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2. Contribution to comparison of methods for the investigation of chloride ingress related resistance

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Abstract: The quality of the resistance of concrete structures to chloride penetration may be determined via the diffusion coefficient. This parameter can be derived from several laboratory based tests through long-term penetration testing approaches or accelerated experiments using electrochemical methods, such as NT Build 443 on which sample surface is exposure to NaCl solution and AASHTO TP-95 where correlation of different physical mechanism with chloride profiling is investigated. Two sample mixtures made of cement type I 42.5 R of which strength are classified as C50/60 and C90/105, representing for ordinary Portland cement (OPC) and high-performance concrete mixtures, respectively. Both samples are intended for prestressed concrete structures. Estimated time-dependent diffusion coefficient were analysed with respect to resistance of prestressed concrete structures against chloride ingress. Results of this work could be used for the current research of prestressed concrete structures and also for studies on potential corrosion risk of reinforcement.

Keywords: chloride ingress, diffusion coefficient, chloride penetration tests, prestressed concrete structures, resistance.

2.1. Introduction

The concept of prestressed concrete structures originated from the need for concentric or eccentric forces acting in the longitudinal direction of the structural member to prevent early cracking cracks (Nawy, 2009). Also the current trend is to improve the performance of concrete and reduce the use of cement by utilizing advanced high performance materials (Aïtcin, 2010; Ghosh *et al.*, 2017; Konečný *et al.*, 2017). In practice, prestressed concrete design methods has been significantly developed in recent decades (Nawy, 2009) and the current trend is driven to the evaluation of advanced nonlinear modelling capabilities (Sucharda *et al.*, 2017).

Prestressed concrete structures, e.g. beams in Fig. 2.1, must be studied in point of view of the static behaviour (Le, Konečný and Matečková, 2018), however, chemical and physical properties of concrete mixtures are very important too. One of the serious problems of the prestressed concrete structures is the corrosion of the reinforcement. Since this kind of structure is oftenly used as the bridge parts, salt encounter must be considered during the processes of durability design and assessment. This calls for the knowledge of the diffusion of chloride into concrete structures.

It is worth mentioning that diffusion coefficient is an important parameter since it represents the material characteristics of concrete. The coefficient is usually integrated in diffusive based models in respect to Fick's law. It can be either constant (time independent) in simple models of steady state systems or time dependent in rather complicated models of non-steady-state processes (Crank, 1975; Basheer, Chidiac and Long, 1996; Costa and Appleton, 1999). However, this parameter can be derived through laboratory based tests (Andrade, 1993; Morris, Moreno and Sagüés, 1996; Andrade and Sanjuán, 2012; Layssi *et al.*, 2015). Although many robust tests were available, their testing scheme can be classified as: (i) chloride profile analysis via long-term exposure to NaCl solution, and (ii) chloride profiling based on the correlation of various physical mechanism of diffusive processes. The former is often exploited with NT Build 443 (Nordtest NTBuild 443, 1995) while the latter is usually conducted with rapid chloride penetration ASTM C1202 or electrical resistivity based test AASHTO TP-95 (ASTM C1202, 2012; AASHTO TP95, 2014). Diffusion coefficient of concrete estimated from electrochemical testing methods is then used to predict the behaviour of experimental samples.

This research is aimed at the comparison of the two testing approaches on chloride ingress into prestressed reinforced concrete structures. Two concrete mixture samples made of cement type I 42.5 R are used and they are classified based on Eurocode as C50/60 (ordinary Portland cement concrete) and C90/105 (high performance concrete), respectively. Both mixtures will be examined through NT Build 443 and AASHTO TP-95. Aging effect is considered. Derived time-dependent diffusion coefficient will be comparatively calculated and by which resistance of the prestressed concrete structure is investigated.

Fig. 2.1. Prestressed reinforced concrete beams.

2.2. Material and mechanical properties

The composition of mixtures is under patent protection, but at least basic knowledge of composition can help evaluate the results. The incomplete composition of the mixtures is shown in Table 2.1.

Table. 2.1. Characteristics of mixtures

Mixture No.	**C50/60**	**C90/105**
Cement type I 42.5 R	450 kg	650 kg
Water	180 kg	165 kg
Slag	0 kg	60 kg
Natural crushed aggregate 0/4	690 kg	400 kg
Natural crushed aggregate 4/8	215 kg	600 kg
Natural crushed aggregate 8/16	845 kg	0
Superplastificator	0	17 kg
Pucolanically curing additive	0	75 kg
Polycarboxylate plastificator	4.5 kg	
Water/cement ratio (W/C)	0.40	0.25

Cylindrical samples of standard dimensions were prepared for the diffusion tests presented herein (diameter 150 mm, height 300 mm). For NordTest NT Build 443, three samples were prepared for each mixture. The markings were C50/60-A, C50/60-B, C50/60-C and C90/109-A, C90/109-B, C90/109-C, respectively. Furthermore, to measure the electrical resistance using the AASHTO TP-95, the same sized cylinders were prepared in two pieces for each mixture. The electrical resistance results below are average values.

