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Experimental study for ZnO nanofibers effect on the smart and mechanical properties of concrete

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Abstract. Due to the superior properties of nanoparticles, using them has been increased in concrete production technology. In this study, the effect of zinc oxide (ZnO) nanoparticles on the mechanical and smart properties of concrete was studied. At the first, the ZnO nanoparticles are dispersed in water using shaker, magnetic stirrer and ultrasonic devices. The nanoparticles with 3.5, 0.25, 0.75, and 1.0 volume percent are added to the concrete mixture and replaced by the appropriate amount of cement to compare with the control sample without any additives. In order to study the mechanical and smart properties of the concrete, the cubic samples for determining the compressive strength and cylindrical samples for determining tensile strength with different amounts of ZnO nanoparticles are produced and tested. The most important finding of this paper is about the smartness of the concrete due to the piezoelectric properties of the ZnO nanoparticles. In other words, the concrete in this study can produce the voltage when subjected to mechanical load and vice versa it can induce the mechanical displacement when subjected to external voltage. The experimental results show that the best volume percent for ZnO nanoparticles in 28-day samples is 0.5%. In other words, adding 0.5% ZnO nanoparticles to the concrete instead of cement leads to increases of 18.70% and 3.77% in the compressive and tensile strengths, respectively. In addition, it shows the best direct and reverse piezoelectric properties. It is also worth to mention that adding 3.5% zinc oxide nanoparticles, the setting of cement is stopped in the concrete mixture.

Keywords: experimental study; zinc oxide nanoparticles; compressive strength; tensile strength; piezoelectric

1. Introduction

Concrete is a material which consists of cement, water and aggregate. Additives are sometimes used as a combination with concrete components or as a part of concrete composites to create specific properties or increase and improve the abilities and properties of concrete. The dynamic fracture behavior of polyester/TiO_2 nano-composites was characterized and compared by Évora *et al*. (2005) with that of the matrix material. The potential of exposure to synthetic nanoparticles released during construction activities for application of photocatalytic pavements was measured by Dylla and Hassan (2011) during laboratory-simulated construction activities of photocatalytic mortar overlays and in an actual field application of photocatalytic spray coat. The study results indicated that the properties of concrete containing 2.0% TiO_2 were improved (Chung *et al*. 2013). The effects of TiO_2 nanoparticles on physical, thermal and mechanical properties of concrete using ground granulated blast furnace slag as binder were presented by Nazari and Riahi (2011a). Oltulu and Şahin (2011) studied the effect of iron oxide nanoparticles, aluminum oxide, and silica oxide on the compressive strength of mortar. They showed that the best composite for improving the compressive strength at the end of 180 days was obtained with 1.25% aluminum oxide and 0.5% silica oxide. Nazari *et al* added copper oxide nanoparticles with 1, 2, 3, 4, and 5 weight percent to cement to study the effect of CuO on the compressive strength of self-consolidating concrete. Their study results indicated that the compressive strength of concrete containing 4% copper oxide nanoparticles was improved (Nazari and Riahi 2011b). Dagher *et al*. (2014) studied influence of reactant concentration on optical properties of ZnO nanoparticles. Kawashima *et al*. (2014) studied the negative effects of fly ash on the early-age properties of cementitious materials with the use of calcium carbonate ($CaCO_3$) nanoparticles. The influence of powdered and colloidal nano-silica (NS) on the mechanical properties of cement mortar was investigated by Singh *et al*. (2015). Spinazzè *et al*. (2016) assessed the occupational exposure of workers engaged in the application of nano-TiO_2 onto concrete building materials, by means of a multi-metric approach (mean diameter, number, mass and surface area concentrations). Thermal and oxidation protection of carbon fiber by continuous liquid phase pre-ceramic coatings for high temperature application in CF reinforced concrete (CFRC) composite were presented by Abu Shayed *et al*. (2016). In order to improve microwave absorption which would be used for in situ repair of asphalt pavement, Fe_3O_4 was enriched by Miao *et al*. (2017) on the surface of steel slag particles through an activated carbon-reduction method. Tao Ming *et al* studied the effect of TiO_2 nanoparticles on the mechanical properties of cement mortar. The study results

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Table 1 Mechanical properties and chemical analysis of used cement

