of Portland cement lowered the coefficient of thermal expansion of the hardened cement paste. Moreover, due to the continuous hydration of cement phases and the pozzolanic reaction of nano-silica, the thermal expansion of hydrated cement pastes incorporating 3% nano-silica dosage increased with curing time. The nano-sized SiO_2 up to 5% proved to be an effective mineral addition for blending with OPC to improve its chemical, physico-mechanical, and thermal properties [3]. Finally, incorporating nano-silica increased the compressive strength because of the nano-filler effect, which improved the microstructure and promoted the highly pozzolanic reaction.

Hongjian Du et al. [4] studied the durability properties of OPC concrete that contains nano-silica at dosages of 0.3% and 0.9%. Three different mix designs were prepared to be tested in this experiment, which are OPC concrete, 0.3 nano-silica concrete, and 0.9 nano-silica concrete. The compressive strength of each mix design was determined at 7, 28, and 91 days by preparing three (100 × 200 mm) cylinders for each day, while the water penetration depth was obtained by testing two (100 × 200 mm) cylinders at a water pressure of 0.75 MPa for seven days. On the other hand, water sorptivity was determined by using (100 × 500 mm) cylindrical slices. Along with the other tests used in this experiment, the researchers were able to come up with multiple conclusions. First, nano-silica showed a clear pozzolanic reaction with the Portland cement. This reaction, along with the nanofiller effect of nano-silica, made the microstructure of the concrete more homogeneous and less porous. Consequently, the permeability was reduced, which increased the compressive strength and the resistance of the concrete against water penetration and chemical attacks such as chloride ions.

Jing Yu et al. [5] investigated the use of nano-silica to improve mechanical and fractural properties of a fiber-reinforced high-volume fly as cement mortar. The materials used in this study were nano-silica, OPC type I 42.5 N, fly ash class F, PVA fibers, and river sand. Four series (16 mixes) of experiments were carried out to evaluate the effect of nano-silica (NS) on the fractural and mechanical properties of polyvinyl alcohol fiber-reinforced high-volume fly ash mortars (PVA/HVFAM), with the fly ash/binder ratio fixed at 50 wt%, NS/binder ratios of 0–1.5 wt%, and PVA fiber dosages of 0–1.0 vol% [5]. After conducting the tests, multiple conclusions were drawn. First, the incorporation of 0.5–1.5 wt% nano-silica improved the compressive strength, tensile strength, elastic modulus, fracture energy, fracture toughness, brittleness index, and critical tip opening displacement compared to plain high-volume fly ash mortars (HVFAM). Second, compared to plain HVFAM, the incorporation of 0.2–1.0 vol% PVA fibers had no pronounced effect on the elastic modulus and compressive strength. However, it improved the tensile strength, fracture energy, fracture toughness, brittleness index, and critical tip opening displacement. Third, the synergetic effect of NS and PVA was observed, in terms of the post-peak behavior under static bending as well as the fracture parameters [5]. Finally, the microstructure analysis, which was performed using the scanning electron microscopy, showed that additional C-S-H was formed and covered the surface of the PVA fibers due to the accelerated hydration process that occurred due to the high reactivity of NS. This improved the bond between the PVA fibers and the cement-based matrix and resulted in an efficient load-transfer by fiber bridging [5].

D. Adak et al. [6] conducted a study about the effect of nano-silica on the strength and durability of fly ash-based geopolymer mortar. Fly ash-based geopolymer mortar has a shortcoming, which is the need for heat activator to develop early strength. To overcome this, the researchers developed an experiment of using low calcium fly ash geopolymer with different molar concentrations of activator liquid and different nano-silica percentage dosages. The addition of 6% of nano-silica to the fly ash-based geopolymer mortar showed an obvious increase in compressive, flexural, and tensile strength at 28 days under ambient temperature curing. Furthermore, the same percentage of nano-silica reduced water absorption. The modification that took place in the geopolymer with 6% of nano-silica is due to the transformation of the amorphous compound to the crystalline compound.

A.M. Said et al. [7] investigated the properties of concrete incorporating nano-silica. Two types of concrete were investigated in this experiment, which are concrete with ordinary cement and concrete with ordinary cement plus class F fly ash. To link macro and micro-scale trends and study the effect of using nano-silica, the research included tests of adiabatic temperature, rapid chloride ion permeability, mercury intrusion porosimetry, thermogravimetry, and backscattered scanning electron microscopy. Based on the test results, multiple conclusions were reached. Both types of concrete used in this experiment showed a remarkable improvement in performance due to the addition of nano-silica. The nano-silica was responsible for accelerating the kinetics of hydration reactions. The addition of nano-silica showed a modification to the inherently slower rate of gaining strength of concrete that contains class F fly ash. The physical penetration depth was decreased, which consequently decreased the conductivity. The specimens showed a significant reduction in porosity and threshold pore diameter.

Morteza Bastami et al. [8] studied the performance of nano-silica modified high strength concrete at elevated temperatures. The main focus of this experiment was on the effect of elevated temperature on the compressive strength, tensile strength, spalling, and mass loss of high strength concrete modified with nano-silica. Six samples with different percentage dosages of nano-silica were considered in this experiment along with two samples without nano-silica. The performance of the nano-silica modified high strength concrete was measured by using (150 × 100 mm) cylinders that were heated to 400, 600, and 800 °C at a rate of 20 °C/min. In general, the results of this experiment demonstrated that the mass loss is decreased as the dosage of nano-silica is increased, and that is due to the improvement in tensile strength, which helped in preventing spalling. Moreover, the nano-silica also increased the residual compressive strength of the heated specimens.

Kiachehr Behfarnia et al. [9] investigated the effect of nano-silica and nano-alumina on frost resistance and the mechanical properties of normal concrete. Seven different mixtures were used in this experiment. NSC3, NSC5, and NSC7 denoted the concrete containing 3 wt%, 5 wt%, and 7 wt% nano-silica, by the weight of cement, respectively [9]. NAC1, NAC2, and NAC3 denoted the concrete containing 1 wt%, 2 wt%, and 3 wt% nano-alumina, by the weight of cement, respectively [9]. The specimens were subjected to numerous tests. The compressive strength was determined at seven, 28, and 120 days. The percentage of water absorption was obtained after 28 days of moisture-curing. Furthermore, the seven mixtures were subjected to cycles of freezing and thawing. The loss of mass, change in length, increase in water absorption, and reduction in compressive strength of specimens was measured after a specified number of freeze and thaw cycles [9]. The experiment results demonstrated that the addition of nanoparticles increased the compressive strength whether they were nano-silica or nano-alumina. However, the nano-silica addition showed a remarkable increase in the compressive strength compared to the addition of nano-alumina. For example, at 28 days, the NSC5 mixture showed an increase of 31.13% in the compressive strength, while the NAC3 mixture showed an increase of 8.00% in the compressive strength. Moreover, the mixtures that incorporated nanoparticles showed a remarkable decrease in the water absorption compared to the control specimen due to the nano-filler effect, which improved the pore structure of the concrete. The experimental results also showed that the addition of nanoparticles improved the frost resistance considerably. However, the frost resistance of concrete that incorporates nano-alumina was better than the concrete that incorporates the same amount of nano-silica.

Chenglong Zhuang and Yu Chen [10] studied the effect of nano-silica on the properties of concrete. The partial replacement of Portland cement with nano-silica accelerated the hydration process and reduced the setting time due to the high pozzolanic activity of nano-silica. Nano-silica has a large specific surface due to its small particle size. In the process of concrete mixing, a large number of unsaturated bonds promoted the nano-SiO_2 to absorb more water molecules, which led to a decrease of a concrete slump [10]. Chemically, due to the pozzolanic activity of nano-silica, more C-S-H was produced in the concrete mixing process, which reduced the number of pores. Physically, due to the nano-filler effect of nano-silica, the microstructure of nano-silica-based concrete was more compact and less porous. In the early stage, the early strength improvement effect of nano-silica concrete was more obvious due to the more sufficient pozzolanic reaction [10]. As the curing time increased, the particle size decreased, which weakened the pozzolan response of nano-silica. Therefore, the improvement effect of nano-silica on concrete strength in the later period was reduced [10].

M. Berra et al. [11] conducted a study about the effects of nano-silica addition on the workability of Portland cement pastes. The nano-silica slurry used in this experiment consisted of 10.2 PH, 30 silica content (wt%), 0.56 titrable alkalis (wt% as Na2O), 1.22 Density (g/cm^3), 5.5 viscosity (mPa s), 10 mean particle size (nm), and 345 specific surface area (m^2/g). The workability of fourteen mixtures with different water/binder ratio and nano-silica concentrations in the liquid phase were evaluated using mini-slump tests. The addition of nano-silica to cementitious mixes produced a remarkable reduction of the mix workability, due to instantaneous interactions between the nano-silica sol and the liquid phase of the cementitious mixes (mainly dissolved alkalis), with the formation of gels characterized by high water retention capacities [11]. The delayed addition of mixing water aliquots proved to be an effective way of reducing the adverse effect of nano-silica on mix workability, without changing the water/binder ratio and/or adding superplasticizer [11]. However, the delayed water addition did not improve the workability of the Portland cement mixes. Moreover, due to the reduction of the nano-silica reactivity caused by the instantaneous interaction between superplasticizer and nano-silica, the immediate superplasticizer addition was considered to be useless in improving the workability of the mixtures. On the contrary, delayed addition of the superplasticizer, coupled with the use of an appropriate mixer for the break-down of the gels formed from nano-silica sol destabilization, proved to be the best procedure to uniformly disperse the mix ingredients, without significantly penalizing the nano-silica reactivity [11].