It should be noted that laboratory experiments were also composed of several mechanical tests related to other requirements of the entire research. Some results are shown in the Table 2.2.

Table. 2.2. Mechanical properties

Mixture No.	**C50/60**	**C90/105**
Compressive Strength (Cube test) 28 days	85 MPa	106 MPa
Compressive Strength (Cylindrical test) 28 days	54 MPa	99 MPa
Modulus of elasticity – statically, 28 days	35 GPa	41 GPa
Modulus of elasticity – dynamic, 28 days	38 GPa	49 GPa

2.3. Chloride profile by NT Build 443

A modified NordTest NT Build 443 (Nordtest NTBuild 443, 1995) is selected for diffusion coefficient analysis. Concrete samples were immersed in NaCl solution for 90 days (see Fig. 2.2). This natural diffusion test gives enough data to produce a curve for the measured chloride profile. It is then approximated by the least squares method (Lehner, Turicová and Konečný, 2017). Because there was no tool available for grinding the surface with the collection of concrete dust according to NT Build 443, the procedure was modified based on removing the chloride profile by drilling according to AASHTO T95 (AASHTO TP95, 2014).

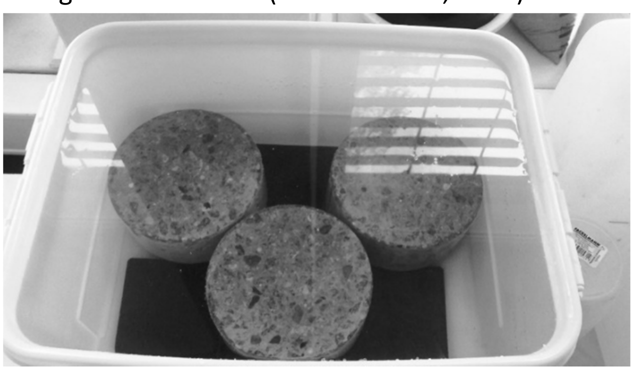

Fig. 2.2. Probes in the NaCl solution for test according NT Build 443.

After subsequent laboratory chemical evaluation of the collected dust, a chloride profile was prepared for each sample. The amount of chloride in the concrete powder obtained can be determined by potentiometric titration. These profiles for the mixture C50 / 60 can be seen in Fig. 2.3, the results for the mixture C90 / 105 are shown in Fig. 2.4. We can observe that the C50 / 60 mixture has a much greater slope of the curves than the C90 / 105 one. This factor, among other things, influences the subsequent calculation through the diffusion coefficient.

When the concentration of chlorides in given depths known, then the measured chloride profile is approximated. For best fit calculation, the method of least squares is used. The whole process is described in great detail in the article (Lehner, Turicová and Konečnỳ, 2017).

It should be noted that the unknown parameters are both diffusion coefficient and surface chloride concentration. Both parameters serve as inputs for modelling of chloride diffusion and subsequent using for estimating the life of concrete structures.

Since one diffusion coefficient value for each mixture from the selected method is needed for the evaluation, the average values of the diffusion coefficients from the mixture of C50 / 60 and C90 / 105 are presented below.

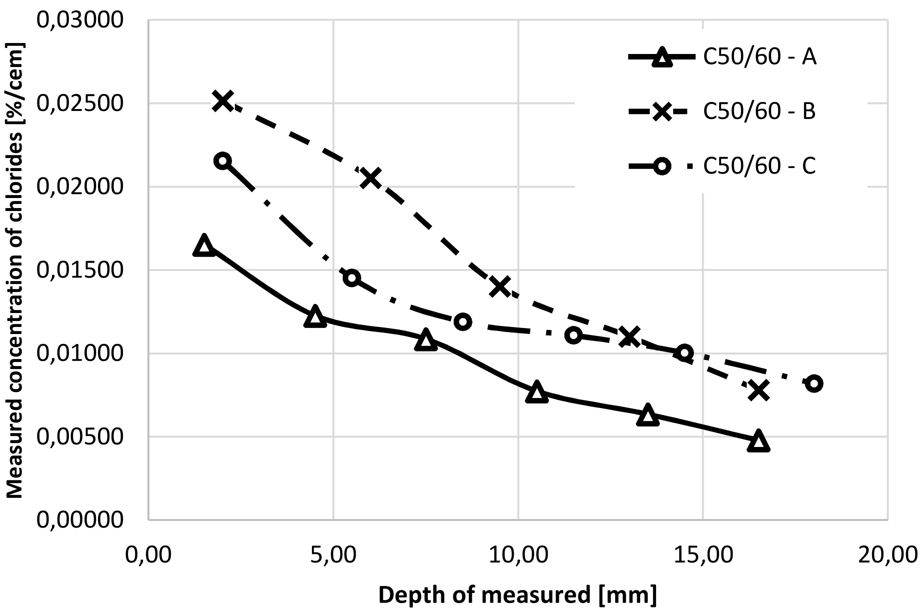

Fig. 2.3. The measured chloride profile of mixture C50/60 from NT Build 443 test.

