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# DURABILITY 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 binary and ternary high performance concrete mixtures are selected for the analysis. The effect of concrete maturing is investigated as well. The data set from complementary laboratory investigation is used for the description of resistance of concrete against ingress of chlorides. The Finite Element-based numerical model is applied in order to evaluate the effect of concrete type as well as the effect of aging. The influence of extended concrete maturing on the chloride ingress related durability is indicated.

**Keywords:** concrete mixtures, corrosion, chloride, diffusion coefficient, finite element analysis, time-dependence, durability.

## INTRODUCTION

Durability of concrete bridge deck is frequently governed by the corrosion of reinforcing steel caused by the ingress of chloride-based deicing agents. The protection measures to prevent the chloride-induced corrosion are based on the protection of steel reinforcement. Application of High-Performance Concrete is one of the typical protection measures in order to slow down the chloride ion ingress as well as corrosion process [2].

In case of bridge decks, the chloride ion penetration process is dominantly governed by diffusion [8], [13], [10] and [15]. Thus it is important to select optimal concrete mixture design with respect to mechanical properties related to safety, serviceability limit states as well as physical properties such as resistance against chloride penetration related to durability.

The mechanical properties are related to the strength and modulus of elasticity while the diffusion parameters are related to concrete electrical conductivity [7]. The rapid Chloride Penetration Test (RCPT) is able to assess the concrete performance against chlorides. Experimental measurement of surface resistivity using the Wenner probe was conducted [9] at the Florida Department of Transportation. The study investigated suitability of resistivity for the replacement of standardized RCPT test (ASTM C1202-05).

The ionic flow during the concrete Rapid Chloride Penetration Test or electrical resistivity test can be related to the diffusion coefficient [3], [7].

Another study electrical resistivity of different binary and ternary based HPC mixtures that tested relationship between the resistivity data with RCPT data for different binary and ternary based HPC mixtures showed their correlation [14]. The comprehensive study of electrical resistivity of 33 binary and ternary mixtures was conducted [6] with respect to strength and resistivity allowing evaluating the diffusion coefficient that influences the reinforced concrete durability.

The Ordinary Portland Cement (OPC) is technically considered as mature after 28 days while the concrete with cement replacement by fly ash, slag and silica fume typically needs more time to mature. The diffusion properties are developing much longer than strength. The consideration of the effect of aging on the analysis of concrete durability is recommended [3], [5].

The influence of long-term maturing on the durability analysis of the ideal HPC reinforced concrete bridge deck without cracks is the aim of the paper.

## MATERIALS AND METHODS

The durability analysis is based on the laboratory test data [6], evaluation of diffusion coefficient for chloride penetration to concrete [7] and diffusion based 1-d finite element numerical model [11], [12].

### Concrete mixture design description

The binary and ternary HPC concrete mixtures laboratory test data for surface and bulk concrete electrical resistivity is used [6]. The study investigates thirty three different binary and ternary based HPC mixtures containing large numbers of supplementary materials. The 100 % ordinary Portland cement based mixture is used as a control one. The tests that highlights pattern of chronological development have been conducted from 7 to 161 days. All the supplementary cementitious materials were replaced by mass. Tests were performed on mixtures using:

- Type II-V cement (TII-V)
- Ground granulated blast furnace slag of grade 120
- (G120S)
- Ground granulated blast furnace slag of grade 100
- (G100S)
- Class C fly Ash (C)
- Class F fly Ash (F)
- Silica fume (SF)
- Metakaolin (M)

The table containing all investigated mixtures is given in Table-1.

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**Table-1.** Concrete mixture design dataset [6].

| No. | Mixture |
|---|---|
| 1 | 100TII-V |
| 2 | 80TII-V/20C |
| 3 | 80TII-V/20F |
| 4 | 60TII-V/20C/20F |
| 5 | 60TII-V/30C/10F |
| 6 | 60TII-V/30F/10C |
| 7 | 75TII-V/20C/5SF |
| 8 | 75TII-V/20F/5SF |
| 9 | 65TII-V/35G120S |
| 10 | 60TII-V/35G120S/5SF |
| 11 | 50TII-V/35G120S/15C |
| 12 | 50TII-V/35G120S/15F |
| 13 | 95TII-V/5SF |
| 14 | 93TII-V/7SF |
| 15 | 65TII-V/5SF/30C |
| 16 | 65TII-V/5SF/30F |
| 17 | 55TII-V/5SF/40G120S |
| 18 | 45TII-V/40G120S/15C |
| 19 | 45TII-V/40G120S/15F |
| 20 | 65TII-V/35G100S |
| 21 | 60TII-V/35G100S/5SF |
| 22 | 50TII-V/35G100S/15C |
| 23 | 50TII-V/35G100S/15F |
| 24 | 45TII-V/35G100S/20F |
| 25 | 60TII-V/30F/10M |
| 26 | 60TII-V/30C/10M |
| 27 | 50TII-V/40G120S/10M |
| 28 | 60TII-V/25F/15M |
| 29 | 60TII-V/25C/15M |
| 30 | 50TII-V/35G120S/15M |
| 31 | 65TII-V/28F/7M |
| 32 | 65TII-V/28C/7M |
| 33 | 57TII-V/35G120S/7M |

The mixtures are indentified by the mass percentage of cement replacement, e.g. the mixture No. 31 65TII-V/28F/7M consists of 65 percent of Portland cement type TII-V, 28 percent of fly ash class F, and 7 percent replacement by metakaolin.

