Optimizing Durability of the High Performance Nano-Concrete Applying Taguchi Method and Desirability Function

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Abstract:

Due to considerable increase in concrete using in different areas of construction industry around the world, an intense need is currently felt for improving concrete properties, especially its durability. Furthermore, the necessity for the new types of concrete with higher durability and better performance for specific purposes, as compared to the available types, is sensed more than ever. The concrete durability, affected by different variables such as compressive strength, electrical resistance and permeability, has already attracted the attention of many researchers. In the present study the effects of adding various nanoparticles to the concrete, changes in the humidity and temperature of the curing surrounding atmosphere are investigated to find out whether they will cause any increase in compressive strength and electrical resistance of concrete and/or any decrease in its permeability. For this study, the Taguchi method is applied as a method of design of experiment to get the optimal level for each variable, followed by applying the regression method to model the variables. Eventually, the final optimal levels for the durability are presented based on the desirability function.

Keywords: Nanoparticles, Compressive strength, Electrical resistance, Permeability, Desirability function

1. Introduction

Iran as a seismic country is located on the earthquake belt of the world and regarding scientific documented information and twentieth century observations, it can be considered as one of the most dangerous locations around the world due to its vigorous earthquakes. In recent years, on average, every five years one earthquake with heavy property damages and death toll has been taken place in each part of this country and nowadays Iran is placed at the top of the list of countries in which earthquake brings about a lot of casualties [1]. Although avoiding damages caused by severe earthquakes entirely is so problematic, fortifying governmental organizations, fundamental installations and pivotal pathways are deemed as governments' priorities. Therefore, applying durable and strenuous building materials especially stable and long-lasting concrete can have substantial effects to diminish earthquake-caused losses.

In the last 80 years concrete has been used in many construction fields and has proved durable material during its long and useful life. Along with regular projects, concrete has been used in industrial projects as well. It has been exposed to very harsh environmental conditions and revealed structural and applicational weak points over its life. Durability of the concrete made of the portland cement refers to its resistance against weather conditions, chemical attacks, abrasion and erosion, and any other destructive processes [2].

During the concrete life numerous research studies have been conducted to improve its durability. Among the studies which currently hold the interest of goverments, investors, organizations and researchers, application of nano technology in concrete industry particularly for improving the concrete durability is most favorable. Study of materials at nano level in the concrete industry intends to improve the concrete properties such as coming to a new group of high performance and multipurpose construction materials [3].

Jalal et al. [4] investigated the mechanical, rheological, durability and micro-structural properties of high performance self-compacting concrete (HPSCC) by adding SiO_2 micro and nanoparticles. Moreover, the durability properties were evaluated by water absorption, capillary absorption, Cl ion percentage and resistivity tests. In their study, for different binder contents and at a constant ratio of water/binder, a fraction of cement was replaced by nanosilica and microsilica. They resulted that nanosilica and microsilica caused a decrease in water absorption of the high performance self-compacting concrete, and as a result, an increase in its durability. Li et al. [5] conducted an experimental study on the abrasion resistance of the concrete containing Tio_2 and Sio_2 nanoparticles to be used for pavement, as compared to the plain concrete and the concrete containing polypropylene (PP) fibers. The experiment results showed significant improvement in the abrasion resistance of the concretes containing nanoparticles and PP fibers, although the index of abrasion resistance for the concrete containing nanoparticles stood much higher than the index of the concrete with PP fibers. Givi et al. [6] and Nazari et al. [7] indicated that concrete containing SiO_2 and Fe_2O_3 nanoparticles had higher compressive, flexural and tensile strength in comparison to concrete without SiO_2 and Fe_2O_3 nanoparticles. Bhuvaneshwari et al. [8] has explored the possible usage of nano-oxides such as nano-SiO_2, nano-ZrO_2, nano-Al_2O_3, nano-Fe_2O_3 and nano-TiO_2 to improve the mechanical properties of concrete.

Recently, Taguchi method has been used in several studies [9-11]. Gu et al. [12] used a Taguchi method to improve the mechanical properties of recycled plastic blends. The experimental design was carried out by four controllable factors such as melt temperature, mold temperature, injection speed and packing pressure. It was observed that deteriorations in the mechanical properties of products produced from recycled plastic could be promoted by optimizing the processing parameters during the injection molding procedure. An application of Taguchi method to optimize the system parameters of centrifugal evaporative air cooler was implemented by Kumar and Srinivasan [13]. It was concluded that the rate of air and water flow and disc speed had major impacts on system performance in comparison with the other parameters such as, pin orientation, disc diameter, evaporation chamber length and pin geometry. Houng et al. [14] applied the Taguchi design to optimize the asymmetric decline of ethyl 4-chloro acetoacetate using bakers' yeast. They used L_{18} orthogonal array to optimize reaction yield and the product's optical purity which were considered as two product quality variables. Their results showed that the product's optical purity could be boosted to 95% by adjusting the operational level of the main factors. Cai et al. [15] optimized the process of ultrasound-assisted ultrafiltration for Radix astragalus mixtures. They used analysis of variance (ANOVA) to demonstrate the appropriate regression models and the desirability function approach to find the optimum conditions to minimize the response variables such as fouling degree and process duration simultaneously. Nowadays one of the foremost techniques that can be used as a practical tool to optimize several responses simultaneously when there are many responses is desirability function [16]. Lately, this approach has been applied to investigate optimum conditions for several optimization researches such as multiple characteristics of electrical discharge machining (EDM) parameters [17], biohydrogen production process [16] and continuous sputtering process [18].

