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Probabilistic Optimum Percentage of Recycled Aggregates Contaminated with Chloride Ion in Concrete Mix

A. Gh. Dehvari[1], M. Khazaei[2*], M. R. Sohrabi[3], M. Miri[3]

[1] Department of Civil Engineering, University of Velayat, Iranshahr, Iran.
[2] Department of Civil Engineering, Quchan University of Technology, Quchan, Iran.
[3]Department of Civil Engineering, University of Sistan and Baluchestan, Zahedan, Iran.

ABSTRACT: This paper studies the analysis of probabilistic service life in reinforced concrete structures exposed to chloride penetration and concrete made with recycled aggregate. Therefore, by modeling this procedure, the corrosion process can be better evaluated as well as the structural durability. In this study, such durability properties of concrete samples namely electrical resistance as corrosion and diffusion evaluation indicators have been investigated. The prediction models for durability parameters of concrete is obtained by using the neural network, namely Group Method of Data Handling and linear regression first, then these models are evaluated by using a simple and fast usability new method of probability evaluation, and eventually, the probabilistic values of using recycled aggregates with and without chloride ion pre-contamination and probability of failure in specific service life for achieving an environmentally friendly concrete are calculated. Probabilistic evaluation results reveal that for service lifetime of 25 years in a highly corrosive environment with the humidity of 70%, the temperature of 23 °C and aggregates chloride ion pre-contamination percentage of 3%, 5%, 8%, 10% and with adding 10% silica fume, using of recycled aggregates for above different chloride ion pre-contamination is limited to (100%, 46.60%), (100%, 34.57%), (100%, 16.69%) and (32.72%, 1.20%) for recycled coarse and fine aggregates, respectively. Also, it is concluded that in the mean value of recycled aggregate (50%, 50%) and aggregates chloride ion pre-contamination percentage of 5% and target reliability index $\beta_t = 3.0$, the time to corrosion initiate is achieved about $t_i = 22(year)$.

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1- Introduction

Since the annual global demand for aggregates has risen to more than a billion tons, the use of construction wastes has become an urgent need. Drilling, processing, and aggregate transfer require much energy and hence cause the emission of a significant amount of CO_2 with reverse effects on the ecology of forest areas and riverbeds making aggregate replacement a vital issue. In recent years, extensive research has been done on the recycling of the wastes from the destruction of non-exploitable buildings, which can be used to replace natural aggregates (NA) in concrete. A study of different methods of recycled aggregate(RA) utilization for new concrete can solve many economic and environmental problems caused by the expanding activities of the construction industry [1-6]. A recent popular method to assess the corrosion risk of steel rebar in concrete is using the concrete electrical resistance [7-12]; corrosion evaluation of the concrete-steel rebar is based on the concrete electrical resistance-corrosion rate relationship. According to the reported results, the electrical resistance is inversely related to the corrosion rate of the concrete-steel rebar. Yu et al. [13, 14] observed that the corrosion process of the concrete reinforcement steel is under electrical resistance control. If the current density is high, the corrosion rate will decrease with an increase in the electrical resistance. Different experimental models have been developed to measure the concrete electrical resistance in terms of both the environmental and material parameters based on the nonlinear regression analysis of the lab data Yu et al. [13, 14]; To summarize, the main purpose of the present study finds probability value of recycled aggregates (RA) in reinforced concrete structures exposed to a corrosive environment. To reach this goal according to the article framework, first, durability and mechanical parameter of concrete were obtained in the experimental part, section 2. To add to these, the effects of important parameters of a corrosive environment such as relative humidity, temperature, and concentration of chloride are tested on the electrical resistance of concrete as the corrosion risk evaluation index. The prediction models for electrical resistance (ER) of concrete are then created by using the Group Method of Data Handling (GMDH) [15-18] based on two parameters of the percentage of recycled coarse aggregate and recycled fine aggregate. Afterward, compressive strength (CS) and chloride diffusion coefficient are defined with linear regression analysis based on electrical resistance, section 3. In consequence, in section 4, these obtained models are evaluated probabilistically by applying simulation methods, for example, the weighted simulation method (WSM)

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*Corresponding author's email: m.khazaei@qiet.ac.ir

[19, 20], to show the trend of changing in the probability of failure for three failure modes in this study (electrical resistance, chloride diffusion coefficient, and compressive strength of concrete) in the different mean value of recycled coarse aggregate (RCA), recycled fine aggregate (RFA) and chloride concentration content. In the end, in section 5, these models are evaluated to reach probability values of RA for a green concrete in a probabilistic evaluation procedure by weighted simulation method (WSM) [19, 20]. In short, the results of analyses indicate different ranges of using RA for environmental conditions with high corrosion risk levels and target reliability index ($\beta_t = 3.0$). The general objective of the research is presented as below:

1. Investigating the mechanical and chemical characteristics of the recycled aggregates.
2. Finding recycled aggregate concrete mechanical and durability parameters.
3. Developing estimation models for compressive strength and electrical resistance from Experimental data.
4. Determining the probabilistic optimal value of recycled coarse and fine aggregates in the multi-objective reliability-based design optimization forms.

2- Theory

2- 1- Electrical resistance

Electrical resistance is an inherent property of materials, which can be used for different purposes, one of which is determining the fresh concrete properties in early ages. The electrical resistance of the concrete is affected by several factors, including water to cement ratio, type of cement and aggregate, mineral additives, age, environmental conditions [7].

2- 1- 1- Corrosion rate based on concrete resistivity

The corrosion rate of steel reinforcement embedded in concrete is inversely proportional to the concrete resistivity, and their relationships can be expressed as [13, 14]:

$$i_{corr} = \frac{\kappa}{\rho} \tag{1}$$

Where, i_{corr} is the corrosion rate of steel reinforcement embedded in concrete ($\mu A/cm^2$); ρ is concrete resistivity ($\Omega.m$); k is fitted parameter to define the relationship between concrete resistivity and corrosion rate of steel reinforcement, which can be calculated by the regression analysis of the laboratory data (e.g., k = 101.20 $\mu A/cm^2\Omega, m$) [13, 14].

2- 1- 2- Chloride diffusion coefficient based on concrete resistivity

For each porous material, therefore, the Nernst-Einstein equation expresses the following general relationship between the emission factor and the electrical resistance of the material [21-25]:

$$i_{corr} = \frac{\kappa}{\rho} \tag{2}$$

Where D_i is the diffusion coefficient, m^2/s, R is gas constant, J/K.mol, T is absolute temperature, K, Z is ion capacity, F indicates Faraday constant, c/mol, t_i denotes conversion number of chloride ions, γ_i is activity coefficient of chloride ions, c_i means chloride ions concentration in pore water, mol/m^3, and ρ is electrical resistance, $\Omega.m$. As a result, according to the above equation, the chloride diffusion coefficient in concrete is inversely proportional to the concrete resistivity and can be described as [21- 25]:

$$D = k.\frac{1}{\rho} \tag{3}$$

2- 2- Group Method of Data Handling (GMDH)

GMDH neural networks or polynomial neural networks are one of the interesting ways to solve modeling or regression problems. Polynomial neural networks construct a model based on the relationships between input and output data for a complex system using layer structure. This type of neural network has a complex set of simple structures based on the complexity of these simple structures, first introduced by A. Ivakhnenko in 1968 and a self-organizing method used for complex modeling [15-18].

In this type of neural network, first, a series of partial models are created through the least-squares algorithm, and then the efficient partial models are selected and as evolutionary methods are allowed to produce other partial models from these selected base models and during a final model recursive process. Hence, the best model is produced, the one with the least error and the most predictive power. In this neural network, the relationship between the input and output variables can be expressed using the polynomial function as follows:

$$g(x) = c_0 + \sum_{i=1}^{n} c_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} c_{ij} x_i x_j x_k + \dots \tag{4}$$

This is called the Kolmogorov-Gabor polynomial. In many cases the functional form has a quadratic and bivariate polynomial:

$$\begin{aligned} \hat{g}(x) = Y(x_i, x_j) = c_0 + c_1 x_i + \\ c_2 x_j + c_3 x_i^2 + c_4 x_j^2 + c_5 x_i x_j \end{aligned} \tag{5}$$

The unknown coefficients are determined by regression techniques such that the difference between the actual output, g, and the calculated values, g is minimized for each input variable pair x_i and x_j. A set of polynomials is constructed whose unknown coefficients are obtained using the least squares method. For each function Y_i (each neuron made), the coefficients are obtained to minimize the total neuron error and the optimal fit for all pairs of input-output sets. The least-squares method leads to Multiple-Regression Analysis:

$$c^T = YX^T(X^TX)^{-1} \tag{6}$$

This equation gives the vector coefficients of the above equation [15-18].

2- 3- Probability of failure

The reliability analysis is defined as calculating the probability of failure of a limit state function subjected to constraints. Mainly, in the reliability evaluation is needed to define the random variables as $X = [x_1, x_2, ... x_n]$ in the general probability of failure is calculated as below [22, 23]:

$$P_f = \int_{G \le 0} f_x(x_1, x_2, ..., x_n) dx_2, dx_2, ..., dx_n \tag{7}$$

$$P_f = \Phi(-\beta) \tag{8}$$

Where P_f is the probability of failure calculated by WSM, $\Phi(.)$ denotes the standard normal cumulative distribution functions, and β is the objective reliability index. Variables probability distributions can be defined by engineering judgments, statistical analysis, and laboratory measures. Then critical failure modes are defined as limit state function, LSF(X). Although in most cases an explicit expression of the limit state function is often not possible. In this paper, the limit states are defined using the failure modes calculated by Eq. (9) [22, 23]
.

$$LSF(X) = G_i(X) - G_{thr} \tag{9}$$

2- 3- 1- Weighted simulation method (WSM)

1. Selecting range

Here, the Monte Carlo sampling with a PDF is utilized to determine the samples' upper and lower bounds; range can be the region between these maximum and minimum values, and the region selected by this method is the smallest range required for simulation [19, 20].

2. Uniform sample distribution in the selected range

Uniform sample distribution in the range obtained for each variable can adequately cover the design space and provide a proper view of the failure region.

