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Comparative study on uniaxial and triaxial strength of plastic concrete containing nano silica

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HIGHLIGHTS

- Obtaining strength parameter of PC by performing uniaxial and triaxial compressive strength.
- Obtaining elastic modulus of PC from stress–strain graph in UU situation.
- The effect of confined pressure on the mechanical properties of PC was investigated.Obtaining the shear strength parameter (ø and c) of PC.

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ABSTRACT

Plastic concrete is used in the manufacture of cut off wall and its mechanical properties is important for performance of dam. In this paper, in order to investigate the durability and mechanical properties of plastic concrete, uniaxial and triaxial compressive strength tests were performed on plastic concrete specimens in different ages (7, 14, 28, 56 and 90 days) and different percentage of replacement cement by nano silica (0, 1.5, 3, 4.5 and 6%) and compressive strength, the stress–strain behavior, elastic modulus, shear strength parameters of plastic concrete have been evaluated. According to the result, as the age of the specimen increases, elastic modulus, compressive strength and triaxial strength of the plastic concrete enhances. Furthermore, although by increasing the amount of nano silica the strength parameters of plastic concrete are improved and workability of concrete is reduced and the amount of elastic modulus of the specimen is almost constant. The results of shear strength parameters also show that the addition of up to 3% of nano silica increases the cohesion and internal friction angle decreases and with over 3% nano silica this trend is reversed and cohesion decreases and friction angle increases.

1. Introduction

The rheology and permeability of various concrete and advantage of nano material as a partial replacement for cement is well established in previous papers [1–11]. Besides, plastic concrete of cut-off wall is buried inside the soil in geotechnical project [12–14]. Two main attributes are necessary. Firstly, they should have enough strength to bear the weight of the dam body and secondly, a low elastic modulus that works seamlessly integrated with the surrounding environment soil [15–19]. If the elastic modulus is much higher than the surrounding soil of cut-off wall, soil and wall do not have load bearing capacity for unified action and cut-off wall will be cracked and its performance will be lost. The high elastic modulus of normal concrete is the reason for not using normal concrete in making the cut-off wall. As a result, plastic concrete satisfies both of the above conditions, and so is used to construct a cut-off wall. The water to cement ratio of plastic concretes is usually considered in the range of 1.5–4 to achieve the low elastic modulus; however, in normal concretes, this range varies between 0.35 and 0.65 [16,20–24].

In the previous researches [25,26], the compressive strength parameters of plastic concrete are investigated by performing uniaxial compressive strength. They showed that the compressive strength of concrete specimens depends on various parameters such as cement and bentonite content, aggregate size and specimen age.

The strength of the concrete and the elastic modulus of the concrete are directly related to each other and with the increase of the concrete strength, the elastic modulus also increases [27–29].

This increase in the elastic modulus of plastic concrete is not acceptable for designers due to its non-compliance with the ICOLD recommendation [20]. In this recommendation, the values of

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elastic modulus of cut-off wall are suggested to be about 4 times the surrounding soil.

On the other hand, the cut-off walls are buried inside the earth and the plastic concrete of these walls is experiencing triaxial conditions. Therefore, in other researches, the triaxial tests are carried out on plastic concrete specimens [30,31]; although most researches on the mechanical behavior of plastic concrete have been carried out in unconfined compression tests [20,32].

In some past studies, to control the changing elastic modulus of plastic concrete, additives have been used. It was initially proposed that some additive such as silica fume would be added to the mixture design of the plastic concrete, which would increase the strength and decrease the permeability, but the elastic modulus would increase unacceptably [33]. As a result, in recent research it was suggested that silica fume replace some of the initial cement mixture design and the results of the studies showed that this solution resulted in an increase in the strength of the plastic concrete and elastic modulus modifications were also controlled [34].

In this paper, according to the past research, the authors decided to perform the uniaxial and triaxial compressive strength test on plastic concrete specimen. The results of the strength parameters and the elastic modulus are extracted from these experiments. In addition, it was decided that nano silica as a Portland cement replacement material was added to the concrete mortar because the nano size of these particles resulted in a uniform dispersion of silica in the specimens and also this process cause the more precise effect of different amount of silica on the durability and mechanical properties of plastic concrete has been investigated.

2. Experimental program

2.1. Mixture design

The main purpose of this experimental program was to investigate the effect of different amounts of nano silica instead of cement on the triaxial behavior of plastic concrete. In this way, the percentage of cement content was eliminated and replaced with the same amount of nano silica particles. For this experimental program, 1.5, 3, 4.5 and 6 percent of nano silica was replaced by weight of cement. Table 1 presents the mixture design. In this mixture design numbers of 1.5, 3, 4.5 and 6 following the aforementioned code show the percentage of cementitious material replacement by nano silica. For instance, the concrete mixture containing 3 percent nano silica is referenced with codes PC3. Other parameters are assumed to be consistent in all of the design mixtures.

2.2. Materials

For the construction of plastic concrete, the same materials are used as normal concrete with the difference being that, in the construction of plastic concrete specimens, a material called bentonite is also added to mixture design; so the materials needed to make plastic concrete are water, cement, bentonite and aggregate.

The cement type II according to ASTM C150 [35] was used. The chemical and physical properties of cement is shown in Tables 2 and 3 (the time of initial and final setting of cement is determined by the Vicat needle test according to ASTM C191 [36]). In addition, the physical properties and chemical composition of bentonite is presented in Tables 4 and 5. Drinking water was used to prepare the concrete specimens.

