Influence of Addition of Nano-Silica on Physical and Mechanical Properties of Ultra-High Performance Mortar and Concrete

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Abstract - *Concrete is the most used universal element or ingredients among all other building materials. Certain admixtures are added to cement to overcome the problems such as durability, toughness, strength, low permeability and resistance to chemical attack. The application of nanotechnology in concrete has added a new dimension to the efforts to improve its properties. Addition of nanomaterial modifies the properties of concrete by changing its microstructure by their small particle size. The objective of this research is to study the physical and mechanical properties of mortar and concrete with addition of nano materials such as nano-silica. The addition of nano-silica will be in the range of 0.6% for partial replacement of cement by weight. Different kinds of aggregates such as dolomite, crushed granite were used in different mixes of concrete and only one mix with sand without any coarse aggregate. Water binder ratio of 0.2 is used. Optimum compression, splitting tensile and flexure strength results were observed at 0.6% nano-silica admixtures and dolomite as aggregate concrete mix. Minimum absorption results were obtained at 0.6% nano-silica admixtures and dolomite as aggregate concrete mix properties at age 28 days of curing. Compressive strength was studied at 2,7 and 28 days of curing while splitting tensile strength, flexural strength and absorption test are studied and evaluated at 28 days only.*

Key Words: Crushed granite, Nano-Silica, Compressive strength, Flexural strength, Absorption test, Mortar, Concrete.

1. INTRODUCTION

Nanotechnology has gained major attention with its potential uses of particles. Integration of Nano materials such as nano-silica which considered as fine convergent material of 10^{-9} m size with traditional building could possess outstanding and significant properties that can be applied in the construction of buildings [1]. The concrete which possess high durability, high strength, high density, low permeability and resistance to chemical attack when compared to conventional concrete is termed as High Performance Concrete. In high performance concrete usually the concrete contains one or more mineral admixtures such as nano-silica, Meta kaolin, pulverized fly ash, micro silica, Ground Granulated Blast Furnace Slag etc. and super plasticizers as chemical admixture along with conventional concrete elements [2]. The use of nanoparticles in ultra-high performance concrete (UHPC) seems also perspective. These are, for example, nano-silicon dioxide (nano-SiO_2), calcium nano-carbonate (nano-$CaCO_3$), nano-aluminum oxide (nano-Al_2O_3), nano-titanium dioxide (nano-TiO_2) and nano-iron oxide (nano-Fe_2O_3). Their features include a large surface area. Nanoparticles contribute to cement hydration due to their high reactivity, they can act as nano-reinforcement and as filler when they compact the microstructure and the transit zone, thereby decreasing porosity [3]. Most investigations on UHPC described in the literature remain only laboratory research that is not implied for a larger scale concrete production. One of the reasons for this is the absence of relevant standards and lack of experience in interpreting the presented results, as there is no common agreement on the test procedures, geometry of tested samples, concrete age upon testing and curing conditions [4]. In the available literature it can be found that with the addition of Nano-silica in cement or concrete, even at small dosages, Nano-silica can significantly improve the mechanical properties of cementitious materials [5]. For instance, Nazari and Riahi [6] showed that a 70% compressive strength improvement of concrete can be achieved with an addition of 4% (by mass of cement) of nano-silica. Li et al. [7] found that when 3% and 5% Nano-silica were added to plain cement mortar, the compressive strength increased by 13.8% and 17.5% at 28 days, respectively. However, some contradictory experimental results can also be found in the literature. For example, Senff et al. [8] found that the contribution of nano-SiO2, nano-TiO2, and nano-SiO2 plus nano-TiO2 defined by factorial design, did not lead to any significant effect on the compressive strength. Moreover, they also found that the values of torque, yield stress and plastic viscosity of mortars with Nano-additives increased significantly. P. J. et al. [1] studied the strength and durability behavior of UHPC with Nano-silica as admixture partially replacing cement with ratios 0%,5%,10%15%,20% with particle size 15 nm. Sorptivity test, Alkalinity measurement test and water absorption test was investigated at age of 28 days on 30 cubes (10× 10× 10) cm^3 and 15 cylinders (20 ×10) cm. the results showed that nano-silica of 20% by weight of cement reduces the pores amount and makes the concrete denser in micro-structure level which in turn increases the strength and durability. Land and Stephan [9] observed that the hydration heat of Ordinary Portland Cement blended with nano-silica in the main period increases significantly with an increasing surface area of silica. Thomas et al. [10] showed that the hydration of tri-calcium silicate (C_3S) can be accelerated by the addition of nano-scaled silica or C–S–H-particles.