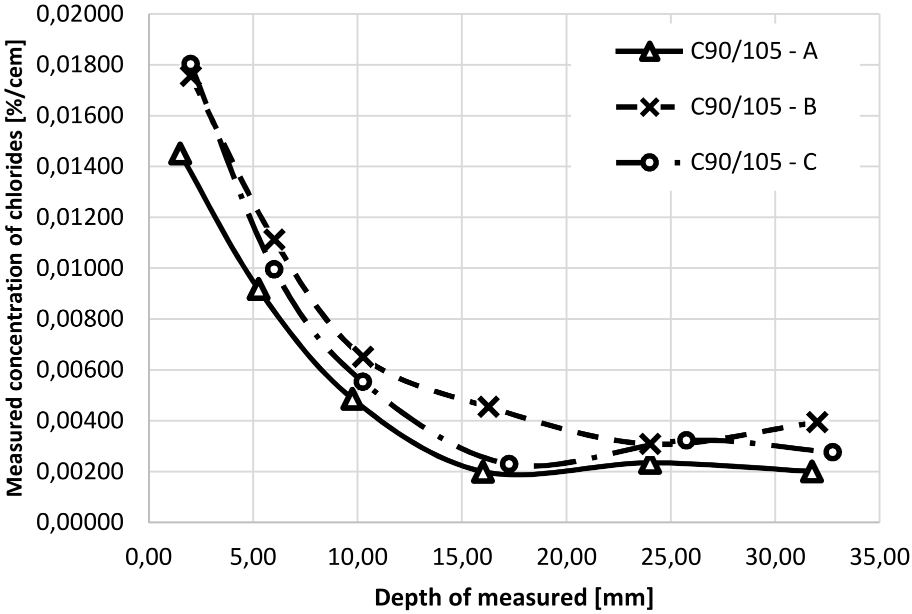

Fig. 2.4. The measured chloride profile of mixture C90/105 from NT Build 443 test.

2.4. Electrical resistivity and aging effect

For the electrical resistance measurement, the Wenner's probe was also selected (see Fig. 2.5). This measurement is based on the AASHTO T95. The basic information are provided in the articles (AASHTO TP95, 2014).

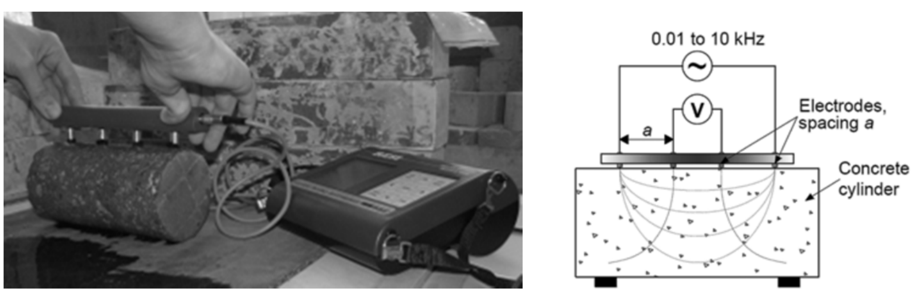

Fig. 2.5. Photo and scheme of surface resistivity measuring by the AASHTO T259.

The method is non-destructive, so the repeated measurement is possible to be able to determine the time depending of diffusion. On the other hand, this measurement method may have a relatively large variation, partly due to the heterogeneity of the test material and the usage of rather uncontrollable contact conditions. These findings should be considered in the evaluation. As mentioned, this is a non-destructive test. It is, therefore, possible to measure electrical properties during maturing of concrete. In this case, it was tested at 7, 14, 28, 56, 91 and 161 days after concreting. The initial results of these tests for both mixtures are shown in Fig. 2.6.