Coarse aggregates were divided into two classifications of 4.75–9.5 and 9.5–19 mm. The crushed and washed fine aggregates were in the range of 0–4.75 mm. The physical characteristics of aggregates are shown in Table 6 and classification of aggregates is presented in Tables 7 and 8 and Fig. 1.

Nano silica was used as liquid solution and its chemical composition is given in Table 9. It should be noted that the amount of liquid along with nano silica has been reduced from the total amount of water in the mixture design and it is recorded in Table 1.

2.3. Plastic concrete specimens preparation

For making bentonite slurry according to the ICOLD recommendation [20], the entire amount of bentonite powder considered in the mixture design, is poured into the mixer and then mixed at a speed of 1450 rpm. After mixing, due to adequate hydration of bentonite the bentonite slurry remains for 24 h and water evaporation is prevented [37,38].

Afterward, the nano silica is mixed in bentonite slurry. For the blend of nano silica in mortar, the method of high speed combination (dispersion method) was selected and they are stirred together well at high speed for 5 min (120 rpm) [39]. Since nano-silica particles act as fillers in cement paste and activator to promote pozzolanic reactions; therefore, dispersion of nano silica particles plays an important role. Then, the amount of cement and slurry are mixed for one minute in the mixer. This mixing will not be too long, because the cement should not be hardened. After performing the above steps, first the coarse aggregates and then

Table 1
Mixture proportion of plastic concrete specimens.

Mix code	Water/ Binder*	Nano silica (% of cement)	Water (kg/m^3)	Cement (kg/m^3)	Nano silica (kg/m^3)	Bentonite (kg/m^3)	Gravel 4.75–9.5 mm (kg/m^3)	Gravel 9.5–19 mm (kg/m^3)	Sand 0–4.75 mm (kg/m^3)	Slump (cm)
PC0	2.94	0	450	152.7	0	30.5	279.4	475.8	617.9	23
PC1.5	2.94	1.5	444.66	150.44	2.26	30.5	279.4	475.8	617.9	22
PC3	2.94	3	444.44	148	4.7	30.5	279.4	475.8	617.9	20
PC4.5	2.94	4.5	434	145.6	7.1	30.5	279.4	475.8	617.9	18.5
PC6	2.94	6	428.6	143.8	8.9	30.5	279.4	475.8	617.9	17.5

* Summation of nano silica and cement content is assumed as binder.

Table 2
Physical and mechanical properties of cement.

Specific surface area (cm^2/gr)	Initial setting time (min)	Final setting time (min)	Specific gravity (gr/cm^3)	Compressive strength (gr/cm^2)	
				7 days	28 days
2870	130	164	3.05	185	285

Table 3
Chemical properties of cement.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
(%)	20.38	4.13	3.82	62.96	3.5	2.87	0.31	0.95

Table 4
Physical and mechanical properties of bentonite.

Specific surface area, (m^2/kg) × 10^{-3}	413
pH (1:10, soil–water ratio)	9.5
Specific gravity (g/cm^3)	2.79

the fine aggregates are poured into the mixer and mixed for 8–10 min.

Plastic concrete are poured into cylindrical and cubic molds after construction. Fig. 2 shows cubic and cylindrical specimens. After two days, plastic concrete specimens are taken from molds and kept in water-lime tanks until the day of the tests.

Table 5
Chemical properties of bentonite.

Characteristic	Content
Mineral composition in decreasing abundance	Montmorillonite, Calcite, Quartz
Carbonate content (%)	8
Organic content (%)	1.4
CEC, (cmol/kg soil)	68.2
Exchangeable Na^+	48.5
Exchangeable Ca^{2+}	14.2
Exchangeable K^+	3.4
Exchangeable Mg^{2+}	2.1

Table 6
Physical properties of plastic concrete aggregate.

Specific gravity of sand (g/cm^3)	1.55
Saturated surface dry (SSD) of sand	3.4
Specific gravity of gravel (g/cm^3)	1.7
Saturated surface dry (SSD) of gravel	2.3

Table 7
Sand gradation result.

Sieve size (mm)	Percentage passed
9.5	100
4.75	99.5
2.36	82
1.18	46.6
0.6	16.8
0.3	5.7
0.15	1.7
0.075	1.3

Table 8
Gravel gradation result.

Sieve size (mm)	Gravel 4.75–9.5 mm percentage passed	Gravel 9.5–19 mm percentage passed	Combined gravel percentage passed
25	100	100	100
19	100	100	100
12.5	100	59.4	71.2
9.5	95.4	9.3	43.2
4.75	4.6	0.1	0.1

3. Test procedure and apparatuses

3.1. Slump test

After completion of mixing process, slump test is carried out according to ASTM C143 [40]. Based on the recommendation, plastic concrete slump is approximately 18–23 cm [41].