The objective of this study is to investigate the characteristics properties effect of nano-silica of ratio 0.6% by weight of cement on the physical and mechanical and development of properties of UHPC with low binder amount using different kinds of aggregates and analyze strength of concrete by comparing the different hardened concrete specimens of different kinds of aggregates used.

2. Materials

In this study, ordinary Portland cement, silica fume, coarse sand, crushed granite, crushed dolomite, Nano silica, super plasticizer and ordinary tap water were used for the development of UHPC mix and for the entire tests. More specifically, the raw materials used in this study were described as follows.

2.1. Portland cement

The cement used in this study was ordinary Portland cement Type I CEM 52.5 N from El-Arish Portland cement company. Testing cement was conducted according to (ESS4756-1/2013). Tables 1 and 2 illustrate physical and chemical properties of used cement respectively.

Table -1: Physical and mechanical properties of Portland cement (CEM I 52.5N).

Properties	Test results	Limits (ESS 4756-1/2013)
Specific gravity	3.15	-----
Initial setting time (min.)	114 min.	Not less than 45 min.
Final setting time (min.)	240 min.	Not more than 10 hours
Fineness of cement (sieve No.170)	0.04	Not more than 10%
Expansion of cement (mm)	2mm	Not more than 10mm
Compression strength of standard mortar	2 days (MPa)=23.3	Not less than 10 MPa
	28 days (MPa)=81.4	≥ 52.5MPa

Table -2: Chemical composition of Portland cement (CEM I 52.5N).

CEM I 52.5 N	Chemical analysis (%)	ESS 4756-1/2013
SiO_3	22.43	
Al_2O_3	4.82	
Fe_2O_3	3.44	
CaO	61.92	
MgO	1.18	
SO_3	2.45	≤ 4.0% for 52.5 N and R
L.O.I.	2.25	
Na_2O	0.43	
K_2O	0.24	
TiO_2	0.47	
P_2O_5	0.18	
Mn_2O_3	0.06	
Total	99.87	
Ins.Res.	0.49	≤ 5.0%
CI	0.08	≤ 0.10%
Na_2O Eq	0.60	
LSF	0.85	
C_3A	6.97	

2.2. Aggregates

2.2.1. Fine aggregate

Locally available natural sand obtained from was used as fine aggregate in the preparation of all test specimens according to (ECP:203-2018). Physical properties of fine sand used for the entire mixtures is shown in Table 3.

Table -3: Physical properties of sand.

Properties	Test results	Limits
Specific gravity	2.5	2.5-2.35
Absorption test (%)	1.523	Not more than 2%
Clay and fine impurities (by weight%)	2.5	Not more than 2.5 %
Fineness modulus	2.6	-------

2.2.2. Coarse aggregate

Locally available crushed granite and dolomite obtained from were used as coarse aggregate according to (ECP: 203-2018) in this research study. Tables 4 ,5 and 6 show the chemical composition of crushed granite, dolomite and physical properties of each one respectively.

Table -4: Chemical composition of crushed granite.

Crushed granite	Chemical analysis (%)
Oxygen (O)	58.01
Sodium (Na)	0.89
Magnesium (Mg)	1.26
Aluminum (Al)	6.91
Silicon (Si)	17.76
Potassium (K)	3.01
Calcium (Ca)	0.92
Titanium (Ti)	0.96
Iron (Fe)	10.28

Table -5: Chemical composition of dolomite.

Dolomite	Chemical analysis (%)
SiO_3	0.49
Al_2O_3	0.1
Fe_2O_3	0.1
CaO	31.78
MgO	20.85
Na_2O	0.1
K_2O	0.1

Table -6: Physical properties of dolomite and crushed granite.

Properties	Test results	Limits
For dolomite:		
Specific gravity	2.7	2.6-2.7
Absorption test (%)	1.39	Not more than 2.5 %
Clay and fine impurities	2.5	Not more than 3%
Maximum nominal size (mm)	9.5mm	--------
For crushed granite:		
Specific gravity	2.7	2.6-2.8
Maximum nominal size (mm)	9.5 mm	----------

2.3. Admixtures

2.3.1. Mineral admixtures

Mineral admixtures such as silica fume was used in this research work as a replacement of cement. The percentage used in silica fume was 15% by weight of cement used [11]. Table 7 illustrates the physical and chemical properties for both silica fume respectively.

Table -7: Physical and chemical properties of silica fume.

