Final report of RILEM TC 246-TDC

"Test methods to determine durability of concrete under combined environmental actions and mechanical load"

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Abstract:

By now there exist several methods to predict durability of reinforced concrete structures. In most cases one dominant deteriorating process such as carbonation or chloride penetration is taken into consideration. Experimental results as well as observation in practice show that this is not a realistic and certainly not a conservative approach. To develop more realistic test methods, RILEMTC 246-TDC has worked on the determination of durability of concrete under combined environmental actions and mechanical load since September 2011.

This report introduces a test method which can realistically determine the chloride ion diffusion coefficient of concrete under compressive and tensile stress. Comparative test results among 5 international labs showed that the combination of mechanical and environmental loads may turn out to be much more severe than each single environmental load alone in the mechanically unloaded case. Modelling and probabilistic analysis also showed that the obvious synergetic effects can't be neglected in service life prediction.

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1. Introduction

The design of stress-carrying structures has a long history in civil engineering. In Europe it is now based on Eurocode 2 [1]. Similar codes for structural design exist in other regions (see for example [2-4]). More recently a Model Code for service life design [5] has been set up in an analogous way, compared to Eurocode 2. In this document the stress is replaced by environmental actions such as carbonation, chloride penetration, and freeze-thaw attack with and without de-icing agents and mechanical resistance is replaced by resistance of concrete against environmental actions such as carbonation, chloride penetration or freeze-thaw cycles.

Based on this concept the following limit states can be formulated: (1) corrosion initiation induced by chloride ingress or carbonation, (2) cracking due to steel corrosion, (3) spalling of concrete cover due to steel corrosion, and (4) structural collapse due to corrosion of reinforcement. The Model Code suggests four different options for service life design: (1) full probabilistic approach, (2) semi-probabilistic approach, (3) deemed to satisfy rules, and (4) avoidance of deterioration. Based on this Model Code the safety of structures under the influence of environmental actions can be expressed in terms of a reliability index β in a similar way as it is common practice for structural design.

The actual service life of reinforced concrete structures and of bridges in particular, is in many cases significantly shorter than the designed service life (see for instance ASCE 2013 Report Card [6]). According to this document more than 20 % of bridges in the US are structurally deficient or functionally obsolete. In many industrialized countries a similar situation exists. As a consequence, it has become difficult to keep pace with the growing costs for maintenance and repair of aging infrastructure.

The Model Code for service life design [5] may be considered to be a significant step forward, as durability and service life of reinforced concrete structures can be taken into consideration during the design stage. According to the Model Code, the necessary material parameters such as the inverse carbonation resistance or the chloride migration coefficient have to be determined under well-defined laboratory conditions. More recently, however, it has been shown that these parameters also depend on an applied stress. Rate of chloride penetration for instance can be doubled [7, 8] under the influence of an applied tensile stress. Hence, if the influence of an applied stress is not taken into consideration prediction of service life will not be realistic.

Before relevant comparative tests were started by members of the TC 246-TDC the state-of-the-art of this topic was carefully investigated. As a result, a comprehensive annotated bibliography could be published [9]. That publication is the starting point for the following investigations reported here.

2. Experiments and materials

2.1 Preparations of Specimens

Concrete with the mix proportion of cement : water : fine aggregate : coarse aggregate equal to 1:0.45:2.28:2.79 was prepared. All 5 labs from CBMA, GHENT U., TU DELFT, TUM and DALIAN U. were required to use type I Portland cement as binder (corresponding to Chinese National Standard GB 175 [10], EN 197 [11], and ASTM Type I Portland cement). The cement content was 368 kg/m^3. Polycarboxylate superplasticizer was used to adjust the concrete slump as about 15 cm. The concrete was cast into (100 x 100 x 400) mm^3 prisms and dumbbell-like specimens for compression and tension, respectively.

The ultimate compressive strength of the concrete prism specimens at 28 d is shown in Table 1. The ultimate tensile strength of the dumbbell-like concrete specimens at 28 d from CBMA was 3.3 MPa.

Table 1 The ultimate compressive strength of concrete specimens

Laboratory	CBMA	GHENT U.	TU DELFT	TUM	DALIAN U.
Strength (MPa)	36.60	56.90	38.89	72.00	26.24

A thin film of Teflon was applied to the internal faces of all the moulds to avoid the effects of demoulding oil. After casting, the specimens were stored in a room maintained at 20 ℃ and about 95 % relative humidity (RH) for 24 h. Then, the samples were then de-moulds and further cured in water at 20 ℃ until testing.

The specimens were removed from the water and the free surface water was removed with a dry towel, then the surface was immediately sealed with two layers of self-adhesive aluminum foil. An open window (80 x 160) mm^2 on one moulded side surface was left uncovered, but was protected temporarily until the salt solution tank was attached. A plastic tank with the inner dimensions of (80 x 160 x 50) mm^3 was adhered to the open window using silicone to achieve the penetration of salt solution into concrete.

2.2 Test methods

2.2.1 Specimens under compression

Compressive stress was applied on the prismatic concrete specimens using a test rig as shown in Figure 1, which fulfils the requirements of the Appendix of RILEM TC 107-CSP [12]. The compressive stress ratio, which is the ratio of applied stress to the ultimate compressive stress, is taken as 0, 30 %, and 60 %. A constant flow pump was adopted to circulate the 3 wt. % chloride sodium salt solution with a pre-defined speed of 5±1 ml/s. The concentration of the solution was checked regularly at least once a week during the whole exposure period, and the chloride solution was isolated from the atmosphere by a cap to avoid evaporation and contamination. The specimens were unloaded after an exposure time of 2, 6, 18 and 36 weeks, or any other designed duration, after which the specimens were ready for chloride profile determination.