L.P. Singh et al. [12] investigated the beneficial role of nano-silica in cement-based materials. The nano-silica in the concrete acted as a nucleation site to accelerate the hydration of cement and also filled the pores to give higher packing density, which led to higher strength with lesser porosity [12]. The development of nano-silica based high-performance concrete will help in decreasing the consumption of cement for specific grades, which will help in protecting the environment to a great extent. Furthermore, due to the high compressive strength, the nano-silica based high-performance concrete will produce smaller structural members, which will reduce the total amount of materials placed and consequently reduce the overall cost of the structure. Moreover, the high early strength development of nano-silica based high-performance concrete will accelerate the construction process, which will save time, money, and materials. Finally, the long service life of the nano-silica based high-performance concrete will reduce the maintenance costs to a great extent.

Sattawat Haruehansapong et al. [13] studied the effect of the particle size of nano-silica on the compressive strength and the optimum replacement content of cement mortar containing nano-silica. Three different particle sizes of nano-silica (12, 20, and 40 nm) were used in this experiment. Two groups of mixtures were tested, in which the first group incorporated different dosages of silica-fume, and it consisted of four mixtures, and the second group incorporated different dosages of nano-silica, and it consisted of four mixtures. Compared to the silica-fume mixtures, the compressive strength of the nano-silica mixtures was greater due to the pozzolanic activity and the packing ability. The mixture that incorporated 40 nm nano-silica showed the highest compressive strength compared to the mixtures with 12 and 20 nm nano-silica. One possible reason is poor dispersion and agglomeration of small particles of 12 and 20 nm-SiO_2 [13]. The optimum replacement content of cement mortars with NS particle size of 12, 20, and 40 nm, as well as cement mortar with SF, was obtained with NS 9% by weight of cement, independent of NS particle size [13]. SEM photographs showed that the microstructure of the cement pastes was improved by the incorporation of nano-silica making the paste more compact, homogeneous, and denser.

Bibhuti Bhusan Mukharjee et al. [14] investigated the influence of nano-silica on the properties of recycled aggregate concrete. The properties of colloidal nano-silica used in this study are 1.12 specific gravity, 39% solid content, 8–20 nm particle size, 99.1% SiO_2 content, and 10.11 pH value. Eight different mixtures were cast, in which four of them contained natural coarse aggregate (NCA) and the other four contained recycled coarse aggregate (RCA). Multiple conclusions were obtained. As the percentage of nano-silica increased, the slump values decreased due to the high surface area of colloidal nano-silica, which causes absorption of mixing water by the nanoparticles. Furthermore, replacement of natural coarse aggregates with recycled coarse aggregates reduced the workability of the concrete mixture due to the high water absorption capacity of RCA, and a further decrease in workability was observed due to the addition of NS to RAC mixes [14]. Moreover, the addition of nano-silica enhanced the compressive strength results in early days because of the nano-silica's high pozzolanic activity at initial periods. A decrease of 14% of compressive strength was observed when replacement of NCA was done with 100% RCA [14]. However, the addition of NS enhanced the compressive strength of RAC, and with the incorporation of 3% NS, the 28 days compressive strength equalized with control concrete [14]. Compared to the natural coarse aggregate mixes, the recycled coarse aggregate mixes had weaker tensile strength. However, the decrease in tensile strength caused by using recycled coarse aggregate can be compensated by incorporating nano-silica.

Ehsan Ghafari et al. [15] studied the influence of a nano-silica addition on the durability of ultra-high performance concrete (UHPC). The properties of nano-silica (NS) used in this experiment are (160 ± 20 m^2/g) specific surface area, (<99.9%) purity, amorphous crystal phase, (15 ± 5 nm) diameter, (<0.15 g/cm^3) density, and spherical morphology. Three different sets of mixtures were considered for this test, consisting of UHPC containing NS, UHPC without NS, and high-performance concrete (HPC) [15]. Based on the obtained results, multiple conclusions were drawn. First, UHPC-NS presented the best corrosion resistance performance, as the time to crack effectively increased with the NS addition [15]. Second, incorporating nano-silica contributed to extending the service life of concrete structures by delaying corrosion in steel rebars. Corrosion rate measurements, based on LPR and Tafel techniques, pointed out that the UHPC specimens containing NS addition had the lowest corrosion rate when compared with HPC and UHPC specimens [15].

G. Quercia et al. [16] conducted a study about the self-consolidating concrete (SCC) modification by the use of amorphous nano-silica. Three different SCC mixes were studied in the experiment, in which the first mix did not contain nano-silica, the second mix contained colloidal nano-silica, and the third mix contained powder nano-silica. Under the laboratory conditions, the compressive and tensile splitting strength of the reference SCC was improved by the addition of both types of nano-silica [16]. The colloidal nano-silica SCC mix had higher compressive strength and lower splitting tensile strength compared to the powder nano-silica SCC mix. All durability indicators of the SCC studied (conductivity, chloride migration and diffusion coefficients, and freeze–thaw resistance) were significantly improved with the addition of 3.8% of both types of the nano-silica [16]. Compared to the powder nano-silica SCC mix, the colloidal nano-silica SCC mix showed slightly better performance in terms of durability properties.

Ramesh. N and Eramma. H [17] studied the behavior of ground granulated blast-furnace slag (GGBS) and nano-silica on the strength properties of concrete. The properties of nano-silica used in this experiment are 23.6 pH (1.08–1.11). It used specific gravity and a 219 nm particle size. Eight different mixes were tested, in which mixes 1, 2, 3, and 4 contained zero nano-silica and 0%, 10%, 20%, and 30% GGBS, respectively, and mixes 5, 6, 7, and 8 contained 1%, 2%, 3%, 2% nano-silica and 0%, 0%, 0%, and 30% GGBS, respectively. Based on the test results, multiple conclusions were obtained. First, mix #8 (30% GGBS and 2% nano-silica) achieved the highest seven-day and 28-day compressive and split tensile strength results. Similarly, mix 8 had the highest flexural strength compared to the other mixes. Second, the SEM test shows that the microstructure of nano SiO_2 concrete was more uniform and compact than the normal concrete [17]. Third, the silica nanoparticles addition improved the pore structure of concrete.

D. V. Prasada Rao and U. Anil Kumar [18] conducted an experimental investigation on the strength properties of concrete containing micro-silica and nano-silica. The properties of nano-silica used in this experiment are 39.5–41% nano solids, 9–10 pH, 1.29–1.31 specific gravity, and milky white liquid texture. Seven different mixtures were tested in which the mixes contain 0, 19, 38, 19, 38, 19, and 38 kg micro-silica and 0, 0, 0, 14.25, 14.25, 28.5, and 28.5 L colloidal nano-silica, respectively. The addition of 1.5% nano-silica to the 5% and 10% micro-silica mixes had better mechanical properties compared to the addition of 3% nano-silica to the 5% and 10% micro-silica mixes. Overall, in terms of its strength performance, the addition of 1.5% nano-silica and 10% micro-silica achieved the highest results compared to the other mixes.

Maitri Mapa et al. [19] investigated the mechanical properties of silica and GGBS incorporated cement mortar. The properties of nano-silica used in this experiment are 2.4 specific gravity, 2200 kg/m^3 bulk density, 640 m^2/g fineness, and white color. Eleven different mixes were tested consisting of different dosages of GGBS, densified silica fume, and nano-silica. Numerous conclusions were obtained from this experiment. First, the initial and final setting times were directly proportional to the GGBS content. The increase in initial setting time of GGBS incorporated cement paste was higher than the increase of final setting time for cement paste [19]. Therefore, the incorporation of GGBS retarded the initial hydration of cement. Second, the compressive strength of silica added mortar mixes showed good improvement in the early age's compressive strength as compared with the GGBS cement mix [19].

Hongru Zhang et al. [20] studied the modification effects of a nano-silica slurry on microstructure strength and strain development of recycled aggregate concrete applied in an enlarged structural test. Three concrete groups were prepared in this study, i.e., the commercial natural aggregate concrete (CNAC), the original recycled aggregate concrete (ORAC), and the modified recycled aggregate concrete (MRAC) [20]. For both ORAC and MRAC, the percentage replacement of recycled aggregate was 50%. The strengthening slurry prepared for this experiment contains 100 kg cement, 50 kg water, 1 kg superplasticizer, and 1 kg nano-silica dispersant. Multiple conclusions were obtained during this experiment. First, mechanical properties of ORAC and MRAC, i.e., the compressive strength and the splitting strength, were inferior to those of CNAC, given the mixture proportions employed in this study, i.e., the dosage of water, cement, and aggregates were kept the same among the three concrete groups [20]. Second, at an early age (before 28 days), the resistance of CNAC to shrinkage caused by deformation in the target beam was found to be inferior to ORAC and MRAC. However, after 90 days, CNAC showed long-term superiority to ORAC and MRAC in its deformability against loads, given the loads applied to the target beams similar [20]. Third, the employed nano-slurry had verified a beneficial role in the deformability against shrinkage and loads of MRAC, which were applied in RC beams in a real project.

Jing Xu et al. [21] studied the modification effects of nano-silica on the interfacial zone in concrete. At macro-scale level, compressive and flexural strength tests showed that the addition of nano-silica is beneficial for the improvement of the interfacial transition zone (ITZ) performance in particular [21]. On the other hand, at the micro-scale level, the addition of nano-silica accelerated the hydration process, which played a major role in improving the interfacial transition zone (ITZ) at an early age.

A. Ghazy et al. [22] studied the nano-modified fly ash concrete as a repair option for concrete pavements. Numerous outcomes were obtained from this research. The incorporation of 6% nano-silica in concrete with up to 30% fly ash significantly shortened the dormant period and accelerated the rate of hydration reactions, which discounted some of the retarding effect of class F fly ash on the rate of hardening concrete [22]. Furthermore, the addition of nano-silica improved the early-age and the long-term compressive and tensile strength. Moreover, it refined the pore structure of the fly ash concrete. Hence, the nano-modified fly ash concrete presented a viable option for a suite of repair applications in concrete pavements [22].