The aim of this work is to find ways to improve the durability of the concrete containing nanoparticles. In fact, none of construction materials are neither durable nor non-durable by itself, and it is the interaction between materials and surrounding atmosphere that determines its durability [19]. For concrete, resistance against penetration of external factors derived from environment or internal factors can also increase its life. As the attack takes place in the inside of the concrete and the invading factors should be able to penetrate into the mass, the penetrebility and electrical resistance of the concrete are taken into account significantly [20]. In the research study the factors of compressive strength, electrical resistance and permeability were selected as the response variables effective on durability and the kind of nanoparticles, humidity and temperature of curing surrounding atmosphere were recognized as influential factors. Then the optimum levels of effective factors on each of these variables were determined by the design of experimental methods particularly the Taguchi method. In next step by means of the regression models, the desirability function approach and the outcomes from Taguchi method, the optimal levels affecting the final response variable or durability were presented.

2. Matherials and methods

2.1. Selection of variables effective on durability

Based on the conducted investigations about the concrete durability, It seems that concrete durability is not directly measurable, so to estimate it indirectly, one or more variables which can reflect the feature have to be chosen. Therefore, three variables of compressive strength, electrical resistance and permeability were selected to evaluate durability:

a. *Compressive strength*, which is measured according to the BS EN12390-3:2002 standard [21].
b. *Electrical resistance*, Can be metered by applying a current using two electrodes attached to the ends of a uniform cross-section specimen. Electrical resistivity can be obtained from the Eq.(1) [22]:

$$R = \rho \frac{\ell}{A} \qquad (1)$$

Where R is the electrical resistance of the specimen,ρ is the ratio of voltage to current (measured in ohms, Ω), ℓ is the length of a piece of material (m) and A is the cross-sectional area of the specimen (m²).
c. *Permeability*, the performance of concrete subjected to many aggressive environments is a function to a large extent of the penetrability of the pore system. In unsaturated concrete, the rate of ingress of water or other liquids is largely controlled by absorption due to capillary rise based on ASTM standards [23]. In this research, method for determining the depth of penetration of water under pressure in hardened concrete is according to BS EN12390-8:2009 standard [24].

2.2. Selection of Factors Effective on Response Variables

Curing plays an important role on strength development and durability of concrete. It is also a key player in mitigating cracks in the concrete, which severely impacts durability. The curing period depends on the ambient conditions, ie. the temperature and relative humidity of the surrounding atmosphere [25,26]. The present work studies the influence of temperature and relative humidity of the surrounding atmosphere on the durability of the high performance nano-concrete. In other word, in order to find out if adding nanoparticles to the concrete would yield similar impacts and to realize in which conditions the highest compressive strength, electrical resistance and lowest water permeability will be gained, the following parameters are selected:

1. Nanoparticles

Using nanoparticles approves mechanical properties improvement [27,28] and the augmentation of cement and concrete quality [29]. Furthermore, the application of nanoparticles and nano-coating preclude penetration of destructive external factors into concrete which cause concrete durability degradation and the growth of destruction rate. High Performance Concrete (HPC) and Self-Compacting Concrete (SCC) can be considered as some applications of nano-structures in concrete industries. Adding nano-SiO_2 to concrete not only improves particle density but also increases concrete strength and averts water penetration. TiO_2 adds self-cleaning and disinfecting properties and provides white color and brilliance for concrete and nano-Fe_2O_3 also enhances concrete stability [30-33].

In this study, the nanoparticles factor, including the four types of nano-Al_2O_3, nano-Fe_3O_4, nano-ZrO_2 and nano-TiO_2, with three different 1.0, 1.5 and 2.0 wt.% of the cementitious material was taken at twelve levels. The mentioned levels are reflected in Table 1.

2. Humidity of the curing surrounding atmosphere

To study the humidity of the curing factor, two different surrounding atmospheres, namely, the laboratory and the construction site, were selected. For the lab experiment a waterpool (1st level) was used for submerging of concrete samples, and for the construction site experiment (2nd level) the concrete samples were wrapped in cotton to be splashed with water three times a day for the first three days and kept in cotton with no water in the following days. Table 1 briefly shows the levels of humidity of the curing surrounding atmosphere.

3. Temperature of the curing surrounding atmosphere

The environment temperature is the major factor in concrete curing. The increase in the enviromant tempreture results in faster hydration. In the present study, three ranges of temperature were adopted to cure the samples.

- 10-20 degrees of Celsius that is related to a low tempreture which implies a rather slow concrete growth (1^{st} level).
- 20-25 degrees of Celsius that is standard lab temperature for curing the concrete growth (2^{nd} level).

- 25-35 degrees of Celsius that is a rather high range of temperature which expectes to cause faster concrete growth (3rd level).

Table 1 shortly displays the levels of the temperature of the curing surrounding atmosphere and Fig1 shows the method of implementing durability experiments.