3. Assigning an index function for samples

Now, the limit state function should be assessed for the generated samples, the indices of which are found in the design space by calling $G(X_1, X_2)$ for n samples by the Monte Carlo method.

$$\begin{cases} 1 ......if G(X_i) \le 0 \\ 0 ....otherwise \end{cases} \tag{10}$$

4. Coefficients of samples' weights

Now, a weight coefficient is calculated as follows for each generated sample:

$$w_i = \prod_{j=1}^{s} f_j(i) \tag{11}$$

Where w_i is the weight of the i^th^ sample, s is the number of random variables, and f_j is the PDF of the j^th^ variable.

5. Approximation of the failure probability

After the above steps, the failure probability is obtained by calculating the following equation [19, 20]:

$$P_f = \frac{\sum_{i=1}^{N} I W_i}{\sum_{i=1}^{N} W_i} \tag{12}$$

This approach is demonstrated to be accurate and robust for the analysis of many complex engineering problems, as discussed by [24–26]. As known, the limit state function defines the boundary between safe and failure domains. Hence, in the chloride penetration problem, the limit state function can be written in terms of time for corrosion initiation: in which is the time for corrosion initiation that depends on the group of random variables X; is the structural lifetime expected in design which is considered as a deterministic parameter. The time is evaluated using Eq. (13) by assuming the chloride concentration C (d, t) as known at a given position d inside the concrete. C (d, t) is assumed to be equal to the chloride concentration threshold, d is the concrete cover. It assumes zero at the external surface of the structural member and the cover value at the reinforcement´s surface inside the concrete. In this approach, the time for corrosion initiation can be defined explicitly from Eq. (13) as [22, 23]:

$$t_i = \frac{1}{D_0} \left\{ \frac{d}{2erfc\left[\dfrac{C(d,t)}{C_0}\right]} \right\}^2 \tag{13}$$

Based on these models, the structural safety variation along time can be calculated. As a result, one of the most important products of these coupling is the possibility to choose

Table 1. Properties of Normal and Recycled Aggregates

	Mechanical Test			**Germany Specification [26]**	
material	Specific gravity	Bulk density (kg/m^3)	Water absorption (%)	Standard Water absorption (%)	Standard Specific gravity
NCA(Natural coarse aggregate)	2.73	1561	0.73	≤ 15	≥ 2.0
NFA	2.65	1622	0.79	≤ 15	≥ 2.0
RCA	2.71	1356	6.33	≤ 15	≥ 2.0
RFA	2.36	1278	9.77	≤ 15	≥ 2.0

Chemical Analysis	
material	C_{cl^-} (%)
NA	0.05
RA	0.05

the time of structural maintenance based on a given reliability index target. So, the determined amount of using recycled aggregate in concrete mix for assessing service life according to mechanical and durability behavior of the concrete structure is the main goal of this paper.

2- 3- 2- Reliability-based design optimization

The reliability-based design optimization (RBDO), an important structure optimization area that involves uncertainties, is an attempt to search for the best agreement between cost reduction and safety assurance based on probabilistic constraint assessments. In short, it not only finds the construction costs but is also responsible for the reliability level; total cost is the sum of the construction, design, defects, and repairs costs. The reliability-based structure optimization is generally formulated as follows [20]:

$$\begin{aligned} &Minimize: f(X) \\ &Subjectto: P\left[G(X_1, X_2)\langle 0\right] \leq P_f \\ &X_1^L \leq X_1 \leq X_1^U \\ &X_2^L \leq X_2 \leq X_2^U \end{aligned} \tag{14}$$

Where $f(X)$ is the objective function, X is the vector of random variables, $G(X_1, X_2)$ is the optimization problem constraint, and X^L X^U are the random variables' lower and upper bounds, respectively. The objective failure probability is simply expressed in terms of the objective reliability index $P_f = \Phi(-\beta)$. Where $\Phi(.)$ is the standard normal cumulative distribution function.

3- Experimental Work

3- 1- Materials

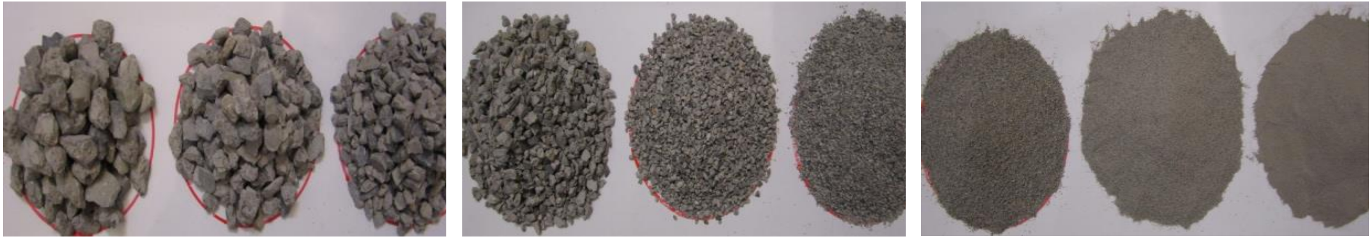
In studying the effects of replacing natural aggregates(fine and coarse) with recycled ones, the density of fine and coarse aggregates and water absorption of both natural and recycled aggregates were measured, see Table 1 following ASTM C29 [27], ASTM C127 [28], and ASTM C128 [29]. Table 2 shows the specifications of Type II Portland cement used in this research.3.1.1. Silica Fume (SF)

Silica fume is used in concrete to improve its properties. It has been found that silica fume improves compressive strength and electric resistance, reduces permeability, and therefore helps in protecting the reinforced steel from corrosion. Silica Fume suitable with American Society for Testing

Table 2. Portland cement type II chemical and physical properties.

Chemical Analysis	Result
Silicon dioxide (SiO_2): %	21.05
Aluminum oxide (Al_2O_3): %	4.76
Iron oxide (Fe_2O_3): %	3.43
Calcium oxide (CaO): %	62.86
Magnesium oxide (MgO): %	3.46
Physical Test	**Result**
Loss on ignition: %	1.2
Specific Gravity	2.95
Blaine fineness: m^2/kg	312

(a) Recycled materials



(b) Sieved coarse and fine aggregates

Fig. 1. Recycled coarse and fine aggregates.

Table 3. Silica Fume properties.

Properties	Result
Specific Gravity	2.2
Bulk Density	720 kg/m^3
Specific Surface	720 m^2/g
Particle size	$\langle 1\mu m$
color	White
SiO$_2$	(80-85)%

and Materials "Standard Specification for Silica Fume Used in Cementitious Mixtures" (ASTM C 1240-12) [30] is used in the concrete mixtures. The SF are given in Table 3.

3- 2- Methods

Natural and recycled coarse and fine aggregates, see Fig. 1(a)-(b), were weighed (ASTM C33 [31]), cement and water were mixed and poured in cylindrical molds (300 mm × 150 mm and 200 mm × 150 mm) and in cubical molds (150 mm × 150 mm and 100 mm × 100 mm), compressive strengths of 28 and 90 days specimens were obtained (ASTM C39 [32]), see Fig. 2(a)-(b).

3- 2- 1- Test methods of concrete resistivity

According to the two-electrode method (TEM), the concrete resistivity in the laboratory is accomplished. Fundamentals of the TEM test are shown in Fig. 3. As shown in the figure, the TEM imposes an alternating current between two parallel electrodes placed on both ends of the concrete specimen and then measures the electrical potential between them. Based on Ohm's law, the electric resistance of concrete can be measured. Eventually, the concrete electrical resistivity examined by the TEM can be calculated by [13, 14]:

$$\rho_{TEM} = \frac{RA}{L} \tag{15}$$

\Where ρ_{TEM} is concrete resistivity tested by the TEM $(\Omega.m)$; R is the resistance between two electrodes (Ω); A is the contact area between electrode and concrete specimen (m^2); L is the length of concrete specimen (m). As shown in Fig. 3, the electrical resistance test (ASTM C1760-12 [33]) is performed after 28 and 90 days of curing under saturation conditions with a dry surface.

3- 2- 2- Test methods of the chloride diffusion coefficient

The specimens are molded with 100 mm diameter and then 200 mm diameter and cut into three plates with 50 mm thickness in the middle. These specimens are made with various mixtures and tested under NT-Build 492 [34, 21-25], known as the Rapid Chloride Migration (RCM) method. , see Fig. 3. After performing the RCM test, the colorimetric indicator for chlorides (Ag/NO$_3$ solution) is sprayed onto freshly split concrete samples to determine the chloride penetration depth. The colorimetric boundary between the regions with and without chlorides is visible due to the chemical reaction of Ag^+ with Cl^- or OH^- and formation of white or dark precipitate regions, as illustrated in Fig 4. Hence the penetration depth is evaluated [21-25].

(a) Prepared samples **(b) Compressive strengths test equipment**

Fig. 2. Compressive strengths specimens test.

