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Effect of using nano-silicates in concrete strength properties (A laboratory study)

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ABSTRACT

The presented study attempted to investigate mechanical properties of concrete containing nanosilicates based on experimental uniaxial compressive strength test (UCS). For this purpose, different nanosilica dosages including 0%, 2%, 4% and 6% with considering the cement/water ratio are used to preparing the totally 10 mixing scheme and 30 concrete laboratory samples (10×10×10 cm cubic specimens) which is tested under 7, 28 and 90 days age. According to the experimental results by increasing the amount of nanosilica in the samples, UCS is increased and mechanical properties of concrete improved under loading. But in 6% nanosilica specimens incremental slope is get smooth then 4% nanosilica specimens. This was also observed for the 28-day and 90-day samples. In the meantime, some samples containing 6% nanosilica under uniaxial pressure experienced a resistance drop in strength features, indicating a decreasing trend of durability improvement at values above 6% nanosilica.

1. Introduction

Concrete is the most adaptable material because of the constant and persistent requests made on engineers which are consistently pushing the confinement points to improve its performance with the assistance of creative chemical admixtures and supplementary cementitious materials like fly ash, silica fume, granulated blast furnace slag, steel slag and so on. As known, concrete must be capable to service under many conditions and during its lifetime which have appropriate performance. Such concrete is called durable or strength concrete. The lack of stability or durability in concrete may be due to internal or ambient factors that are imposed on the concrete components such as cementitious materials (Dodds et al., 2017). The authority of these materials in the construction task and civil projects is very worthy of attention which their variety of applications must not hide their complexity where develop gradually in our time (Gaitero et al., 2008). Generally, concrete is a composite material which composed of fine and coarse aggregate bonded together by fluid cement that hardens over time were most frequently in the past a lime-based cement binder (e.g. lime putty), but sometimes with other hydraulic cements (e.g. calcium aluminate cement) or with Portland cement to form Portland cement concrete (Li, 2004). By modifying this concrete mixing system it is possible to change the structure and properties of these materials. For example, use of plug-ins likes geosynthetics, fibers, nanomaterials, etc. in concrete help to improve the primary conditions.

Meanwhile, in recent years, concrete technology applied the cement composites modification by nanoparticles which are highly considered as novel concept in concrete modification task by many researchers for fabricate concrete composite materials with new functionalities. Nanoparticles due its high surface-area-to volume ratio capacity always influenced directly on mechanical properties and concrete behavior (Aggarwal et al., 2015). These cementitious based materials performance is strongly dependent on nanoparticles (e.g. calcium silicate hydrate particles) or nano porosity at interfacial transition zone between cement and aggregate particles (Li et al., 2004; Collepardi et al., 2005; Senff

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et al., 2009). The main engineering propertied of concrete which is highly affected by nanoparticles is classified in strength, durability, shrinkage and steel-bond features. In the meantime, nano-silicates (SiO_2) can infill the interpolated space between the calcium silicate hydrate particles were acting as nano-filler and by taking the pozzolanic reaction with calcium hydroxide produced the more densification matrix of calcium silicate hydrate mixture that leads to increased uniaxial concrete strength, durability, stability, crack controlling, interlocking, etc. (Choolaei et al., 2012; Hou et al., 2013; Zapata et al., 2013; Aggarwal et al., 2015; Azarafza et al., 2015; 2017).

In concrete mixing, nano-silica decreased the mortar setting time compared with silica fume and reduced water bleeding and segregation which is improved the cementitious mixtures cohesiveness (Tegguer et al., 2013; Janković et al., 2016; Norhasri et al., 2017; Behfarnia and Rostami, 2017). Nanosilicate added to cement in addition to reducing concrete retention time (Singh et al., 2011; 2012), shortened dormant duration, induction hydration period, reduction in hydration peak heat time reach and increased calcium hydroxide production at early days (Ltifi et al., 2011; Shaikh et al., 2014; Taghavi et al., 2018).

Exclusively, the application of nanoparticles has had a great impact on concrete technology in past decade. Several scholars presented studied on nanoparticles especially nanosilicates and attempted to provide a logical link between nanomaterials and mechanical and engineering properties of concrete (Shih et al., 2006; Land and Stephan, 2012; Shaikh et al., 2014; Janković et al., 2016; Behfarnia and Rostami, 2017; López-Carrasquillo and Hwang, 2017). Also, the some articles indicate the nanofibers and nanotubes utilizations on engineering characteristics of concrete (Sanchez and Sobolev, 2010; Peyvandi et al., 2013; Eftekhari and Mohammadi, 2016; Bosque et al., 2017; Zhu et al., 2018).

In this study tried to investigate the nanosilicates affect on concrete specimens under uniaxial compressive strength test (UCS) which is used for preparing the empirical relationships between the nanoparticles and strength characteristics of concrete.