3.2. Compressive strength

This test was carried out according to ASTM C39 [42]. The device used to carry out this test, is a conventional pressure jacking

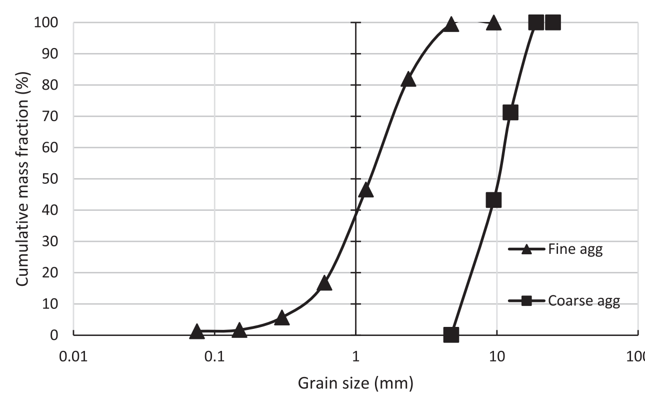

Fig. 1. Particle size distribution (PSD) curves of fine and coarse aggregates.

Table 9
Chemical analysis on nano-silica.

SiO_2 content (%)	30 ± 0.5
pH value	9.5–10.0
Mean particle diameter (nm)	9.30–10.50
Surface area (m^2/g)	250–280
Specific gravity at 25 °C (g/cm^3)	1.200–1.218
Viscosity at (on ford B cup) 27 °C (in seconds)	12.50–13.00

Fig. 2. Cylindrical and cubic specimen.

device. This device records all data in an automatic way. A compressive strength test was performed on these specimens at the age of 7, 14, 28, 56 and 90 days and for each sample with the same conditions, the compressive strength test was repeated three times. Failure of plastic concrete specimen occurs during 70 ± 15 s of the start of loading.

3.3. Triaxial strength

A device for performing triaxial test is designed and its frame has a load bearing capacity up to 5 MPa. The triaxial device used in this test is fully automatic. The cell which the specimen is placed in, will tolerate a pressure of 2 MPa. To applying the confining pressure, a compressor with a power of 10 bars is used and this compressor can control the pressure applied by the regulators. Tests were carried out in strain control method with constant confining pressure. For applying deviation stress a jack is embedded inside the device. The speed of jack is controlled with an accuracy of 0.00001 mm/min. In addition, the applied axial loads are measured by a load cell with capacity of 10 ton and the precision of 1 kg-force. To obtain a strain, the amount of cell displacement was recorded by a LVDT with the accuracy of 0.01 mm. All information is collected by load cell and LVDT and they are recorded simultaneously by the computer.

According to the mechanical behavior of the plastic concrete and the observations made in the preliminary results of the experiments, it was observed that the peak of deviatoric stress has occurred in the strain of 3–6%. Therefore, it is possible to compare plastic concrete with brittle material. Therefore, according to the recommendation of ASTM-D 2850 [43] that is about the unconfined and triaxial test on cohesive soil, the axial strain rate value has been recommended equal to 0.3% min^{-1}. Consequently, it was decided that the loading speed for plastic concrete specimens in the triaxial test would be 0.3% min^{-1}. Thus, the loading rate for a cylindrical specimen with a height of 200 mm, is equal to 0.5–0.6 mm/min. Also, this will reduce the effect of concrete damping and allow the growth of micro cracks in concrete in order to provide the static condition requirement for the experiment. Triaxial apparatus is shown in Fig. 3. In this test, cylindrical samples were made with a diameter of 10 cm and a height of 20 cm and triaxial test was performed on these specimens at the age of 7, 14, 28, 56 and 90 days.

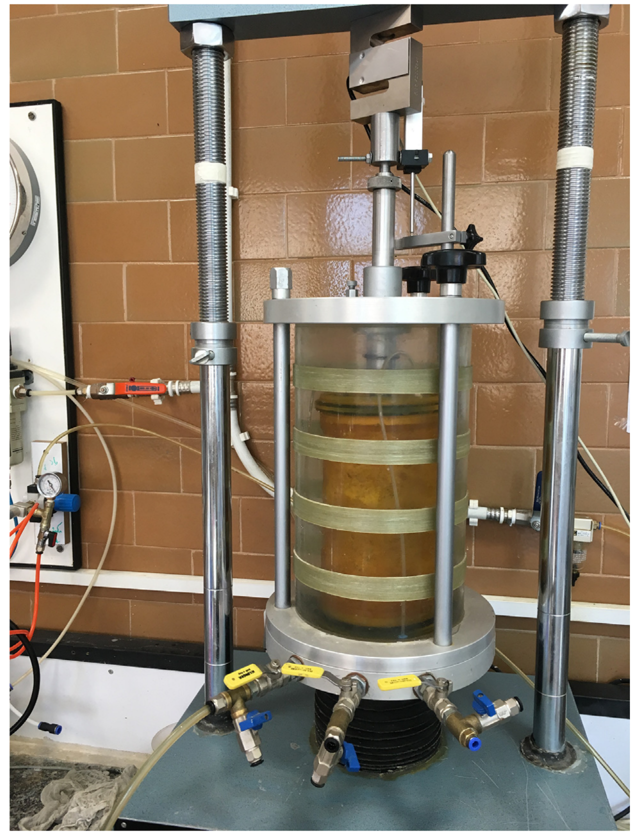

Fig. 3. Triaxial apparatus during testing.

3.4. Elastic modulus

This result was carried out in according to ASTM D2850 [43]. After obtaining a stress–strain diagram from a triaxial test, according to geotechnical relations, the value of the plastic concrete modulus is obtained from the strain-strain graph. From stress–strain graph, E_{u50} parameter was obtained and considered as the elastic modulus (Fig. 4) [44].