Youkun Cheng and Zhenwu Shi [23] conducted an experimental study on nano-silica improving concrete durability of bridge deck pavements in cold regions. The materials used in the study were OPC grade 42.5, fine aggregate, coarse aggregate, water reducer agent, defoaming agent, and nano-silica. The technical parameters of the used nano-silica are 15 nm average grain diameter, 99.5% purity, globospherite crystal form, 300 m^2/g specific surface area, 0.05 g/cm3 apparent density, and white color. It was found out that the addition of nano-SiO_2 in bridge deck pavement concrete improved the durability of the concrete effectively, prolonged the service life of the bridge deck pavement, reduced the early onset of damage to bridge deck pavement, and reduced repair and maintenance costs; consequently, using it has significant social and economic value [23]. Furthermore, the incorporation of nano-silica greatly improved frost resistance, resistance to CI^- ion permeability, and abrasion resistance of concrete. Nano-silica incorporated into concrete effectively absorbed $Ca(OH)_2$, which is released in the early stage of hydration of cement and increased the content of hydrated calcium silicate, which improved the interface between the hardened cement paste and aggregate [23].

Comparison between Nano-Silica and Micro-Silica

Both of them are not crystalline materials (amorphous); therefore, they will not dissolve in concrete. Nano-silica is more reactive than micro-silica, because it contains more silicon dioxide content. Nano-silica has a smaller particle size than micro-silica. Consequently, it has a larger surface area. Therefore, nano-silica has a larger impact on the reactivity, strength development, and the refinement of the pore structure of the concrete. The weight per unit volume (bulk density) of nano-silica is lighter than both as produced and densified micro-silica due to its lighter mass. Both of them have a specific gravity of 2.2, which is lighter than Portland cement. Thus, adding nano-silica or micro-silica will not increase the density of the concrete. Nano-silica has a larger specific surface than micro-silica due to its smaller particle size. However, due to its smaller particle size, it has a higher water demand. Thus, it is necessary to use a water-reducing admixture or a superplasticizer in the mixture.

The purpose of this study is to develop nano-silica sustainable concrete mixtures and evaluate the fresh and mechanical properties of the developed nano-silica concrete mixtures. Furthermore, the purpose is to study the morphological characteristics of nano-silica concrete.

2. Materials and Methods

2.1. Materials

The materials used to prepare the concrete mixtures are nano-silica (NS), ground granulated blast furnace slag (GGBS), Portland cement (OPC), water, 20 mm aggregate, 10 mm aggregate, 5 mm washed sand, 5 mm crushed sand, red dune sand, and mega flow 1000 polycarboxylate superplasticizer. The characteristics of nano-silica are 99+% SiO_2, 20 nm average particle size, spherical morphology of particles, ≤120 m^2/g specific surface area, hydrophilic surface performance, amorphous crystallographic structure, 0.03–0.05 g/cm^3 bulk density, white color, 5.5–6.5 pH, ≤6.0 wt% loss on drying (110 °C/2 h), and ≤10.0 wt% loss on calcination (850 °C/2 h). The chemical analysis of the GGBS is 33.0 SiO_2, 0.28 IR, 14.7 AL_2O_3, 0.4 Fe_2O_3, 39.7 CaO, 7.7 MgO, 0.08 SO_3, 0.86 S, 0.42 Na_2O, 0.29 Mn_2O_3, 1.9 LOI corrected for sulfide, 0.01 Cl^-, and 98.8 glass content. The Portland cement was manufactured to comply with BS EN 197–1:2000 CEM I, grade 42.5 N and ASTM C-150-2000 Type I. The chemical composition of the Portland cement is 20.5 SiO_2, 0.34 IR, 5.0 Al_2O_3, 3.9 Fe_2O_3, 64.2 CaO, 1.5 MgO, 2.1 SO_3, 0.50 Na_2O, 2.6 LOI, 0.02 Cl^-, and 6.6 C_3A. Mega flow 1000 polycarboxlate superplasticizer is a high range water reducer (HRWR), and it was selected due to the high demand for water that occurs with the addition of nano-silica to the concrete mixture.

2.2. Mix Proportions

Two different cases were studied in this experiment: the influence of nano-silica addition on the durability and strength of concrete mixtures that consist of a 70% dosage of GGBS (M1, M2, and M3) and 30% dosage of GGBS (M4, M5, and M6). M1 and M4 were used as control mixturesm because they contain zero nano-silica dosage. On the other hand, M2 and M3 incorporated 1% and 2% dosages of nano-silica, respectively, and their various test results were compared with their control mixture, M1. Similarly, M5 and M6 incorporated 1% and 2% dosages of nano-silica, respectively, and their various test results were compared with their control mixture M4. Table 1 shows a tabular summary of the mix designs of all the mixtures.

Table 1. Concrete mix designs proportions of all the mixes.

	Final Weights (Kg/m^3)										
Mix.	**OPC**	**GGBS**	**NS**	**20 mm Agg.**	**10 mm Agg.**	**5 mm Washed Sand**	**5 mm Crushed Sand**	**Red Dune Sand**	**Water**	**Megaflow 1000**	**Total**
M1	120	280	0	668	364	338	306	254	156	4.5	2491
M2	116	280	4	668	364	338	306	254	156	4.5	2491
M3	112	280	8	667	364	338	306	254	156	4.75	2490
M4	280	120	0	673	367	341	308	256	157	3.5	2506
M5	276	120	4	672	367	340	308	256	157	4	2504
M6	272	120	8	672	367	321	326	256	157	5	2504

2.3. Sample Preparation

The mixing process started by adding 20 mm crushed rock aggregate, 10 mm crushed rock aggregate, 5 mm washed sand, 5 mm crushed rock sand, and uncrushed sand (dune sand), respectively. After that, water was added while the mixer was running for half a minute to allow the aggregate to absorb it. In a different bucket, nano-silica was mixed with Megaflow 1000 polycarboxlate superplasticizer and some water until it dissolved completely. Then, GGBS and Portland cement were added to the immobile concrete mixer. Once they were added, water along with the mixed solution of dissolved nano-silica, water, and Megaflow 1000 polycarboxlate superplasticizer were added while the mixer was running for two minutes for the concrete to disperse in the mixer. Three batches of 20 L were mixed to cast twelve cubes (100 × 100 × 100 mm), three cylinders (150 × 300 mm), three small cylinders (100 × 200 mm), and three beams (500 × 100 × 100 mm) for each mixture. The total number of specimens was seventy-two cubes, eighteen cylinders, eighteen small cylinders, and eighteen beams. The specimens were cured in 25 °C temperature to be tested after 1, 3, 7, and 28 days. The cubes, cylinders, and beams were cast to be tested for the compressive strength, modulus of elasticity, and modulus of rupture, respectively. The small cylinders were sliced to (100 × 50 mm) samples to be tested for the Rapid Chloride Permeability Test (RCPT). For the scanning electron microscopy (SEM) test, to ensure that the specimens were representatives and they contained different concrete components, they were taken from the center of the small cylinders by slicing a thin disk using a saw-cut machine. After that, a small concrete piece was taken from the middle of the sliced disk. Then, the small concrete piece was placed at the bottom of a mounting cup. In a separate mixing cup, a resin was prepared by mixing ClaroCit powder with ClaroCit liquid. Once the resin was prepared, it was poured in the mounting cup over the concrete piece. Next, the mounting cup was placed in an oven for half an hour for the resin to solidify. Afterward, the solid resin, which contains the concrete piece, was taken out of the mounting cup and its surface was polished, as shown in Figure 1.

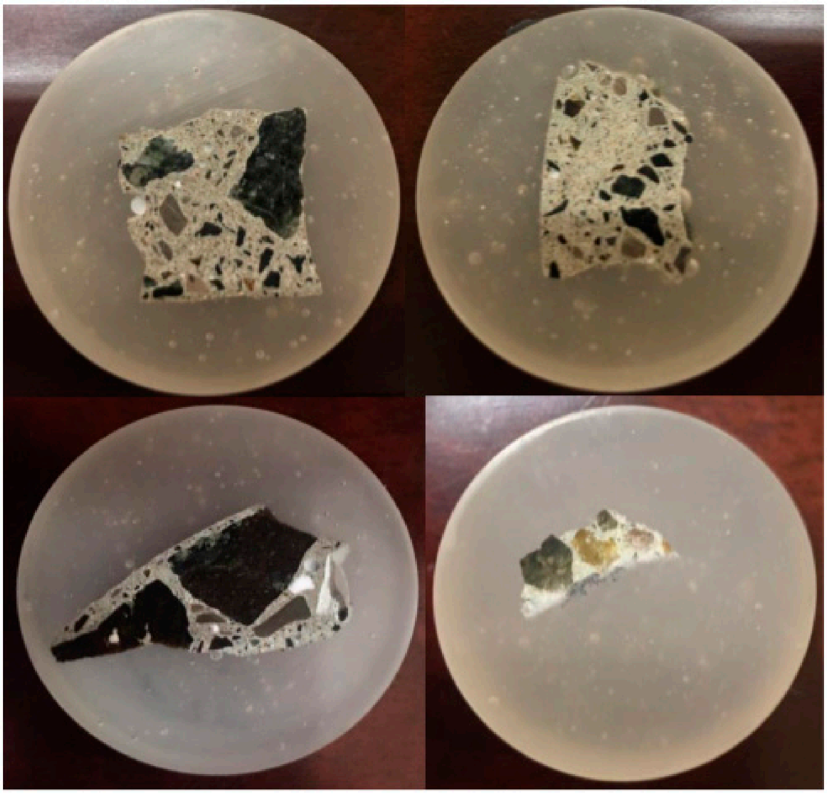

Figure 1. Concrete pieces inside the solid resins.

