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PROBABILISTIC DURABILITY EVALUATION OF BINARY AND TERNARY CONCRETE MIXTURES CONSIDERING AGING EFFECT

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ABSTRACT

The paper is focused on the evaluation of the effect of concrete long-term maturity with respect to chloride ion ingress related durability. The random variation of input parameters is considered. The attention is paid to the durability prediction related to steel reinforcement corrosion initiation based on the chloride penetration. The binary and ternary high performance concrete mixtures are selected for the analysis. The data set from complementary laboratory investigation is used for the description of resistance of concrete against ingress of chlorides. The corrosion initiation risk is expressed in the form of probability over intended life span of the bridge deck. Thus finite element chloride ingress model combined with Monte Carlo simulation technique considering the effect of aging is applied.

Keywords: concrete mixtures, probabilistic model, SBRA, Monte-Carlo simulation, durability.

INTRODUCTION

The reliability of reinforced concrete bridge structures is depending on many factors. One of the most important is corrosion of reinforcing steel caused by the ingress of chloride-based deicing agents. It is desirable to study and evaluate protection effect of concrete on the onset of corrosion of steel reinforcement [20], [21].

For example, application of High-Performance Concrete is one of the typical options [3] where the ability of concrete to resist chloride penetration is typically described by using the diffusion coefficient and aging factor [4], [19]. The diffusion parameters are related to concrete electrical conductivity [1], [7].

The rapid Chloride Penetration Test (RCPT) is able to assess the concrete performance against chlorides while resistivity measurements are more feasible [2]. It can be measured using the Wenner probe or conductivity meter [6].

This paper directly follows the article Durability of binary and ternary concrete mixtures considering aging effect [9], where was analyzed influence of long-term concrete maturing on the durability of the ideal HPC reinforced concrete bridge deck without cracks. Since there was deterministic approach adopted, it is of question how random variation of input parameters influences the resulting durability.

Research significance

The paper is focused on the durability evaluation of 33 binary and ternary concrete mixtures with special aim to compare the results of deterministic and probabilistic analysis. This comparison is realized on a model example of reinforced concrete bridge deck. It is loaded by chloride-induced corrosion process. The durability assessment is focused on the initiation phase herein.

PROBABILISTIC ASSESSMENT OF RELIABILITY

The Monte Carlo approach is selected from the available probabilistic approaches [8], 11, 12, 14, 15, 22], in order to evaluate the random variation of input parameters.

Performance functions

Analysis of performance function allows for the evaluation of probability of corrosion initiation of steel reinforcement. As such, the performance function RF_t is a function of time.

The two main inputs to the assessment of performance are deicing agents induced concentration of chloride at reinforcement level C_z and chloride threshold level C_{th} [10]:

$$RF_t = C_{\mathrm{th}} - C_z. \tag{1}$$

The chloride concentration at reinforcement level is computed using the numerical finite element model [9], [13]. The comparison of concentration with chloride threshold to start corrosion yields time to corrosion initiation as shown e.g. in [9] for deterministic case without consideration of randomness.

RANDOM INPUT VARIABLES

The probabilistic model used FEA algorithm prepared in MatLab [13]. It contains evaluation of durability expressed in the form of the period to the initialization of corrosion of bridge deck.

The solution of this procedure is carried out repeatedly as part of a Monte Carlo simulation with randomly generated input variables according to the assigned probabilistic distribution.

Random variables are diffusion coefficient, aging factor, cover depth, surface chloride concentration and chloride threshold. All of these important parameters are described below.