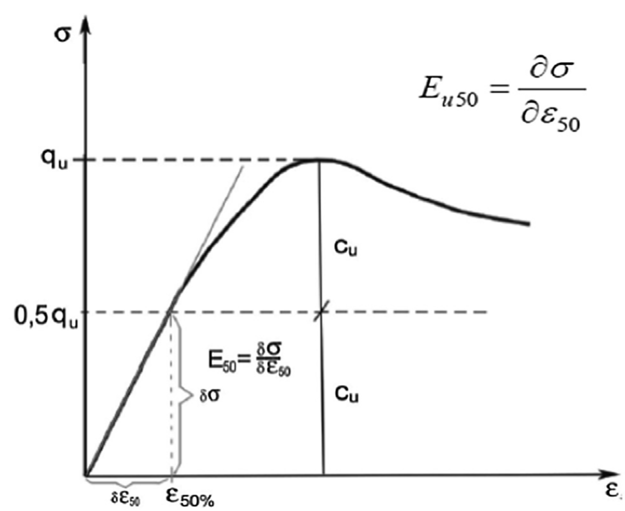

Fig. 4. Elasticity modulus (E_{u50}) determination from nonlinear stress–strain relationship.

3.5. Shear strength parameter

The shear strength parameters include friction angle and cohesion parameters. As shown in Fig. 5, the shear strength parameters are obtained by drawing a Mohr circle for three specimens with the same condition under 200, 350 and 500 KPa confining pressure.

4. Results and discussion

The results of laboratory work including slump, compressive strength, triaxial test, elastic modulus and shear strength parameter are presented below and discussion of the result is given in the following section.

4.1. Slump test

The slump test results are presented in Fig. 6. As can be seen, by increasing the percentage of nano silica from 0 to 6 percent, the amount of slump was measured from 23 to 17.5 cm. Thus, it can be concluded that as the amount of nano silica increases, the amount of measured slump and workability of plastic concrete are reduced.

The reason for slump reduction is that nano silica is a hydrophilic (water-loving) material and this property is due to the

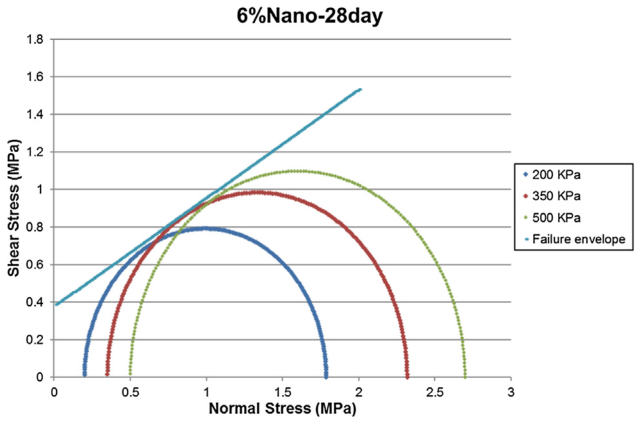

Fig. 5. Mohr circles for PC6 specimen at age of 28 days.

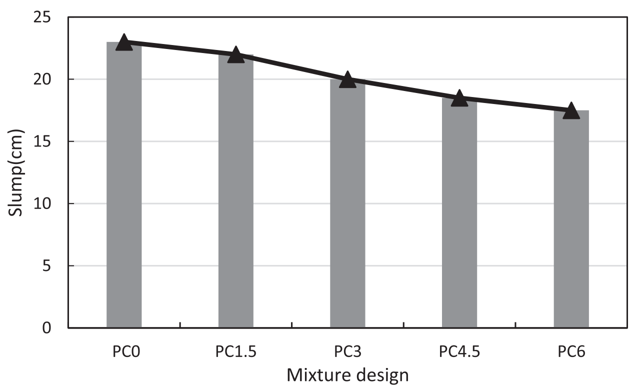

Fig. 6. Slump test result.

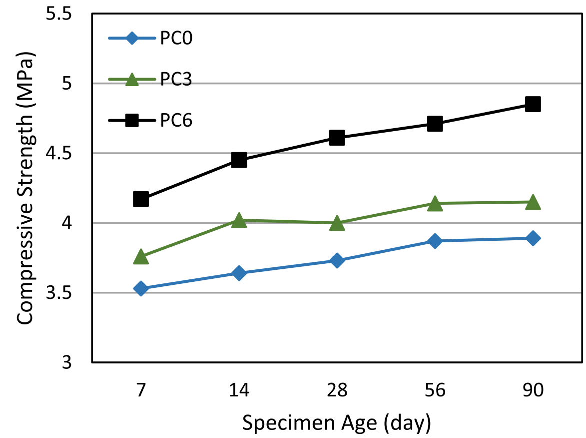

Fig. 7. Compressive strength for different mixture design and different specimen age.

electrically charged particles and the high specific surface of this material. Therefore, the high amount of water is inside the specimen and the nano silica collects particles of water molecules around itself and acts as a central nucleus. Hence, its process reduces water in plastic concrete material and as a result, slump is reduced.

In previous study [16], the addition of silica fume to plastic concrete has also reduced the workability of plastic concrete, and replacing silica fume up to 15% has reduced the slump from 20 cm to 18.5 cm. It seems due to lower specific surface of silica fume than nano silica particles, the effect of silica fume on reducing the workability of plastic concrete is less than that of nano silica. If the reduction in the workability of plastic concrete was significant with the use of nano silica, it has to be rectified by the use of plasticizing admixtures.