Table1. The Factors and coorresponding levels effective on response variables

Nanoparticle (X_1)			Temperature of the curing surrounding atmosphere (X_2)			Humidity of the curing surrounding atmosphere (X_3)		
level	Name	code	level	Name	code	level	Name	code
1	TiO_2(1%)	-11	1	10-20 deg of Celsius	15	1	Water pool	1
2	TiO_2(1.5%)	-9	2	20-25 deg of Celsius	22.5	2	Water splash	-1
3	TiO_2(2%)	-7	3	25-35 deg of Celsius	30			
4	ZrO_2(1%)	-5						
5	ZrO_2(1.5%)	-3						
6	ZrO_2(2%)	-1						
7	Fe_2O_3(1%)	1						
8	Fe_2O_3(1.5%)	3						
9	Fe_2O_3(2%)	5						
10	Al_2O_3(1%)	7						
11	Al_2O_3(1.5%)	9						
12	Al_2O_3(2%)	11						

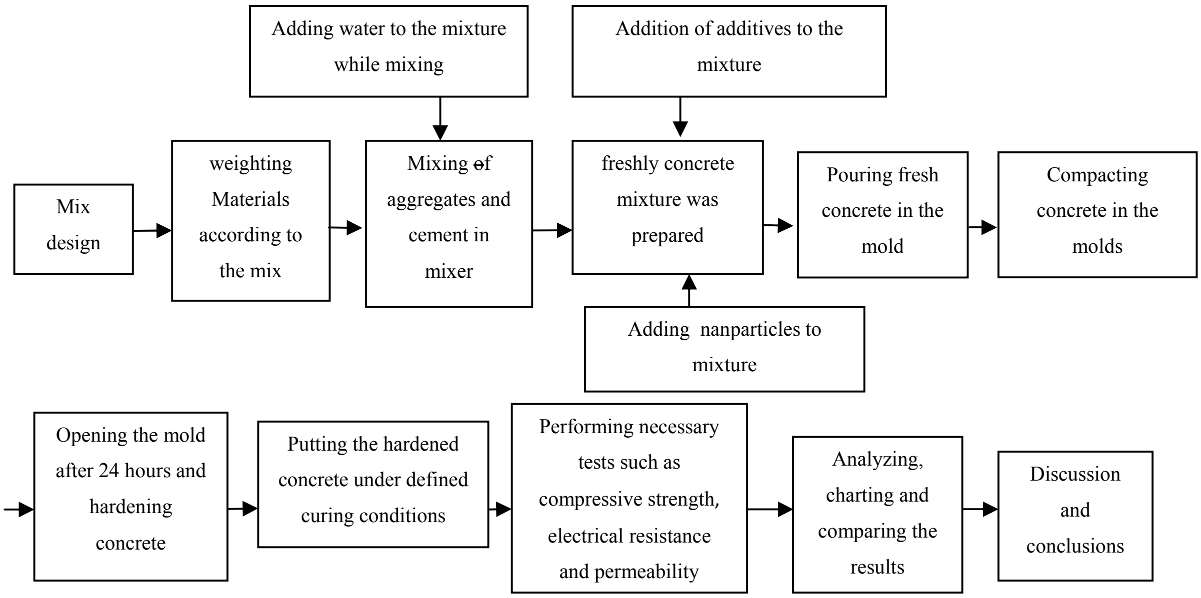


Fig. 1. The method of implementing durability experiments

2.3. Using Taguchi Approach

Since using design of experiments (DOE) which can be mainly classified as full factorial and fractional factorial design was established, it has been applied in many various studies such as mineral aggregates [34], high strength concrete beams [35], and aerostatic bearings [36]. Regarding the fact that the experiments are costly and take too much time and they involve complex calculations derived from full factorial and fractional factorial design, a Taguchi method to overcome these difficulties that are emerged in practice. A Taguchi method [37] which employs an orthogonal array and signal-to-noise ratio (S/N ratio) analysis was introduced to enhance the effectiveness of DOE. Recently, Taguchi method has been applied successfully for various engineering systems to solve problems of

properties in some materials such as fly ash geopolymer concrete [38], steel fiber reinforced high strength concrete [39], and recycled aggregate concrete mixtures [40].
As the factors are studied in this approach included a 12-level factor (nanoparticles), a 3-level factor (temperature of the curing surrounding atmosphere) and a 2-level factor (humidity of the curing surrounding atmosphere), the total degrees of freedom are fifteen, so an array of at least fifteen rows from Taguchi approach was chosen. But since the approach does not cover an array with fifteen rows, we have to go for the available arrays. An available array in Taguchi approach is $L_{18}(2^1 \times 3^7)$ which contains eighteen experiments, but since it does not contain a 12-level factor, it should be developed. For this purpose, by considering the method to create a 4-level column and then an 8-level column [41], a 12-level factor was created in Table L_{18}. After selection of the proper table and allocation of the columns appropriate to each factor degree of freedom, the layouts for 2-level, 3-level and 12-level factors are placed in the three first columns in Table 2.

2.4. Durability Tests

In this stage, with regard to the selected factors and the number of their levels, a set of eighteen experiments were designed according to the selective orthogonal array of Taguchi method. Furthermore, for precision control and repeatability purposes, it was decided that two samples must be prepared for each experiment. In order to carry out the expreriments, thirty six cubic specimens with respect to the kinds of the response variables were made and tested. The results of the
measured values for compressive strength, electrical resistance and permaebility are demonstrated in the Table 2.
Compressive strength: The 100 mm concrete cubes were used for the compressive strength tests when the specimens were at the age of 28-day. The procedure followed during the test was in conformity with BS EN 12390-2-2000 [42].
Electrical resistivity: when the test was in progress , the specimens were took away from the water tank and turn back to the water again after testing. To this aim, an electrical resistivity meter which produced 100 Hz AC was used. Two copper plates (120mm× 100mm× 2mm) with a thin layer of low slump cement paste which were put on two opposite faces of each saturated surface dry specimen, and the resistance was measured between them [43].
Permeability: The 150 mm cubic specimens were used for penetration of water and the test was started when the specimens were at least 28 days old. Moreover, the water pressure to a trowelled surface of a specimen were not applied. The specimens were placed in the apparatus and the water pressure of (500 ±50) kPa for (72 ± 2) h were used according to BS EN12390-8:2009 [24].