2. Material and Methods

Materials used for the concrete specimen's preparation include cement, aggregates (sand and lycra), nanosilica additives, water and super-lubricant. The cement used for testing Portland pozzolani cement (PPC) from Ardebil cement factory which cement specification is 3130 kg/m^3 (according to the factory catalog). Drinking water is the most suitable water for concrete preparation. In this experiment, Tabriz drinking water was used for mixing.

The utilized aggregate grading curve was performed according to ASTM-C136 which is shown in Figure 1. For nanosilica additives, the colloidal silica solution is used which specified as Table 1. The lubricants are manufactured according to the ASTM-C494 requirements as A&F types and 2930 Iranian standard code for concrete. The table 1 is representing the utilized concrete materials characteristics.

Table 1 Used materials specification in this study

Cement composition				
Compounds	C_3S	C_2S	C_3A	C_3AF
Percent	35-60	20-35	9-11	9-12
Nanosilica properties				
Specific weight (gr/cm^3)	Particle content (%)		Particle size (nm)	
1.37	50.9		Less than 50 nm	
Lubricant feature				
pH	Specific weight (kr/lit)		Color	
7±1	1.112		Brown	

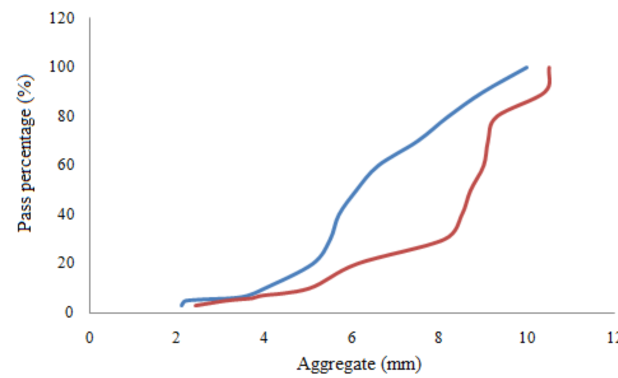

Figure 1. Particle-size distribution of aggregate

Specimens used in each mixing (totally 10 mixing scheme) prepared for the mechanical properties testing of concrete including 30 cubic samples (10×10×10 cm) for compressive strength test (UCS) at 7, 28 and 90 days of age. The Figure 2 shows an overview of the some used examples. It should be noted during the sample preparation phase, inside the samplers is entirely lubricated which that there is no cohesion between the mold and the concrete sample.

Figure 2. An overview of the some used concrete specimens

The 10 mixing scheme are prepared for samplings which is contained 3 step of nanosilicate additives (0%, 2%, 4% and 6%) were classified in 30 samples. The ACI-211 standard absolute volume method was used to determine the mixing ratios of the concrete components and aggregates volume. The water/cement ratio (W/C) in concrete mixing scheme (after reduction of aggregates moisture content) has been assumed as 0.35 which is obtained from overall mixing scheme formula presented by American concrete institute (ACI). Table 2 is presented the 10 mixing scheme were used in this study, the mix1 is considered as reference mix due non nanosilicate contains. Other mixtures are contained 2%, 4% and 6% nanosilicates. After mixing, the concrete is poured into the molds and after 24 hours the specimens are opened and molded in ordinary water at 20 °C for processing. After the processing time (7, 28 and 90 days), the concrete was removed from the water and weighed, then placed in the oven at 105 °C to dry completely for 24 hours. After drying, the samples were brought to normal temperature for several hours to prepare for testing (If the samples do not return to their normal temperature, the strength values will associate with the errors).

Table 2 The mixtures scheme for preparing concrete samples

#	W/C	Water (Kg/m^3)	Cement (Kg/m^3)	Nano slica	Coarse-grained	Light-grained	Lubricant ratio	Sample
1	0.35	175	500	0	844	120	0	3
2	0.35	171.5	490	2	844	120	2	3
3	0.35	168	480	2	844	120	2	3
4	0.35	164.5	470	2	844	120	2	3
5	0.35	161.7	462	4	844	120	2	3
6	0.35	158.2	452	4	844	120	2	3
7	0.35	154.7	442	4	844	120	2	3
8	0.35	150.5	430	6	844	120	2	3
9	0.35	145.2	415	6	844	120	2	3
10	0.35	141.7	405	6	844	120	2	3

Uniaxial compressive strength (UCS) is key methodologies for investigation under axial loading for evaluate concrete mechanical behavior assessment. Compressive strength or compression strength is the material (nature of artificial) capacity to withstand loads tending to mechanical deformation (reduce size, shortening and pulping) which related to mechanical behavior of materials. In other words, UCS is representation of compressing behavior of concrete of materials as stress-strain curve. When a specimen of material is loaded in axial direction, the material is falls in stress field in different scale (all trend surface and subatomic levels) for reduction of stress field conditions, the materials are deformed as strains. By definition, the material's compressive strength fails completely when that UCS stress value reached to ultimate compression stress. The UCS is usually obtained experimentally by means of a compressive test were illustrated by ASTM D7012, ASTM D2938 and ASTM C39/C39M. The UCS of the material was corresponding to the stress value in rapture point in stress-strain curve which is shows the final tolerance (Kett, 2009).