2.4. Test Methods

The following tests were carried out to determine the fresh properties, mechanical properties, and morphological characteristics of the six nano-silica concrete mixtures in this study.

a. The slump and flow tests of concrete were carried out in the lab according to ASTM C143/C143M-15a and BS 1881: Part 105: 1984, respectively. The slump and flow tests were indicators of the concrete's workability.

b. The density (unit weight) of freshly mixed concrete was carried out according to ASTM C138/C138M-17a. This test is a great tool in controlling the quality of the newly mixed concrete. A high or low unit weight gave different indications such as that the concrete suffered from high or low air content, high or low water content, or change of the ingredients' proportions had taken place.

c. The compressive strength test was performed according to BS 1881: Part 116: 1983. Compressive strength is one of the main structural design requirements to ensure that the structure will be able to carry the intended load [24]. The test was performed on cubical specimens by applying axial compressive load with a specified loading rate until failure took place after 1, 3, 7, and 28 days of curing. Three cubical (100 × 100 × 100 mm) specimens were tested at each day and the results were reported as an average of the three tests' results.

d. The modulus of elasticity of concrete cylinders was carried out according to ASTM C 469-02. For a homogeneous isotropic and linear elastic material, the proportional constant between normal stress and normal strain of an axially loaded member is the modulus of elasticity or Young's modulus [24]. A slowly increasing longitudinal compressive strength was applied to a cylindrical specimen. Longitudinal strains are determined using either a bonded or unbonded sensing device that measures the average deformation of two diametrically opposite locations to the nearest 5 millionths of strain [25]. The applied load and longitudinal strain are recorded when the longitudinal strain is 50 millionths and when the applied load is equal to 40% of the cylinder compressive strength [25]. Three cylindrical (150 × 300 mm) specimens were tested after 28 days of curing for each mixture, and the results were reported as an average of three tests' results.

e. The modulus of rupture of concrete beams was performed according to ASTM C293/C293M-16. Three (500 × 100 × 100 mm) beams were tested in the three-point loading apparatus after 28 days of curing for each mixture and the results were reported as an average of the three tests' results. The load was continuously applied at a specified rate until rupture [24]. The modulus of rupture was calculated when the fracture initiates in the tension surface within the middle third of the span length by using the following equation [24].

$$R = \frac{3PL}{2bd^2} \quad (1)$$

where

R = Flexure strength, MPa
P = Maximum applied load, N
L = Span length, mm
b = Average width of the specimen, mm
d = Average depth of the specimen, mm

f. The rapid chloride permeability test was carried out according to ASTM C1202. Originally developed in the early 1980s, and standardized as ASTM in 1991, the rapid chloride permeability test is now being used extensively in specifications, quality control, and concrete durability research [26]. The RCPT is performed by monitoring the amount of electrical current that passes through a sample 50 mm thick by 100 mm in diameter in 6 h [27]. Throughout the test, a 60V DC voltage was maintained across the ends of the specimen. One lead is immersed in a 3.0% salt (NaCl) solution and the other in a 0.3 M sodium hydroxide (NaOH) solution [27]. A qualitative rating was concluded about the permeability of the concrete against chloride penetration based on the passing charge through the specimen in which a >4000 Coulombs charge passing was classified as high, a 2000 to 4000 Coulombs charge passing was classified as moderate, a 1000 to 2000 Coulombs charge passing was classified as low, a 100 to 1000 Coulombs charge passing was classified as very low, and a <100 Coulombs charge passing was classified as negligible. Three cylindrical (50 × 100 mm) specimens were tested after 28 days of curing for each mixture, and the results were reported as an average of the three tests' results.

g. Microstructure analysis using scanning electron microscopy (SEM) according to ASTM C1723. The SEM provides images that can range in scale from a low magnification (for example, 15×) to high magnification (for example, 50,000× or greater) of concrete specimens such as fragments, polished surfaces, or powders [28]. These images can provide information indicating compositional or topographical variations in the observed specimen [28]. The SEM functions by generating an electron beam over the surface of the concrete specimen. The beam impinges on the specimen and produces signals, which can be detected as backscattered electrons (BE or BSE), secondary electrons (SE), and X-rays [29]. Backscattered electrons (BSE) and secondary electrons (SE) images were taken of one specimen for each mixture after 28 days of curing

3. Results

3.1. Slump/Flow

The slump and flow tests were performed in the lab at three different times, which were immediately, thirty minutes, and sixty minutes after the concrete mixing process, as shown in Table 2. The specific surface of nano-silica's particles was large due to its small size, which increases the water demand of the concrete mixes. Therefore, as the nano-silica dosage increased from one mixture to another, the Megaflow 1000 polycarboxylate superplasticizer dosage was increased to maintain the same water/cement ratio (0.36) in all the mixtures.

Table 2. Slump/flow test results.

Mix.	Initial Slump (mm)	Slump after 30 min (mm)	Slump after 60 min (mm)	Initial Flow (mm)	Flow after 30 min (mm)	Flow after 60 min (mm)
M1	240	240	240	630	630	600
M2	230	220	220	590	580	580
M3	220	220	130	470	400	0
M4	240	240	240	600	620	600
M5	230	220	200	620	520	460
M6	230	160	110	520	0	0

Comparing the initial slump and flow test results of (M2 and M3) to (M1) and (M5 and M6) to (M4) showed that adding nano-silica reduced the slump and the flow spread of the mixtures, which in consequence reduced the workability of the concrete. Furthermore, comparing the slump and flow test results after 30 and 60 min to the initial slump and flow test results showed that using nano-silica reduced the setting time, because the nano-silica accelerated the hydration process. Moreover, the 30% GGBS concrete mixtures (M5 and M6) required more high range water reducer (HRWR) superplasticizer dosages as the nano-silica dosage increased from one mixture to another to maintain the water/cement ratio, compared to the 70% GGBS concrete mixtures (M2 and M3). Therefore, the 30% GGBS mixtures (M5 and M6) had higher water demand in comparison to the 70% GGBS mixtures (M2 and M3). Finally, the mixtures that contain a 2% dosage of nano-silica (M3 and M6) had a significant slump and flow reduction especially after sixty minutes compared to the mixtures that contain a 1% dosage of nano-silica (M2 and M4). Thus, as the dosage of nano-silica increased, the workability of the concrete decreased.

3.2. Density (Unit Weight)

The unit weight test was conducted on the freshly mixed concrete in the lab. Results, which are shown in Figure 2, illustrated that incorporating 1% and 2% dosages of nano-silica reduced the unit weight of M2 and M3 by 3.8% and 1.6%, respectively, when compared to the control mixture (M1).

On the other hand, adding a 1% dosage of nano-silica did not increase nor decrease the unit weight of M5 compared to the control mixture M4, while adding a 2% dosage of nano-silica increased the unit weigh of M6 by 1.1% for the control mixture (M4). In general, the percentage increase or decrease that took place for all the mixtures was low when compared to their respective control mixtures, which indicates that the addition of nano-silica does not densify nor shrink the unit weight of the concrete.

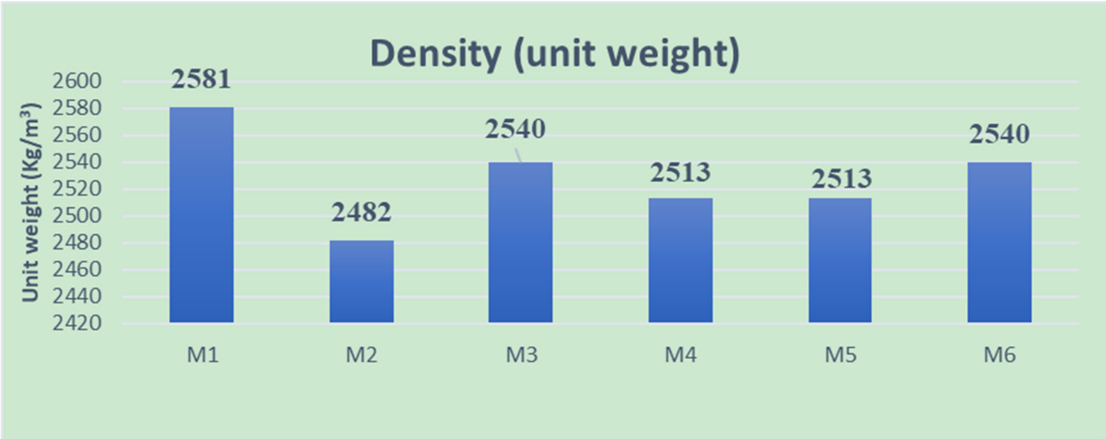

Figure 2. The unit weight of all the mixtures.

3.3. Compressive Strength

The compressive strength test was performed after one day, three days, seven days, and 28 days of curing. The compressive strength test results, which are average of three specimens for each mixture, are shown in Table 3.

Table 3. Compressive strength test results.