Table 2. The L_{18} final design (including 2,3 and 12 level factors) and the amounts for response variables

Run	X_1	X_2	X_3	Compressive strength (kg/cm^2) Y_1		Electrical resistance (kΩ/cm) Y_2		Permeability (mm) Y_3	
1	1	1	1	688	652	977	963	35	33
2	6	2	1	842	808	718	702	23	23
3	8	3	1	1049	1031	811	803	29	29
4	4	3	1	853	815	741	729	23	21
5	5	1	1	739	703	692	684	22	18
6	8	2	1	979	949	799	781	31	31
7	1	3	1	888	866	1127	1123	30	30
8	3	1	1	772	766	1022	1016	37	33
9	12	2	1	1112	1108	675	665	33	33
10	10	1	2	694	678	502	498	44	40
11	9	2	2	758	772	671	655	40	38
12	11	3	2	974	944	618	610	31	29
13	2	2	2	695	657	1025	1015	31	29
14	6	3	2	756	728	590	578	24	22
15	2	1	2	511	529	898	878	35	31
16	3	2	2	697	665	1016	1014	39	35
17	5	3	2	759	751	656	642	20	18
18	7	1	2	523	491	555	549	44	40

2.5. Optimization Method

In optimization of a multiple response variable, usually the optimum for one of the response variables cannot be the final optimized solution. There are different methods to get to the final optimal response. In the present paper the desirability function [44] has been applied in order to optimize the multiple response variable of durability. The method identifies operating conditions "*x*" that provides the most desirable response values. For each response $Y_i(x)$, a desirability function $d_i(Y_i)$ assigns numbers between 0 and 1 to the probable values of Y_i, with $d_i(Y_i)=0$ which represents a completely undesirable value of Y_i and $d_i(Y_i)=1$ representing a perfectly desirable or ideal response value. The individual desirabilities are then merged using the geometric mean, which gives the overall desirability D and can be evaluated through Eq. (2): [45]

$$D=((d_1(Y_1)(d_2(Y_2)....(d_k(Y_k))^{1/k} \tag{2}$$

where k denotes the number of responses. Notice that the overall desirability is considered zero when any response Y_i is completely undesirable ($d_i(Y_i)=0$). Practically, appropriate response values $\hat{y}_i$ are used in place of the Y_i. Various desirability functions $d_i(Y_i)$ can be used based on whether a particular response Y_i is to be maximized, minimized, or assigned a target value. If a response variable is to be maximized (larger-the-better (LTB) type), its individual desirability function is expressed as:

$$d_i(\hat{y}_i) = \begin{cases} \circ & if \quad \hat{y}_i(x) < L_i \\ \left(\dfrac{\hat{y}_i(x) - L_i}{T_i - L_i}\right)^s & if \quad L_i \le \hat{y}_i(x) \le T_i \\ 1 & if \quad \hat{y}_i(x) > U_i \end{cases} \tag{3}$$

Let L_i ,U_i and T_i denote lower limit, upper limit and target value (in this case interpreted as a large enough value for the response) respectively for the variable Yi and $L_i \le T_i \le U_i$. The exponent s determines how important it is to hit the target [44].

3. Results and Discussion

3.1. Study of the Effects by the S/N Ratio

Since the purpose of studying durability test is to improve the compressive strength, electrical resistance and reduction of permeability, the amounts of the S/N ratio for each level of the given factors had to be calculated and used in order to calculate delta amounts. As the delta amounts were obtained, the ranking process was carried out [46, 47]. The outcomes for all responses are reflected in Tables 3-8.

Table 3. Responses for S/N ratios for compressive strength

Level	S/N ratio for Nanoparticles	S/N ratio for temperature of the curing surrounding atmosphere	S/N ratio for humidity of the curing surrounding atmosphere
1	57.69	56.08	**58.66**
2	55.45	58.30	56.74
3	57.19	**58.70**	
4	58.42		
5	57.35		
6	57.86		
7	54.09		
8	60.01		
9	57.67		
10	56.72		
11	59.63		
12	**60.91**		
Delta	6.82	2.62	1.92
Rank	**1**	**2**	**3**

Table 4. Optimized level for compressive strength based on S/N Ratio

Rank	Factor	Optimized level	Corresponding factors	Corresponding S/N ratio
1	Nanoparticles	12	Al_2O_3(2%)	60.91
2	Temperature	3	25-35	58.70
3	Humidity	1	waterpool	58.66

Table 5. Responses for S/N ratios for electrical resistance

Level	S/N ratio for Nanoparticles	S/Nratio for temperature of the curing surrounding atmosphere	S/N ratio for humidity of the curing surrounding atmosphere
1	**60.38**	57.41	**58.29**
2	59.57	**58.04**	56.87
3	60.15	57.30	
4	57.32		
5	56.50		
6	56.18		

7	54.84		
8	58.04		
9	56.43		
10	53.98		
11	55.76		
12	56.52		
Delta	6.40	0.73	1.42
Rank	**1**	**3**	**2**

Table 6. Optimized level for electrical resistance based on S/N Ratio

Rank	Factor	Optimized level	Corresponding factors	Corresponding S/N ratio
1	Nanoparticles	1	TiO_2(1%)	60.38
2	Temperature	2	20-25	58.04
3	Humidity	1	waterpool	58.29