Type of cement	L.O.I%	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Blaine (cm^2/g)
Type I	1.18	21.6	5.4	3.64	62.6	2.3	2.0	0.75	0.45	3080

indicated that by adding Titanium oxide nanoparticles to cement mortar, the strength increased at the early ages while it decreased in other ages (Chung *et al*. 2013). Arefi and Rezaei-Zarchi (2012) studied the synthesis method and effect of ZnO nanoparticles on strength and adjusting the setting time of self-consolidating concrete. Zinc oxide nanoparticles with 0.5, 0.1, 0.2, 0.5, and 1.0 weight percent was added to cement. The study results indicated that the maximum strength of concrete was obtained by adding 0.5% zinc oxide nanoparticles to the concrete mixture (Chung *et al*. 2013). Dvorkin and Peled (2016) modified the microstructure of carbon fabrics with mineral or organic fillers absorbed between the filaments of the fabric strands in order to optimize the composite tensile properties. Real-time stress measurement in SiO_2 thin films during electrochemical lithiation/delithiation cycling was presented by Rakshit *et al*. (2018). Heidari *et al*. (2018) studied vibration of concrete beams reinforced by agglomerated silicon dioxide (SiO_2) nanoparticles based on numerical methods. Dynamic analysis of the agglomerated SiO_2 nanoparticles-reinforced by concrete blocks with close angled discontinues subjected to blast load was presented by Bakhshandeh Amnieh and Zamzam (2018).

The study of composite and nanocomposite paltes was presented by Duc *et al*. (Duc 2014a, b, Duc and Minh 2010, 2013, 2015, 2018). Chung *et al*. (2013) investigated Polymeric Composite Films Using Modified TiO_2 Nanoparticles. Large amplitude vibration problem of laminated composite spherical shell panel under combined temperature and moisture environment was analyzed by Mahapatra and Panda (2016). The nonlinear free vibration behaviour of laminated composite spherical shell panel under the elevated hygrothermal environment was investigated by Mahapatra and Panda (2016). Mahapatra *et al*. (2016b) studied the geometrically nonlinear transverse bending behavior of the shear deformable laminated composite spherical shell panel under hygro-thermo-mechanical loading. Nonlinear free vibration behavior of laminated composite curved panel under hygrothermal environment was investigated by Mahapatra *et al*. (2016c). Nonlinear flexural behaviour of laminated composite doubly curved shell panel was investigated by Mahapatra *et al*. (2016c) under hygro-thermo-mechanical loading by considering the degraded composite material properties through a micromechanical model. The flexural behaviour of the laminated composite plate embedded with two different smart materials (piezoelectric and magneto-strictive) and subsequent deflection suppression were investigated by Dutta *et al*. (2017). Suman *et al*. (2017) studied static bending and strength behaviour of the laminated composite plate embedded with magnetostrictive (MS) material numerically using commercial finite element tool. Vibration and nonlinear dynamic response of eccentrically stiffened functionally graded composite truncated conical shells in thermal environments were

Table 2 The properties of zinc oxide nanoparticles

Appearance	Density	Molecular weight	SSA (M2/g)	Purity	Particle size
Type I	1.18	21.6	5.4	3.64	62.6

presented by Chan *et al*. (2018). Nonlinear response and buckling analysis of eccentrically stiffened FGM toroidal shell segments in thermal environment were studied by Vuong and Duc (2018). In this work, buckling analyses of composite concrete plate reinforced by Piezoelectric nanoparticles is studied.

Limited laboratory studies were conducted on the effect of zinc oxide nanoparticles on the strength parameters of concrete, but no study has been found on the smart properties of concrete with zinc oxide nanoparticles. This study attempted to investigate the replacement effects of cement with zinc oxide nanoparticles on the strength parameters of regular concrete. In the present study, all parameters of concrete production were unchanged and only a certain amount of zinc oxide nanoparticles was replaced with concrete mixture cement for studying the samples. In case of piezoelectric properties of zinc oxide nanoparticles and using zinc oxide smart potentials under electric field, no study was found for the direct operation of concrete.

2. Construction of the concrete

In this section, the used materials and mixing plan for construction of the concrete are reported.

2.1 Materials

- **Cement**

Based on Table 1, the used cement in mixing plan for producing all samples is Portland type 1 made in Kavir Kashan Cement Company based on standards with 3000 cm/s Blaine softness and 370 kg/m^2 average compressive strength. The desired density for cement was 3.15.