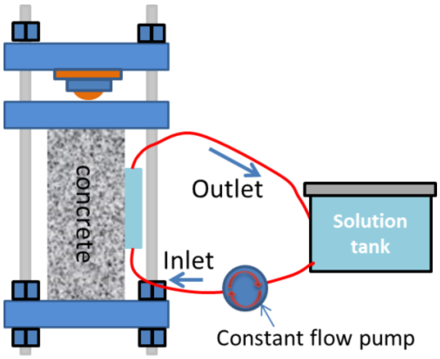


Fig. 1 Experimental setup for compression combined with chloride penetration

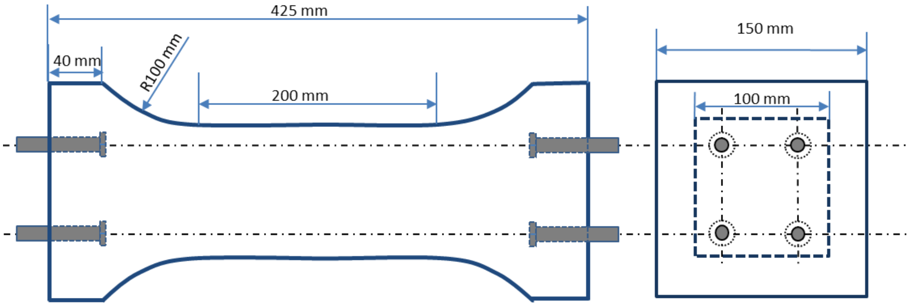


Fig. 2 Dimensions of specimen for tension

2.2.2 Specimens under tension

To connect with the tensile testing rig, four bolts were embedded in each end of the dumbbell-like tension specimen before casting (see Figure 2). A special test rig was designed to apply tensile stress. Two joint plates were adopted to link the 4 bolts in each side of the dumbbell-like tension specimen with the spherical hinges, which are employed to minimize the uniaxial eccentricity of the tension specimen (see Figure 3). Note that the test rig for tensile stress application is not limited to the one shown in Figure 3; any other test rig with the same principle can also be used. The tensile stress ratio, which is the ratio of applied stress to the ultimate tensile stress, is taken at 0, 50 % and 80 %. The operation of the tensile setup is further detailed in the minutes of the 2nd plenary meeting of RILEM TC 246-TDC [13]. Similar to Figure 1, a chloride solution circulation setup was applied on the open window of the dumbbell-like specimens with the same flow speed. The dumbbell-like specimens were unloaded after an exposure time of 2, 6, 18 and 36 weeks, or any other duration, after which the specimens were ready for chloride profile determination.

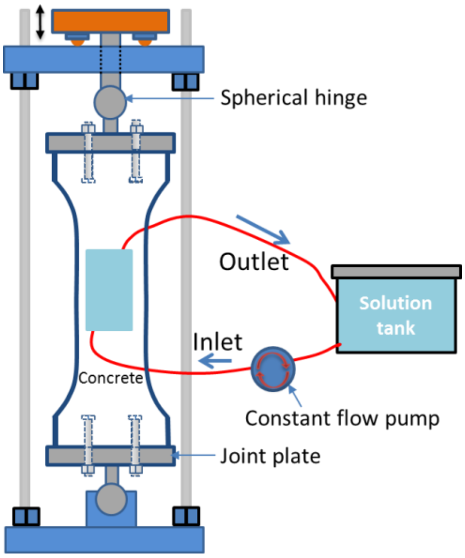


Fig. 3 Sketch of experimental setup for tension

2.3 Determination of chloride profiles

The plastic tank was removed from the unloaded specimens. Powder from the exposure surface of all the specimens was obtained stepwise by milling layers of 1 to 2 mm thickness. The thickness of the layers was adjusted according to the expected chloride profile so that a minimum of eight points covered the profile between the exposed surface and a depth where the chloride content reached the initial chloride content. The sampling was performed over a surface area of at least 2500 mm^2 and with a distance of 10 mm from the border of the exposure zone to avoid the influence of edge effects and disturbances from the glue for self-adhesive aluminium foil. Longer time was needed for chloride extraction when the aggregate powder was larger than 1mm. Chloride contents dissolved in acid were determined by chemical analysis according to EN 14629 [14]. It is recommended that the tests shall run at least in triplicate, and average values of chloride ion diffusion coefficient are calculated from three specimens.

3. Test results

3.1 Compression

3.1.1 Typical chloride profiles for 0 and 30 % stress ratio

In Figures 4 and 5 the typical profile tested by GHENT U. is shown corresponding to the 0 and 30 % stress ratio respectively. The chloride penetration is expressed in % by weight of concrete and the diffused depth is shown in mm.