4.2. Compressive strength

The results of compressive strength that are measured at high water to cementitious material ratio of 2.92, are presented in Fig. 7. As can be seen by increasing the amount of nano silica, the compressive strength of the plastic concrete specimen has increased. For instance, compressive strength at the age of 90 days has been reported 3.89 MPa for control mix and this strength has reached 4.15 and 4.85 MPa for the PC3 mixture design for the PC6 mixture design. As a result, compressive strength increased about 7% and 27% for PC3 and PC6 mixture design, respectively.

On the other side, the results of the age vs. nano silica content can be considered. As shown in Fig. 7, if the amount of compressive strength was 4 MPa for design, adding nano silica is much more effective than the age of the specimens. For instance, in control specimen, compressive strength of 90 days was reported to be 3.89 MPa; however in the PC3 mixture, the compressive strength of 3.89 MPa was obtained in the first 7 days of the specimen's age and compressive strength at the age of 14 days was reported 4.02 MPa. Thus, it can be argued that the replacement of nano silica reduces the required time to reach the design strength. The same comparison can be made for PC 3 and PC6.

The significant impact of silica material on increasing the compressive strength of concrete is known as a phenomenon. This phenomenon causes events such as pore size refinement, pozzolanic reaction with calcium hydroxide and improvement of the quality of cement aggregate transition zone and all of them are reasons for increasing the compressive strength in concrete [45-48].

Similar result was reported by Bagheri [16]. They show that replacing silica fume instead of cement has a significant effect on the compressive strength of concrete, and this increase is reported to be up to 200% at high w/c ration; although for lower water to cementitious material ratio, this increase is reported about 80%. According to reports on the normal concrete and with the typical range of the w/c ratio (0.35–0.6), the improvement of compressive strength by adding silica fume is usually reported as 30–40% [33,49].

4.3. Triaxial test

In this section, triaxial test results are considered which include maximum deviatoric stresses (peak stress), elastic modulus and shear parameter strength. Additionally, the age of specimens, the effect of substituted nano silica, and the amount of confining pressure on these parameters are discussed.

4.3.1. Deviatoric stress

The peak stress results were obtained from a triaxial test and results shown in diagrams of Figs. 8 and 9. Fig. 9 shows the strain stress diagrams obtained from the triaxial test. As can be seen, the stress–strain graphs have no peak after increasing to a strain of 3% and it has a steady trend. The maximum deviatoric stress value occurs in the strain interval of 3–6%. They are shown for each test in Fig. 8 (the results of the stress–strain curve are considered to be 5% strain because the concrete specimen maintains its efficiency by up to 5% strain). As shown in Fig. 8, peak stress of PC0 specimen was reported 0.9 MPa and 1.18 MPa (33% increasing in peak stress) at the age of 7 days and 28 days, respectively. Also, in the age range of 7–28 days, the peak stress for the specimen of PC3 and PC6 increased by 27% and 30%, respectively. Thus, the percentage of peak stress which generally increases between 7 and 28 days for

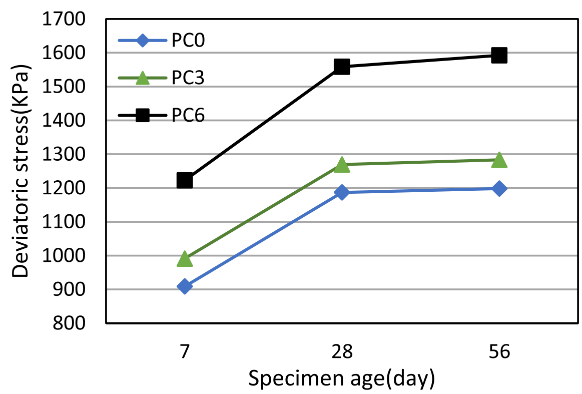

Fig. 8. Deviatoric stress for different mixture design and different specimen age.