In this study used the universal testing machine (UTM) for evaluate the uniaxial compressive strength of concrete samples after preparations. Figure 3 are is the view of the UTM device and a sample which being tested on this device.

Figure 3. The UTM test device

After conducting the UCS test on studied samples the variation of concrete compressive strength (σ_c) for 7, 28 and 90 day ages are estimated and prepared the results which is attempted to find relationship between nanosilicate percentage and σ_c.

3. Results and discussions

Table 2 is presented the mix design scheme of concrete samples preparation. In this mix design the first mix (Mix 1) is used as a control example to evaluate the nanosilicate behavior compared to the initial state. The results of the observational tests are presented in Table 3 and figure 4. According to this figure, the variations of σ_c for samples are increases form 7 day to 90 day ages and nanosilicate contain in these samples are zoro. As results of UCS, the 22.13 MPa to 29.31 MPa is measured for the samples.

Table 3 Results of UCS test for mix design 1 (non nano-silicate)

Mix No.	Sample	Uniaxial compressive strength (MPa)		
		7 day age	28 day age	90 day age
1	M1A1	22.13	27.55	29.11
1	M1A2	22.17	27.96	29.31
1	M1A3	22.25	28.02	28.59

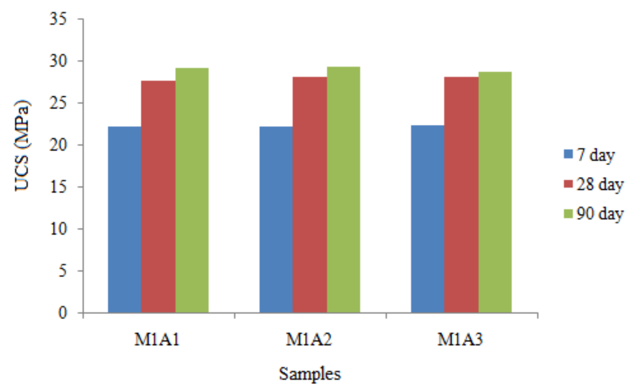

Figure 4. UCS variation of Mix 1 samples

By addition of the nanosilicate to the concrete mixture, it is expected that the resistance value of uniaxial samples show increase which is represented the link of nanoparticles impact of strength of concrete. For this purpose, it has been attempted to increase the percentage of nanomaterials added to the concrete in a stepwise manner to evaluate the variation of different ratios for concrete strength vs variation of different ratios for nanosilicate. The table 4 and figures 5 to 7 are present the variation of UCS for concrete samples contain 2% nanosilicate in mixture (Mix 2 to Mix 4). According to the results of UCS experiments, the σ_c for samples are increases form 7 day to 90 day ages were 28.11 MPa to 36.88 MPa.

Table 4 Results of UCS test for mix design 2/4 (2% nanosilicate)

Mix No.	Sample	Uniaxial compressive strength (MPa)		
		7 day age	28 day age	90 day age
2	M2A1	28.71	36.36	38.70
2	M2A2	28.69	35.98	38.63
2	M2A3	28.11	36.57	38.85
3	M3A1	28.59	36.04	38.83
3	M3A2	29.01	36.45	38.71
3	M3A3	28.63	36.99	38.49
4	M4A1	28.98	35.98	38.24
4	M4A2	28.63	36.12	38.88
4	M4A3	29.01	36.56	38.79