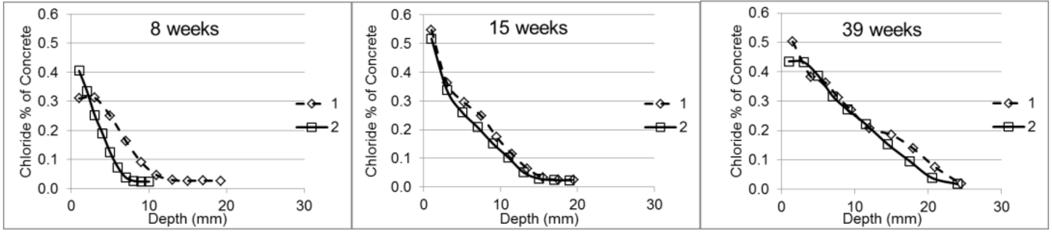


Fig. 4 Chloride profiles at different exposure times for two similar concrete samples at 0 % stress ratio

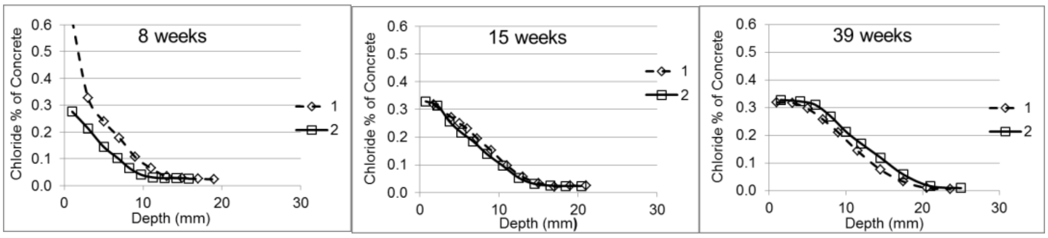
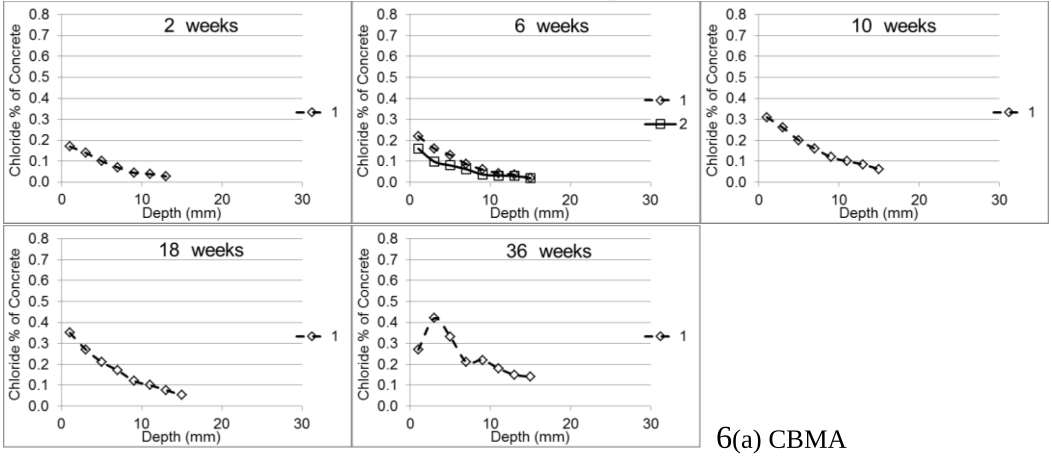


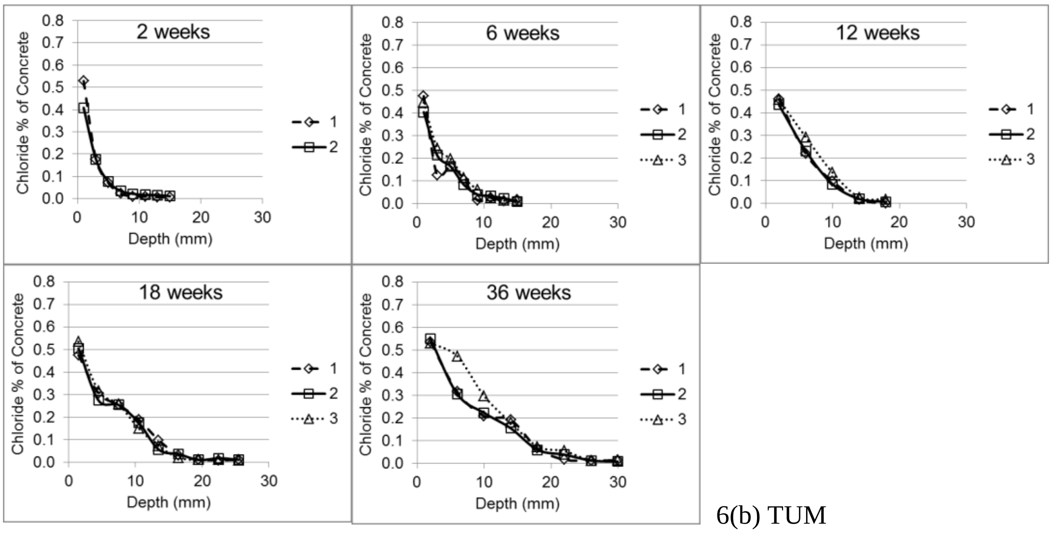
Fig. 5 Chloride profiles at different exposure times for two similar concrete samples at 30 % stress ratio

As seen from Figures 4 and 5, the chloride profiles showed a progressively smooth decrease in the chloride values, except in the first few mm beneath the surface at longer exposure times. This diffusion behaviour led to the conclusion that chlorides are interacting with a more or less homogeneous microstructure. The repeatability of the test is also fairly good.