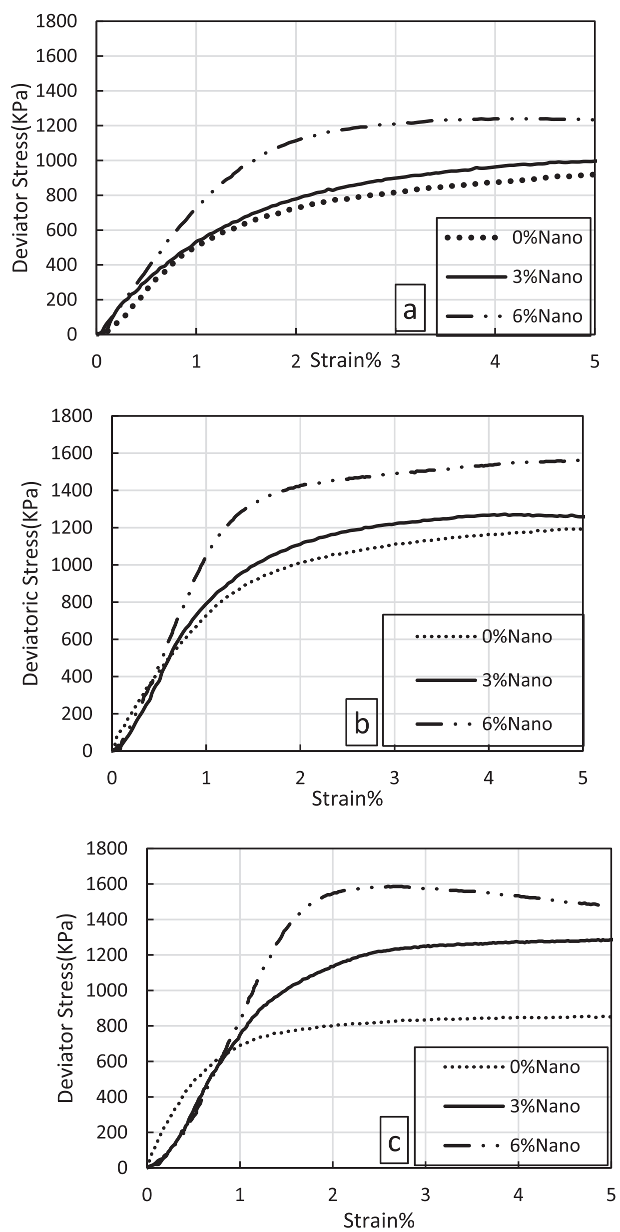

Fig. 9. Effect of nano silica content on peak stress in specimen with (a) 7 days age, (b) 28 days age and (c) 56 days age.

different mixture designs were obtained approximately 30%. Regarding the trend of diagrams, it can be concluded that after 56 days, no particular changes occur in the peak stress of the specimens and the peak stress is sustained by a constant trend.

Furthermore, it can be seen that the specimen with a control mixture design at 56 days tolerated a deviatoric stress of 1.2 MPa; however, in the specimen, by replacing 6% nano silica, it was able to withstand a deviatoric stress of 1.2 MPa in the first week and obtained the final strength of the control mixture design specimen. These results are similar to the results of compressive strength tests.

The reason for achieving more strength in the early days is the performance of nano silica as the core which provides the amount of water needed to complete the hydration reaction in the silicate gel (C_S_H) that surrounds the aggregates and this process helps to achieve greater coherence of the silicate gel which is an effective factor in gaining strength [50,51].

In previous study [52], it has been proved that the specimen age increases, the peak stress increases but increases slowly in higher age. The increase in peak stress has been reported 25% for specimen with age of 28 days to three months, but at an age of more than three months this increase has been very small. Fig. 10 shows the failure mode of plastic concrete by performing triaxial compressive strength.

In Figs. 11 and 12, the effect of different confining pressure on maximum of deviatoric stresses is observed. Fig. 11 shows the results of triaxial test on three specimens with the same condition under 200, 350 and 500 KPa confining pressure. The peak values were obtained in the graphs and all of them are shown in Fig. 12. As shown in Fig. 12, the peak stress of plastic concrete specimens increases with increasing confining pressure in all specimens with different mixture designs and different specimen ages. The peak stress variations for PC6 specimens are greater than PC3 specimens. The peak stress for a specimen with a PC6 mixture design at 56 days of age with a confining pressure of 200, 350 and 500 KPa is 1.58, 1.91 and 2.16 MPa respectively and with increasing confining pressure from 200 to 500 KPa, the stress tolerance capacity in the specimen increased by 37%. For PC3 specimen mixture design, confining pressure increased from 200 to 500 KPa, the

Fig. 10. Failure mode of plastic concrete under triaxial compressive strength test.

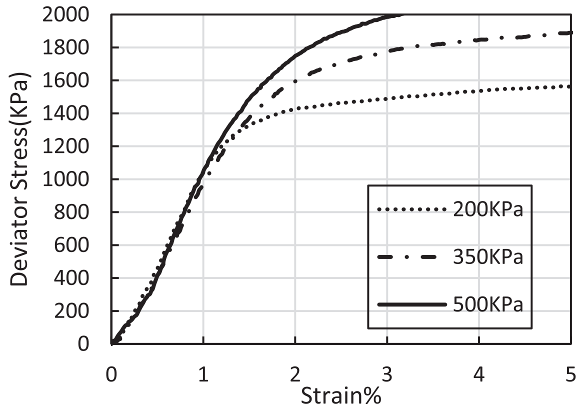

Fig. 11. Effect of confining pressure on peak stress on PC6 specimen mixture design and 28 days specimen age.

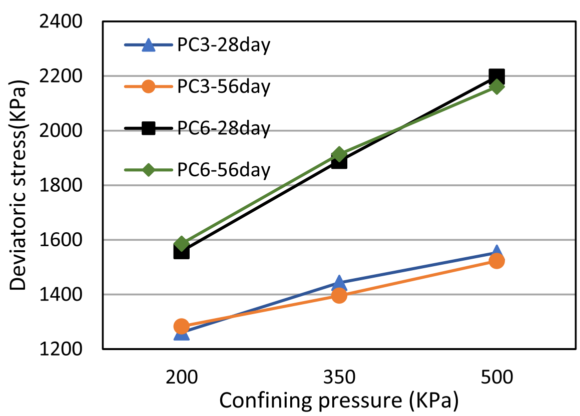

Fig. 12. Effect of different confining pressure on peak stress with different mixture design.

peak stress changed from 1.28 to 1.52 MPa; as a result, the peak stress has increased by 19%.

In the other hand, while the amount of nano silica replacement in plastic concrete increases, the specimen shows a more brittle behavior. To justify this behavior it is stated that the behavior of plastic concrete specimen varies from brittle behavior to ductile behavior when confining pressure increases and the ductile materials tolerate more stress.