Diffusion coefficient

Description of concrete resistance against chloride penetration via diffusion coefficient and aging factor (see in Table-1) are evaluated in equation (2). Equation (2) is applied to compute nominal value of time-

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ARPN Journal of Engineering and Applied Sciences

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dependent diffusion coefficient:

$$D_{c,\text{nom}}(t) = D_{c,28} \cdot \left(\frac{t_{28}}{t}\right)^{m} , \tag{2}$$

where $D_{c,nom(t)}$ is diffusion coefficient [m^2/s] for a selected age t [years], t_{28} is reference period of measurement at age of 28 days [years] and m is aging factor [-]. The parameters of studied concrete mixtures are adopted from the laboratory test campaign [6]. The diffusion coefficient $D_{c,(28)}$ was calculated for sample of the age 28 days and aging factor m (see in Table-1).

Table-1. Concrete mixture material parameters [9].

No.	Mixture	Diffusion coefficient $D_{c,(28)}$ (m^2/s)	Aging factor m
1	100TII-V	5,585E-12	0,284
2	80TII-V/20C	6,060E-12	0,382
3	80TII-V/20F	5,375E-12	0,513
4	60TII-V/20C/20F	6,308E-12	0,523
5	60TII-V/30C/10F	5,113E-12	0,432
6	60TII-V/30F/10C	4,804E-12	0,421
7	75TII-V/20C/5SF	4,242E-12	0,570
8	75TII-V/20F/5SF	3,275E-12	0,597
9	65TII-V/35G120S	7,919E-12	0,152
10	60TII-V/35G120S/5SF	5,188E-12	0,362
11	50TII-V/35G120S/15C	7,535E-12	0,300
12	50TII-V/35G120S/15F	7,020E-12	0,331
13	95TII-V/5SF	6,623E-12	0,330
14	93TII-V/7SF	5,267E-12	0,436
15	65TII-V/5SF/30C	5,693E-12	0,520
16	65TII-V/5SF/30F	4,254E-12	0,624
17	55TII-V/5SF/40G120S	6,141E-12	0,397
18	45TII-V/40G120S/15C	7,508E-12	0,206
19	45TII-V/40G120S/15F	2,055E-12	0,649
20	65TII-V/35G100S	2,678E-12	0,663
21	60TII-V/35G100S/5SF	2,309E-12	0,831
22	50TII-V/35G100S/15C	3,125E-12	0,417
23	50TII-V/35G100S/15F	2,856E-12	0,398
24	45TII-V/35G100S/20F	2,750E-12	0,403
25	60TII-V/30F/10M	5,995E-12	0,511
26	60TII-V/30C/10M	8,959E-12	0,476
27	50TII-V/40G120S/10M	2,111E-12	0,572
28	60TII-V/25F/15M	5,035E-12	0,444
29	60TII-V/25C/15M	8,991E-12	0,383
30	50TII-V/35G120S/15M	2,418E-12	0,594
31	65TII-V/28F/7M	4,176E-12	0,288
32	65TII-V/28C/7M	6,457E-12	0,273
33	57TII-V/35G120S/7M	3,402E-12	0,464

Second step is description of diffusion coefficient scatter while respecting the obtained variation coefficient:

$$D_{c,(t)} = D_{c,nom(t)} + D_{c,var} \times D_{c,nom(t)} , \tag{3}$$

where $D_{c,var}$ is dispersion of diffusion coefficients [m^2/s]. The first choice for probabilistic distribution model is typically normal one. However it is replaced herein by more suitable Gumbel distribution (see in Figure-1).

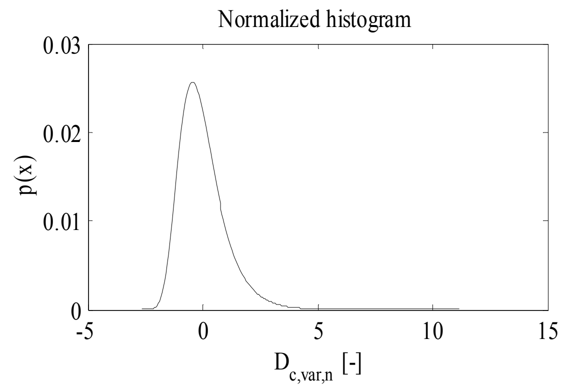

Figure-1. The histogram of the dispersion of the diffusion coefficients of concrete for a probabilistic analysis based on normalized Gumbel distribution.