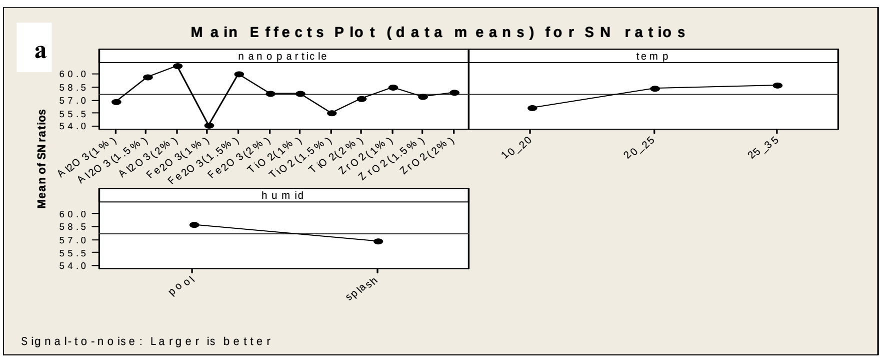
Table 7. Responses for S/N ratios for permeability

Level	S/Nratio for Nanoparticles	S/N ratio for temperature of the curing surrounding atmosphere	S/N ratio for humidity of the curing surrounding atmosphere
1	-30.09	-30.49	**-28.96**
2	-29.97	-30.03	-30.05
3	-31.14	**-28.00**	
4	-26.86		
5	**-25.83**		
6	-27.24		
7	-32.47		
8	-29.54		
9	-31.82		
10	-32.47		
11	-29.55		
12	-30.37		
Delta	6.65	2.48	1.09
Rank	**1**	**2**	**3**

Table 8. Optimized level for permeability based on S/N Ratio

Rank	Factor	Optimized level	Corresponding factors	Corresponding S/N ratio
1	Nanoparticles	5	ZrO_2(1.5%)	-25.83
2	Temperature	3	25-35	-28.00
3	Humidity	1	waterpool	-28.96

With regard to Tables 3, 5 and 7, it is obvious that the highest amount of delta variable belongs to nanoparticles factor. Therefore, it has maximum effect on the response variables. Moreover, according to Taguchi method and in order to choose the suitable level, the levels of the factors which have the highest amount of S/N ratio, are considered as optimal levels. According to S/N ratios that are obtained from Tables 3, 5 and 7, the optimal levels for response variables are summarized in Tables 4, 6 and 8.



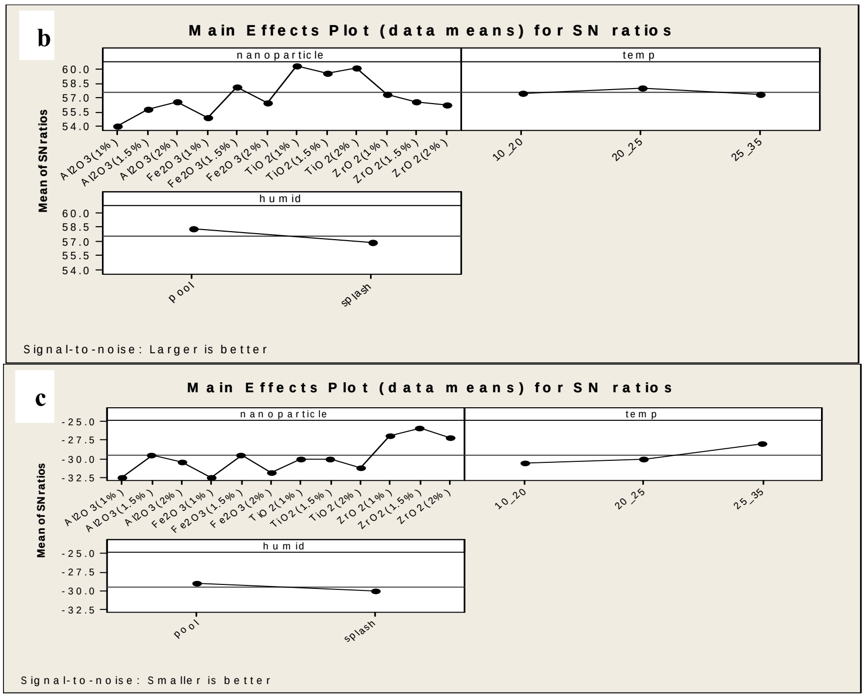


Fig. 2. S/N graph for: (a) Compressive strength, Y_1, (b) Electrical resistance, Y_2, and (c) Permeability Y_3.

Drawing main effects plot according to S/N ratio helps accurate understanding of the various factors. Fig.2 shows the plots of main effects for compressive strength, electrical resistance and permeability. These plots expose that nanoparticles is the most important factor and confirm the results that are displayed in Tables 4, 6 and 8.

3.2. Modeling Response Variables by Regression Method

One of the foremost approaches to model the response variables is considering all effective factors on response variables and using maximum adjusted R-squared to represent the regression models [48].

In this investigation, the factors influential on the compressive strength, electrical resistance and permeability were recognized and their regression models were prepared by the Minitab 15 software package [49].

As a matter of fact, using Best Subset method, the main effect of factors, their interactions, quadratic terms and triple effect of all factors were considered in regression models and regarding to the high amount of R-Sq(adj), the effective factors were derived. Then by considering the p-values which were achieved in the coefficient tables, meaningful factors were recognized and the final regression models were presented. In the next step, so as to check the fittness of presented models, the coefficients Tables 9-11, and the coefficients amounts had been explored and the normality test were implemented.