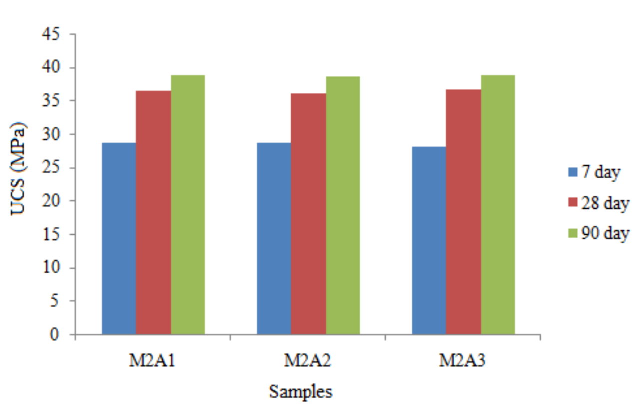

Figure 5. UCS variation of Mix 2 samples

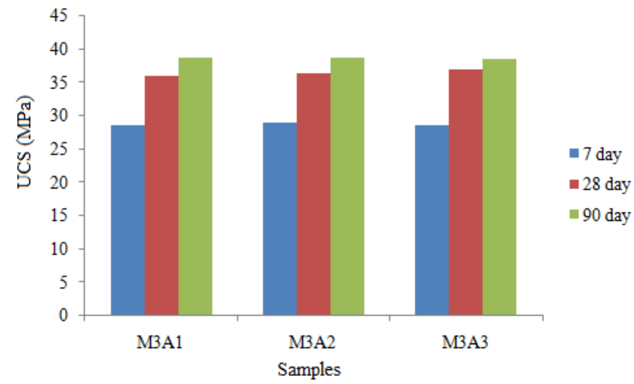

Figure 6. UCS variation of Mix 3 samples

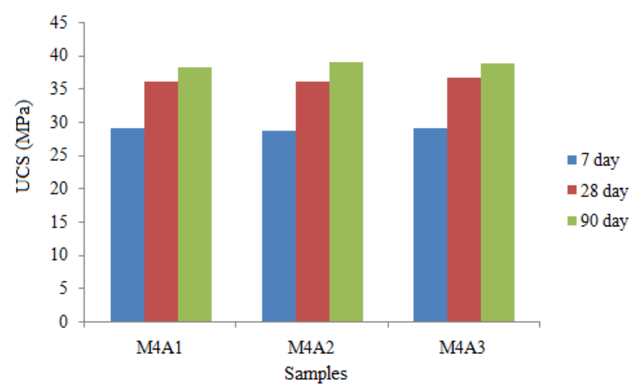

Figure 7. UCS variation of Mix 4 samples

As can be seen in the above figures, an increase of 2% nanosilicate to concrete samples approximately increases its uniaxial compressive strength from 5.98 MPa for 7 day ages to 7.57 MPa for 90 day ages. In the next step, we increase the nanosilicate content of concrete samples from 2% to 4%. In this increase other concrete properties are considered as same for all mixtures. Table 5 and figures 8 to 10 are illustrated the variation of UCS for concrete samples contain 4% nanosilicate in mixture (Mix 5 to Mix 7). According to the results of UCS experiments, the σ_c for samples are increases form 7 day to 90 day ages were 24.58 MPa to 42.46 MPa.

Table 5 Results of UCS test for mix design 5/7 (4% nanosilicate)

Mix No.	Sample	Uniaxial compressive strength (MPa)		
		7 day age	28 day age	90 day age
5	M5A1	24.45	38.72	42.42
5	M5A2	24.48	37.92	42.36
5	M5A3	25.71	38.63	42.58
6	M6A1	25.11	38.63	42.46
6	M6A2	25.56	38.46	42.22
6	M6A3	24.68	38.84	42.42
7	M7A1	24.63	37.99	42.35
7	M7A2	25.49	38.51	42.48
7	M7A3	24.56	38.72	42.55