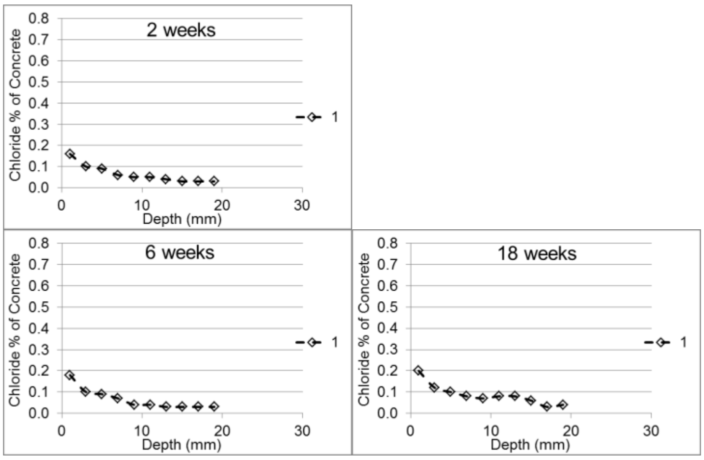
Figure 6 shows the complementary chloride profile information at 0 % stress ratio from the other laboratories involved in the comparative test.



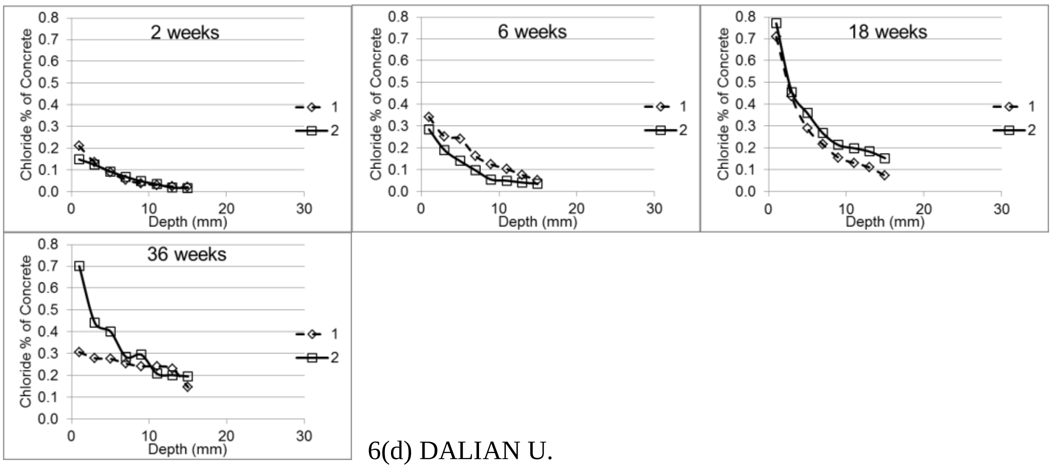
6(a) CBMA



6(b) TUM



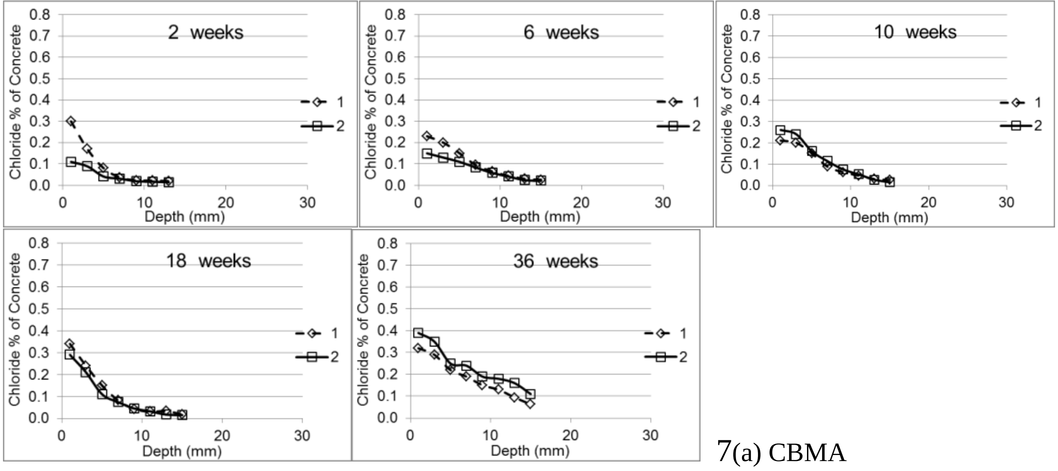
6(c) TU DELFT



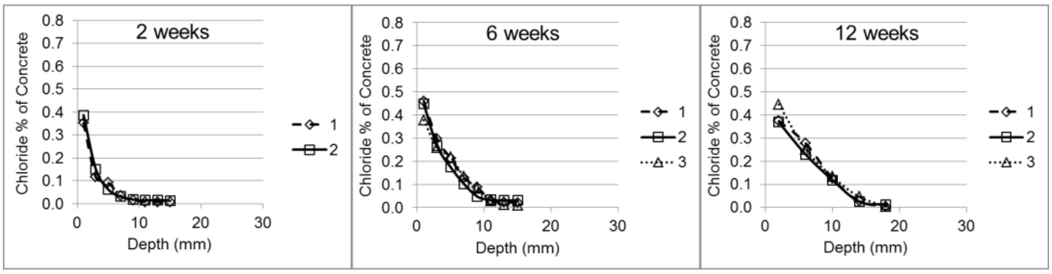
6(d) DALIAN U.