In previous study [52], it has also been shown that for a specimen with a confining pressure increase from 200 to 500 KPa, deviatoric stress increased by 20% that is consistent with the results of this research.

4.3.2. Elastic modulus

According to Fig. 13, the consequences show that with increasing the age of specimen and amount of nano silica, the elastic modulus was increased. For instance, at 7 days of specimen age and for the PC0, PC3 and PC6 mixture design, the elastic modulus was reported to be 33.87, 51.26 and 69.75 MPa, respectively. At the age of 56 days, the elastic modulus increased to 82.61, 72.79 and 105.17 MPa, respectively; In other words, the elastic modulus increased by 143, 40 and 50 percent for PC0, PC3 and PC6 specimen of mixture design respectively.

As can be seen from the results, replacing nano silica with cement, the amount of percentage change in elastic modulus decreases as compared to PC0 specimen. Therefore, by using nano silica in plastic concrete can help avoid an unacceptable enhancement in elastic modulus. The reason for this behavior is the reduction in the amount of crystallization in concrete by replacing nano silica instead of cement.

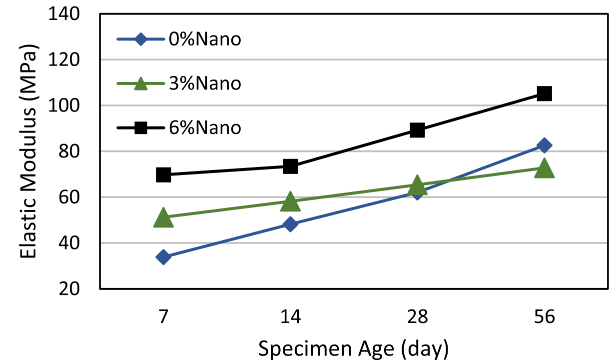

Fig. 13. Effect of nano silica and specimen age on elastic modulus.

In the previous study, researchers have concluded that as the age of specimen increases, the elastic modulus of plastic concrete also increases substantially. This enhancement has been reported twice as much as the initial value over time [21]. Other studies have also reported a more enhancement in the elastic modulus amount in specimens containing silica fume than nano silica [52]; because the nano particles are much smaller and they disperse easily and they fill the cavities in the specimen more regularly and form a denser structure than silica fume.

Fig. 14 shows the effect of confining pressure on the elastic modulus. In the PC3 mixture design, at age of 28 days and 56 days, there was no change in the elastic modulus with increasing confining pressure and the elastic modulus traverses a constant trend; however, in a PC6 specimen mixture design at different ages, with increasing confining pressure from 200 to 500 KPa, the value of the modulus of elasticity increases by 35%.

The reason can be stated for the PC6 specimen behavior, due to the higher amount of nano silica, PC6 specimen has a more brittle behavior than the PC3 specimen mixture design; therefore, the increase in confining pressure will be more effective on the elastic modulus of the PC6 specimen mixture design.

In previous studies, it has also been proven that the effect of confining pressure on the elastic modulus depends on several factors; so if these factors increase the brittle condition of plastic concrete, the confining pressure is more effective on the elastic modulus [21].

4.3.3. Shear strength parameter

The results of the cohesion parameter are shown in Fig. 15. As shown in Fig. 15, for the PC0 specimen and PC3 mixture design

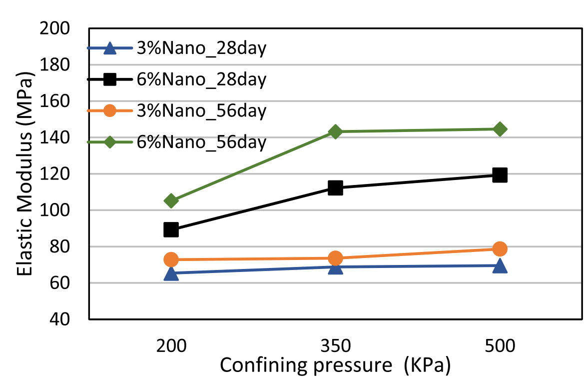

Fig. 14. Effect of confining pressure on elastic modulus of plastic concrete with nano silica (28 and 56 days specimen age).

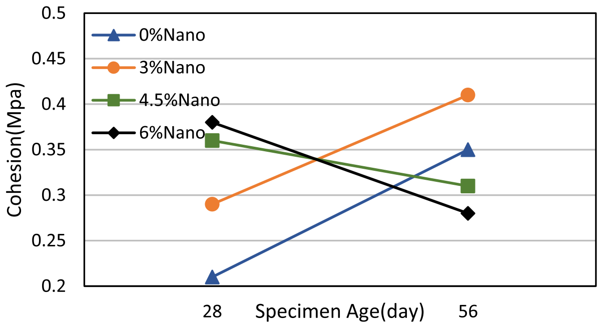

Fig. 15. Effect of nano silica on cohesion parameter with different specimen age.

specimen with increasing specimen age, the cohesion parameter increases but with an enhancement of more than 3% of nano silica in the material, this trend is reflected and as the age of specimen increases in PC4.5 and PC6 mixture design specimen, the cohesion parameter is reduced.

In Fig. 16 the results of the friction angle parameter are shown. In PC0 specimen and PC3 mixture design, the friction angle parameter decreases with increasing age of specimens but in the higher amount of nano silica in plastic concrete, the friction angle parameter of the specimen increases with the increasing age of specimen.