Mix.	1 Day–Compressive Strength (MPa)	3 Day–Compressive Strength (MPa)	7 Day–Compressive Strength (MPa)	28 Day–Compressive Strength (MPa)
M1	25.5	48.7	61.7	71.8
M2	25.6	44.9	52.8	57.9
M3	21.1	43.3	54.2	59.1
M4	20.8	39.9	55.6	63.1
M5	23.6	43.0	60.1	64.5
M6	25.5	41.3	55.9	64.1

For the 70% GGBS concrete mixtures, the incorporation of 1% of nano-silica at one day almost did not affect the compressive strength, while the incorporation of 2% of nano-silica at one day reduced the compressive strength by 17.3% for the control mixture (M1). After three days, adding 1% and 2% dosages of nano-silica to the 70% GGBS concrete mixtures reduced the compressive strength by 7.8% and 11.1%, respectively, when compared to the compressive strength of M1. Unlike the one-day and the three-day compressive strength results, the seven-day compressive strength of M3 was higher than M2 by 1.4 MPa. However, both seven-day compressive strength results of M2 and M3 were lower than the control mixture M1, as shown in Figure 3. At 28 days, the percentage decrease in compressive strengths of M2 and M3 compared to the control mixture M1 increased remarkably to 19.4% and 17.7%, respectively. The reduction in compressive strength that took place in the mixtures that incorporated nano-silica (M2 and M3) can be attributed to the consumption of calcium hydroxide, which was released by the Portland cement during the hydration process, by the high dosage of GGBS. Therefore, this would leave almost no chemical hydration between nano-silica and calcium hydroxide. In terms of compressive strength, it is not recommended to use nano-silica with the 70% GGBS concrete mixtures.

For the 30% GGBS concrete mixtures, the addition of 1% and 2% dosages of nano-silica increased the one-day compressive strength by 2.8 MPa and 4.7 MPa, respectively, compared to the control mixture (M4). Unlike the one-day compressive strength, the combination of 30% GGBS and 1% nano-silica (M5) improved the three-day compressive strength more than the combination of 30% GGBS and 2% nano-silica (M6), as demonstrated by Figure 4.

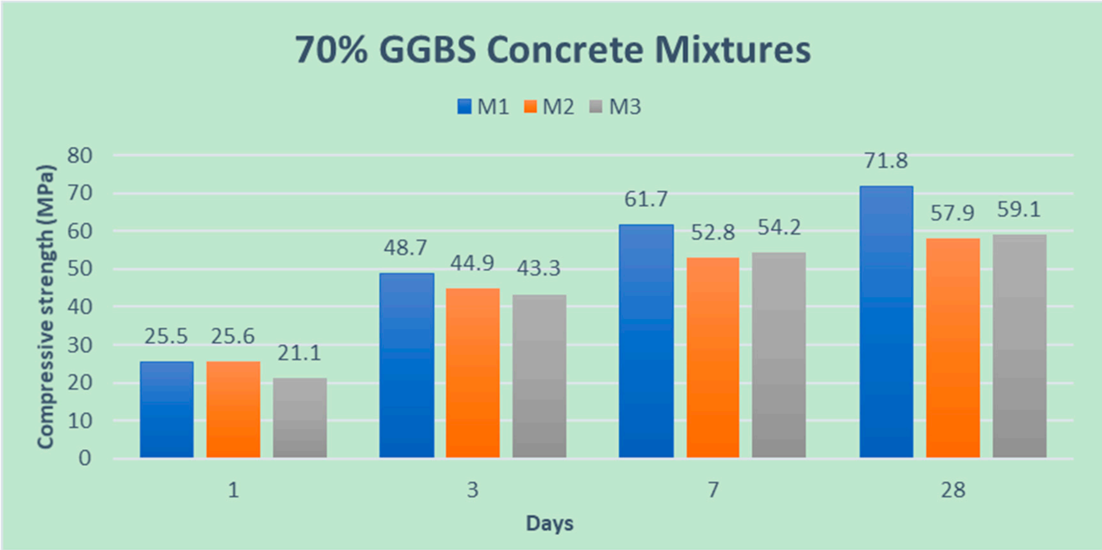

Figure 3. The compressive strength results of the 70% GGBS concrete mixtures.

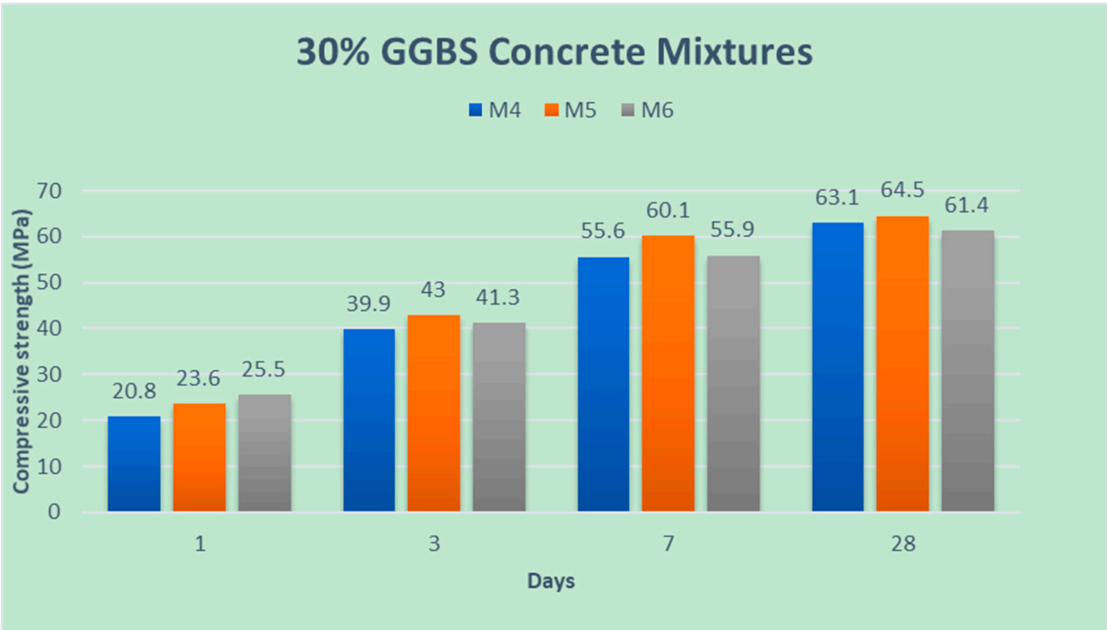

Figure 4. The compressive strength results of the 30% GGBS concrete mixtures.

At seven days, the addition of 2% nano-silica to the 30% GGBS concrete mixture (M6) almost had an equal compressive strength to the control mixture (M4) with a minor percentage increase of (0.5%). On the other hand, the addition of 1% nano-silica to the 30% GGBS mixture (M5) improved the seven-day compressive strength by (8.1%) in comparison to the control mixture (M4). At 28 days, M5 had a compressive strength of 64.5 MPa, which is 2.2% higher than the control mixture (M4), while M6 had a compressive strength of 61.4 MPa, which is 2.7% lower than the control mixture (M4). In general, the improvement in the compressive strength for the 30% GGBS concrete mixtures that incorporated nano-silica can be ascribed to the high pozzolanic activity and the nano-filler effect of nano-silica, which makes the concrete's microstructure denser, compact, and homogeneous. Most of the compressive strength's improvement took place within the first seven days. Furthermore, the 1% dosage of nano-silica had a greater impact on the compressive strength development of the 30% GGBS concrete mixtures compared to the 2% dosage of nano-silica. One possible reason is that the combination of 30% GGBS and 1% nano-silica reacted more efficiently with released calcium hydroxide from the Portland cement during the hydration process to form the additional calcium-silicate-hydrate gel. Another possible reason is the agglomeration effect. Nanoparticles, due to their small size, have high inter-particle van der Waal's forces, causing the nanoparticles to agglomerate [1]. Therefore, the optimum dosage of nano-silica to be added to the 30% GGBs concrete mixture is 1%.

3.4. Modulus of Elasticity

The modulus of elasticity test was performed after 28 days of curing. The results are shown in Figure 5. For the 70% GGBS concrete mixtures, the incorporation of 1% nano-silica increased the Young's modulus remarkably by 42.6% compared to the control mixture (M1). On the other hand, the incorporation of 2% nano-silica increased the Young's modulus by 2.7% for the control mixture (M1), which is less than M2. Similarly, the addition of 1% of nano-silica to the 30% GGBS concrete mixtures had a greater effect than the 2% dosage of nano-silica by 4.4% as illustrated in Figure 5. Nano-silica decreased the deformation of the concrete specimens by nano-filling the pores, which caused the modulus of elasticity of the mixtures to increase.

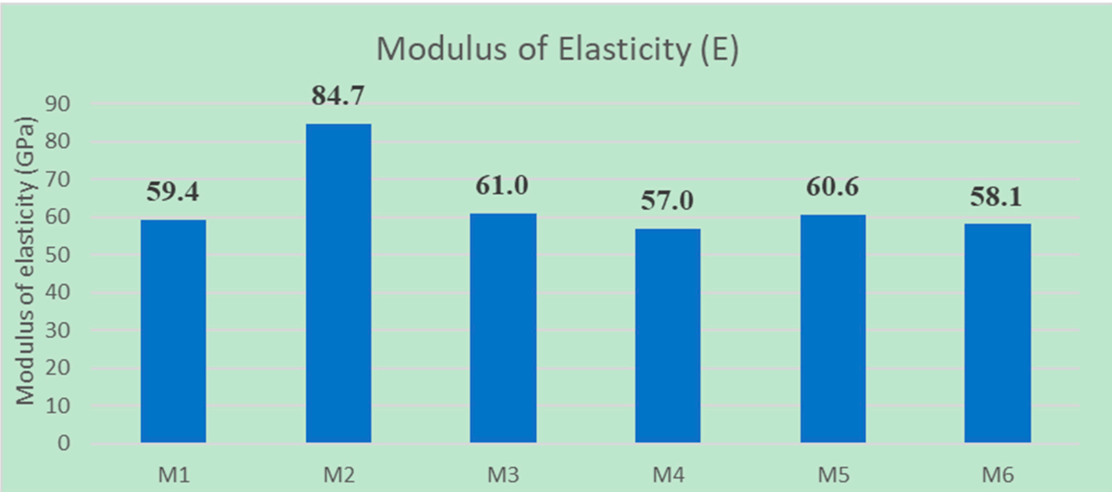

Figure 5. The modulus of elasticity results in all the mixtures.