- **Aggregates**

In order to study the aggregates, two types of coarse materials (almond and pea) as fractured materials and one type of fine material (gravel) as river materials are used. For coarse materials such as almond and fractured with D_{max} = 25 *mm*, specified weight = 2.63 gr/cm^3 and pea with D_{max} = 2.68 *mm* and for materials, gravel of river materials with specific weight = 2.68 gr/cm^3 are used. Before testing, all rock materials are rinsed separately and had no dust or other materials.

- **Water**

The used water for producing the samples of this study is drinking water in Kashan with ph = 7.5.

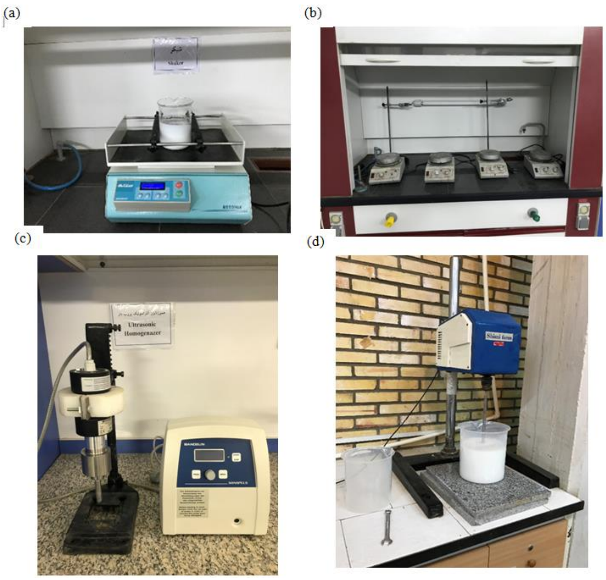


Fig. 1 The procedure of dispersing zinc oxide nanoparticles in the water (a) shaker; (b) magnetic stirrer; (c) ultrasonic devices; (d) mechanical mixer

➢ **Zinc oxide nanoparticles**

The zinc oxide nanoparticles used in this study is produced in US Nano Company, America. Its properties are given in Table 2.

2.2 Mixing plan

Since the nanoparticles are not solved in water without any specific process, before producing concrete samples, zinc oxide nanoparticles with 5% concentration (mass-volume) are dispersed by using shaker, magnetic stirrer, and ultrasonic devices and finally mechanical mixer based on the number of used nanoparticles than cement at specific times. This procedure is shown in Fig. 1.

The produced samples in this study are Z, $Z_{0.2}$, $Z_{0.5}$, $Z_{0.75}$, $Z_{1.0}$ and $Z_{3.5}$ in which 0.00%, 0.25%, 0.50%, 0.75%, 1.00% and 3.50% zinc oxide nanoparticles are replaced with the used cement. The accurate details of samples were given in Table 3.

The made samples are placed in several layers in metal molds with cylindrical 300×300 *mm* dimensions, cubic 150×150×150 *mm*, and concrete beam 100×100×500 *mm* and then are vibrated by metal bar and plastic hammer. The conditions of keeping and processing the samples based on the status of each sample series are kept within mold for the first 24 hours and then transferred to water basin.

3. Experimental tests and results

In this section, the compressive and tensile strengths of the concrete reinforced by zinc oxide nanoparticles as well as smart properties of the samples are investigated.

3.1 Compressive strength test

In order to determine the average compressive strength of the concrete, cubic samples with 150×150×150 *mm* dimensions are used and the compressive strength development process is studied for 7, 14, and 28-day ages.

Table 3 The properties of mixing plan for producing concrete samples

Samples	W/C	Nanoparticles (%)	Slump	Quantities (kg/m^3)					
Z_0	0.43	0.00%	5-8 cm	163	376.00	650	471	696	0.00
$Z_{0.25}$	0.43	0.25%	5-8 cm	163	375.91	650	471	696	0.94
$Z_{0.5}$	0.43	0.50%	5-8 cm	163	374.12	650	471	696	1.88
$Z_{0.75}$	0.43	0.75%	5-8 cm	163	373.18	650	471	696	2.82
$Z_{1.0}$	0.43	1.00%	5-8 cm	163	372.24	650	471	696	3.76
$Z_{3.5}$	0.43	3.50%	5-8 cm	163	362.84	650	471	696	13.16

Fig. 2 (a) Automatic compression machine for determining the compressive strength of the concrete (b) broken sample

Table 4 The results of cubic samples compressive strength at different ages in terms of kg/cm^2