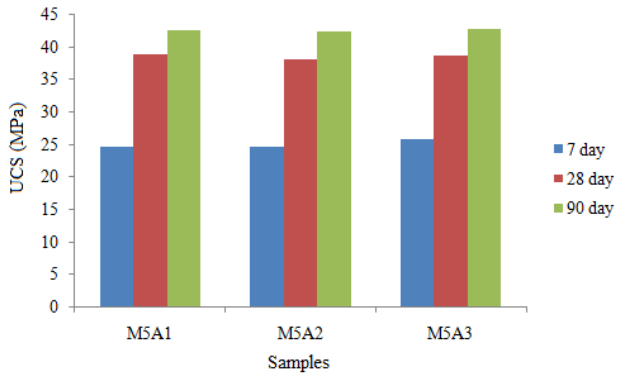

Figure 8. UCS variation of Mix 5 samples

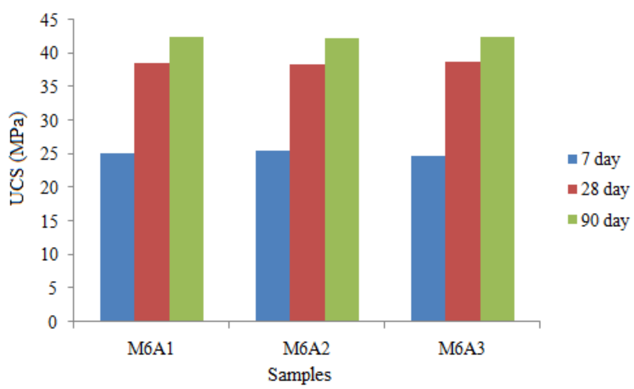

Figure 9. UCS variation of Mix 6 samples

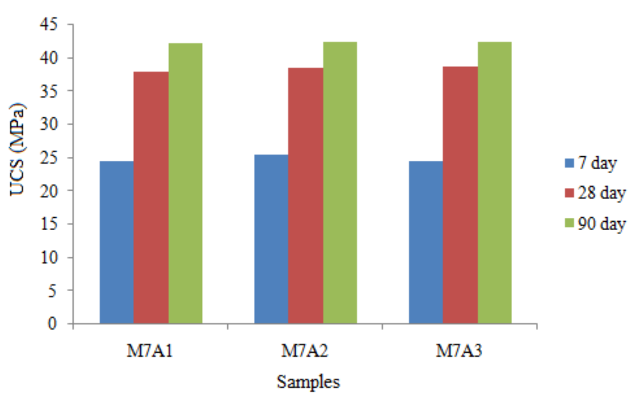

Figure 10. UCS variation of Mix 7 samples

According to the above figures, an increase of 2% to 4% nanosilicate to concrete samples approximately increases its uniaxial compressive strength from 3.53 MPa for 7 day ages to 5.58 MPa for 90 day ages (compared to 2% nanosilicate samples) and increases UCS from 2.45 MPa for 7 day ages to 13.15 MPa for 90 day ages (compared to observational samples). Based on the measured results, it can be concluded that the slope of the changes has a significant trend in increasing uniaxial strength in concrete specimens. During the final stage, the nanosilicate content in concrete samples is increasing from 4% to 6%. Table 6 and figures 11 to 13 are illustrated the variation of UCS for concrete samples contain 6% nanosilicate in mixture (Mix 8 to Mix 10).

Table 6 Results of UCS test for mix design 8/10 (6% nanosilicate)

Mix No.	Sample	Uniaxial compressive strength (MPa)		
		7 day age	28 day age	90 day age
8	M8A1	37.87	42.77	47.38
8	M8A2	37.45	42.58	47.63
8	M8A3	37.50	42.69	47.47
9	M9A1	37.45	42.59	47.19
9	M9A2	38.03	42.74	47.38
9	M9A3	37.96	42.63	47.60
10	M10A1	37.44	42.70	47.55
10	M10A2	37.89	42.77	47.63
10	M10A3	38.03	42.75	47.47