The Gumbel distribution showed a greater conformity with the measured data of the diffusion coefficient for high performance concrete according to the recipes of Simon [17]. The coefficient of conformity is 0,698 in range of 0-1, where 0 means no agreement between original data and selected distribution and 1 means best fit respectively.

Cover depth

Cover depth is also important parameter for corrosion initiation. Thus we incorporated scatter of this factor via histogram of cover depth (see in Figure-2).

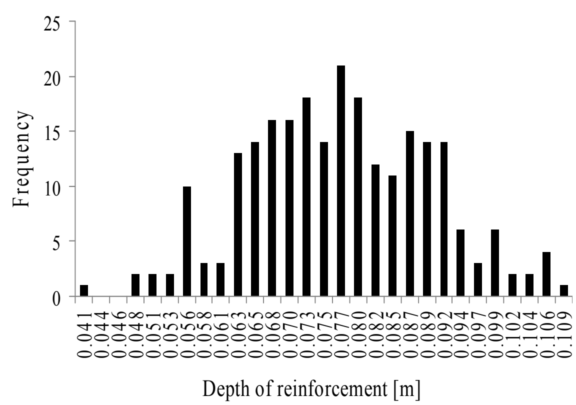

Figure-2. Histogram for depth of reinforcement [18].

It is based on the measurement of chloride penetration and concrete cover from more than 200

ARPN Journal of Engineering and Applied Sciences

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samples taken from 40 bridge decks constructed under a single specification [18].

Surface chloride concentration

Concentration of chlorides on the surface of the concrete is the driver of the chloride ingress. This random variable parameter is prepared on the basis of field data from USA bridge decks [15].

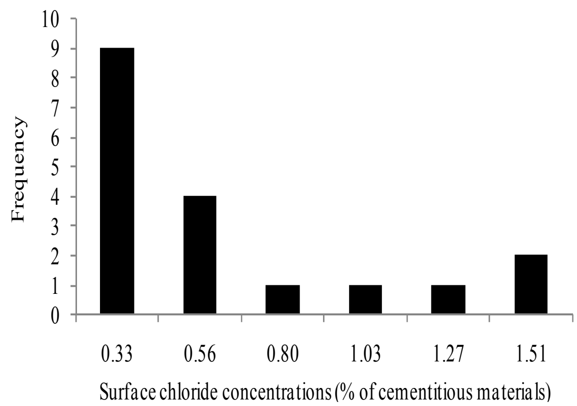

Figure-3. A histogram of the concentration of chlorides on the surface C_0 [% of the weight of material with cementation capabilities] [15].

Chloride threshold

Histogram of threshold shown on Figure-4 is used to describe the ability to withstand chloride environment of unprotected steel reinforcement [5].

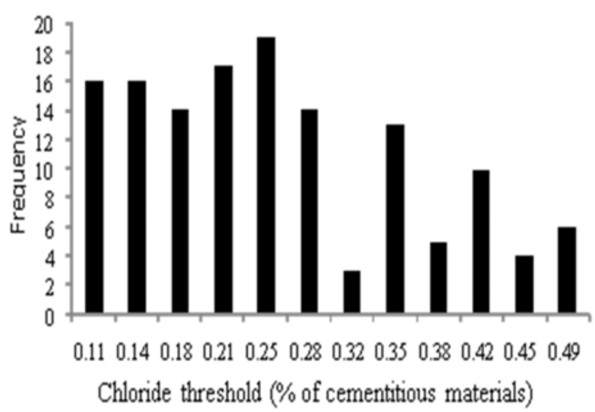

Figure-4. Histogram for chloride threshold [5].

Other parameters

The durability is evaluated on a concrete slab with a thickness of 0.23 m. Since the model is non-steady state finite element one, the evaluated end time of chloride ingress shall be selected.