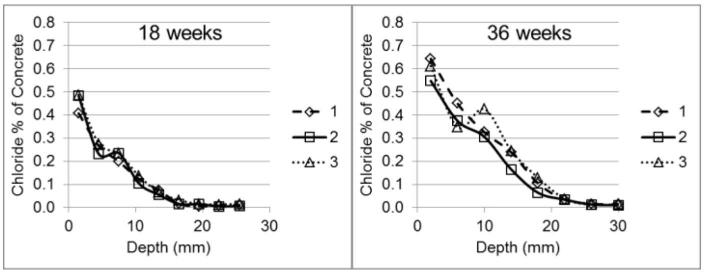
Fig. 6 Chloride profiles at different exposure times at 0 % stress ratio

Figure 7 shows the complementary chloride profile information at 30 % stress ratio from the other laboratories involved in the comparative test.



7(a) CBMA





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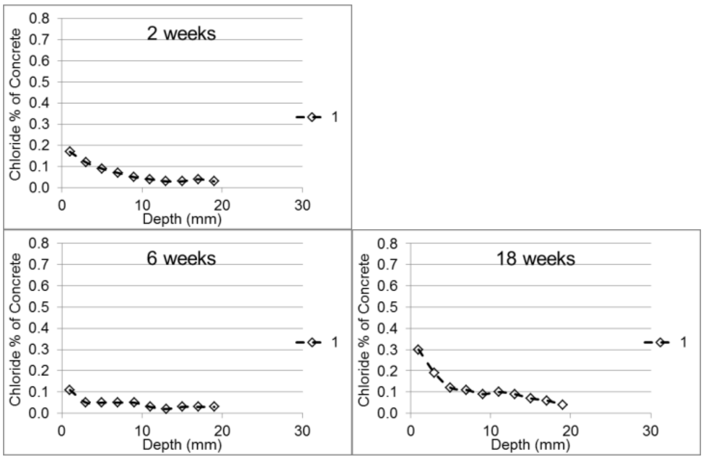

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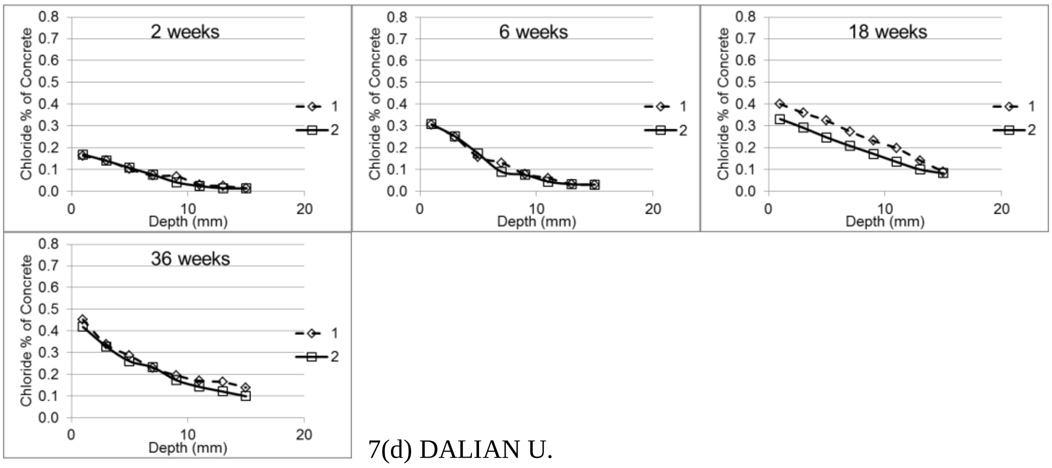
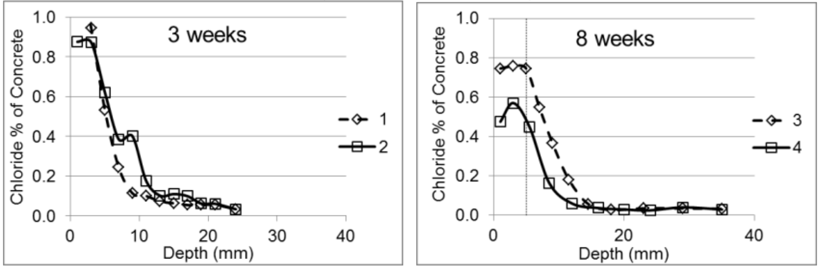


7(d) DALIAN U.

Fig. 7 Chloride profiles at different exposure times at 30 % stress ratio

3.1.2 Typical chloride profiles for 60 % stress ratio

Figure 8 shows the typical profile from GHENT U., corresponding to the 60 % stress ratio. Figure 8 shows chloride profiles that differ in nature from the homogeneity found in the two previous cases. The vertical line shows the convection zone depth provoked by micro cracking.