3.5. Modulus of Rupture

The modulus of rupture test was performed after 28 days of curing. The maximum applied load and the calculated modulus of rupture are shown in Table 4. The addition of 1% and 2% dosages of nano-silica increased the flexural strength of 70% GGBS concrete mixtures (M2 and M3) by 3.4% and 35.9%, respectively, compared to the control mixture (M1). Therefore, the flexural strength of the 70% GGBS concrete mixtures increased as the nano-silica's dosage increased.

Table 4. The modulus of rupture of all the mixtures.

Mix.	Maximum Applied Load (KN)	Modulus of Rupture (MPa)
M1	15.6	11.7
M2	16.1	12.1
M3	21.2	15.9
M4	19.2	14.4
M5	20.2	15.0
M6	17.0	12.7

Similarly, the addition of a 1% dosage of nano-silica increased the flexural strength of the 30% GGBS concrete mixture (M5) by 4.2% compared to the control mixture (M4). However, the 2% dosage of nano-silica decreased the modulus of rupture of M6 by 11.8% compared to the control mixture (M4). This possibly due to the agglomeration effect, the mixing process, or the released calcium hydroxide from the Portland cement during the hydration process was not consumed efficiently by the 2% dosage of nano-silica.

3.6. Rapid Chloride Permeability (RCP)

The average passing charges of three specimens and the penetrability class as specified by ASTM C 1202 of each mixture are shown in Table 5. Partially replacing the Portland cement with 1% and 2% dosages of nano-silica improved the resistance of the 70% GGBS concrete mixtures (M2 and M3) to chloride penetration by 34.8% and 52.7%, respectively, when compared to the control mixture (M1). Therefore, the chloride ingress of the 70% GGBS concrete mixtures decreased as the nano-silica dosage increased. On the other hand, the partial replacement of cement with 1% dosage of nano-silica reduced the passing charges of the 30%

Table 5. RCPT results of all the mixtures.

Mix.	Charge Passing (Coulombs)	Penetrability Class
M1	775.5	Very low (100 to 1000 Coulombs)
M2	505.5	Very low (100 to 1000 Coulombs)
M3	367.0	Very Low (100 to 1000 Coulombs)
M4	1458.3	Low (1000 to 2000 Coulombs)
M5	614.7	Very low (100 to 1000 Coulombs)
M6	967.0	Very low (100 to 1000 Coulombs)

GGBS concrete mixture (M5) by 57.8% with respect to the control mixture (M4), changing the penetrability class from low to very low. Similarly, the 2% nano-silica addition reduced the chloride ingress of the 30% GGBS concrete mixture (M6) by 33.7% and changed the penetrability class from low to very low when compared to the control mixture (M4). However, the addition of a 2% dosage of nano-silica was not as effective compared to the 1% dosage of nano-silica in improving the resistance of the 30% GGBS concrete mixtures against chemical attacks. In general, adding small dosages of nano-silica had a noticeable effect on decreasing the conductivity of the concrete and refining the pore structure of all the mixtures due to the pozzolanic reaction and the nano-filler effect of nano-silica, which made the microstructure of the concrete mixtures more homogeneous and less porous. Consequently, this improved the resistance of the concrete mixtures against the physical penetration of chloride ions. Thus, nano-silica addition improves the durability of the concrete making it more sustainable.

3.7. Scanning Electron Microscopy (SEM)

SEM Images Analysis

Figure 6A–C shows the secondary electron and backscattered electrons images of the 70% GGBS concrete mixtures (M1, M2, and M3), respectively, while Figure 7A–C shows the secondary electron and backscattered electrons images of the 30% GGBS concrete mixtures (M4, M5, and M6), respectively. The secondary electron images show the cementitious paste–aggregate interface and the microstructure of the concrete mixture. On the other hand, the backscattered electron images show the micro-cracks that took place in the cementitious paste–aggregate interface and other areas of the specimen. Generally, the 70% GGBS mixtures, due to incorporating 70% dosage of GGBS, have homogeneous microstructures and great interface structure, which is shown clearly in the SE and BSE image of M1 (Figure 6A). However, using 1% and 2% dosages of nano-silica further refined the microstructure and increased the bond strength of the cementitious paste–aggregate interface by nano-filling the micro-cracks and the pores, as shown in (Figure 6B,C). The 2%

dosage of nano-silica had a more pronounced effect compared to 1% dosage of nano-silica in refining the microstructure and the interface structure of the 70% GGBS mixtures.