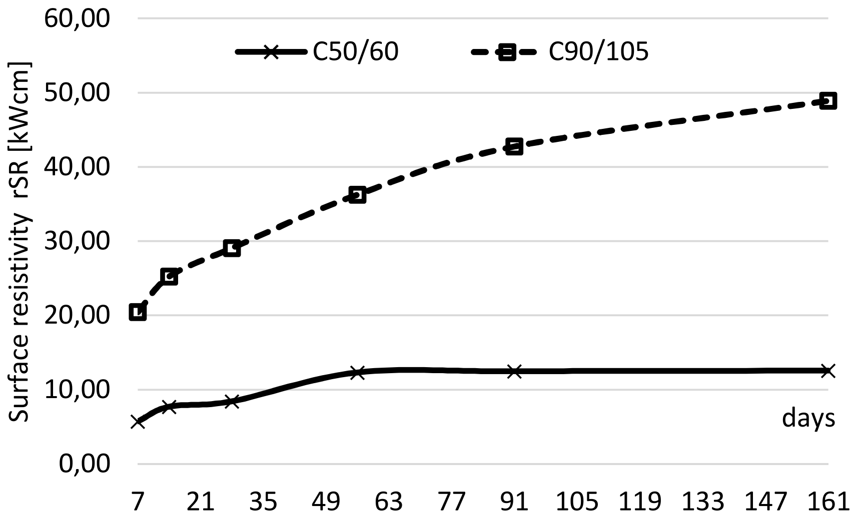

Fig. 2.6. The measured surface resistivity of mixture C50/60 and C90/105 by the AASHTO T259.

After measuring, the results of surface resistivity can be converted to volume resistance using geometric correlation relationships (Morris, Moreno and Sagüés, 1996). From these values, a diffusion coefficient can be determined by the Nernst-Einstein equation (Lu, 1997; Ghosh, 2011; Lehner, Ghosh and Konečný, 2018).

2.5. Results and discussion

A diffusion coefficient is a suitable parameter to determine the resistance of concrete to chloride ions contained in road salt. If this parameter is smaller, resistance is higher. In Fig. 2.7, we can see the results of the diffusion coefficients in the logarithmic scale from both mixtures and both presented methods.

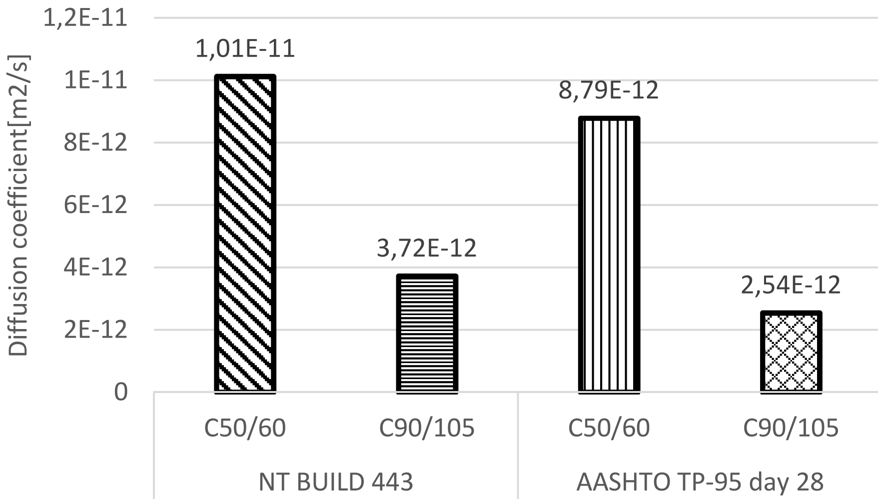

Fig. 2.7. Comparison of the diffusion coefficient calculate from the NT BUILD 443 and AASHTO T259.

At the first sight, there are quite large differences in diffusion coefficients of both mixtures. On the other hand, the comparing of mixtures using two methods is quite satisfactory. The value of the diffusion coefficient must be considered better if its value is close to zero. Thus, in Figure 7, these are the lower columns. The mixture C90/105 have better values than the C50/60 one in both methods. If we look at Figure 6, we can observe that the behaviour of both concrete mixtures meets expectations. Concrete C50/60 shows a light increase in resistance until 50 days from concreting before keeping at almost constant value. Conversely, C90/105 concrete shows a gradual increase over the entire measurement period.

2.6. Conclusions

The resistance of concrete structures to chloride penetration can be expressed through the diffusion coefficient. This parameter was derived from two electrochemical methods: NT Build 443 on which sample surface is exposures to NaCl solution and AASHTO TP-95 where correlation of electrical resistivity and diffusion of ions is investigated. Two sample mixtures made of cement type I 42.5 R of which strength are classified as C50/60 and C90/105 were presented. Both mixtures are intended for prestressed concrete structures and the research focuses on improving properties in different areas.

The study shows expected differences in the results from both used methods. Concrete with higher strength class, i.e. C90/105, is more resistant. The difference between the diffusion coefficient of NT BUILD 443 and AASHTO TP-95 is visible in both mixtures. But due to the same order, the difference is almost negligible. Results should be taken with caution, but they are good enough to use for comparing mixtures. The results of this work could be used for current research of prestressed concrete structures and for studies of possible corrosion risk of reinforcement.

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