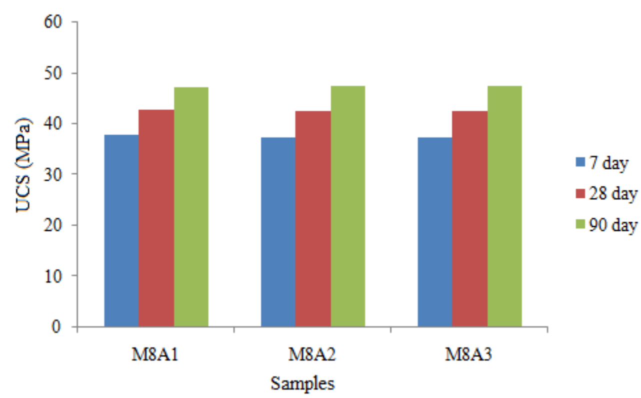

Figure 11. UCS variation of Mix 8 samples

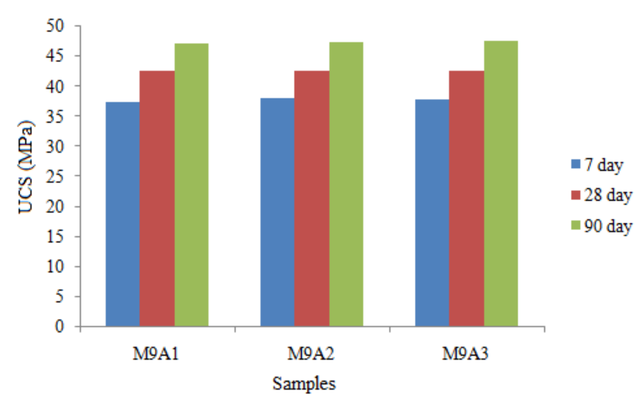

Figure 12. UCS variation of Mix 9 samples

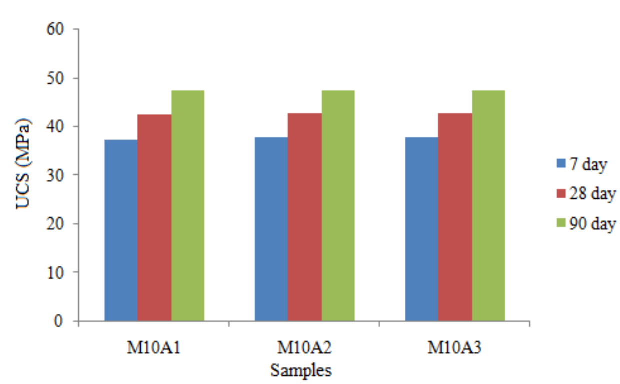

Figure 13. UCS variation of Mix 10 samples

According to the results, the σ_c for samples are increases form 7 day to 90 day ages were 37.45 MPa to 47.63 MPa which an increase of 4% to 6% nanosilicate to concrete samples approximately increases its uniaxial compressive strength from 12.87 MPa for 7 day ages to 5.17 MPa for 90 day ages (compared to 4% nanosilicate samples); increases UCS from 9.34 MPa for 7 day ages to 10.75 MPa for 90 day ages (compared to 2% nanosilicate samples) and increases UCS from 15.37 MPa for 7 day ages to 18.32 MPa for 90 day ages (compared to observational samples).

By applying the regression analysis on nanosilicate changes with concrete samples's UCS, able to evaluate the strength fluctuations in concrete samples. Table 7 is present the statistical analysis of UCS results variation and figure 14 is illustrate the UCS variations measured form samples and figures 15 and 16 is presented nanosilicate impact on concrete compressive strength enhancement.

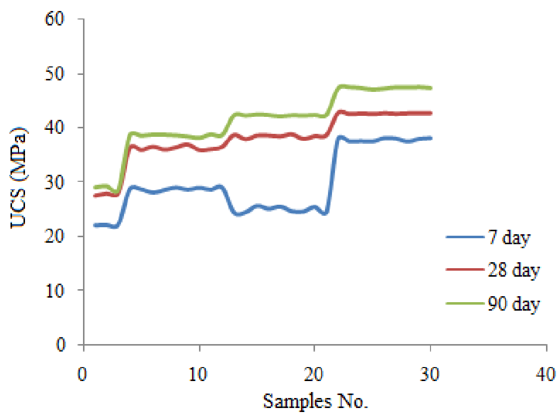

Figure 14. Variation of UCS in samples

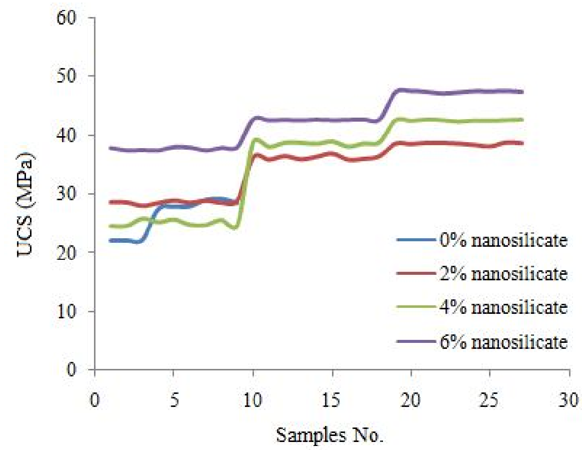

Figure 15. Variation of nanosilicate vs UCS in samples

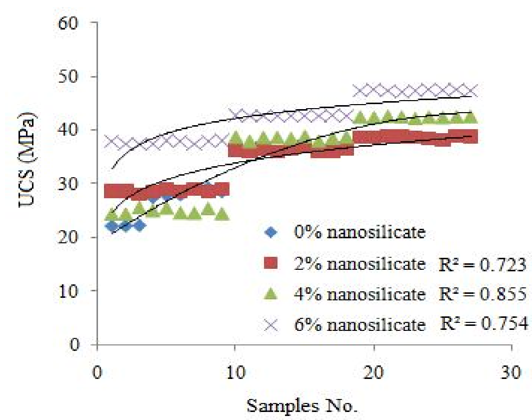

Figure 16. Regression analysis of nanosilicate vs UCS in samples

Table 7 Statistical analysis of UCS vs nanosilicate results variation

Mix No.	Samples	Standard deviation			Variance			Skew		
		7 day	28 day	90 day	7 day	28 day	90 day	7 day	28 day	90 day
1	M1A1/ M1A2/M1A3	0.061	0.255	0.371	0.003	0.065	0.138	0.935	-1.625	-1.185
2	M2A1/ M2A2/M2A3	0.340	0.299	0.112	0.116	0.089	0.012	-1.725	-0.822	1.007
3	M3A1/ M3A2/M3A3	0.231	0.476	0.172	0.053	0.227	0.029	1.674	0.405	-0.837
4	M4A1/ M4A2/M4A3	0.211	0.302	0.346	0.044	0.091	0.012	-1.693	1.324	-1.601
5	M5A1/ M5A2/M5A3	0.719	0.438	0.113	0.516	0.192	0.012	1.728	-1.650	1.205
6	M6A1/ M6A2/M6A3	0.440	0.190	0.128	0.193	0.036	0.016	0.068	0.313	-1.545
7	M7A1/ M7A2/M7A3	0.517	0.375	0.101	0.268	0.141	0.010	1.696	-1.144	-0.852
8	M8A1/ M8A2/M8A3	0.229	0.095	0.126	0.052	0.009	0.016	1.640	-0.467	0.801
9	M9A1/ M9A2/M9A3	0.316	0.077	0.205	0.100	0.006	0.042	-1.637	1.229	0.218
10	M10A1/ M10A2/M10A3	0.308	0.036	0.080	0.095	0.001	0.006	-1.339	-1.152	-3.996