There is theoretical 1000 years of chloride penetration investigated here in. All values of the used random input variables are presented at Table-2. Constant parameters are shown too.

Table-2. The random variables and deterministic input parameters.

Parameter	Range	Distribution
Diffusion coefficients D_c [10^{-12} m^2/sec]	-0.12- 0.48	Gumbel distribution
Cover depth, x[m]	0.04 - 0.11	Histogram [18]
Surface chloride concentration, C_o [%]	0.21 - 1.63	Histogram [15]
Chloride threshold C_{th} [%]	0.09-0.51	Histogram [5]
Depth of slab, D_{depth}, [m]	0.23	Constant value
Life span, t [years]	1000	Constant value

A MODEL EXAMPLE

Three types of mixtures had been selected to present the fragility curve, which is curve of probability of corrosion initiation in time. These are mixtures No.1: 100TII-V, No. 31: 65TII-V/28F/7M and No. 33: 57TII-V/35G120S/7M. See Figure-9.

First mixture is based on ordinary Portland cement. Second mixture consists of 65 percent of Portland cement type TII-V, 28 percent of fly ash class F and 7 percent replacement by metakaolin. Mixtures No. 33 consists of 57 percent of Portland cement type TII-V, 35 ground granulated blast furnace slag of grade 120 and 7 percent replacement by metakaolin.

Histogram of time to the initiation of corrosion

The probabilistic analysis used Monte Carlo method with 10,000 of simulations. The level of reliability of unprotected steel reinforcement can be expressed with the aid of the distribution of the time to the occurrence of corrosion, above mentioned fragility curve.

Histogram of corrosion initiation for mixture No. 1 is presented in Figures-5. Since the model is a numerical, the analysis is stopped at theoretical durability of 1000 years. That is reason why there is a spike at the right end of histogram.

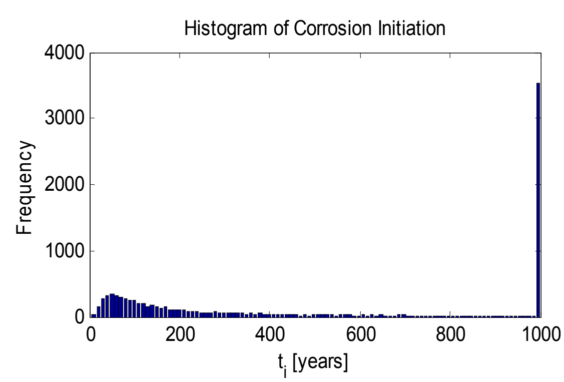

Figure-5. The period of initiation of corrosion t_i for a mixture No. 1: 100TII. There is chosen numerical simulation limit time of 1000 years.

VOL. 11, NO. 3, FEBRUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

It needs to be noted that there is modelled bridge deck without crack so such high theoretical durability might be achieved especially with high performance concrete and high aging factor. In order to show more detailed view of the distribution of time to corrosion initiation the Figures 6, 7 and 8 are showing zoomed histograms for mixture No. 1, 31 and 33.

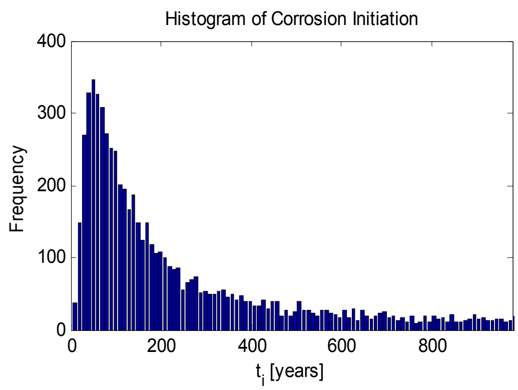

Figure-6. Detail of period of initiation of corrosion t_i for a mixture No. 1: 100TII. Zoomed between 0-980 years.