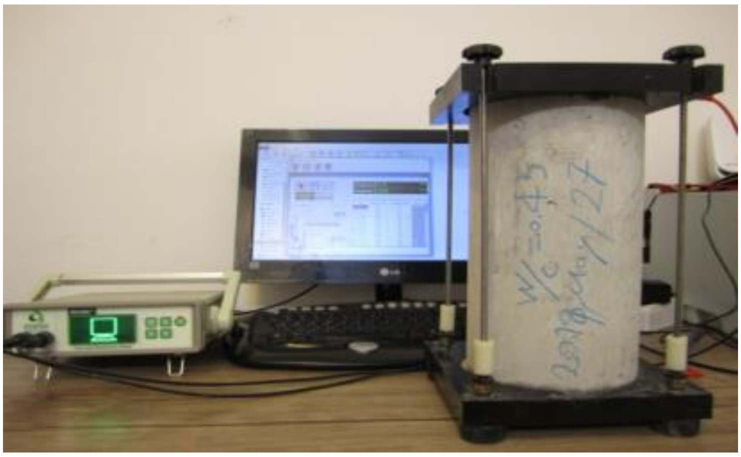
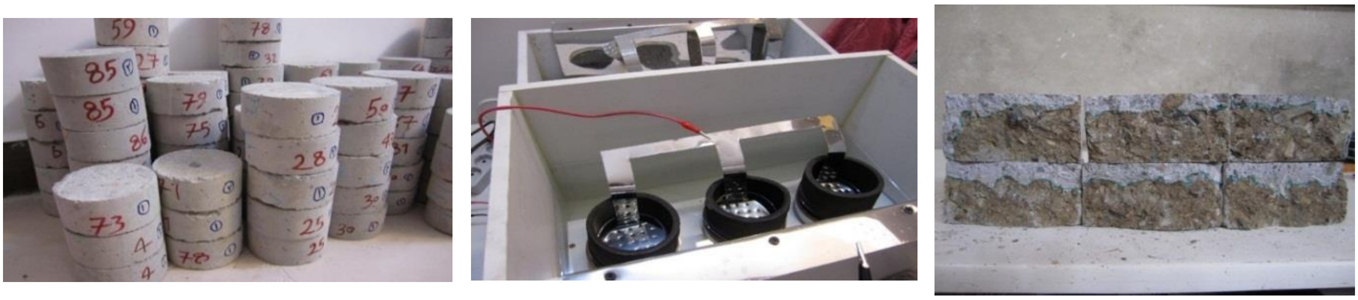


Fig. 3. Electrical resistance specimens test.



(a) Prepared samples (b) RCM test equipment (c) Tested samples

Fig. 4. Rapid chloride migration specimens test.

Table 4. Mix proportion, Basic parameters of Experimental data

No	Specimen		Cement		SF (10%)	$R_{W/C}$	NFA(kg/m3)	NCA(kg/m3)	RCA(kg/m3)	RCA(%)	Free Water(kg/m3)	Water reducing Amount (kg/m3)
	Type	Size(mm)	Type	Amount(kg/m^3)	Amount(kg/m^3)							
1	Cylinder	300×150	OPC	443.25	49.25	0.40	715.75	936.60	0	0	197	0.35
2	Cylinder	200×100					738.45	749.28	162.72	20	197	
							772.54	468.30	406.80	50	197	
3	Cube	100×100 ×100					795.25	280.98	569.52	70	197	
							829.32	0	813.80	100	197	

3.2.2.1. Rapid Chloride Migration Methods

The D_{RCM} is calculated from the following mathematical model [24]:

$$\frac{dc}{dt} = -\frac{\partial J_X}{\partial X} = \frac{D_0}{1+\frac{\partial c_b}{\partial c}}\left(\frac{\partial^2 c}{\partial x^2} - \frac{zFE}{RT}\cdot\frac{\partial c}{\partial x}\right) = D_{RCM}\left(\frac{\partial^2 c}{\partial x^2} - \frac{zEF}{RT}\cdot\frac{\partial c}{\partial x}\right) \tag{16}$$

The solution of this model is presented in and yields the following equation for the D_{RCM} :

$$D_{RCM} = \frac{RT}{zFE}\frac{x_d - \alpha\sqrt{x_d}}{t} \tag{17}$$

Where c: concentration of free-chlorides in pore solution, t: time, x: distance, D_0 , intrinsic chloride diffusion coefficient in the pore solution of concrete, c_b : concentration of bound chlorides, E: electric field, equal to (U − 2)/L, where U: applied electrical voltage, and L: the thickness of the sample (0.05 m), R: gas constant (8.314 J mol^{-1} K^{-1}), T: temperature (293 K), z: ion valence (−1 for Cl^-), F: Faraday constant (96485 $C.mol^{-1}$), X$_d$: chloride penetration depth indicated by the colorimetric indicator AgNO$_3$, α: laboratory constant defined as [24]:

$$D_{RCM} = \frac{RT}{zFE}\frac{x_d - \alpha\sqrt{x_d}}{t} \tag{18}$$

Where c$_d$: free-chloride concentration at color change boundary ($0.07\ mol_{cl}/dm^3_{solution}$) and c_0 : concentration of chlorides in the external bulk solution ($64.95\ g_{cl}/dm^3_{solution} = 1.83 mol_{Cl}/dm^3_{solution}$) [24].

3- 3- Mixing proportions and specimens preparation

The mix design is under the requirements of the GMDH method; the amounts of the recycled aggregates (fine and coarse) are considered as the model variables, see Table 4. In this study, to make the model and perform chloride diffusion, electrical resistance, etc., cylindrical and cubical concrete specimens were prepared with 0, 20, 50, 70, and 100% NA replacement with RA, consistent with RCA and RFA. In this paper, the effects of incorporating silica fume (SF) in the concrete mix design to improve the quality of recycled aggregates in concrete are presented. So, Portland cement is replaced with SF at 0%, 5%, 7.5%, and 10%.

3- 4- Experimental results

Table 1 shows the water absorption of waste concrete aggregates versus natural ones; as shown, water absorption of the recycled coarse aggregates is 8.61 times that of natural ones because recycled aggregates are covered with the primary concrete mortar (the main feature of this aggregate type). Similarly, water absorption of the recycled-fine aggregates is 12.37 times that of the natural ones, which means the latter absorb more mortar from the old concrete mix. In Figs. 5 and 6, with increasing porosity, electrical resistance reduces by approximately 55.74% in the maximum use of RAs (100%).

3- 5- Modelling Result

3- 6-

3- 6- 1- Electrical resistance proposed estimation model

The ER of concrete is a key index for evaluating the quality of concrete for various environmental conditions affected by material-related and environmental parameters. It is worthwhile to mention, the same experimental work is accomplis-

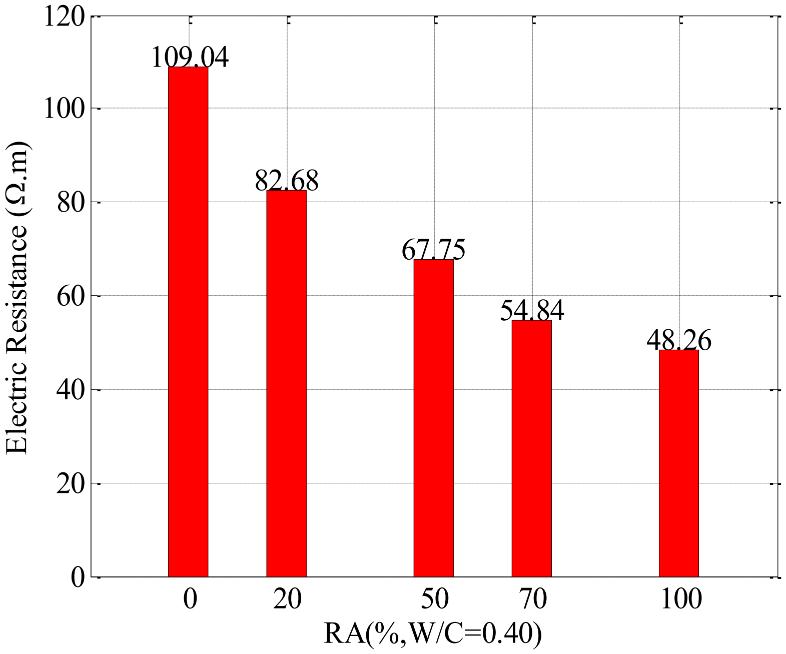


Fig. 5. Electric Resistance RA (%) relationship.

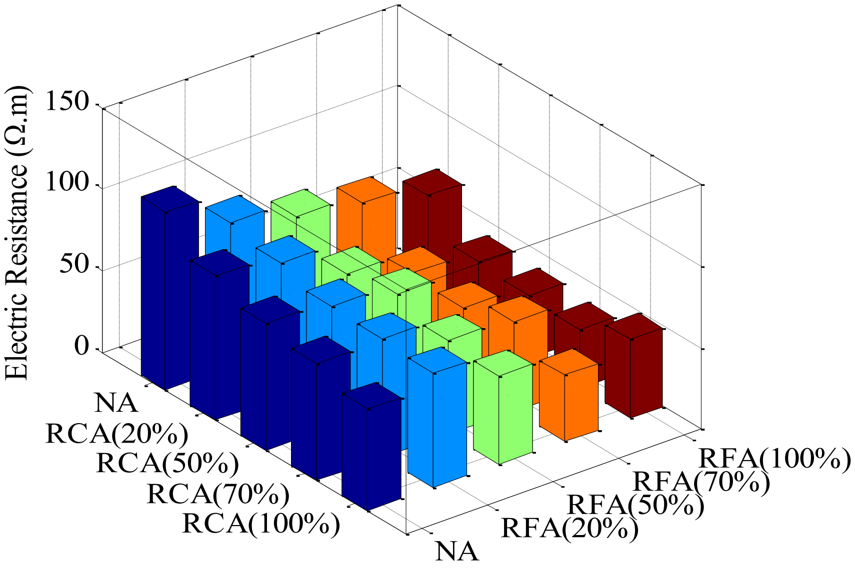


Fig. 6. Electric Resistance RCA (%) – RFA (%) relationship (90 days).