4. Conclusion

The effects of the addition of different nanosilica dosages contain 0%, 2%, 4% and 6% on compressive strength and engineering properties of concrete. For this purpose, totally 10 mixing scheme and 30 concrete laboratory samples (10×10×10 cm cubic specimens) are prepared with water/cement ratio (W/C) as 0.35. According to the experimental investigators by increasing the amount of nanosilica in the samples, UCS is increased and mechanical properties of concrete improved under loading. As results for zero nanosilcate concrete (observational Mix 1) is estimated from 22.13 MPa to 29.31 MPa. By additional 2% nanosilicate in mixture (Mix 2 to Mix 4), the UCS of samples are increases form 7 day to 90 day ages as 28.11 MPa to 36.88 MPa which approximately increases its uniaxial compressive strength from 5.98 MPa for 7 day ages to 7.57 MPa for 90 day ages. By increasing the nanosilicate content of concrete samples from 2%

to 4%, the σ_c obtained as 24.58 MPa to 42.46 MPa for samples which UCS increases 3.53 MPa for 7 day ages to 5.58 MPa for 90 day ages (compared to 2% nanosilicate samples) and increases UCS from 2.45 MPa for 7 day ages to 13.15 MPa for 90 day ages (compared to observational samples). The UCS measured for concrete samples contain 6% nanosilicate in mixture (Mix 8 to Mix 10) are estimated as 37.45 MPa to 47.63 MPa which approximately increases its uniaxial compressive strength from 12.87 MPa for 7 day ages to 5.17 MPa for 90 day ages (compared to 4% nanosilicate samples); increases UCS from 9.34 MPa for 7 day ages to 10.75 MPa for 90 day ages (compared to 2% nanosilicate samples) and increases UCS from 15.37 MPa for 7 day ages to 18.32 MPa for 90 day ages (compared to observational samples).

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References

Aggarwal P., Singh R.P., Aggarwal Y. (2015). Use of nano-silica in cement based materials—A review. *Cogent Engineering*, 2(1): 1078018.

ASTM C39/C39M (2018). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA.

ASTM D2938 (2002). *Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens*. ASTM International, West Conshohocken, PA.

ASTM D7012 (2014). *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures*. ASTM International, West Conshohocken, PA.

ASTM-C136 (2014). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. ASTM International, West Conshohocken, PA.

ASTM-C494 (2017). *Standard Specification for Chemical Admixtures for Concrete*. ASTM International, West Conshohocken, PA.

Azarafza M., Asghari-Kaljahi E., Moshrefy-far M.R. (2015). Effects of clay nanoparticles added to the bonab landfill soil to reduce the permeability and control of leachate. *Iranian Journal of Environmental Geology*, 8(26): 7-18. [In Persian]

Azarafza M., Feizi-Derakhshi M.R., Azarafza M. (2017). Computer modeling of crack propagation in concrete retaining walls: A case study. *Computers and Concrete*, 19(5): 509-514.

Behfarnia K., Rostami M. (2017). Effects of micro and nano-particles of SiO_2 on the permeability of alkali activated slag concrete. *Construction and Building Materials*, 131: 205-213.

Bosque I.F.S.D., Zhu W., Howind T., Matías A., RojasM.I.S.D., Medina C. (2017). Properties of interfacial transition zones in concrete containing recycled mixed aggregate. *Cement and Concrete Composites*, 81: 25-34.

Choolaei M., Rashidi A.M., Ardjmand M., Yadegari A., Soltanian H. (2012). The effect of nanosilica on the physical properties of oil well cement. *Materials Science and Engineering: A*, 538: 288-294.

Collepardi S., Borsoi A., Olagot J.J.O., Troli R., Collepardi M., Cursio A.Q. (2005). Influence of nano-sized mineral additions on performance of SCC. In: *Proceedings of the 6th International Congress, Global Construction, Ultimate Concrete Opportunities*, Dundee, Scotland, July 2005.