Table 9. Coefficients for compressive strength

Predictor	Coef	SE Coef	T	P
Constant	236.3	140.7	1.68	0.104
X_1	12.788	1.060	12.07	0.000
X_2	34.75	13.38	2.60	0.015
X_3	143.28	25.47	5.62	0.000
X_2*X_3	-2.231	1.087	-2.05	0.050
X_1^2	0.8735	0.1630	5.36	0.000
X_2^2	-0.4671	0.2974	-1.57	0.127
$X_1*X_2*X_3$	0.10309	0.05169	1.99	0.056

Table 10. Coefficients for electrical resistance

Predictor	Coef	SE Coef	T	P
Constant	-346.1	252.7	-1.37	0.181
X_1	-33.441	8.358	-4.00	0.000
X_2	93.39	23.57	3.96	0.000
X_1*X_2	0.5851	0.3565	1.64	0.112

X_2*X_3	1.6277	0.5826	2.79	0.009
X_1^2	1.3398	0.3257	4.11	0.000
X_2^2	-1.9769	0.5177	-3.82	0.001

Table 11. Coefficients for permeability

Predictor	Coef	SE Coef	T	P
Constant	-4.72	15.56	-0.30	0.764
X_1	-0.5687	0.5128	-1.11	0.278
X_2	3.511	1.428	2.46	0.021
X_3	-18.871	3.547	-5.32	0.000
X_1*X_2	0.03461	0.02176	1.59	0.124
X_2*X_3	0.6984	0.1486	4.70	0.000
X_1*X_3	-1.5678	0.5097	-3.08	0.005
X_1^2	0.05335	0.01704	3.13	0.004
X_2^2	-0.08520	0.03102	-2.75	0.011
X_1*X_2*X_3	0.05206	0.02172	2.40	0.024

With respect to coefficients tables, the effect of the factors which have more than 0.05 p-values was eliminated and then according to the residuals, the regression models were fitted to data which their results are shown in Tables 12-14.

Table 12. Regression coefficient for compressive strength

Predictor	Coef	SE Coef	T	P
Constant	464.84	32.88	14.14	0.000
X_1	13.280	1.243	10.68	0.000
X_2	13.348	1.322	10.10	0.000
X_3	90.653	8.079	11.22	0.000
X_1^2	0.8313	0.1923	4.32	0.000

The regression equation: $Y_1= 465 + 13.3\ x_1+ 13.3\ x_2+ 90.7\ x_3 + 0.831\ x_1^2$
R-Sq = 92.1% R-Sq (adj) = 91.1%

Table 13. Regression coefficient for electrical resistance

Predictor	Coef	SE Coef	T	P
Constant	-268.6	255.2	-1.05	0.301
X_1	-20.174	2.179	-9.26	0.000
X_2	87.55	23.95	3.66	0.001
X_2*X_3	1.5051	0.5939	2.53	0.017
X_1^2	1.4248	0.3305	4.31	0.000
X_2^2	-1.8787	0.5285	-3.55	0.001

The regression equation: $Y_2= - 269 - 20.2\ x_1+ 87.5\ x_2+ 1.51\ x_2\ x_3+ 1.42\ x_1^2- 1.88\ x_2^2$
R-Sq = 82.9% R-Sq (adj) = 80.1%

Table 14. Regression coefficient for permeability

Predictor	Coef	SE Coef	T	P
Constant	-3.62	15.27	-0.24	0.814
X_2	3.478	1.431	2.43	0.022
X_3	-16.313	3.146	-5.19	0.000
X_2*X_3	0.5822	0.1314	4.43	0.000
X_1*X_3	-1.4775	0.5320	-2.78	0.010
X_1^2	0.05158	0.01810	2.85	0.008
X_2^2	0.08589	0.03162	-2.72	0.011
X_1*X_2*X_3	0.04962	0.02306	2.15	0.040

The regression equation: $Y_3= - 3.6 + 3.48\ x_2- 16.3\ x_3 + 0.582\ x_2\ x_3-1.48\ x_1\ x_3+ 0.0516\ x_1^2- 0.0859\ x_2^2 + 0.0496\ x_1\ x_2\ x_3$
R-Sq = 70.7% R-Sq (adj) = 63.4%

With reference to the new obtained coefficients and probability plots of residuals (Figs 3,4) it was considered that most of the residuals were disseminated around the straight line. Also all of the p-values which were presented for normality test of residuals are more than 0.05. In other words, all of the mentioed points confirm the validity of the presented models. It is important to note that the amount of R-Adj and R-Sqr which were obtained for permeability may not seem very efficient, but according to the process of data gathering and the method of measuring permeability, which is rather difficult, the presented model is satisfying and are accepted by experts [50].