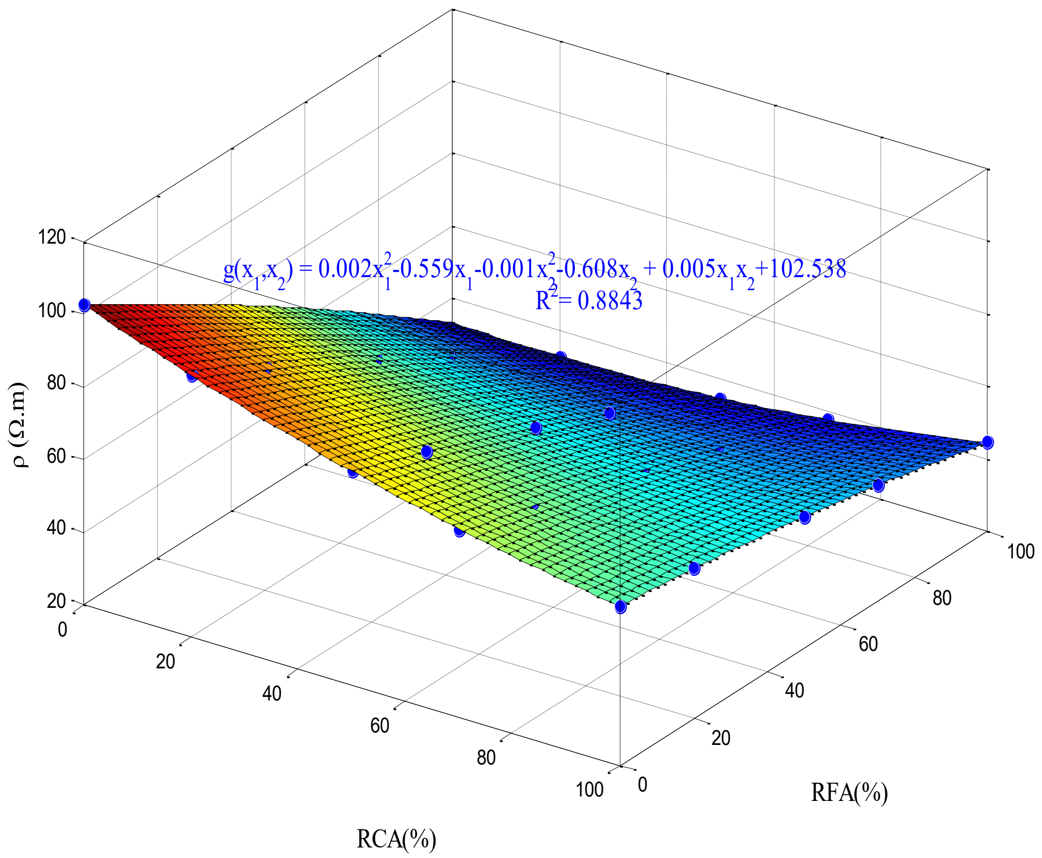


Fig. 7. Electric Resistance RCA (%)-RFA (%) GMDH Response.

hed in this research compared with reference Bo Yu et al. [7, 8], for example, the chloride Concentration (C_{Cl^-}), ambient temperature (T), relative ambient humidity (γ_{RH}) on concrete electrical resistance.

Hence, in the present study, the effects of consuming recycled aggregates and Silica Fume in concrete have been investigated. The ER of concrete at the ages of 28 and 90 days at the saturated conditions with a dry surface is measured (ρ_0). After calculating the coefficients of material and environment, ER is computed using Eqs. (19) and (20):

$$\rho_0(x_1,x_2)=0.0014x_1^2-0.558x_1-0.001x_2^2-0.553x_2+0.005x_1x_2+102.214 \quad (19)$$

$$\rho=K_{SF}.K_{RH}.K_{Cl^-}.K_T.\rho_0(RCA(\%),RFA(\%)) \quad (20)$$

Where, ρ is the concrete electrical resistance, see Figs. 7 and 8, considering material/environmental conditions $(\Omega.m)$, K_{SF} is the Silica Fume influence coefficient, see Fig. 9, K_{RH} is the humidity influence coefficient, see Fig. 10, K_{Cl^-} is the chloride influence coefficient, see Fig. 11, and K_T is the ambient temperature influence coefficient, see Fig. 12. It can be worth to be mentioned here, In Fig. 9., adding silica fume in concrete mix incredibly increases concrete resistivity, so that in 10% SF concrete resistivity became 3.28 times, although compressive strength does not have a significant increase incomparable with electrical resistance.

3- 6- 2- Compressive strength proposed estimation model

Compressive strength is directly proportional to the electrical resistivity; hence the electrical resistivity methods can be used as a Non-destructive testing method to find the Compressive strength of concrete. After measuring the electrical resistance of each sample, their 28-day compressive strength (f_{c28}) is examined in the lab, the following relation is defined between its variables using the collected data and the Regression method, see Fig. 13:

$$f_c=f_{c28}(\rho) \quad (21)$$

Where f_{c28} is the compressive strength of the standard cylindrical specimen in MPa.

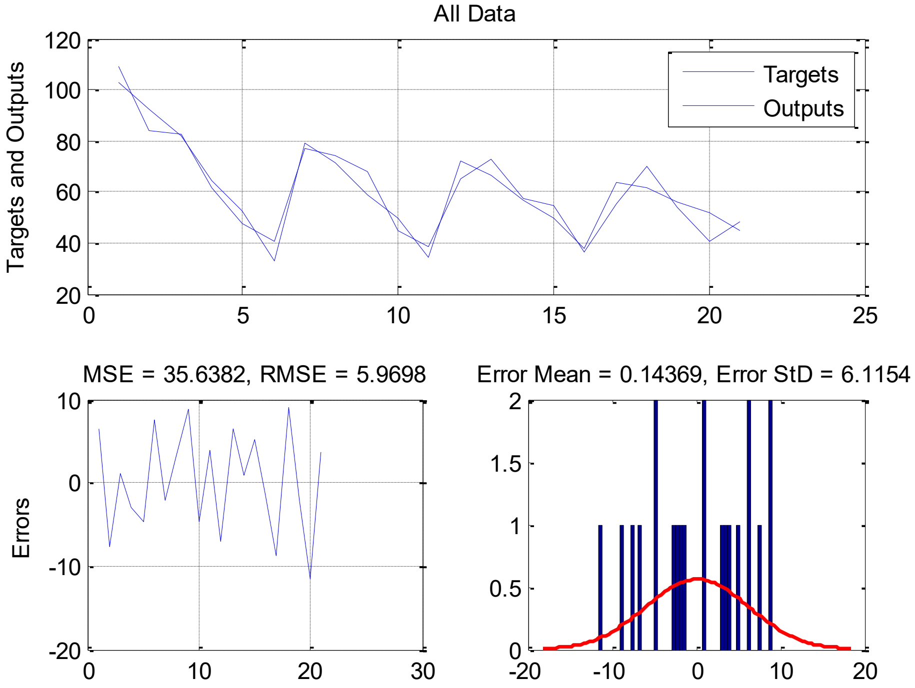


Fig. 8. GMDH Electric Resistance Response Error Estimate

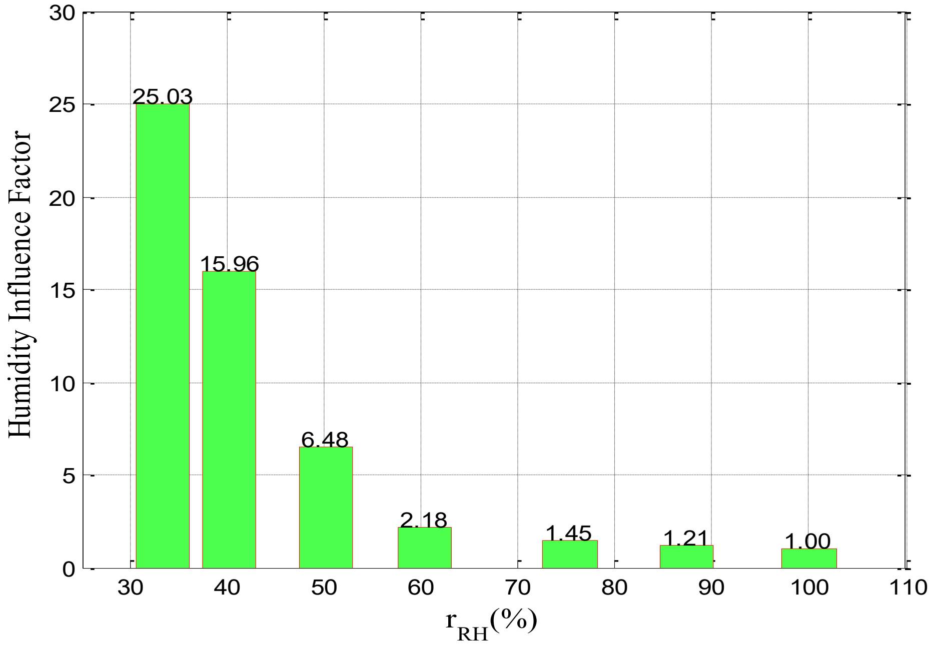


Fig. 9. Silica Fume Influence Factor on Electric Resistance.

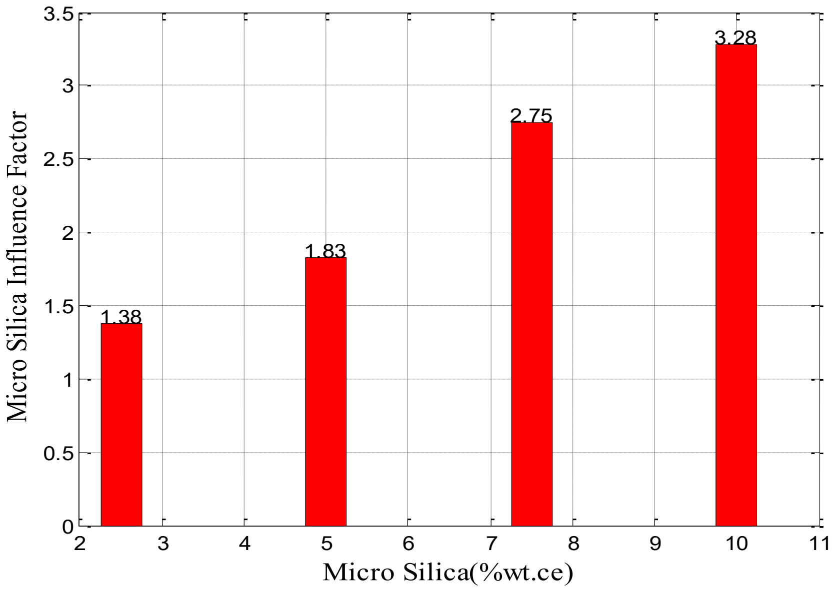


Fig. 10. Humidity Influence Factor on Electric Resistance.