Silica fume	Chemical analysis (%)
SiO_2	96
Fe_2O_3	1.45
Al_2O_3	1.10
CaO	1.20
MgO	0.18
K_2O	1.20
Na_2O	0.45
SO_3	0.25
H_2O	0.85
Physical Properties	
Color	Grey
Specific gravity	2.15

2.3.2. Chemical admixtures

Poly-carboxylate super plasticizer of type G according to ASTMC494 supplied by SIKA Company Limited in Egypt under the commercial name Sika Viscocrete was used in this study to attain workability of concrete mixes.

2.4. Nano-Silica

Nano-silica (NS) created by Malvern Instruments Ltd which was used in this research was obtained from National Research Center, Cairo, Egypt of size 17 nm. It is highly active pozzolanic material which improves the overall strength, microstructure of cement, durability and increases the life span of structures. Figure 1 shows TEM of NS while the properties of physical and chemical composition are given below in Table 8.

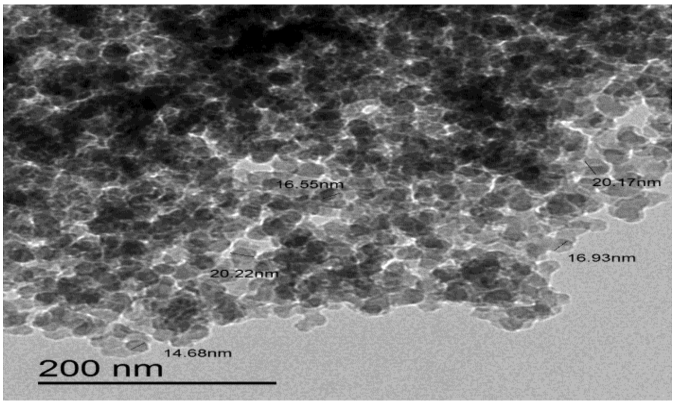

Fig -1: TEM of nano-silica (NS).

Table- 8: Physical and chemical properties of nano-silica.

Description	Results
Molecular	SiO_2
Appearance form	Powder
Color	White
Particle Size (nm)	17
Purity (%)	> 99.9
Dispersant name	Water

2.5. Water

Ordinary drinking water was also used for preparation of the desired concrete mixes and curing.

3. Experimental work

3.1. Mix design for ultra-high performance mortar and concrete

For this study, mortar concrete was developed based on the existing mix proportions through preliminary tests by partial replacement of cement by silica fume and nano-silica. In general, cement was partially replaced by combination of silica fume and nano-silica with different percentages. It was designed using silica fume at 15% by weight [11] and nano-silica at 0.6% by weight [12]. For all mixes, mechanical mixing, standard water curing and uniform water-binder ratio of 0.2 were used. As shown in Table 9, three mixes were utilized.

Table -9: Mix design for 1 M^3 concrete under this study.

Mix	Mix Proportions for 1 M^3 of Concrete(Kg/m^3)							
	CEM	S	Dol.	C.G	SF	NS	SP	W
0.6%NS + dol.	1000	574	574	----	150	6	20	200
0.6% NS+ crushed granite	1000	574	-----	574	150	6	20	200
0.6%NS + sand	1000	982	-----	----	150	6	20	200

3.2. Mix proportion, specimen preparation and curing procedure

In this research, the mix propositions designed in Table 10 were applied. Then, mortar and concrete specimens were prepared based on (ESS4756-1/2013) by preparing watertight and non-absorbent (100×100 ×100) mm^3 cube, (150 × 300) mm^3 cylinder and (100 ×100 ×500) mm^3 prism molds.

For mortar and concrete specimens containing nano-silica, dry mixing of ingredients was done for 1 min. After that, wet mixing was done by adding 75% of water and all of super plasticizer into the dry mixture and was mixed for another 1 min. then nano-silica was sonicated with 25% of remaining water using mechanical sonicator and added to the mixture and remixed for another 1 min. until a visually acceptable mix was obtained.

Mechanical mixing was employed throughout the entire specimen preparations. After getting a uniform mix and placing layer by layer on molds, compaction was employed in three layers by steel compacting rod of square cross-section having (25×25) mm length Once leveling of the surface was made with steel floats, the specimens were left in the molds for one-day till getting dry. After removal of specimens from the mold, the specimens were marked without damaging them. Then, standard curing of the test specimens was done till testing days for 2, 7 and 28 days in water at a temperature of 20 ± 2°C.