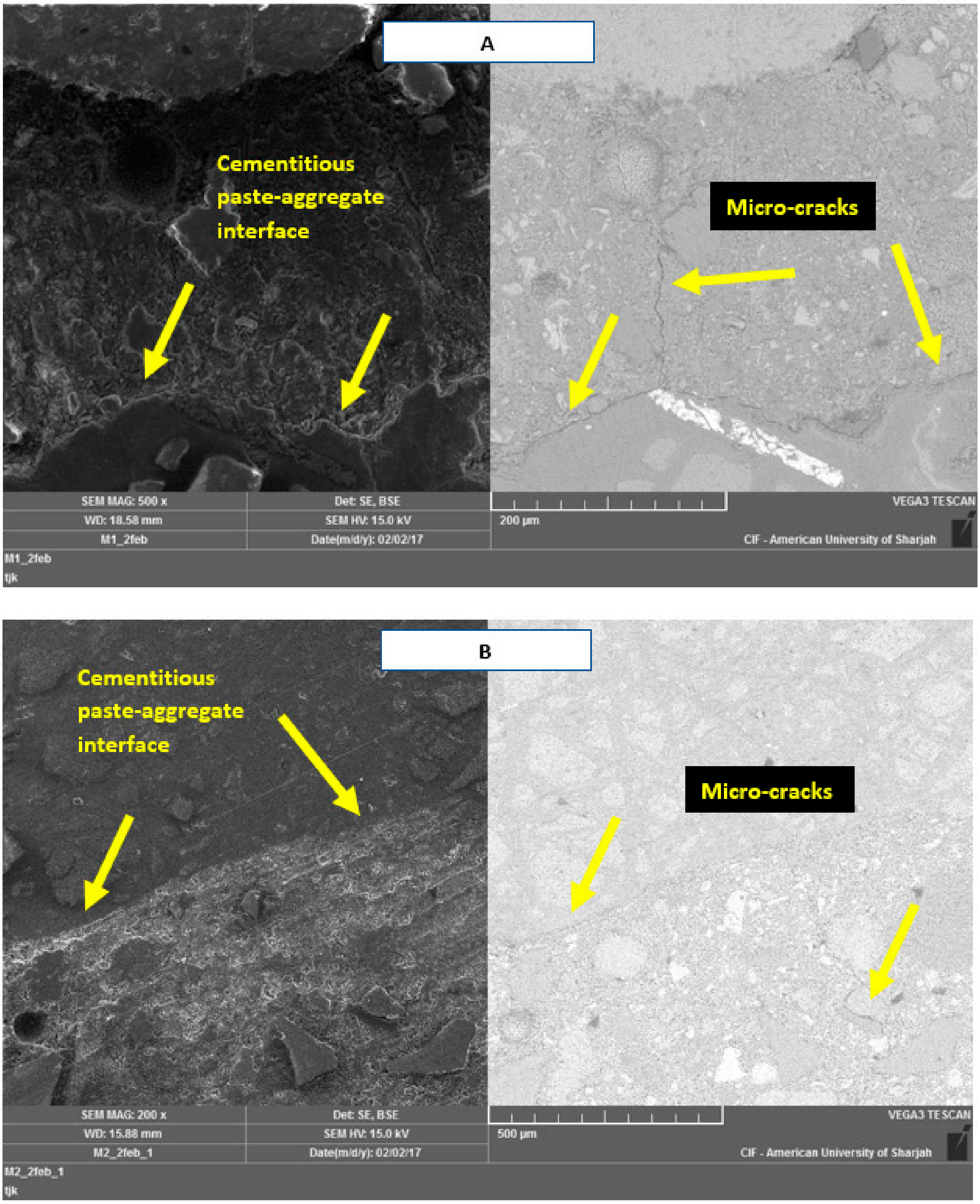

Figure 6. *Cont.*

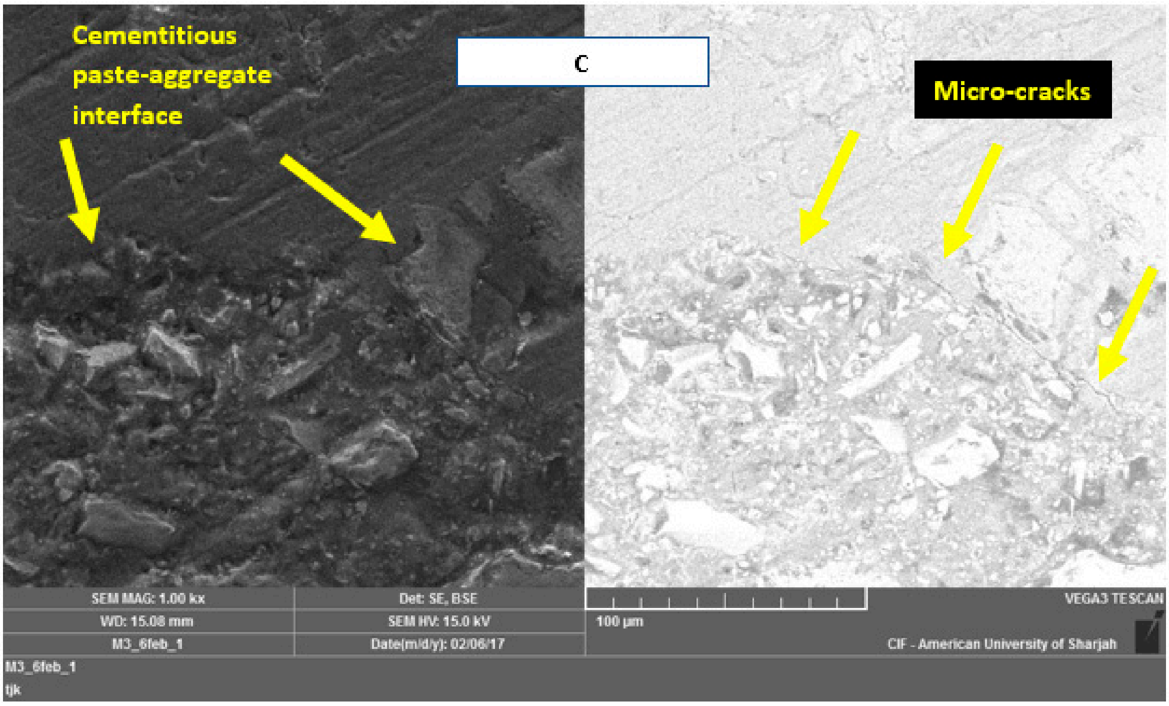

Figure 6. SE and BSE images of (**A**) M1, (**B**) M2, and (**C**) M3.

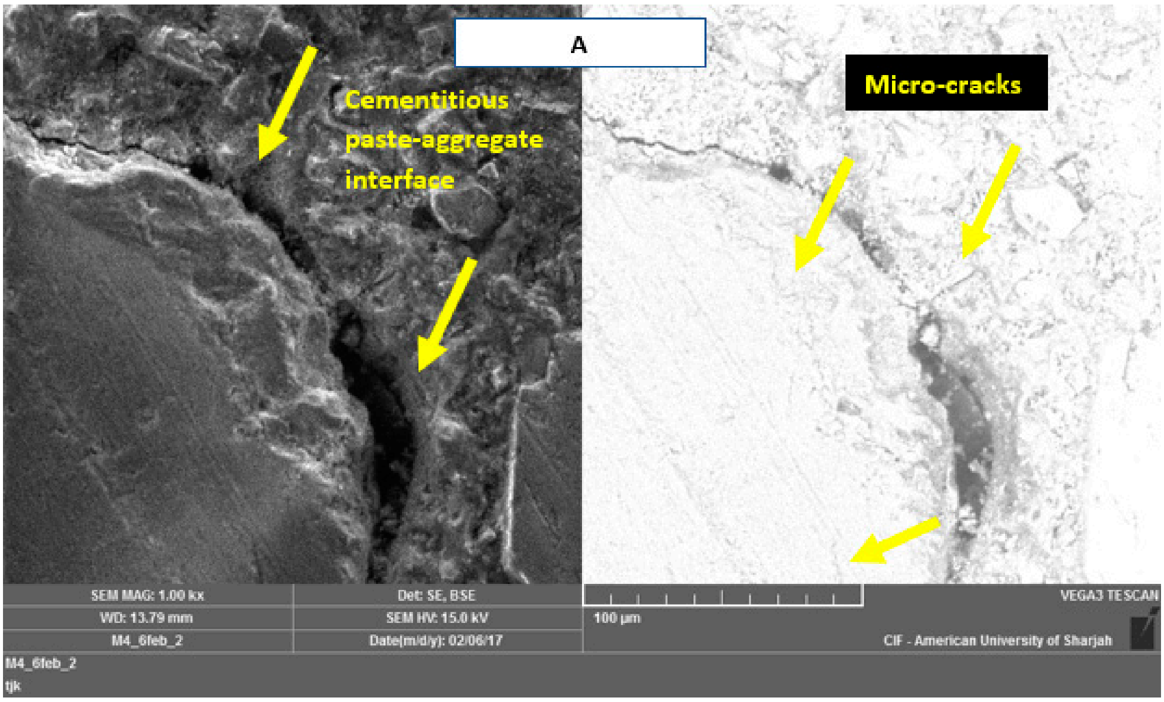

Figure 7. *Cont.*

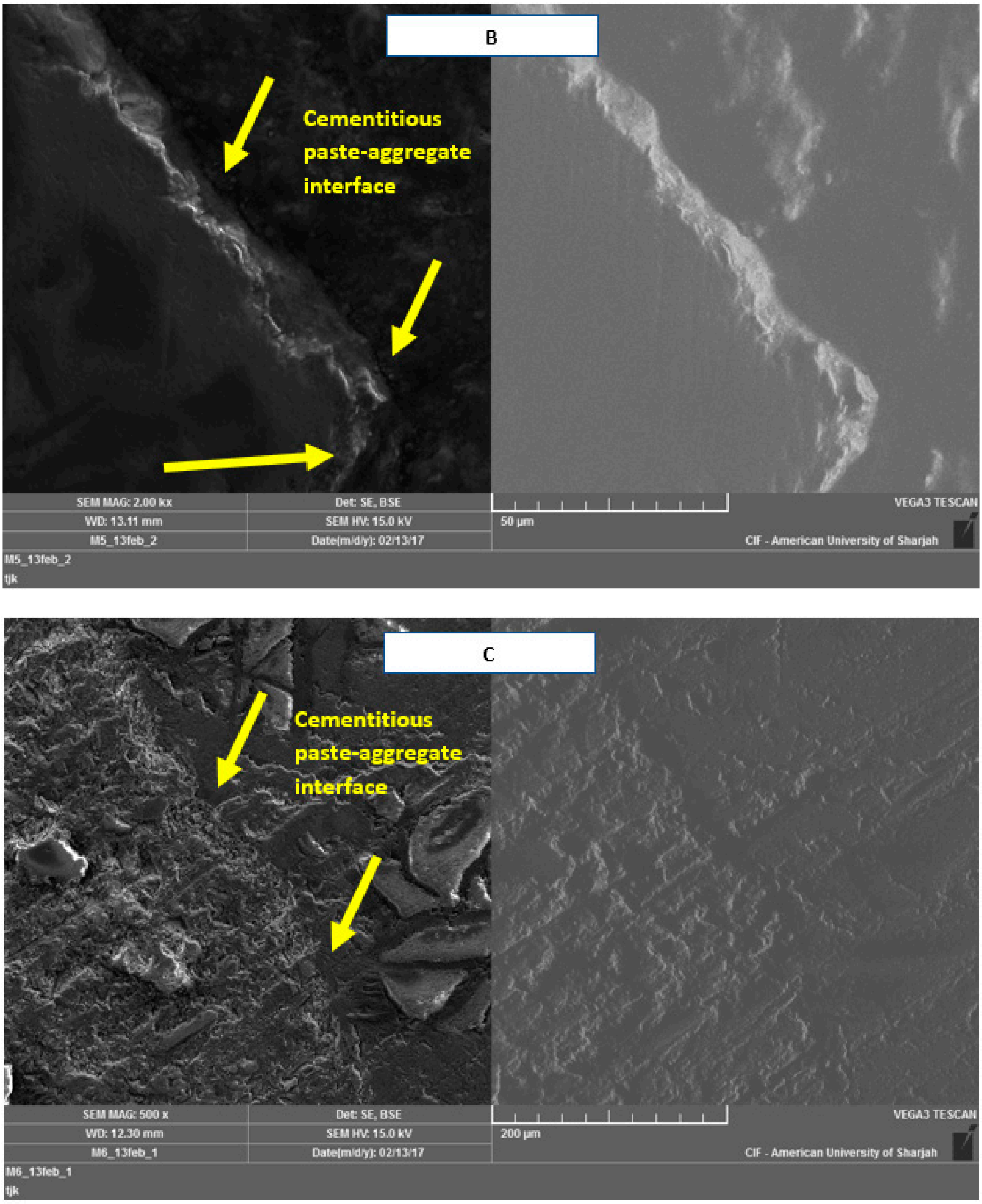

Figure 7. SE and BSE images of (**A**) M4, (**B**) M5, and (**C**) M6.

Therefore, as the nano-silica's dosage increased, the microstructure's homogeneity and bond strength of cementitious paste–aggregate interface increased. Furthermore, the SE and BSE images of the 70% GGBS concrete mixtures reinforced the drawn conclusion from the rapid chloride permeability test results that the incorporation of nano-silica improved the pore structure of the concrete, which results in the reduction of the ingress rate of water and chloride ions due to the packing ability of nano-silica. Thus, nano-silica incorporation improved the durability of the concrete. The SE and BSE images of the control mixture of the 30% GGBS concrete mixtures (M4) illustrate that the cementitious paste–aggregate bond is as weak as the micro-crack in the interface is wide as shown in Figure 7A. Moreover, the microstructure contains micro-cracks and voids. The addition of 1% and 2% dosages of nano-silica improved the cementitious paste–aggregate interface's bond significantly, as there are almost no visible micro-cracks shown at 2.00 KX and 500 X SEM magnification in Figure 7B,C. Furthermore, the microstructure of M5 and M6 became more homogeneous, dense, and compact due to the nano-filler effect of nano-silica, which refined the pore structure of the 30% GGBS concrete mixtures. Additionally, the SE and BSE images of the 30% GGBS concrete mixtures show greater improvement in terms of cementitious paste–aggregate interface's bond due to the incorporation of nano-silica when compared to the 70% GGBS concrete mixtures. All in all, nano-silica addition increases the sustainability of the concrete by enhancing its durability.