**Diffusion coefficient**

The computation of equivalent steady state diffusion coefficients of binary and ternary cementitious mixtures based on bulk resistivity [6] is computed according to the Nernst-Einstein method [4], [7].

Consideration of the level of concrete maturity for selected age can be expressed according to [5] or [3] as:

$$D_c(t) = D_{c,ref} \cdot \left(\frac{t_{ref}}{t}\right)^m, \tag{1}$$

where $D_{c(t)}$ is diffusion coefficient at time $t$ and $D_{c,ref}$ is the diffusion coefficient at some reference time $t_{ref}$ (e.g. 28 days), $m$ is a constant (aging factor) depending on mixture proportions.

**Reinforced concrete bridge deck durability**

The durability of ideal reinforced concrete bridge deck without cracks is analyzed using finite element model [11], [12]. The diffusion based transient numerical model allows for the consideration of change of diffusion coefficient in time. Chloride ion concentration is analyzed at selected time interval at the reinforcement level.

The time until the corrosion is initiated is computed via reliability function evaluation:

$$RF_t = C_{th} - C_{z,t}, \tag{2}$$

where $RF_t$ is reliability function for the time to corrosion initiation estimation [% of chlorides to mass of cementitions material], $C_{th}$ is the chloride threshold [%], $C_{z,t}$ is the chloride ion concentration at the reinforcement level [%]. Computation is conducted in the time frame of up to 1500 years of service. The age was limited with respect to numerical constraints.

There are two analyses considered: (a) with aging factor, (b) without the aging factor.

**NUMERICAL INVESTIGATION**

The computation is conducted on the 1-d type cross-section of ideal uncracked reinforced concrete bridge deck. The durability analysis is investigated for the mixture design given in Table-1. The typical analysis is highlighted on the mixture No. 31 that is marked as 65TII-V/28F/7M. The typical input parameters and sample analysis with selected mixture is given bellow. The overall study is discussed in the section Results and Discussion.

**Input parameters**

Height of the bridge deck is 0.23 m, width of the evaluated part is 0.03 m. Reinforcement cover $z$ is 0.065 m. Initial surface concentration $C_0$ is 0.6 % and the chloride threshold $C_{th}$ is 0.2 % according to ACI [1]. The time dependent diffusion coefficient $D_{c(t)}$ depends on the reference diffusion coefficient analyzed at 28 days $D_{c(28)} = 4.18\times10^{-12}$ and aging factor $m = 0.288$. The development of diffusion coefficient of mixture 31 is given in Figure-1.

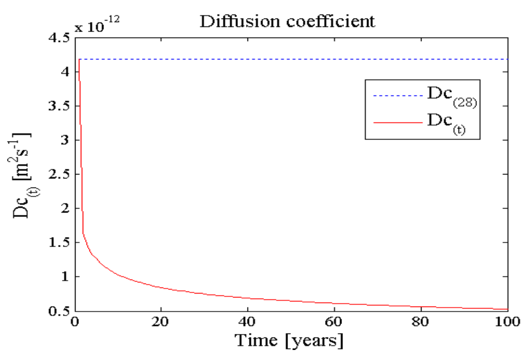


**Figure-1.** Time dependent $D_{c,(t)}$ and independent diffusion coefficients $D_{c,(28)}$ for HPC (65TII-V/28F/7M) mixture.

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There can be observed significant increase of resistance against the chloride penetration within first decade.

The resulting concentration of chloride ions at the reinforcement level computed by non stationary numerical model [11] for given input parameters for the respective mixture is presented in the Figure-2.

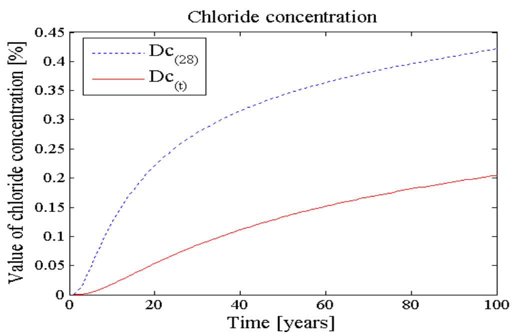


**Figure-2.** Chloride ion concentration computed for time dependent $D_{c,(t)}$ and time-independent diffusion coefficients $D_{c,(28)}$ for HPC (65TII-V/28F/7M) mixture.