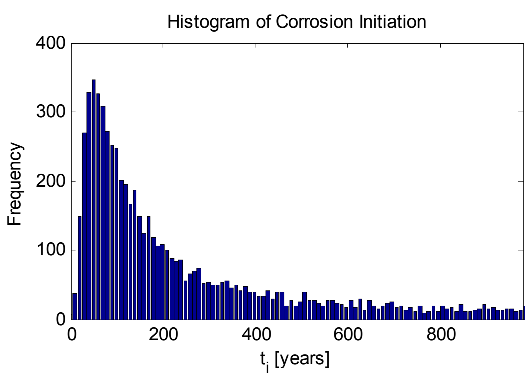

Figure-7. Detail of period of initiation of corrosion t_i for a mixture No. 31: 65TII-V/28F/7M. Zoomed between 0-980 years.

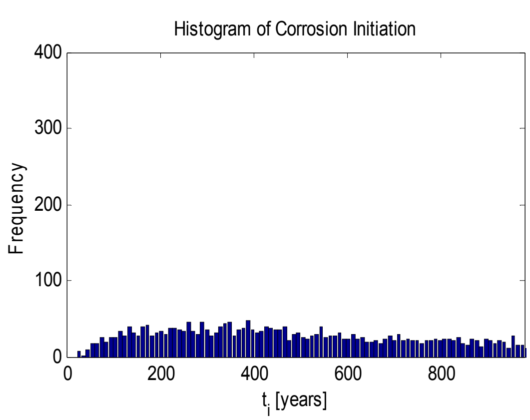

Figure-8. Detail of period of initiation of corrosion t_i for a mixture no. 33: 57TII-V/35G120S/7M. Zoomed between 0-980 years.

Probability of corrosion initiation

Another possibility for expressing the durability as discussed earlier is the probability of corrosion initiation in time $P_{f,t}$. The corrosion initiation likelihood of steel reinforcement is computed for the unit part of bridge deck that is 1 by 1 m. Thus the probability is evaluated per square meter. There was chosen 3 levels of the probability of the initiation of corrosion. First level is 5 [%/m^2], second is 10 [%/m^2] and last is 25 [%/m^2].

Shapes of quantile function of corrosion initiation for all three mixtures are shown on Figure-9.

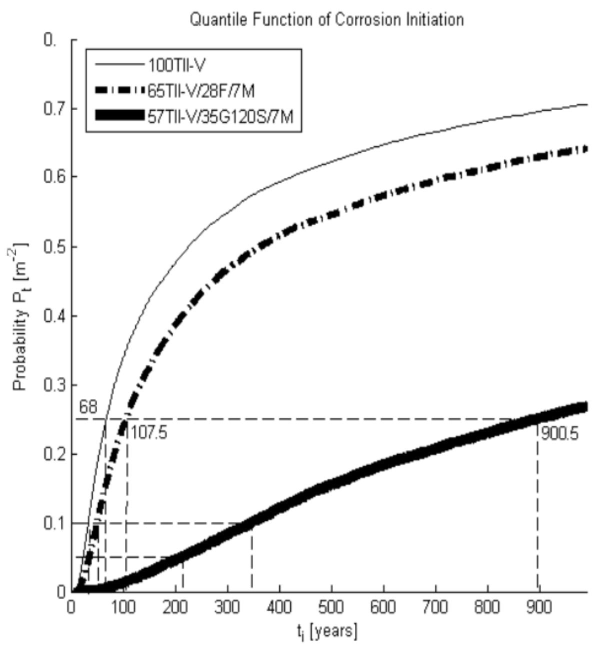

Figure-9. Probability of corrosion initiation t_i for the all chosen variants of type of mixtures. Specific values are shown in Table-3.

RESULTS AND DISCUSSIONS

The first interesting fact is the number of values exceeding a mathematical service life. Figures-5 is showing that excess values can skew the average. The values for durabilities higher than 1000 years also make the histogram less readable thus zoomed histograms were presented. The zoomed histograms on Figure-6, Figure-7 and Figure-8 allow comparison of results for differently behaving mixtures.