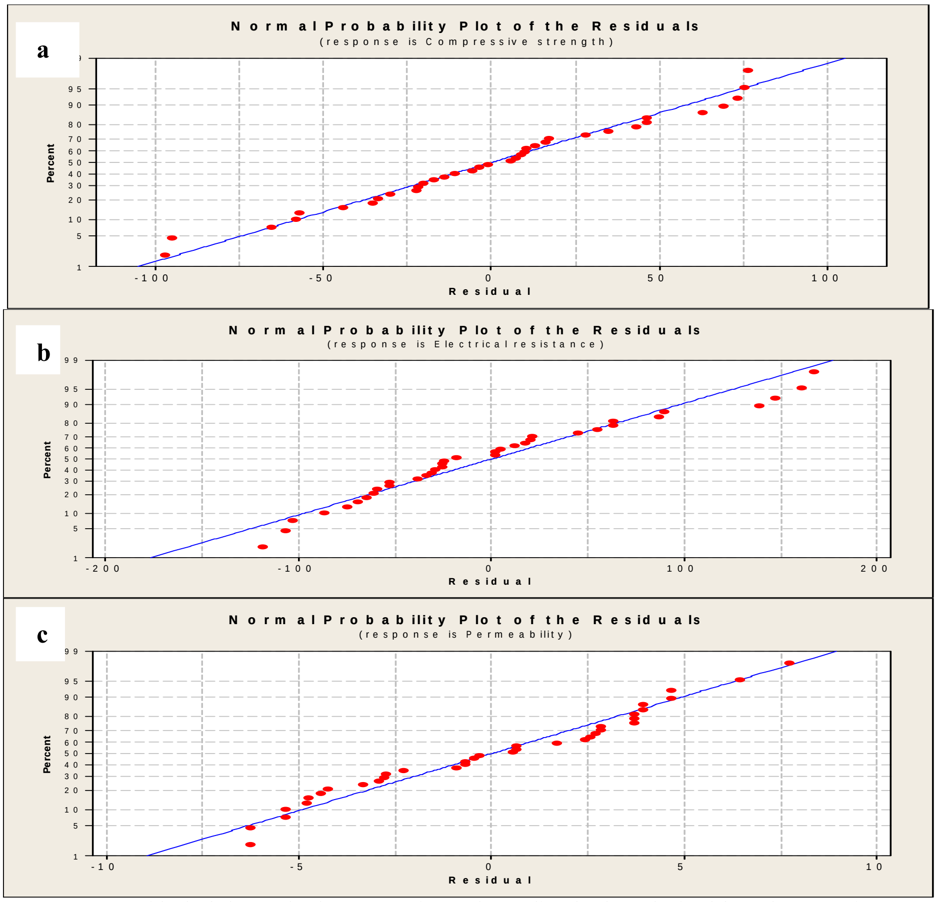
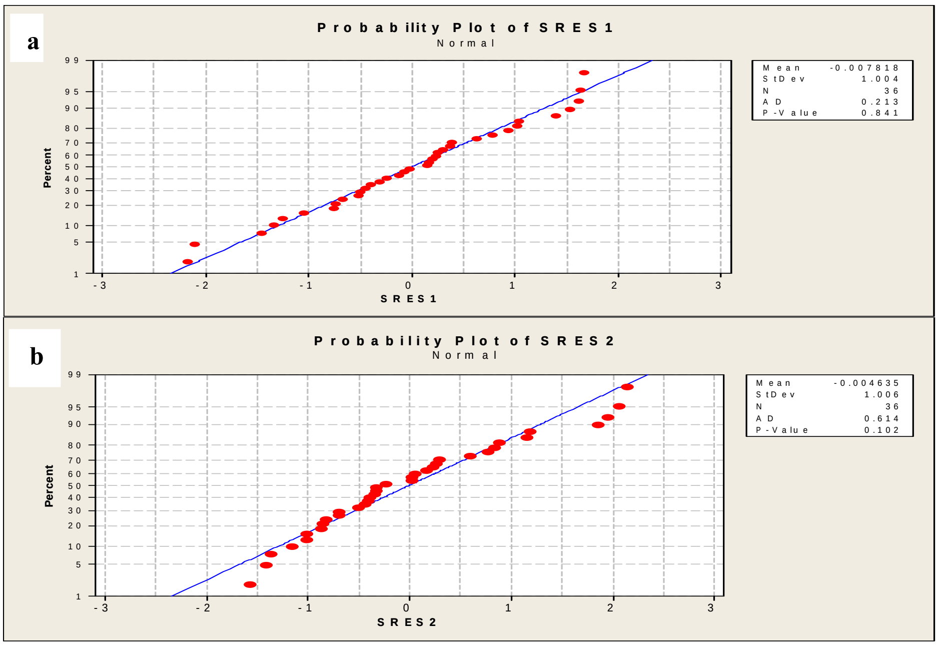


Fig. 3. Residual of observed values comparing to the predicted values obtained from the regression models: (a) Compressive strength, Y_1, (b) Electrical resistance, Y_2 and (c) Permeability Y_3.



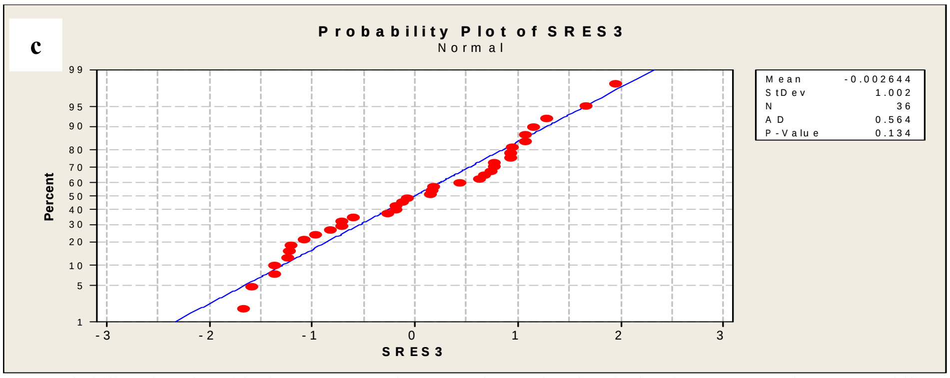


Fig. 4. Probability plot of Residual: (a) Compressive strength, Y_1, (b) Electrical resistance, Y_2 and (c) Permeability Y_3.