Samples	Zinc oxide nanoparticles (%)	Compressive strength (Kg/m^2) 7 day	Compressive strength (Kg/m^2) 14 day	Compressive strength (Kg/m^2) 28 day	Percent increase strength 7 day	Percent increase strength 14 day	Percent increase strength 28 day
Z_0	0.00%	224.60	295	342	---	---	---
$Z_{0.25}$	0.25%	260.00	360	372	15.80%	22.00%	8.70%
$Z_{0.5}$	0.50%	263.00	388	406	17.09%	31.50%	18.70%
$Z_{0.75}$	0.75%	206.00	363	398	-0.08%	23.00%	16.30%
$Z_{1.0}$	1.00%	249.00	314	383	10.90%	6.40%	11.90%
$Z_{3.5}$	3.50%	---	---	---	---	---	---

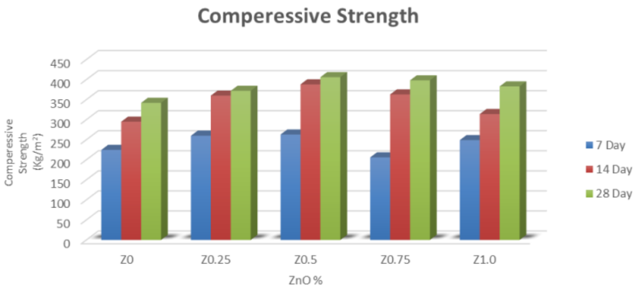


Fig. 3 Comparing the compressive strength of the concrete for different weight percent of zinc oxide (ZnO) nanoparticles

This test is done using automatic concrete pressure test machine ELE ADR 2000 as shown in Fig. 2(a) with the broken sample presented in Fig. 2(b).

The compressive strengths of the cubic samples are given in Table 4 and Fig. 3. Based on the obtained results, it is obvious that the maximum increase of compressive strength is 17.09 for 7-day age by replacing 0.5 weight percent of zinc oxide nanoparticles instead of cement, 31.5 weight percent of zinc oxide nanoparticles instead of cement for 14-day age, and 18.70 weight percent of zinc oxide nanoparticles instead of cement for 28-day age. Based on the conducted studies, the setting process of cement is completely stopped by replacing 3.50% zinc oxide nanoparticles.

Fig. 4 Broken samples in the tensile strength test

3.2 Tensile strength test

In order to determine the tensile strength of the concrete, the cylindrical samples with 150×300 *mm* dimensions are used and the tensile strength cess is studied for 14 and 28-day ages. Automatic concrete pressure test machine ELE ADR 2000 is used to break the samples with the broken samples shown in Fig. 4.

The results of the tensile strength developed by cylindrical samples are given in Table 5 and Fig. 5. Based on the obtained results, it can be seen that the maximum increase of compressive strength is 17.64% for 14-day age by replacing 0.5 weight percent of zinc oxide nanoparticles instead of cement, and 3.77% weight percent of zinc oxide nanoparticles instead of cement for 28-day age. Based on these results, the tensile strength of the produced strength is about 7-9% of its compressive strength.

Table 5 The results of cylindrical samples tensile strength at different ages in terms of kg/cm^2

Sample designation	Zinc oxide nanoparticles (%)	Tensile strength (Kg/m^2) 14 day	Tensil strength (Kg/m^2) 28 day	Percent increase strength 14 day	Percent increase strength 28 day
Z_0	0%	27.88	34.40	---	---
$Z_{0.25}$	0.25%	31.90	35.46	14.40%	3.08%
$Z_{0.5}$	0.50%	32.80	35.70	17.64%	3.77%
$Z_{0.75}$	0.75%	32.40	34.90	16.21%	1.45%
$Z_{1.0}$	1.00%	30.50	31.12	9.39%	-9.50%
$Z_{3.5}$	3.50%	---	---	---	---

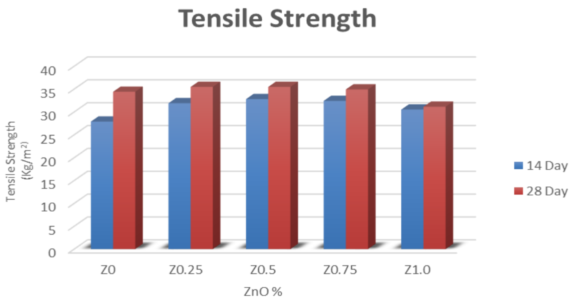
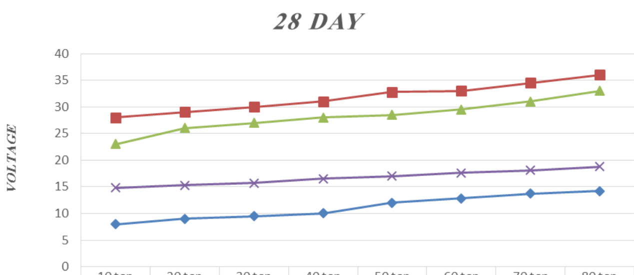