3.3. Testing program

For testing, before placing the test specimens centrally in the testing machine, any excess moisture from the surface of the specimen were wiped. Then, three specimens were tested for the mechanical properties of UHPC as per the Egyptian Standard testing procedure for hardened concrete (ECP:203-2018) in High Institute for Engineering and Technology (College)- Concrete and Materials laboratory.

The compressive strength was tested at the age of 2, 7 and 28 days and the tensile splitting strength at age of 28 days and the average values were reported. In addition to this, the flexural strength was determined at age of 28 days.

Beyond the mechanical performance, absorption test of the developed specimens concrete of all mixes were conducted in this study. For this purpose, samples were taken from each mix and dried for 24 hours in the oven at a temperature of 105±5°C after 28 days then the samples were weighted after drying after that the samples were immersed in the water for another 24 hours and weighted again then the absorption percentage for each mix was demonstrated according to (ECP:203-2018).

4. Results

4.1. The effect of addition of Nano-silica to different kinds of aggregates on mechanical properties of mortar and concrete

Nano-silica as a pozzolanic material has shown improvement in the strength and durability of concrete. Also, it has complex effects on hydration of cements which led to consuming calcium hydroxide in concrete and forms more calcium silicate hydrate [9]. Characteristics like, durability, impermeability and volume stability may be important in some case of designing concrete structure but strength is the most important one since an overall picture of concrete quality is being reflected by the concrete strength [13].

In this study, after partial replacement of cement by nano-silica at 0.6% percentage, using different kinds of aggregates and tested at different ages, its properties were identified and investigated. The mechanical performances of the ultra-high performance mortar and concrete in this study were evaluated by compressive, splitting tensile and flexural strength. Table 10 shows the mechanical properties of ultra-high performance mortar and concrete containing nano-silica and different kinds of aggregates.

Table- 10: Mechanical properties of UHP mortar and concrete containing 0.6% NS and different kinds of aggregates.

Mix designation	2 days (MPa)	7 days (MPa)	28 days (MPa)		
	Comp. str.	Comp. str.	Comp. Str.	Flex. Str.	Split. Ten. Str.
15%SF+0.6%NS + dol.	49	68.6	80.21	11.37	14.15
15% SF+0.6% NS + crushed granite	50.31	62.39	74.375	15	12.38
15%SF+0.6%NS + sand	40.18	43.77	58.33	22.8	10.61

The mean compressive strengths of three concrete specimens including control mix were presented in Chart 1.

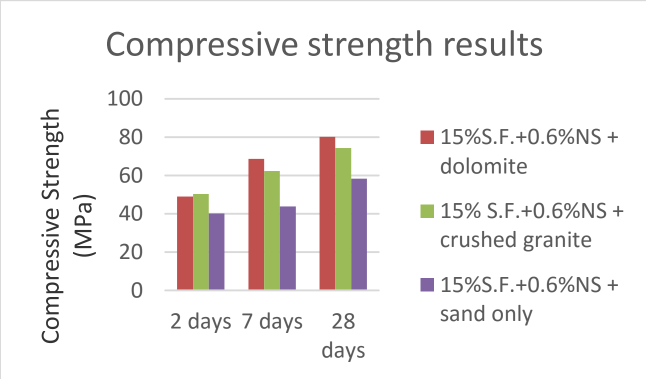

Chart -1: Compressive strength results of four mixes at different ages of curing.

As shown in Chart 1, the compressive strength increases with the curing age in all mix. In early age at 2 days standard curing, 50.31 MPa were observed as a maximum mean value using in mix 2 containing 0.6% nano-silica and crushed granite as coarse aggregate. In 7 days standard curing, 68.6 MPa maximum strength were observed in mix 1 containing 0.6% nano-silica and dolomite. Similarly, in 28 days standard curing, mix 1 gives a maximum mean compressive strength of 80.21 MPa compared to remaining mixes.

On the other hand, the effect of addition of nano-silica to different kinds of aggregates on splitting tensile strength of UHP mortar and concrete were evaluated in this study. Figure3 shows the splitting tensile strength of concrete produced in this study. As it was observed in Chart 2, the maximum splitting tensile strength were in mix 1 containing 0.6% nano-silica and dolomite as coarse aggregate combinations.