3.3. Optimization and Confirmation

As the response variables are formulated by the regression method, regarding the fact that Y_1 and Y_2 should be maximaized and Y_3 should be minimized, the desirability function for each response variable can be calculated. Since the target function is maximizing type, its desirability function would be calculated as Eq. (3). The term $\hat{y}_i(x)$ in Eq. (3) is the regression model for the response variables and the value of exponent s was taken 1 for the this research. It should be noted that the values for L_i and U_i and T_i were determined by the optimal amount of response variables which was obtained by Taguchi method and the related data [50].

Table 15. Responses with specification

SL No.	Response	LSL	USL	Target
1	Compressive strength	481	1190	1500
2	Electrical resistance	485	1267	1500
3	Permeability	18	44	1

Thus Eqs. (7-9) provide desirability functions for the compressive strength, electrical resistance and permeability.

$$d_1(\hat{y}_1) = \frac{1}{1019}\left(-16+13.3x_1+13.3x_2+90.7x_3+0.831x_1^2\right) \quad (7)$$

$$d_2(\hat{y}_2) = \frac{1}{1015}\left(-754-20.2x_1+87.5x_2+1.51x_2x_3+1.42x_1^2-1.88x_2^2\right) \quad (8)$$

$$d_3(\hat{y}_3) = \frac{1}{-43}\begin{pmatrix} -47.6+3.48x_2-16.3x_3+0.582\,x_2x_3-1.48x_1x_3+0.0516\,x_1^2-0.0859\,x_2^2 \\ +0.0496\,x_1x_2x_3 \end{pmatrix} \quad (9)$$

Optimization of D according to Eq. (2) and with respect to x was performed using the Lingo13 software [51]. The best (global) solution is $x^* = (-11,30,1)$ and the relevant results are indicated in Table 16. The overall desirability for this solution is D= 0.428 and all responses are predicted to be within the desired ranges.

Table 16 . Results related to the best solution

i	$d_i(\hat{y}_i)$	$\hat{y}_i(x^*)$
1	0.42	908.98
2	0.61	1104.15
3	0.31	30.67

With respect to the codes given to the factors, the results authenticate that the optimized levels for optimal durability of the concrete using TiO_2 nanoparticle up to maximum level of 1.0 wt% at temperature 25-35 degrees of celsius and in curing condition of the water pool. These results are identified and summarized in the Table 17.

Table 17. Optimized level for durability

Rank	Factor	Optimized level	Corresponding factors
1	Nanoparticles	1	TiO_2(1%)
2	Temperature of the curing surrounding atmosphere	3	25-35
3	Humidity of the curing surrounding atmosphere	1	Waterpool

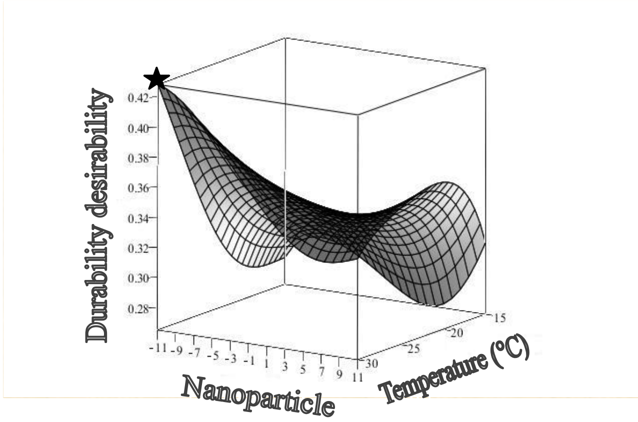


Fig. 5. 3D Surface Plot of Overall Desirability Function (D)

Fig.5 shows a 3D plot of the overall desirability function D(x) for the (x_1, x_2) variables when x_3 is fixed at 1. This plot is drawn in order to give a better understanding of the optimal desirability value and mutual interactions of nanoparticle and temperature of the curing surrounding atmosphere on the overall desirability. The nonlinear nature of 3D response surface indicates that there are considerable interactions between design variables and desirability values. Moreover, the optimal region is located at the left end top region of the plot, which has overall desirability value greater than 0.42. Finally, it should be taken into account that the values of desirability functions reported in this paper are restricted to conditions applied in the experimental work.

4. Conclusion

Most of the researchers put forward that inclusion of nanoparticles will bring about more uniform and compact micro structure to the concrete. The enhancement of concrete properties such as compressive-, flexural- and split-tensile strength containing nanoparticles has been reviewed by many literatures [8].

As the advantages of these nanoparticles on improving the concrete characteristics were proved, the effects of the four kinds of nanoparticles (in twelve levels), temperature of the curing surrounding atmosphere (in three levels), and humidity of the curing surrounding atmosphere (in two levels) on the three variables of compressive strength, electrical resistance and permeability, and eventually on the variable of durability of concrete have been studied.

Initially, depending on the methods for design of experiment, especially Taguchi approach, the optimum levels of each response variable were separately identified. In the next step, each variable was formulated by regression method and in the following step the desirability function was applied for multi-variable optimization and calculation of the final levels. Finally, the optimized solution indicates that the concrete made in combination with nanoparticle TiO_2 (1%) at temperature 25-35 degrees of celsius and in curing condition of waterpool, will have the highest durability.

It is needless to say that, one of the most important characteristics of concrete containing TiO_2 which is paid lots of attention recently, is its self-cleaning and anti-pollution characteristics [52]. Additionally, other reaserches proved the effect of TiO_2 on the split tensile strength, compressive strength and permeability of concrete [53,54]. However, the results obtained in this reserach show that not only concrete containing TiO_2 nanoparticles with 1 wt% enhances the compressive strength and water permeability properties but also in comparison with other discussed nanoparticles and other pecrentage of TiO_2, boosts the durability more.

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Biography

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