Fig. 5 Comparing the tensile strength of the concrete for different weight percent of zinc oxide (ZnO) nanoparticles

Fig. 6 Determining the output voltage due to the input compression to the concrete samples



	10 ton	20 ton	30 ton	40 ton	50 ton	60 ton	70 ton	80 ton
Z0.25	8	9	9.5	10	12	12.8	13.7	14.2
Z0.5	28	29	30	31	32.8	33	34.5	36
Z0.75	23	26	27	28	28.5	29.5	31	33
Z1.0	14.8	15.3	15.7	16.5	17	17.6	18.1	18.8

Fig. 7 The results of recording the voltage due to applying compression to the concrete sample

3.3 Determining the output voltage due to pressure

In order to determine the output voltage due to the input compression, the samples are subjected to pressure using concrete pressure test machine as shown in Fig. 6. Two copper plates which are connected to micro-voltmeter machine via two wire strings are placed on its two sides.

By applying the compression, the output voltage is recorded simultaneously. The results of output voltages due to compression to the samples at 28-day age are presented in Fig. 7. This figure indicates that the voltage is created by applying compression due to the direct effect of piezoelectric materials. The increase of recorded voltage depended on two parameters of sample strength and applied compression to the sample. Negative voltage recording is expected by changing the direction of loading on sample to record the voltage based on changing the direction of polarization of piezoelectric materials. This property of the concrete can be used for health monitoring in the concrete structures.

3.4 Determining the displacement of the samples under electric field

Here, the concrete samples containing zinc oxide nanoparticles are subjected to direct electric field. The displacement changes are recorded by using the strain gauges connected to the samples. The samples are tested as increasing voltage to 300 volt and fixed voltage to 300 volt (Fig. 8).

The results recorded by strain gauges for increasing voltage are presented in Fig. 9. As can be seen, with applying external voltage to the concrete sample, the strain due to the mechanical displacements can be induced in the structure. This property of the constructed sample can be used for actuating the concrete structure. In other words, with applying external voltage to the structure, the deflection of the concrete can be returned to the first situation.

Fig. 8 Determining the displacement of the samples under electric field

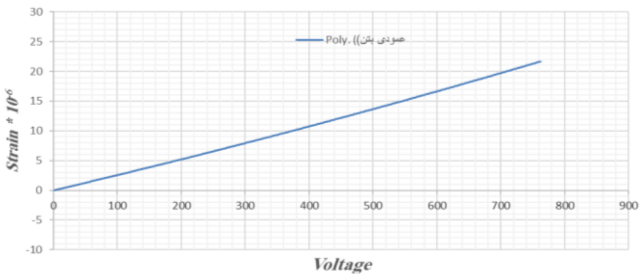


Fig. 9 The results of recording the strain due to applying voltage to the samples

4. Theoretical discussion

4.1 Concrete elasticity modulus

Concrete elasticity modulus depends on the type of concrete, type and speed of loading, properties of concrete components and mixing percent. Concrete static elasticity modulus based on ACI318-14 (2014), for concrete with specific weight W_c, in the range 1440 to 2560 kg/m^3 can be obtained from equation $E_c = 0.043W_c^{1.5}\sqrt{f_c'}$ and for regular concrete with specific weight of about 2300 kg/m^3 can be obtained from $E_c = 4730\sqrt{f_c'}$. ACI 363 regulation (2010) suggested the following equation for calculating the elasticity modulus in concrete with high strength

$$E_c = \left(3320\sqrt{f_c'} + 6900\right)\left(\frac{W_c}{2300}\right)^{1.5} \tag{1}$$

Since the f_c' value is changed to 1.1807 f_c' by adding 0.5% zinc oxide nanoparticles to the concrete, based on the presented equations, the amount of E_c is increased 8.66% for regular concrete and 7.74% for the concrete with high strength.