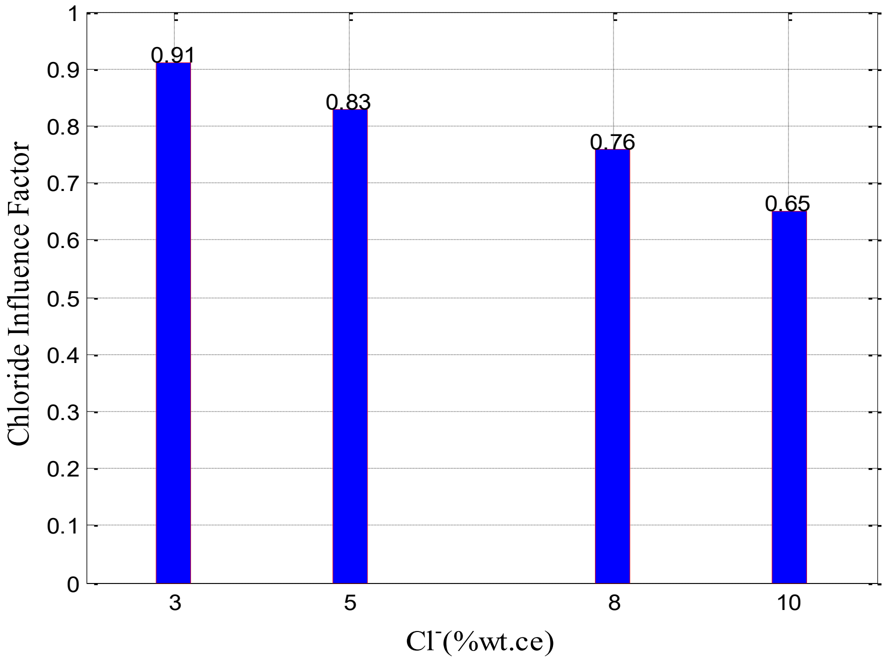


Fig. 11. Chloride Influence Factor on Electric Resistance.

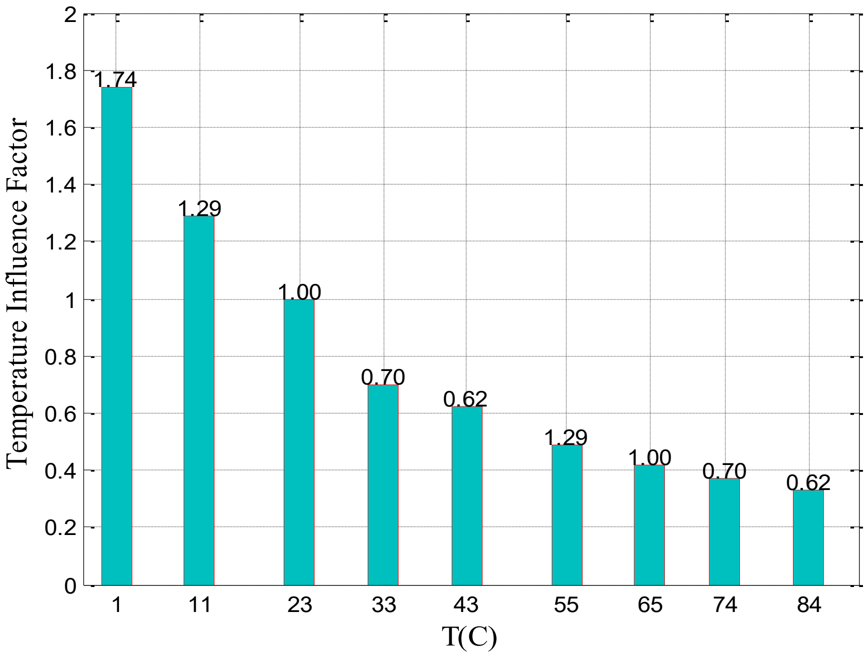


Fig. 12. Temperature Influence Factor on Electric Resistance.

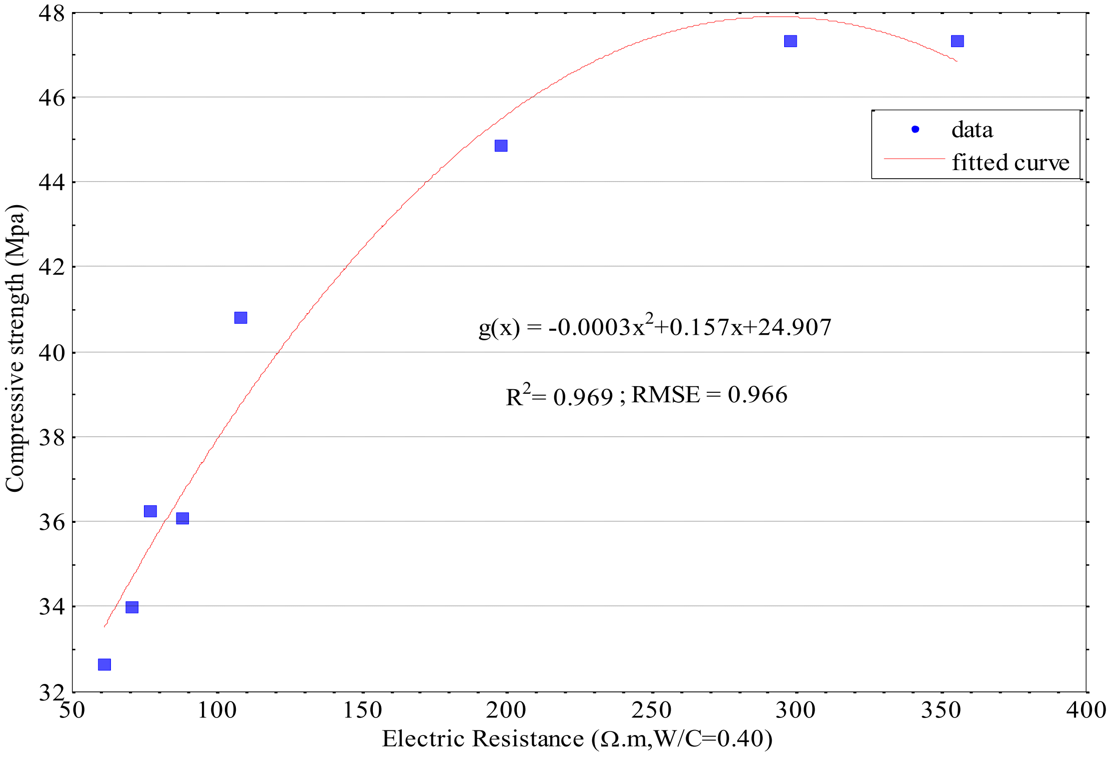


Fig. 13. Compressive strength – Electric Resistance relationship.

Table 5. Test condition and the result of rapid chloride migration coefficient.

Mix. Number	Applied voltage [V]	Initial current (30V) [mA]	Final current [mA]	Test duration [h]	X_d [mm]	$D_{RCM}\left[10^{-12},m^2,s^-\right]$
RCA-0%	25	88.55	73.22	24	10.50	5.68
RCA-20%	20	90.93	73.33	24	10	6.70
RCA-50%	20	91.52	60	24	10	6.70
RCA-70%	20	107.36	69.79	24	10.80	7.30
RCA-100%	20	107.45	69.79	24	11	7.45
RFA-20%	10	198.56	60	24	6.40	7.75
RFA-50%	10	198.56	60	24	7.00	8.59
RFA-70%	10	198.56	60	24	7.90	10.09
RFA-100%	10	198.56	60	24	9	11.75

3- 6- 3- Chloride diffusion coefficient proposed estimation model based on electrical resistance

An average chloride penetration depth is measured and used for the calculation of D_{RCM} (Eq. (17)), as reported in Table 5. It may be observed that the chloride diffusion coefficients results show that the chloride penetration depth increases with an increase in the amount of RCA and RFA (for these two mixtures the same voltage was applied). As illustrated in Figs. 14 and 15, from RCM test result extracted in the maximum use of RCAs (100%) chloride diffusion coefficient increases about 31 and 208% in the maximum use of RFAs (100%). Chloride diffusion coefficient has a close relation with electric resistance as this parameter's inherent property, based on electric flux in a magnetic field. The following relation is obtained by doing regression analysis on experimental data, where D_{RCM} is the rapid chloride migration coefficient.

$$D_{RCM} = D_{RCM}(\rho) \tag{22}$$

4- Probabilistic evaluation and RBDO results

The models of time for corrosion initiation (t_i), compressive strength (f_c), and electric resistance (ρ) are evaluated probabilistically by considering the mean and coefficient variation of random variables with a normal distribution, i.e., percentage of replacement of RCAs and RFAs, which are respectively (50, 50) and (0.20, 0.20), and generated 50000 samples using the Monte Carlo method, and results are explained below, as well as in the time for corrosion initiation equation $C_t = 0.7kg/m^3, c_0 = 6kg/m^3, d = 50$ are considered in this research.

4- 1- Chloride pre-contamination of RAs

Chloride concentration (C_{Cl^-}) is an environmental parameter affecting on ER of concrete [35, 36]. In other words, the conductivity of ions in the concrete is increased by increasing C_{Cl^-}, and when C_{Cl^-} is increased, the ion conductivity channel becomes stronger. In other words, concrete conductivity is enhanced upon the increase in C_{Cl^-} which can easily able to absorb from the humidity of external environment or has already existed in the materials, especially RAs, as a pre-contamination. Fig. 16(a)-(d) show with increasing $C_{Cl^-} = 0\% - 10\%$, failure of probability for electrical resistance following an ascending trend from $P_f = 0.0215\text{-}0.9013$ which indicates the probabilities of service life $(t_f = 25(year))$ for steel reinforcement.

4- 2- Amount of RFAs

Based on Fig. 17, as shown for environmental conditions of $r_{RH} = 70\%, T = 23^\circ C, C_{cl^-} = 5\%, t_{thr} = 25(year)$ and the RCA of 40%, the failure probability of the first failure mode (service life) changes versus the mean of the first random variable (recycled coarse aggregate percentage) within the range of $P_f = 8.3\times10^{-4} - 9.83\times10^{-1}$. Fig 17. also shows in target reliability index $\beta_t = 3.0(P_f = 1.30\times10^{-3})$ probabilistic value of RAs is (40%, 42.43%), RCAs and RFAs, respectively.