The durability is related to the initialization of corrosion. The corrosion is initiated when reliability function in Equation (2) is negative. Chloride threshold is lower than the chloride concentration at the reinforcement level. The outcome of the sample analysis is in the Figure-3.

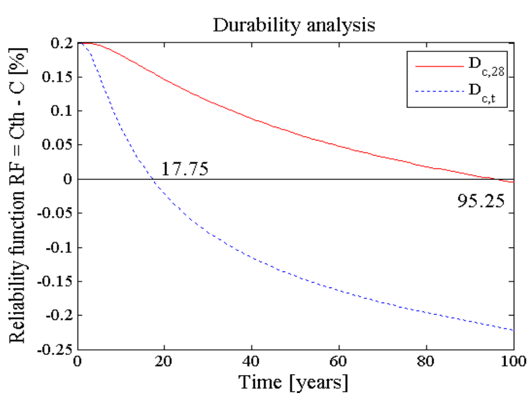


**Figure-3.** Durability analysis of corrosion initiation in the ideal reinforced concrete bridge deck for time dependent $D_{c,(t)}$ and time-independent diffusion $D_{c,(28)}$ coefficients for HPC (65TII-V/28F/7M) mix designs.

The resulting durability for time-independent diffusion $D_{c,(28)}$ is applied is 17,8 years while consideration of aging factor via for time dependent $D_{c,(t)}$ leads to 95.3 years here.

## RESULTS AND DISCUSSIONS

The reference diffusion coefficient along with respective aging factors *m* is presented for considered 33 HPC mixtures in the top of Figure-4. The bottom part of Figure-4 shows the durability expressed as corrosion initiation for two investigated cases. For the detailed description of analyzed mixture, please refer to Table-1 and [6].

The effect of the extended concrete maturing is indicated by the resulting durability of mixtures 8 and 16. Those concrete mixtures performed as average in case of constant diffusion coefficient analysis. The durability with time-independent concrete resistance against chloride penetration was between the range of 17 to 23 years (average was 17.4 years). If aging factor *m* were applied then the durability performance enhanced by extended maturing allowed those mixtures to be free from corrosion for more than 1500 years (average 583). The significant improvement when considering concrete long term maturing of mixtures 8 and 16 is attributed to more than average aging factor *m*. This combination of average $D_{c,(28)}$ and high aging factor *m* allow to over perform other mixtures with better-lower reference $D_{c,(28)}$ in the long run.

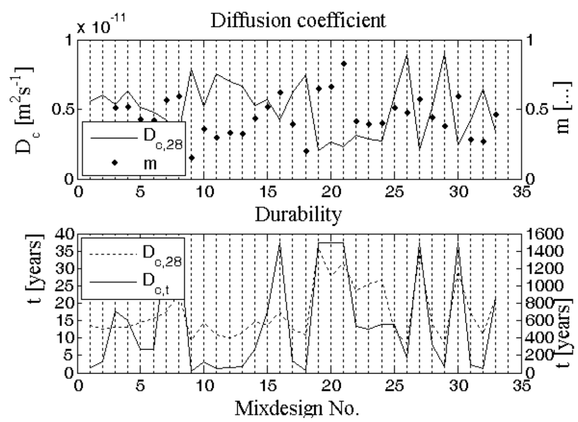


**Figure-4.** Reference diffusion coefficients $D_{c,(28)}$ and aging factor *m* for the mixtures No. 1 to 33 (top). Durability analysis of corrosion initiation in the ideal reinforced concrete bridge deck for time dependent $D_{c,(t)}$ and time-independent diffusion coefficients $D_{c,(28)}$ of HPC mixtures No. 1 to 33 (bottom). For the mixture descriptions refer to Table-1 and [6].

## CONCLUSIONS

The investigation of the aging factor on the durability of chloride ingress related corrosion of bridge deck steel reinforcement is conducted. The numerical evaluation of corrosion initiation is based on the consideration of ideal bridge deck without the crack, unprotected reinforcement, chloride diffusion and comparison of time dependent apparent chloride diffusion coefficient with time independent one.

The results confirm that the concrete mixture with average reference diffusion coefficient and high aging factor have better long term durability comparing to mixtures with lower aging factor. Example of such concrete represent mixtures No. 8 (75TII-V/20F/5SF) and No. 16 (65TII-V/5SF/30F). Cementitious material consists from 75 percent of Portland cement, 20 percent of fly ash class F and 5 percent of silica fume in case of mixture No. 8 while the mixture No. 16 has less Portland cement (65%) and more fly ash (30%).

## ACKNOWLEDGEMENTS

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