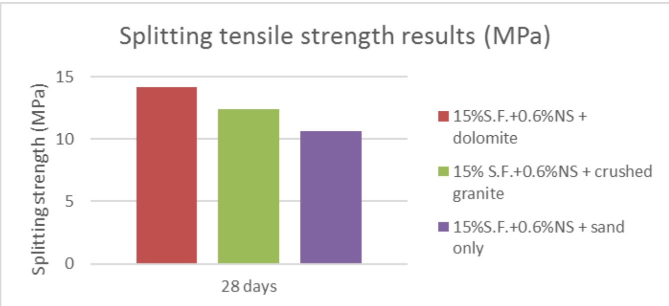

Chart -2: Splitting tensile strength results of four mixes at different ages of curing.

The other mechanical strength evaluation for the developed concrete in this study was performance evaluation by flexural strength of beams. Chart 3 shows the flexural strength of concrete containing 0.6% nano-silica (NS) and different kinds of aggregates in different mixes of concrete and mortar. Accordingly, a maximum flexural strength 22.8 MPa was observed in mix 3 using 0.6% nano-silica (NS) and sand only.

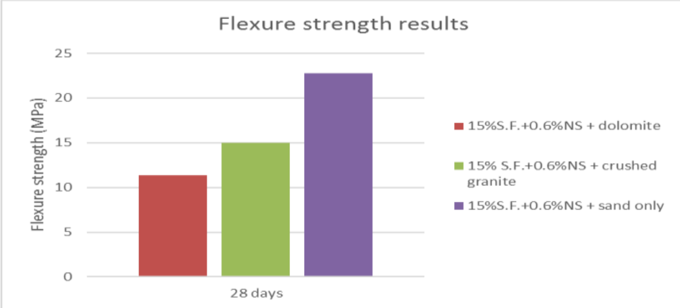

Chart -3: Flexural strength results of four mixes at age28days of curing.

Accordingly, in this study the combined effect was evaluated for partial replacement of silica fume and nano-silica by weight of cement and using different kinds of aggregates in concrete development. The experimental results indicated that a mean compressive strength of 80.21 MPa, and 14.15 MPa splitting tensile strength were developed using dolomite aggregate, while flexural strength of 22.8 MPa was developed using sand only at age of 28 days.

4.2. The effect of addition of nano-silica on different kinds of aggregates on absorption properties of mortar and concrete

4.2.1. Absorption test

The absorption properties of mortar and concrete products are shown in Table 11 and Chart 4 which illustrate the absorption results of alternative specimens of mortar and concrete at age of 28 days of curing. It is shown that minimum absorption result (%) 2.128% was conducted in mix 1 using 0.6% nano-silica and dolomite as coarse aggregate at 28 days.

Table- 11: Absorption results of mortar and concrete containing NS and different kinds of aggregates.

Mix designation	Absorption results (%) at age 28 days
0.6%NS + dolomite	2.128
0.6%NS + crushed granite	2.350
0.6%NS + sand	2.174

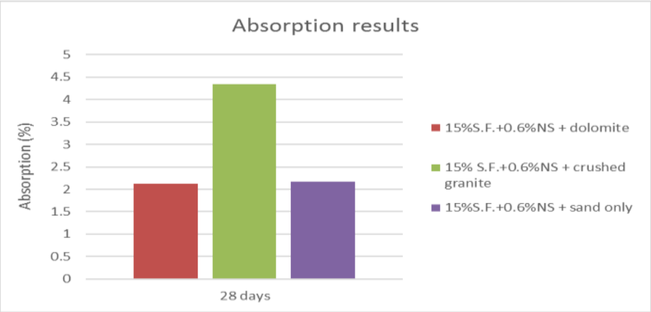

Chart -4: Absorption results (%) of four mixes at age 28 days.

5. CONCLUSIONS

This study was conducted to evaluate the mechanical and durability properties of concrete containing silica fume and Nano-silica for partial replacement of cement as well as different kinds of aggregates. Standard curing was adopted for this study. Accordingly, the following conclusions can be drawn:

- In all concrete mix designs good pozzolanic effect and good density were observed.
- The mechanical strength of concrete was increased with the curing age. Accordingly, for partial replacements of cement by nano-silica using different kinds of aggregates, 80.21 MPa compressive strength, 14.15 MPa tensile splitting strength were observed at age 28 days of curing for mix containing 0.6% nano-silica and dolomite as coarse aggregate while in flexural strength 22.8 MPa was observed using sand only as aggregate.
- Good absorption percentage was observed from the absorption analysis. Hence, for partial replacement of cement by nano-silica using different kinds of aggregates in UHP mortar and concrete, 2.128% absorption analysis was achieved for the mix containing and 0.6% nano-silica and dolomite as coarse aggregate at age 28 days of curing.

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