4- 3- 4.3. Amount of RCAs

Based on Fig. 18, as shown for environmental conditions of $r_{RH} = 70\%, T = 23^\circ C, C_{cl^-} = 5\%, t_{thr} = 25(year)$ and the RFA of 40%, the failure probability of the first failure mode (service life) changes versus the mean of the second random variable (recycled fine aggregate percentage) within the range of $P_f = 3.1\times10^{-5} - 3.59\times10^{-4}$. In addition to this, Fig 18 indicates in target reliability index $\beta_t = 3.0(P_f = 1.30\times10^{-3})$ probabilistic value of RAs is (100%, 40%), RCAs and RFAs, respectively.

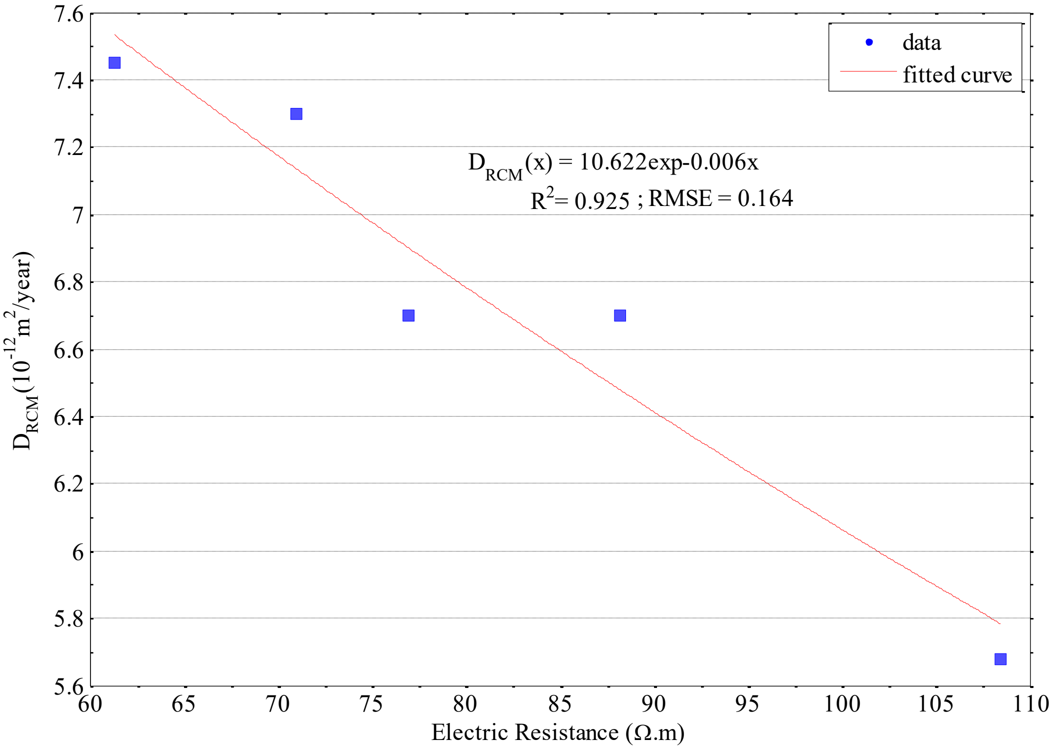


Fig. 14. Chloride Diffusion RCA (%)-W/C (0.40) Response.

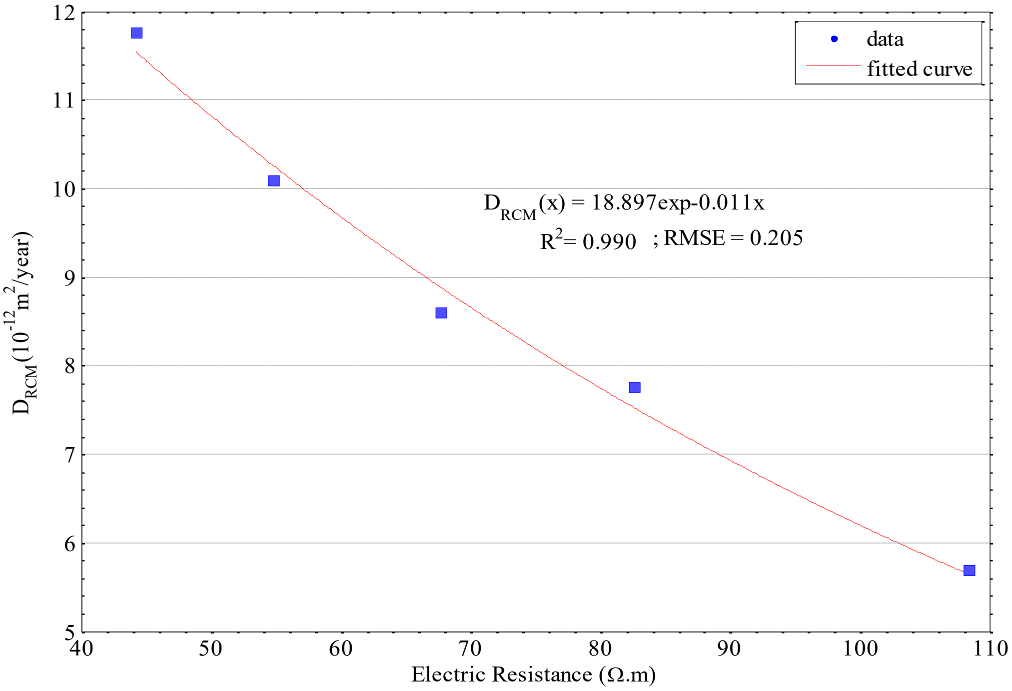
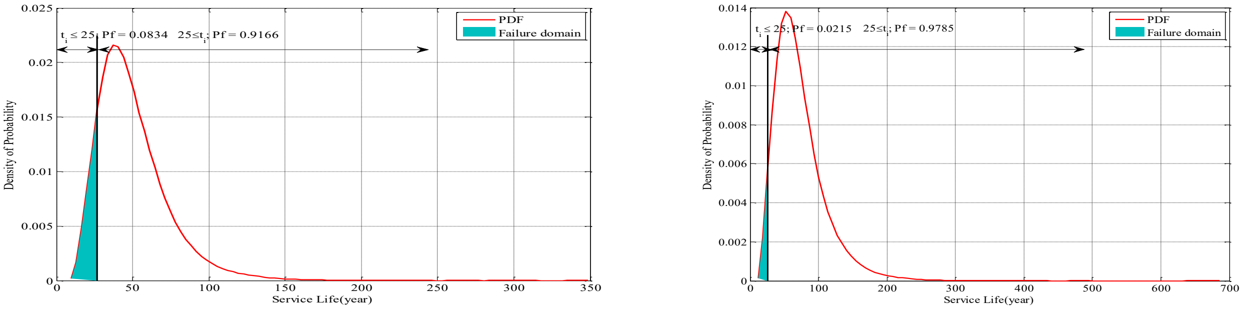
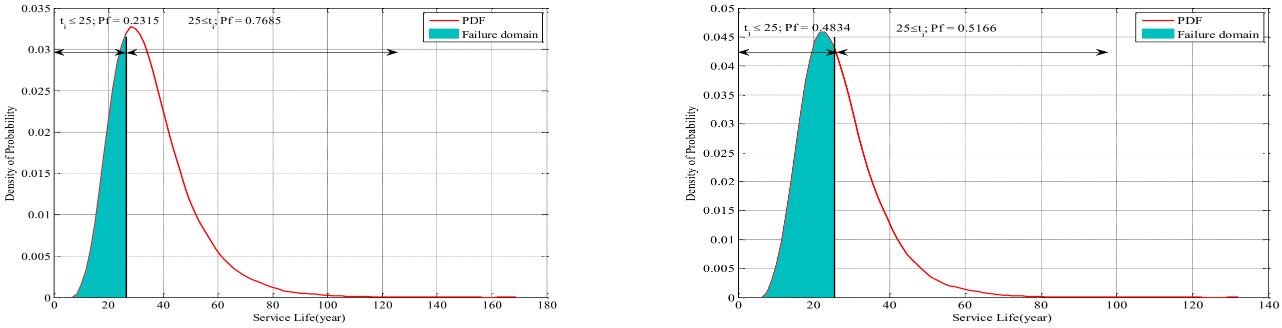


Fig. 15. Chloride Diffusion RFA (%)-W/C (0.40) Response.

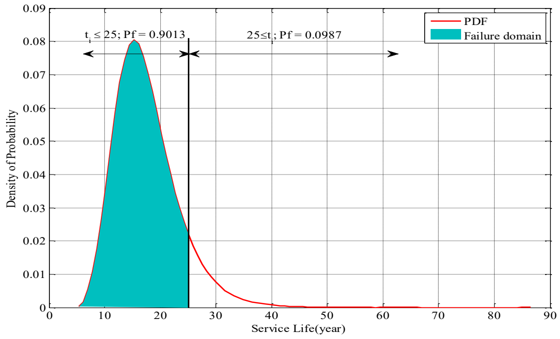


(a) $T=23^\circ C, rh=70\%, C_{cl^-}=0\%, t_i=25(year)$ (b) $T=23^\circ C, rh=70\%, C_{cl^-}=3\%, t_i=25(year)$



(c) (d)

$T=23^\circ C, rh=70\%, C_{cl^-}=5\%, t_i=25(year)$ $T=23^\circ C, rh=70\%, C_{cl^-}=8\%, t_i=25(year)$



(e)

$T=23^\circ C, rh=70\%, C_{cl^-}=10\%, t_i=25(year)$

Fig. 16. Service Life Probabilistic Evaluation.