4. Conclusions

This research presents the influence of nano-silica on the properties of the 70% and 30% GGBS concrete mixtures in terms of strength and durability. Fresh and hardened concrete tests along with the rapid chloride permeability test and scanning electron microscopy were applied to each mixture. Based on the obtained results, the following conclusions were drawn:

- Adding 1% of nano-silica to the 30% (GGBS) mixture (M5) increased the one-day, three-day, seven-day, and 28-day compressive strength by 13.5%, 7.8%, 8.1%, and 2.2%, respectively, compared to the control mixture (M4), whereas adding 2% of nano-silica to the 30% (GGBS) mixture (M6) had less influence on the strength development compared to the 1%. This is possibly due to either the agglomeration effect, the mixing process, or the released calcium hydroxide from the OPC during the hydration process being consumed more efficiently by the combination of 30% (GGBS) and 1% nano-silica. The majority of the compressive strength's development, which was caused by the addition of nano-silica, was within the first seven days. On the other hand, adding 1% and 2% of nano-silica to the 70% (GGBS) mixtures decreased the 28-day compressive strength by 19.4% and 17.7%, respectively, compared to the control mixture (M1). The reduction in compressive strength associated with the addition of nano-silica could be due to the released calcium hydroxide from the OPC in the hydration process being consumed entirely by the 70% (GGBS).
- Nano-silica increased the Young's modulus due to the nano-filler effect, which reduced the concrete's deformability, making it brittle.
- The modulus of rupture of the 70% (GGBS) mixtures (M2 and M3) increased by 3.4% and 35.9% due to the incorporation of 1% and 2% of nano-silica, respectively. On the other hand, the flexural strength of the 30% (GGBS) mixtures had similar behavior as the 28-day compressive strength.
- The RCP test results illustrated that adding nano-silica to the 70% and 30% (GGBS) mixtures reduced the chloride ingress due to the high pozzolanic activity and the packing effect of nano-silica, which made the microstructure of concrete more homogeneous and less porous.
- The SEM images show that adding nano-silica increased the bond strength of the cementitious paste–aggregate interface and made the microstructure more homogeneous due to the nano-filler effect and the accelerated hydration process. The effect of adding nano-silica on the microstructure and the interface structure was more pronounced on the 30% (GGBS) mixtures in comparison to the 70% (GGBS) concrete mixtures. The scanning electron microscopy (SEM) images confirmed the drawn conclusion from the (RCPT) results that nano-silica improves the concrete's durability.
- Nano-silica's particles are small, which makes its specific surface large. Consequently, its water demand is large. Comparing the nano-silica mixtures to their respective control mixtures showed that the addition of nano-silica reduced the slump and the flow spread values, which indicated that nano-silica had a negative influence on the workability of the concrete due to its high water demand. Furthermore, as

the nano-silica dosage increased, the workability of mixtures decreased. Moreover, comparing the slump and flow results after thirty and sixty minutes to the initial values demonstrated that nano-silica accelerated the hydration process and reduced the setting time.

- Due to its high resistance to water penetration and chemical attacks, nano-silica concrete can be used in construction of marine and coastal structures where the reinforced concrete is subjected to harsh environments. Furthermore, it can be used in construction of high-rise buildings, because it allows thereduction in sizes of reinforced concrete members such as columns.

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References

1. Shaikh, F.U.A.; Supit, S.W.M.; Sarker, P.K. A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes. *Mater. Des.* **2014**, *60*, 433–442. [CrossRef]
2. Heikal, M.; Ali, A.I.; Ismail, M.N.; Ibrahim, S.A.N. Behavior of composite cement pastes containing silica nano-particles at elevated temperature. *Constr. Build. Mater.* **2014**, *70*, 339–350. [CrossRef]
3. Aleem, S.A.E.; Heikal, M.; Morsi, W.M. Hydration characteristic, thermal expansion and microstructure of cement containing nano-silica. *Constr. Build. Mater.* **2014**, *59*, 151–160. [CrossRef]
4. Du, H.; Du, S.; Liu, X. Durability performances of concrete with nano-silica. *Constr. Build. Mater.* **2014**, *73*, 705–712. [CrossRef]
5. Yu, J.; Zhang, M.; Li, G.; Meng, J.; Leung, C.K. Using nano-silica to improve mechanical and fracture properties of fiber-reinforced high-volume fly ash cement mortar. *Constr. Build. Mater.* **2020**, *239*, 117853. [CrossRef]
6. Adak, D.; Sarkar, M.; Mandal, S. Effect of nano-silica on strength and durability of fly ash based geopolymer mortar. *Constr. Build. Mater.* **2014**, *70*, 453–459. [CrossRef]
7. Said, A.M.; Zeidan, M.S.; Bassuoni, M.T.; Tian, Y. Properties of concrete incorporating nano-silica. *Constr. Build. Mater.* **2012**, *36*, 838844. [CrossRef]
8. Bastami, M.; Baghbadrani, M.; Aslani, F. Performance of nano-silica modified high strength concrete at elevated temperatures. *Constr. Build. Mater.* **2014**, *68*, 402–408. [CrossRef]
9. Behfarnia, K.; Salemi, N. The effects of nano-silica and nano-alumina on frost resistance of normal concrete. *Constr. Build. Mater.* **2013**, *48*, 580–584. [CrossRef]
10. Zhuang, C.; Chen, Y. The effect of nano-SiO_2 on concrete properties: A review. *Nanotechnol. Rev.* **2019**, *8*, 562–572. [CrossRef]
11. Berra, M.; Carassiti, F.; Mangialardi, T.; Paolini, A.E.; Sebastiani, M. Effects of nanosilica addition on workability and compressive strength of portland cement pastes. *Constr. Build. Mater.* **2012**, *35*, 666–675. [CrossRef]
12. Lsingh, P.; Karade, S.R.; Bhattacharyya, S.K.; Yousuf, M.M.; Ahalawat, S. Beneficial role of nanosilica in cement based materials-A review. *Constr. Build. Mater.* **2013**, *47*, 1069–1077. [CrossRef]
13. Haruehansapong, S.; Pulngern, T.; Chucheepsakul, S. Effect of the particle size of nanosilica on the compressive strength and the optimum replacement content of cement mortar containing nano-SiO_2. *Constr. Build. Mater.* **2014**, *50*, 471–477. [CrossRef]
14. Mukharjee, B.B.; Barai, S.V. Influence of Nano-silica on the properties of recycled aggregate concrete. *Constr. Build. Mater.* **2014**, *55*, 29–37. [CrossRef]
15. Ghafari, E.; Arezoumandi, M.; Costa, H.; Julio, E. Influence of nano-silica addition on durability of UHPC. *Constr. Build. Mater.* **2015**, *94*, 181–188. [CrossRef]

16. Quercia, G.; Spiesz, P.; Husken, G.; Brouwers, H.J.H. SCC modification by use of amorphous nano-silica. *Cem. Concr. Compos.* **2014**, *45*, 69–81. [CrossRef]
17. Ramesh, N.; Eramma, H. Behaviour of GGBS and nano-silica on strength properties of concrete. *Int. J. Res. Eng. Technol.* **2016**, *5*, 142–148.
18. Prasada Rao, D.V.; Anil Kumar, U. An experimental investigation on strength properties of concrete containing micro-silica and nano-silica. *Int. J. Civ. Eng. Technol.* **2014**, *5*, 89–97.
19. Maitri, M.; Hemalatha, T.; Rama Chandra Murthy, A. Investigation on mechanical properties of silica and GGBS incorporated cement mortar. *Int. J. Res. Eng. Technol.* **2015**, *4*, 30–34.
20. Zhang, H.; Zhao, Y.; Meng, T.; Shah, S.P. The modification effects of a nano-silica slurry on microstructure strength, and strain development of recycled aggregate concrete applied in an enlarged structural test. *Constr. Build. Mater.* **2015**, *95*, 721–735. [CrossRef]
21. Xu, J.; Wang, B.; Zuo, J. Modification effects of nanosilica on the interfacial transition zone in concrete: A multiscale approach. *Cem. Concr. Compos.* **2017**, *81*, 1–10. [CrossRef]
22. Ghazy, A.; Bassuoni, M.T.; Shalaby, A. Nano-modified fly ash concrete: A repair option for concrete pavements. *ACI Mater. J.* **2016**, *113*, 231–242. [CrossRef]
23. Cheng, Y.; Shi, Z. Experimental study on Nano-SiO_2 Improving concrete durability of bridge deck pavement in cold regions. *Adv. Civ. Eng.* **2019**, *2019*, 1–9. [CrossRef] [PubMed]
24. Mamlouk, M.S.; Zaniewski, J.P. *Material for Civil and Construction Engineers*; Pearson Education: Harlow, Essex, UK, 2011.
25. Russell, H.G. HPC Bridge Views. Federal Highway Administration and the National Concrete Bridge Council. November 2010. Available online: http://www.hpcbridgeviews.com/i64/Article4.asp (accessed on 2 April 2016).
26. Bentz, D.P. A virtual rapid chloride permeability test. *Cem. Concr. Compos.* **2007**, *29*, 723–731. [CrossRef]
27. Joshi, P.; Chan, C. *Rapid Chloride Permeability Testing*; Hanley-Wood, LLC: Washington, DC, USA, 2002.
28. ASTM C1723-16, Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy. ASTM International. 2010. Available online: https://www.astm.org/Standards/C1723.htm (accessed on 10 October 2016).
29. Balendran, R.V.; Pang, H.W.; Wen, H.X. Use of scanning electron microscopy in concrete studies. *Struct. Surv.* **1998**, *16*, 146–153. [CrossRef]