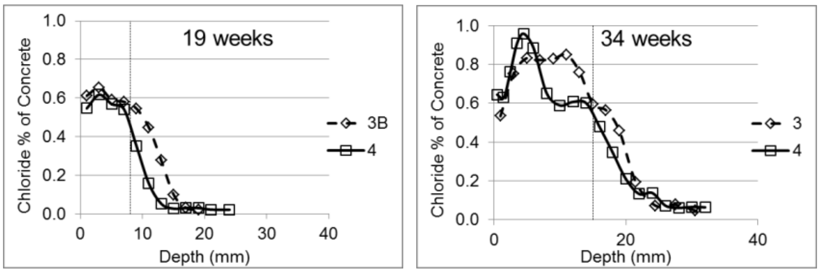


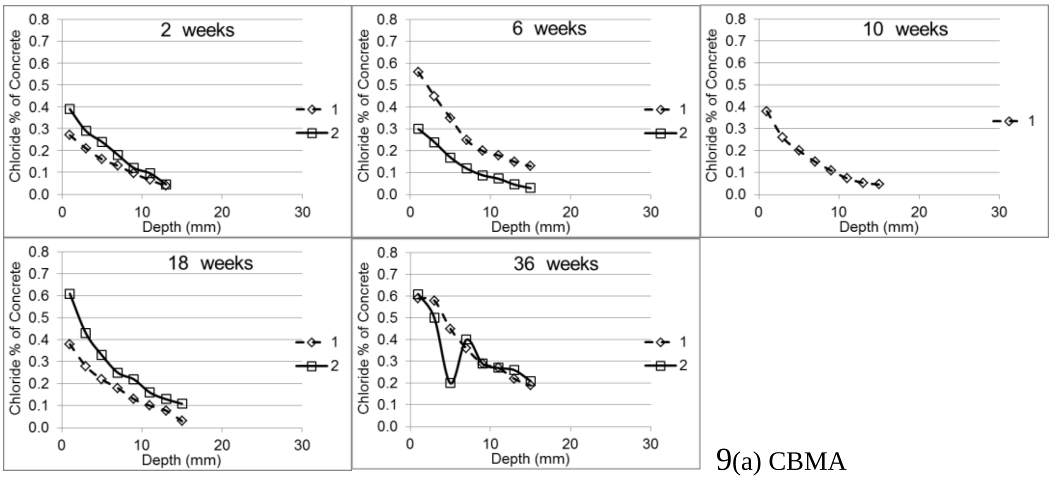
Fig. 8 Chloride profiles at different exposure time for two similar concrete samples at 60 % stress ratio

Contrary to what was observed at the 0 and 30 % stress ratios, the profiles obtained for 60 % stress ratio showed a more irregular profile. When the critical stress ratio was surpassed, a lower chloride content was found for the outermost layers that were located close to the exposed surface. The low chloride values were progressively advancing in depth with exposure time. This general decrease in the chloride content was found to affect depths up to 15 mm from the surface. The chloride content in these layers does not follow the general trend commonly found in Fick’s model. The repeatability of the test is not as good as that found for the 0 and 30 % stress ratio.

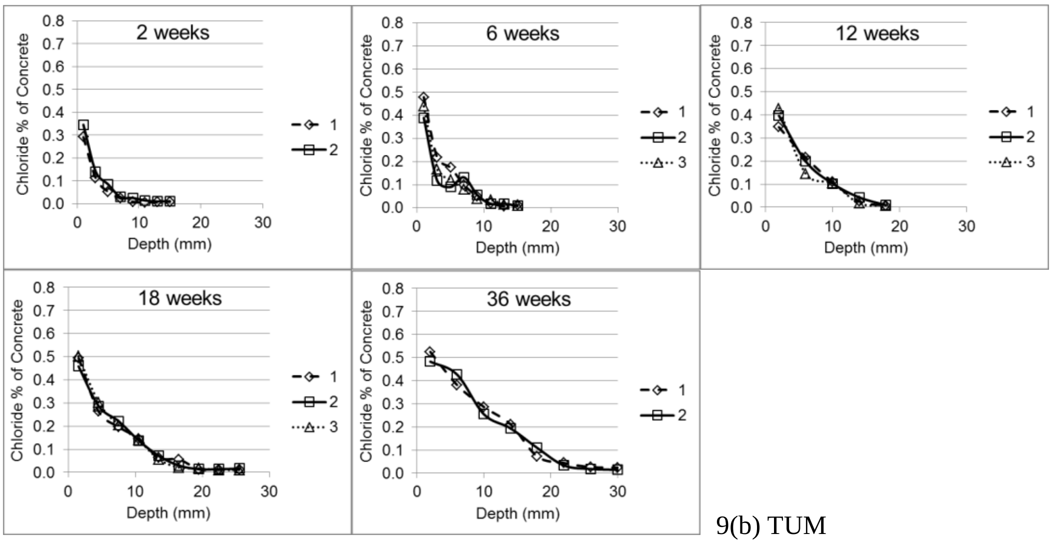
It is believed that chloride ingress is influenced by the micro-cracked system. In such cases, chlorides move directly through the cracks without having enough time to interact with the hydrated paste complexes. Besides, the new specific surface for interaction obtained after cracking is very small compared to that available in unaltered hydrated paste. It is also assumed that chlorides travel faster in a crack network instead of moving through a non-cracked paste which consists of a network of narrow pores. The new intruded chloride solution disrupts the high-alkali background causing calcium lixiviation and pH reduction especially for the outermost layers. Due to the reduction of calcium content, pH and specific surface occurring in the superficial concrete layer, the capacity for chloride adsorption on cement hydrates and therefore the adsorbed chloride content on the binder is reduced. This induces a high mobility of free chlorides in the bulk solution within the crack network towards inner depths. Finally, chloride transportation is decelerated at the innermost sites where the hydrated binder products keep their chemical nature intact. In such sites, a normal accumulation of chlorides is created followed by a sudden drop in the chloride profile that follows the normal Fick’s diffusion model.