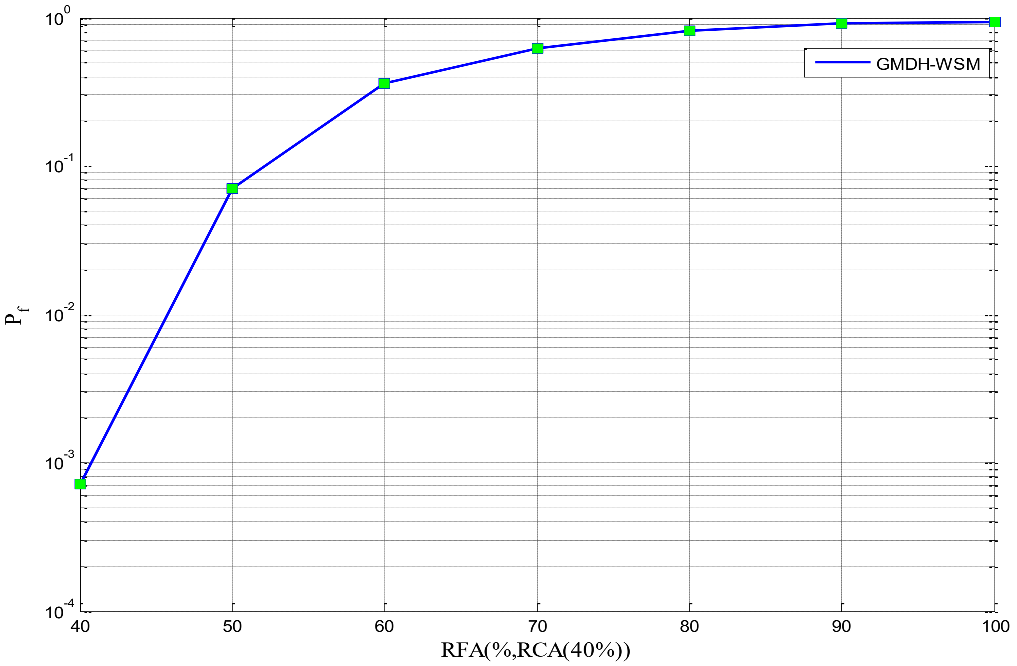


Fig. 17. Service Life Model Failure Probability.

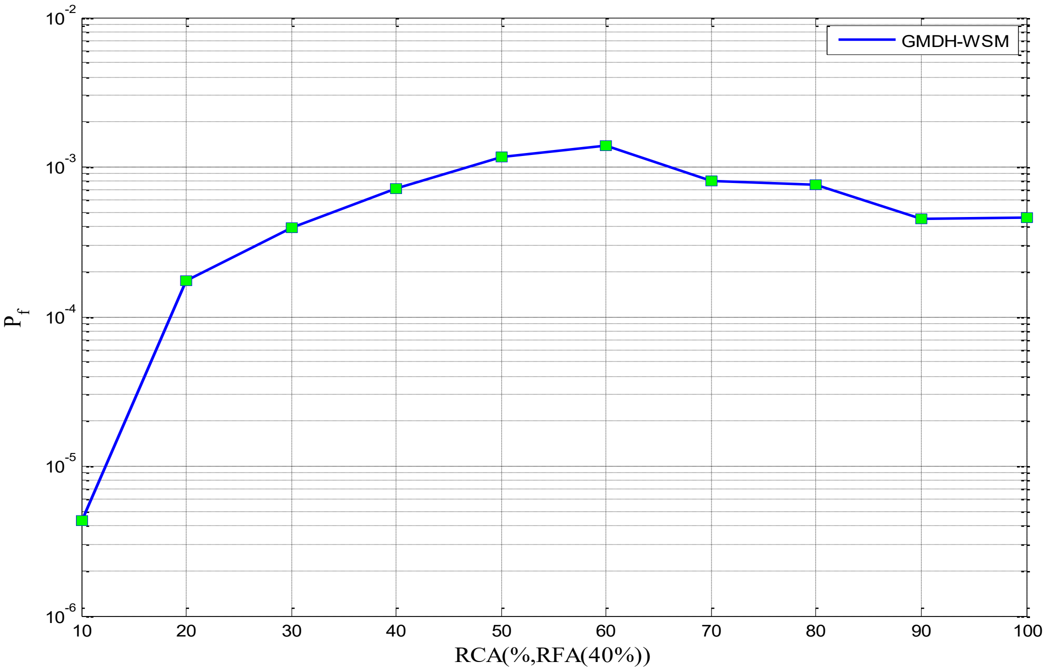


Fig. 18. Service Life Model Failure Probability.

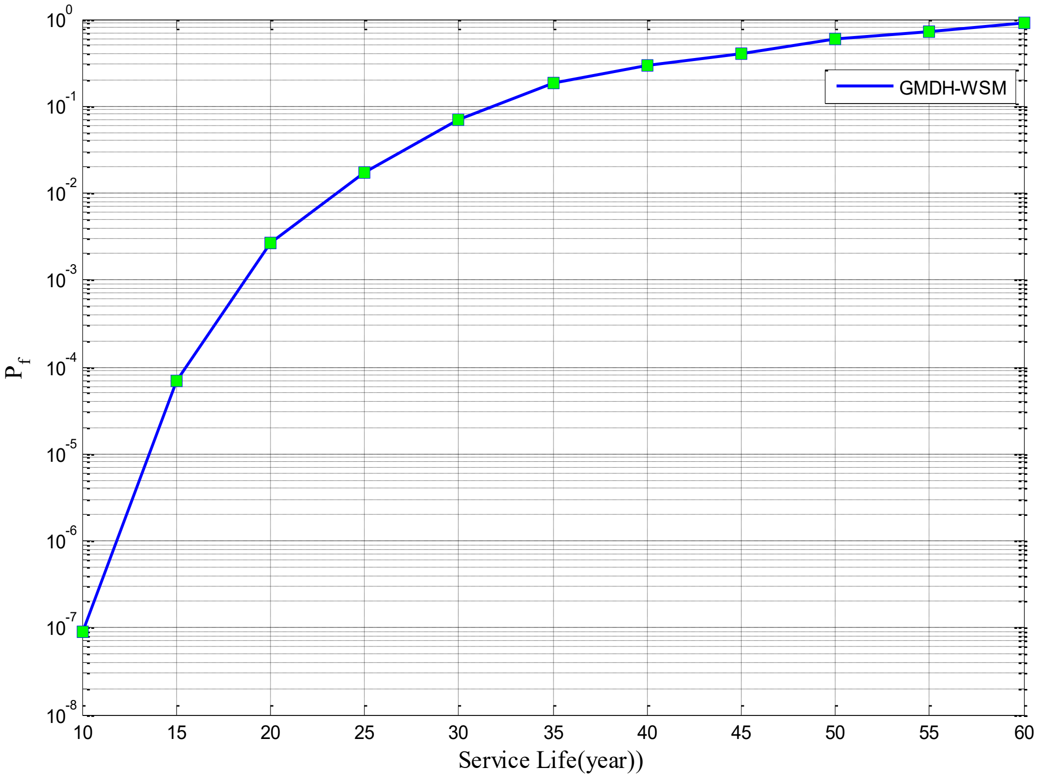


Fig. 19. Model Failure Probability for different Service Life Time.

4- 4- Service life

Based on Fig. 19, as shown for environmental conditions of $r_{RH} = 70\%, T = 23^{\circ}C, C_{cl^-} = 5\%$, in different service life $t_i = 10-60(year)$, in the mean value of RAs and target reliability index $\beta_t = 3.0(P_f = 1.30\times10^{-3})$ the time to corrosion initiate is about $t_i = 22(year)$.

4- 5- RBDO Result

The reliability-based optimization problem in this study can be expressed as follows:

Where $f(X)$ is the objective function, X is the vector of random variables, $G(X_1, X_2)$ is the optimization problem constraint, here chloride diffusion coefficient, and compressive strength defined based on the electrical resistance of concrete, and $\rho_{thr} = 200\Omega.m, f_{thr} = 30MPa, t_{thr} = 25(year)$. The objective failure probability is simply expressed in terms of the objective reliability index as $P_f = \Phi(-\beta)$ where $\Phi(,)$ is the standard normal cumulative distribution function. An objective reliability index of 3.0 is equal to an objective failure probability of 1.30×10^{-3}. Here, the design variables are the amount of RCA and the RFA. The classification of corrosive environmental conditions in this study was considered according to Table 6 [35, 36].

4- 5- 1- WSM – RBDO

As shown in Fig. 20(a)-(e) based on assumed corrosion risk level for steel reinforcement, i.e., high ($\rho \geq 200\Omega.m$), safety level or target reliability index $\beta_t = 3.0(P_f = 1.30\times10^{-3})$, service lifetime $t_i = 25(year)$, the environment with humidity of 70%, the temperature of 23, and chloride concentration of 3%, 5%, 8%, 10% and with adding 10% silica fume using of RAs is limited to (100%, 46.60%), (100%, 34.57%), (100%, 16.69%) and (32.72%, 1.20%), RCAs and RFAs, respectively.

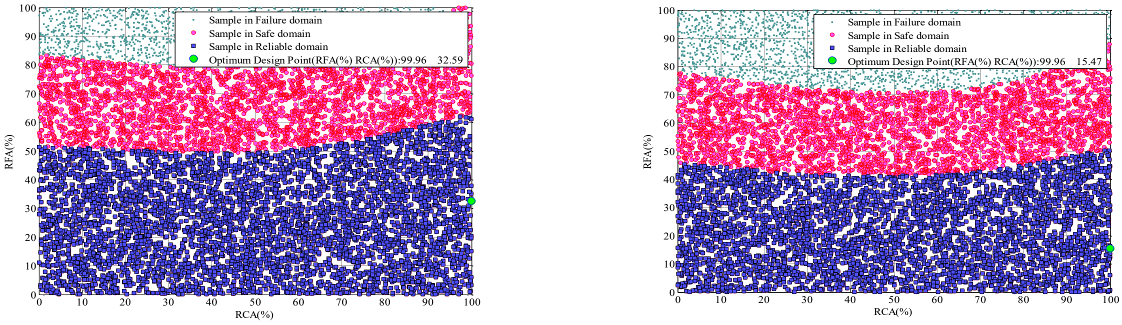
5- Conclusion

Aggregates and hardened concrete tests results and probability evaluation of recycled concrete service lifetime are revealed the following conclusion:

1. Natural aggregates in the waste concrete turn, after breaking, into recycled ones having mortar on their surfaces from the primary concrete. This mortar on the natural aggregate creates a porous area around it and causes it to absorb more water the amount of which depends on the volume of the surrounding mortar. Coarse aggregates that are surrounded by less mortar absorb less water (6.33%) compared to fine aggregates with more mortar (9.77%).