4.2 Nominal bending moment and the minimum amount of cross-sectional

In designing the structures, sometimes the parameters are selected bigger than the values required for bending due to architectural or expected functional requirements. Such sections theoretically need very los values of tensile steel. The nominal bending moment of concrete beam section is obtained from the following equation

$$M_{n1} = \rho f_y b d^2\left(1 - 0.59\rho\frac{fy}{f_c'}\right) \tag{2}$$

By replacing 0.5% zinc oxide nanoparticles as additive instead of cement, the value of $f_{c1}'$is changed to 1.1807 $f_{c1}' = f_{c2}'$. Thus, the nominal bending moment increased and the above equation si modified as follows

$$M_{n2} = \rho f_y b d^2\left(1 - 0.50\rho\frac{fy}{f_c'}\right) \tag{3}$$

Based on the above equations which are calculated for common concrete beam sample and section with equivalent steel, it is observed that using the sample containing zinc oxide nanoparticles lead to the increase of nominal bending moment to 14.3%. By assuming f'_{c1} = 31 Mpa, f'_{c2} = 36.6 Mpa , and f_y = 400 Mpa, the amount of changes in nominal bending moment for balanced steel at different sections are listed in Table 6.

As can be observed, the amount of increase in the nominal bending moment at the balance mode is 14.3% for all sections. ACI 318-14 regulation determined the minimum tensile steel for bending sections as follows

$$\rho_{min} = \frac{\sqrt{f'c}}{4fy} \geq \frac{1.4}{fy} \tag{4}$$

In the above equation, if $f_c' \geq 31$ Mpa, the value $\frac{\sqrt{f'c}}{4fy}$ will determine the P_{min} value. Based on the laboratory results, the concrete sample containing 0.5% zinc oxide nanoparticles at 28-day age had 18.07% strength growth than the sample without any additives. Thus, based on equation $\rho_{min} = \frac{\sqrt{f'c}}{4fy} \geq \frac{1.4}{fy}$, the P_{min} value could be considered as 8.6% less than the regular value by increasing the strength obtained from adding 0.5% nanoparticles to concrete sample. The equation presented in ACI 318-14 is based on the compressive strength obtained from cylindrical samples. However, using the strength results of cubic samples is not unusual and had no effect on the general comparison.

5. Conclusions

In order to study the effect of zinc oxide nanoparticles on the mechanical and smart properties of the concrete, the nanoparticles with 1.0, 0.75, 0.05, 0.25, and 3.45% were added to the concrete and replaced with the appropriate amount of cement. The cubic samples were produced for determining the compressive strength and recording the voltage due to applying compression and changing the displacement due to electric field, cylindrical samples were produced for determining the tensile strength. Replacing 0.5% zinc oxide nanoparticles instead of cement increases

Table 6 Studying the effect of adding zinc oxide nanoparticles on the nominal bending moment with different sections at the balance mode

Section (mm)	$_1\beta$	$_1\beta$	$_{balance}\rho$	$_{balance}\rho$	M_{n1} (Kn.m)	M_{n2} (Kn.m)	Percentage
300×300	0.83	0.79	0.0328	0.0369	265.7	303.7	14.3%
300×400	0.83	0.79	0.0328	0.0369	472.3	540.0	14.3%
400×400	0.83	0.79	0.0328	0.0369	629.8	720.0	14.3%
400×500	0.83	0.79	0.0328	0.0369	984.0	1125.0	14.3%
500×500	0.83	0.79	0.0328	0.0369	12.0.0	1406.2	14.3%
500×600	0.83	0.79	0.0328	0.0369	1771.2	2025.0	14.3%
600×600	0.83	0.79	0.0328	0.0369	2125.4	2430.0	14.3%
600×700	0.83	0.79	0.0328	0.0369	2892.9	3307.5	14.3%

the compressive strength as 17.09%, 31.50%, and 18.70% for 7, 14, and 28-day ages, respectively. Replacing 0.5% zinc oxide nanoparticles instead of cement increases the tensile strength as 17.64% and 3.77% for 14, and 28-day ages, respectively. Replacing 3.5% zinc oxide nanoparticles instead of cement can disrupt the cement setting. Increasing the compression on the sample leads to increasing voltage and the maximum recorded voltage is related to the sample with optimal additive percentages. Based on the direction of polarization and applying load on sample, recording the negative voltage is expected. By applying the direct voltage to samples, strain can be crated in samples in line with creating voltage. The amount of increase in the nominal bending moment at the balance mode is 14.3% for all sections.

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