In summary, two recognizable areas can be observed in a chloride profile obtained at high stress ratio. The outermost zone, where micro-cracks prevail promoting the formation of a convection zone, is characterized by calcium leaching and pH reduction. As a consequence the total chloride content is lowered in this region. This zone ends where the damage has not yet completely penetrated. Deeper down the normal chloride profile is found which follows Fick’s diffusion model.

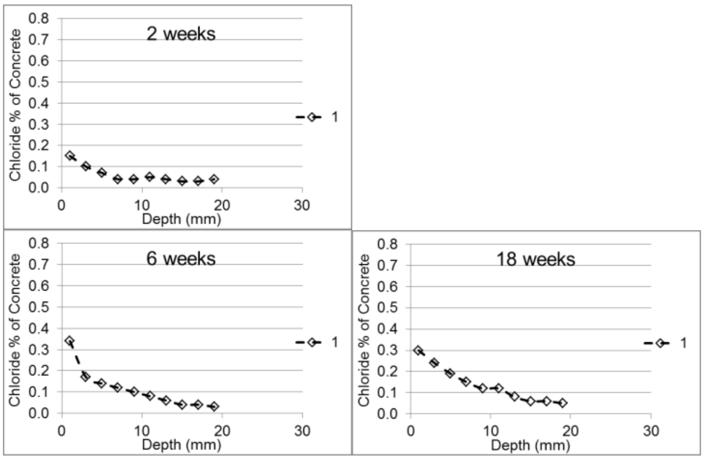
Figure 9 shows the complementary chloride profile information at 60 % stress ratio from the other laboratories involved in the comparative test.



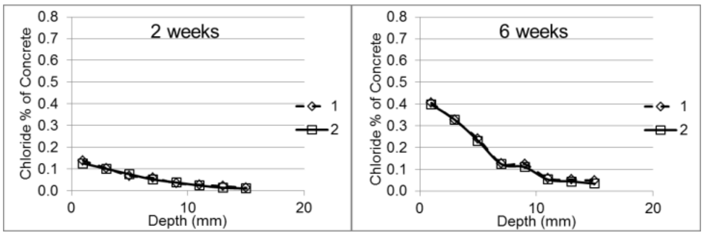
9(a) CBMA

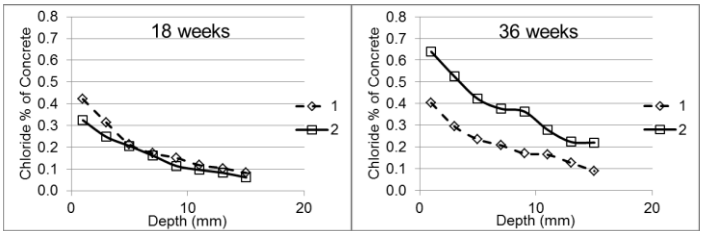


9(b) TUM



9(c) TU DELFT



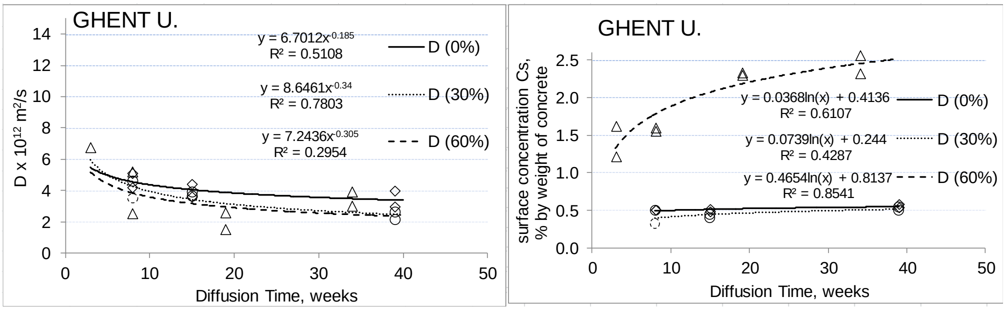


9(d) DALIAN U.

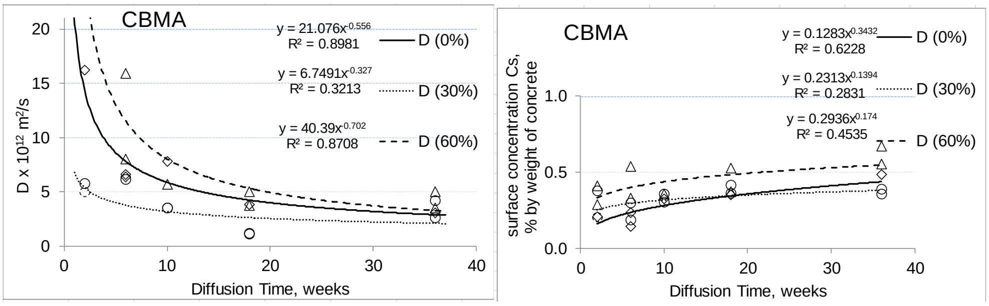
Fig. 9 Chloride profiles at different exposure times at 60 % stress ratio