Table 6. Classification Based on Environment Risk Leve.

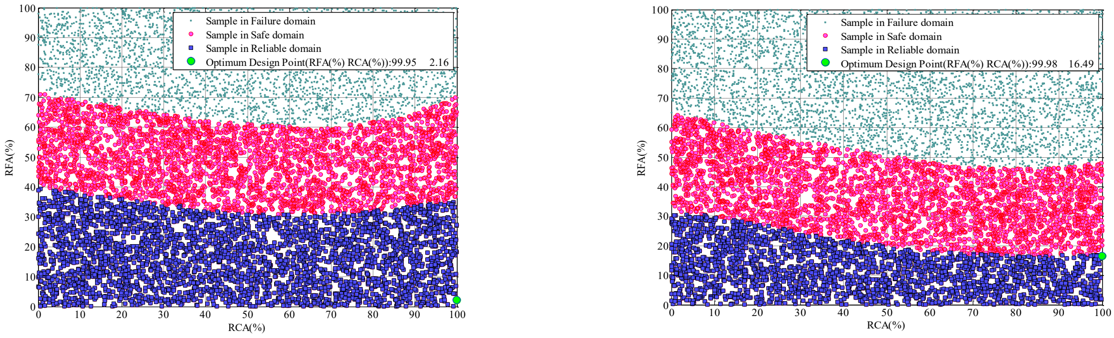
Chloride Penetration	Required Bulk Resistivity $(\Omega - m)$	Chloride Migration Coefficient D(m^2/s)
High	$\langle 50$	$\rangle 16\times10^{-12}$
Moderate	50-100	$8-16\times10^{-12}$
Low	100-200	$2-8\times10^{-12}$
Very Low	200-2000	$\langle 2\times10^{-12}$
Negligible	$\rangle 2000$	-



(a)

$T = 23^{\circ}C, rh = 70\%, C_{cl^-} = 0\%, t_i = 25(year)$

(b) $T = 23^{\circ}C, rh = 70\%, C_{cl^-} = 3\%, t_i = 25(year)$

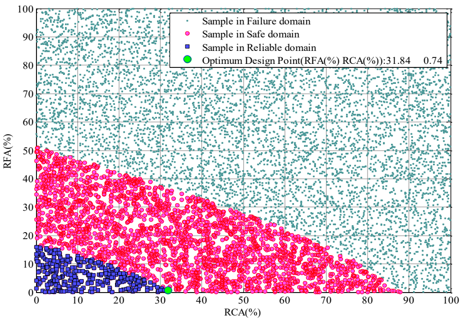


(c)

$T = 23^{\circ}C, rh = 70\%, C_{cl^-} = 5\%, t_i = 25(year)$

(d)

$T = 23^{\circ}C, rh = 70\%, C_{cl^-} = 8\%, t_i = 25(year)$



(e) $T = 23^{\circ}C, rh = 70\%, C_{cl^-} = 10\%, t_i = 25(year)$

Fig. 20. WSM-RBDO results for different environmental conditions.

2. Compressive strength has illustrated a proper relationship with the electrical resistivity; hence the electrical resistivity methods can be used as a Non-destructive testing method to find the Compressive strength of concrete.
3. Chloride diffusion coefficient illustrates a suitable relationship with the electrical resistivity; hence the electrical resistivity methods are known as a simple, low cost and rapid testing method to find Chloride diffusion coefficient of concrete which need to long time and high-cost chemical materials.
4. Results of the probabilistic evaluation demonstrate that the maximum use of RCA and the RFA can be affected by different expected service lifetimes.
5. Using RAs only in some cases of a highly corrosive environment is possible, so for another environmental condition, for example, corrosive environment with higher humidity environment, RAs might be used in the concrete mix with combining additive cementitious materials such as fly ash, metakaolin, and fumed silica.

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References

[1] Y.C.Liang, Z.M.Ye, F. Vernerey, Y. Xi, Development of processing methods to improve strength of concrete with 100% recycled coarse aggregate, Materials in Civil Engineering, 27(2013).

[2] C. Pellegrino, F. Faleschini, Sustainability improvements in the concrete industry, use of recycled materials for structural concrete production, Springer 2016.

[3] E. Vázquez, Progress of recycling in the built environment, final report of the RILEM Technical Committee 217-PRE (Springer Science & Business Media, 8(2012).

[4] N. Biglarijoo, M. Nili, S.M. Hosseinian, M. Razmara, S.Ahmadi, P.Razmara, Modelling and optimization of concrete containing recycled concrete aggregate and waste glass, Magazine of Concrete Research, 69(2017), 306-316.

[5] L.G.Li, J.Zhu, A.H.Huang, A.K.H. Kwan, L.J. Li, Combined effects of micro-silica and nano-silica on durability of mortar, Construction and Building Materials, 157(2017), 337-347.

[6] H.Dilbas, M.Şimşek, O.Çakır, An investigation on mechanical and physical properties of recycled aggregate concrete (RAC) with and without silica fume, Construction and Building materials, 61(2014), 50-59.

[7] M.R Nokken, R.D. Hooton, Electrical Conductivity Testing", American Concrete International, 28 (2006), 58-63.

[8] H.Layssi, P. Ghods, A.R. Alizadeh, M.Salehi, Electrical resistivity of concrete, Concrete International, 37(2015), 41-46.

[9] P.Azarsa, R.Gupta, Electrical resistivity of concrete for durability evaluation, Advances in Materials Science and Engineering, 2017.

[10] M.Jalal, A.R. Pouladkhan, H. Norouzi, Choubdar, Chloride penetration, water absorption and electrical resistivity of high performance concrete containing nano silica and silica fume, American science, 8(2012), 278-284.

[11] T.C.Hou, Y.M.Su, Y.R.Chen, P.J.Chen, Effects of coarse aggregates on the electrical resistivity of Portland cement concrete, Construction and Building Materials, 133(2017), 397-408.

[12] R.A.Medeiros-Junior, M.G.Lima, Electrical resistivity of unsaturated concrete using different types of cement, Construction and Building Materials, 107(2017), 11-16.

[13] B.Yu, L.Yang, M.Wu, B.Li, Practical model for predicting corrosion rate of steel reinforcement in concrete structures, Construction and Building Materials, 54(2014), 385-401.

[14] B.Yu, J.Liu, Z.Chen, Probabilistic evaluation method for corrosion risk of steel reinforcement based on concrete resistivity, Construction and Building Materials, 138(2017), 101-113.

[15] A.G.Ivakhnenko, Polynomial theory of complex systems. IEEE transactions on Systems, Man Cybernetics, 4(1971), 364-378.

[16] S.J. Farlow, The GMDH algorithm of Ivakhnenko, The American Statistician, 35(1981), 210-215.

[17] H.B.Nezhad, M.Miri, M.R.Ghasemi, New neural network-based response surface method for reliability analysis of structures, Neural Computing and Applications, 31(2019), 777-791.

[18] I.Ebtehaj, H. Bonakdari, F. Khoshbin, C. Bong, H. Joo, A. Ab Ghani, Development of group method of data handling based on genetic algorithm to predict incipient motion in rigid rectangular stormwater channel, Scientia Iranica, 24(2017), 1000-1009.

[19] M. Rashki, M. Miri, M.A. Moghaddam, A new efficient simulation method to approximate the probability of failure and most probable point, Structural Safety, 39(2012), 22-29.

[20] M.Rashki, M.Miri, M.A. Moghaddam, A simulation-based method for reliability based design optimization problems with highly nonlinear constraints, Automation in Construction, 47(2014), 24-36.

[21] T.Zych, Test methods of concrete resistance to chloride ingress, Czasopismo Techniczne, 2015.

[22] C.G.Nogueira, E.D. Leonel, Probabilistic models applied to safety assessment of reinforced concrete structures subjected to chloride ingress, Engineering Failure Analysis, 31(2013), 76-89.

[23] B. Saassouh, Z. Lounis, Probabilistic modeling of chloride-induced corrosion in concrete structures using first-and second-order reliability methods, Cement and Concrete Composites, 34(2012), 1082-1093.

[24] V. Elfmarkova, P. Spiesz, H.J.H. Brouwers, Determination of the chloride diffusion coefficient in blended cement mortars". Cement and Concrete Research, 78(2015), 190-199.

[25] P. Konečný, P.Lehner, T. Ponikiewski, P. Miera, Comparison of chloride diffusion coefficient evaluation

based on electrochemical methods, Procedia Engineering, 190(2017), 193-198.

[26] Deutschen Instituts für Normung, Aggregates for concrete and mortar—part 100: recycled aggregates, Germany, 4226, 2002.

[27] ASTM C 29/C 29M-97. Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate.

[28] ASTM C 127-04. Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate.

[29] ASTM C 128-04a. Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate.

[30] ASTM C 1240-12, Standard Specification for Silica Fume Used in Cementitious Mixtures.

[31] ASTM C 33- 01, Standard Specification for Concrete Aggregates.

[32] ASTM C 39/C 39M-05, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

[33] ASTM C 1760-12, Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete.

[34] N.T.Build, 492–Nordtest method, Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments. Finland: NORDTEST, 1999.

[35] R.B.Polder, Test methods for on-site measurement of resistivity of concrete—a RILEM TC-154 technical recommendation, Construction and building materials, 15(2001), 125-13.

[36] Thomas, R. J., Properties and Performance of Alkali-Activated Concrete, Ph.D. Thesis, Clarkson University, Department of Civil Engineering, Potsdam NY, 2016.

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