In this study, it was shown that for a specimen with same conditions, the slope of changing the parameters of cohesion and friction angle is the opposite of each other and this point is also shown in previous research [21,52].

4.4. Simultaneous comparison of different parameters

In this section, the changes of the parameters discussed above are presented simultaneously in Figs. 17 and 18 with the purpose of investigating their variations relative to each other for different specimens. In Fig. 17, the variations diagram of compressive strength and maximum deviatoric stress is drawn and all test results with different specimen age are divided into three mixture designs (PC0, PC3 and PC6). It can be concluded with comparing the incline of the graphs that the addition of nano silica to plastic concrete has a greater effect on deviatoric stress than compressive strength; as shown in Fig. 17, the slope of the graphs increases from PC0 specimen to PC6 specimen.

Fig. 18 shows the relationship between the elastic modulus and the compressive strength of plastic concrete specimens. As shown in Fig. 18, the slope of the PC0 specimens diagram is greater than the slope of PC3 and PC6 specimens diagrams. From this observation, it can be concluded that the effect of replacing nano silica instead of cement in plastic concrete specimens to enhance the compressive strength is more than the elastic modulus; therefore,

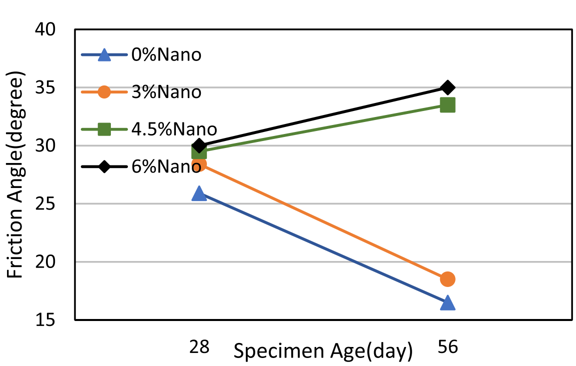

Fig. 16. Effect of nano silica on friction angle parameter with different specimen age in plastic concrete.

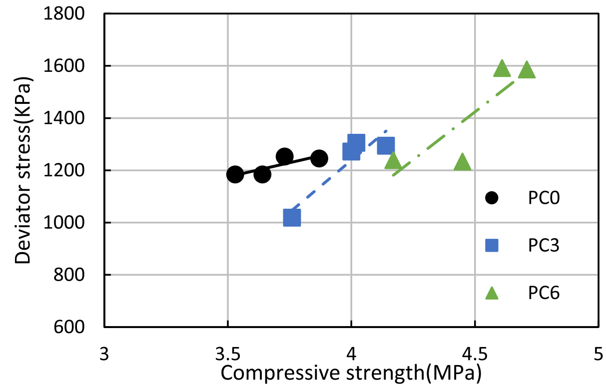

Fig. 17. Relationship between compressive strength and deviatoric stress of plastic concrete mixture designs.

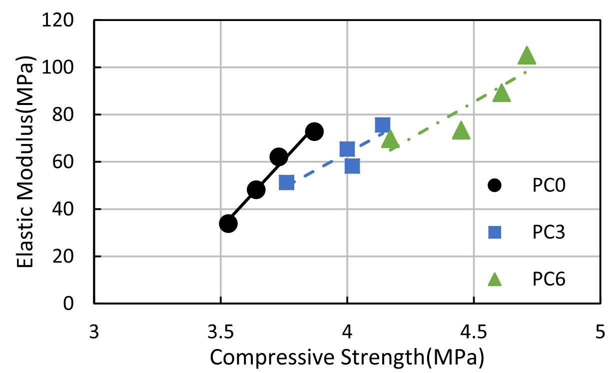

Fig. 18. Relationship between compressive strength and elastic modulus of plastic concrete mixture designs.

nano silica has been able to increase compressive strength while controlling elastic modulus changes.

5. Conclusion

In a laboratory research, the mechanical behavior of plastic concrete material with different nano silica percentage and without nano silica under different triaxial stress state are investigated and effect of specimen age, confining pressure and nano silica amount on elastic modulus, shear strength parameter and peak stress (maximum deviatoric stress) are studied parametrically.

1) By increasing the amount of nano silica in the concrete mixture design, the amount of mortar slump was reduced. As a result, the workability of concrete decreases with the addition of nano silica.
2) The addition of nano silica to plastic concrete resulted that the uniaxial compressive strength increased by 18% at an early age and increased by 27% for 90 days.
3) The triaxial compressive strength test was conducted to investigate the strength parameter of the plastic concrete that is buried in the ground. In specimens with age of 56 days, the deviatoric stress (peak of stress–strain diagram) was recorded 1.6 MPa in specimens containing 6% nano silica and in control samples equal to 1.2 MPa; an increasing about 34%.
4) In specimens with PC0, PC3 and PC6 mixture design after 56 days, the elastic modulus increased by 145, 40 and 50%, respectively. These results indicate that the percentage of elastic modulus changes in specimens containing nano silica is significantly lower.

5) By performing triaxial test with different confined pressures was observed that no significant changes occurred in the results of elastic modulus and deviatoric stresses in specimens with the same conditions.

Author Contributions

All authors contributed to the interpretation of the results and provided critical feedback and helped shape the research, analysis and manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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