Dodds W., Goodier C., Christodoulou C., Austin S., Dunne D. (2017). Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on microstructure and water ingress. *Construction and Building Materials*, 145: 183-195.

Eftekhari M., Mohammadi S. (2016). Multiscale dynamic fracture behavior of the carbon nanotube reinforced concrete under impact loading, *International Journal of Impact Engineering*, 87: 55-64.

Gaitero J.J., Campillo I., Guerrero A. (2008). Reduction of the calcium leaching rate of cement paste by addition of silica nanoparticles. *Cement and Concrete Research*, 38(8-9): 1112-1118.

Hou P., Kawashima S., Kong D., Corr D.J., Qian J., Shah S.P. (2013). Modification effects of colloidal nano SiO_2 on cement hydration and its gel property. *Composites Part B: Engineering*, 45: 440-448.

Janković K., Stankovic S., Bojovic D., Stojanovic M., Antic L. (2016). The influence of nanosilica and barite aggregate on properties of ultra high performance concrete. *Construction and Building Materials*, 126: 147-156.

Kett I. (2009). *Engineered Concrete: Mix Design and Test Methods*. CRC Press, 246 p.

Land G., Stephan D. (2012). The influence of nano-silica on the hydration of ordinary Portland cement. *Journal of Materials Science*, 47(2): 1011-1017.

Li H., Xiao H.G., Yuan J., Ou J. (2004). Microstructure of cement mortar with nano particles. *Composites Part B: Engineering*, 35: 185-189.

Li, G. (2004). Properties of high-volume fly ash concrete incorporating nano-SiO_2. *Cement and Concrete Research*, 34, 1043–1049.

López-Carrasquillo V., Hwang S. (2017). Comparative assessment of pervious concrete mixtures containing fly ash and nanomaterials for compressive strength, physical durability, permeability, water quality performance and production cost. *Construction and Building Materials*, 139: 148-158.

Ltifi M., Guefrech A., Mounanga P., Khelidj A. (2011). Experimental study of the effect of addition of nano-silica on the behaviour of cement mortars Mounir. *Procedia Engineering*, 10: 900-905.

Norhasri M.S., Hamidah M.S., Fadzil A.M. (2017). Applications of using nano material in concrete: A review. *Construction and Building Materials*, 133: 91-97.

Peyvandi A., Sbia L.A., Soroushian P., Sobolev K. (2013). Effect of the cementitious paste density on the performance efficiency of carbon nanofiber in concrete nanocomposite. *Construction and Building Materials*, 48: 265-269.

Sanchez F., Sobolev K. (2010). Nanotechnology in concrete – a review. *Construction and Building Materials*, 24(11): 2060-2071.

Senff L., Labrincha J.A., Ferreira V.M., Hotza D., Repette W.L. (2009). Effect of nano-silica on rheology and fresh properties of cement pastes and mortars. *Construction and Building Materials*, 23: 2487-2491.

Shaikh F., Supit S., Sarker P. (2014). A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes. *Materials & Design*, 60: 433-442.

Shih J.Y., Chang T.P., Hsiao T.C. (2006). Effect of nanosilica on characterization of Portland cement composite. *Materials Science and Engineering: A*, 424(1-2): 266-274.

Singh L.P., Agarwal S.K., Bhattacharyya S.K., Sharma U., Ahalawat S. (2011). Preparation of silica nanoparticles and its beneficial role in cementitious materials. *Nanomaterial Nanotechnology*, 1: 44-51.

Singh L.P., Bhattacharyya S.K., Singh P. (2012). Granulometric synthesis and characterisation of dispersed nanosilica powder and its application in cementitious system. *Advances in Applied Ceramics*, 111: 220-227.

Taghavi S.K., Shahrajabian H., Hosseini H.M. (2018). Detailed comparison of compatibilizers MAPE and SEBS-g-MA on the mechanical/thermal properties, and morphology in ternary blend of recycled PET/HDPE/MAPE and recycled PET/HDPE/SEBS-g-MA. *Journal of Elastomers & Plastics*, 50(1): 13-35.

Tegguer A.D., Bonnet S., Khalidj A., Baroghel-Bouny V. (2013). Effect of uniaxial compressive loading on gas permeability and chloride diffusion coefficient of concrete and their relationship. *Cement and Concrete Research*, 52: 131-139.

Zapata L.E., Portela G., Suárez O.M., Carrasquillo O. (2013). Rheological performance and compressive strength of super plasticized cementitious mixtures with micro/nano-SiO_2 additions. *Construction and Building Materials*, 41: 708-716.

Zhu X., Gao Y., Dai Z., Corr D., Shah S.P. (2018). Effect of interfacial transition zone on the Young's modulus of carbon nanofiber reinforced cement concrete. *Cement and Concrete Research*, 107: 49-63.