Important result of this study is the probability of corrosion initiation in time $P_{f,t}$. Figure-9 is showing shapes of quantile function for selected mixtures, but probabilities are given for all considered mixtures in Table-3. These probabilistic results compared with deterministic given in Table-1 shows that period to the initiation of corrosion for 25% probability of the initiation of corrosion is very similar to results of deterministic durability analysis [5]. This is repeated for all mixtures.

Table-3. Comparison of time to the initiation of corrosion for deterministic [9] and probabilistic solutions.

No.	Durability (t)	P_i (%)		
		5	10	25
1	63.5	23.5	33.6	68.1
2	126.6	38.3	57.3	131.7
3	724.7	147.9	247.7	710.1
4	602.9	134.5	221.5	648.3
5	279.6	79.4	124.5	294.0
6	276.9	77.2	115.6	283.9
7	1000.0	592.1	986.1	1000.0
8	1000.0	1000.0	1000.0	1000.0
9	18.4	8.5	11.2	20.2
10	134.1	43.4	63.3	142.2
11	47.9	18.9	24.8	51.1
12	65.6	22.7	33.4	68.8
13	70.3	25.3	25.6	76.4
14	277.5	80.2	122.9	313.6
15	706.4	150.9	251.0	784.3
16	1000.0	1000.0	1000.0	1000.0
17	142.0	43.2	64.8	152.8
18	26.7	11.4	15.6	28.5
19	1000.0	1000.0	1000.0	1000.0
20	1000.0	1000.0	1000.0	1000.0
21	1000.0	1000.0	1000.0	1000.0
22	543.2	156.8	24.2	592.4
23	508.2	144.4	222.9	529.7
24	572.5	152.8	236.4	589.1
25	564.5	126.2	209.2	602.7
26	166.2	47.5	73.3	195.2
27	1000.0	1000.0	1000.0	1000.0
28	330.8	84.4	134.4	326.5
29	67.1	22.6	32.5	76.3
30	1000.0	1000.0	1000.0	1000.0
31	97.1	35.2	49.8	107.5
32	48.5	18.6	25.3	51.6
33	867.8	204.1	326.4	900.5

The effect of the extended concrete maturing is indicated by the resulting durability of mixtures No. 8, 16, 19, 20, 21, 27 and 30. Service life of these mixtures exceeded the specified threshold of mathematical model even for the probabilities of corrosion initiation of 5 [%/m^2]. For the other mixtures was calculated chosen levels probability of the initiation of corrosion. Comparison Table-1 and Table-3 shows that a mixture with a high value of aging factor m and low value of diffusion coefficient Dc, (28) gives high values of probability of the initiation of corrosion.

CONCLUSIONS

The paper shows the probabilistic reliability assessment of reinforced concrete bridge deck exposed to chloride ingress. The finite element model of chloride ion ingress combined with Monte Carlo simulation.

The significance and character of the input parameters are illustrated. The numerical evaluation of corrosion initiation is based on the consideration of ideal bridge deck considering the effect of aging. The effect of HPC concrete mix design and scatter of input parameters on durabilities of bridge deck without the effect of crack and unprotected reinforcement is evaluated.

Due to the aim of comparing the durability and probability assessment, there are shown results from both possibilities. The results confirms that the concrete mixture with average reference diffusion coefficient and high aging factor have better long term probabilistic durability compared to mixtures with lower aging factor.

The deterministic estimation of durability was closer to the probabilistic one with 25 % probability of corrosion initiation. However deterministic analysis might not give the answer to the level of reliability for the given estimations of corrosion free service life.

There were the effect of HPC mixture design on the variation of durability evaluated. Consideration of crack would significantly reduce the service life and it would be desirable to compare the effect of cracking on the durability as well.

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