3.1.3 Chloride's surface concentration and Diffusion coefficient obtained per laboratory

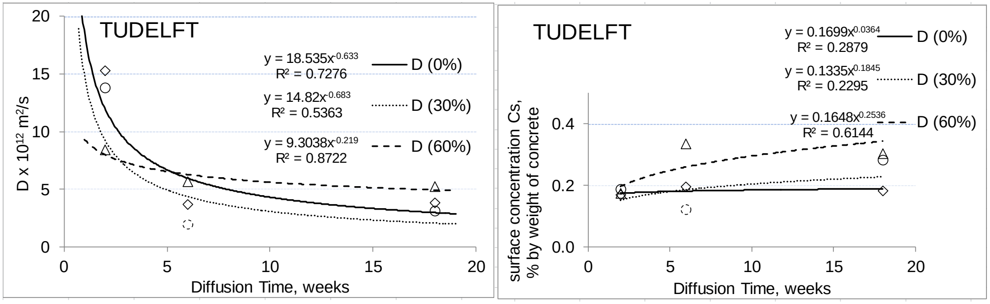
Figure 10 shows the obtained variation with time for the diffusion coefficient and modelled surface concentration for all labs involved. All chloride contents are measured after acid extraction except for the data from DALIAN U., which are provided as water soluble chloride content.



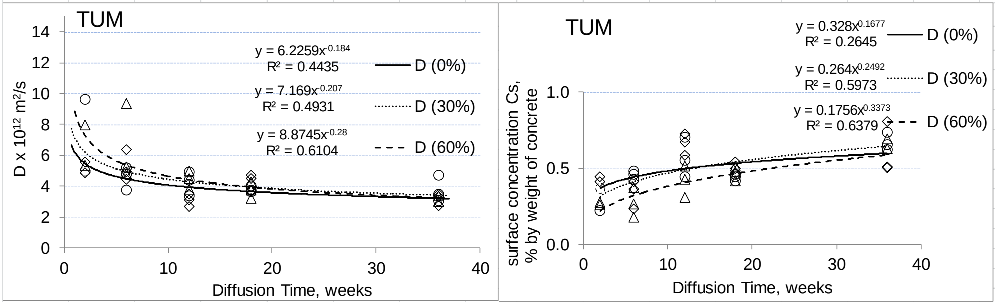
10 (a) GHENT U.



10 (b) CBMA



10 (c) TU DELFT



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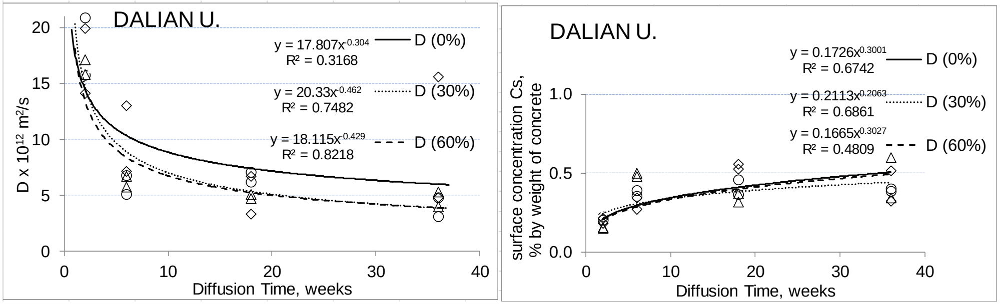

10 (e) DALIAN U.

Fig. 10 Variation in time of the chloride ion diffusion coefficients and modelled surface concentration from 5 laboratories

From Figure 10 it can be concluded that the diffusion coefficients tend to decrease with exposure time while the modelled surface concentrations increase. All the values for the diffusion coefficients tend to stabilize at values approaching 3 x 10^{-12} m^2/s for late ages (36 weeks).

The modelled surface concentration stabilizes around 0.5 % for the same exposure age. The modelled surface concentrations obtained for the 60 % stress ratio data of Ghent University were calculated taken into account the portion of the curve beyond the damaged zone only. It was considered that only in the mentioned portion of the curve the conditions are present for a good fitting of the law of diffusion to the obtained values. At later ages it was necessary to eliminate up to the first 8 points (15 mm) and consider only the final 11 points to fit the curve. Due to the deep ingress of chlorides into the concrete, it was necessary to drill up to 40 mm to reach background values of 0.02 % for chlorides.

The values found for the diffusion coefficient (based on measurements in the undamaged zone) from samples subjected to 60 % stress ratio, were similar to the ones obtained from samples exposed to 30 % stress ratio. This indicates that this property remains constant in the unaltered zone.

It is thought that for service life predictions for 60 % stress ratio it is necessary to link the three obtained parameters: diffusion coefficient, depth of the damaged convection zone and modelled surface concentration. However, only the diffusion coefficient was used for service life prediction in this report since the existing model did not previously take the damaged convection zone and surface concentration into consideration up till now.

3.2 Tension

3.2.1 Typical chloride profiles for 0, 50 % and 80 % stress ratio

Figure 11 shows the influence of different tensile stress ratios on concrete chloride penetration under the exposure duration of 2, 6, 10, 18 and 36 weeks respectively. It can be seen that the chloride content decreases with the increase of depth, gradually reaching to the initial chloride content. The maximum chloride ion penetration depth increases with the exposure time no matter the stress ratio.

When a 50 % tensile stress ratio is applied, the chloride content in a certain layer is higher than for a layer at the same depth without load. And when the stress ratio reaches 80 %, the chloride content at the same depth significantly increases. This shows that cracks inside concrete occur and increase along with the increase of stress ratio and loading time. The chloride transport in concrete under tensile stress is obviously different from concrete without tensile stress.

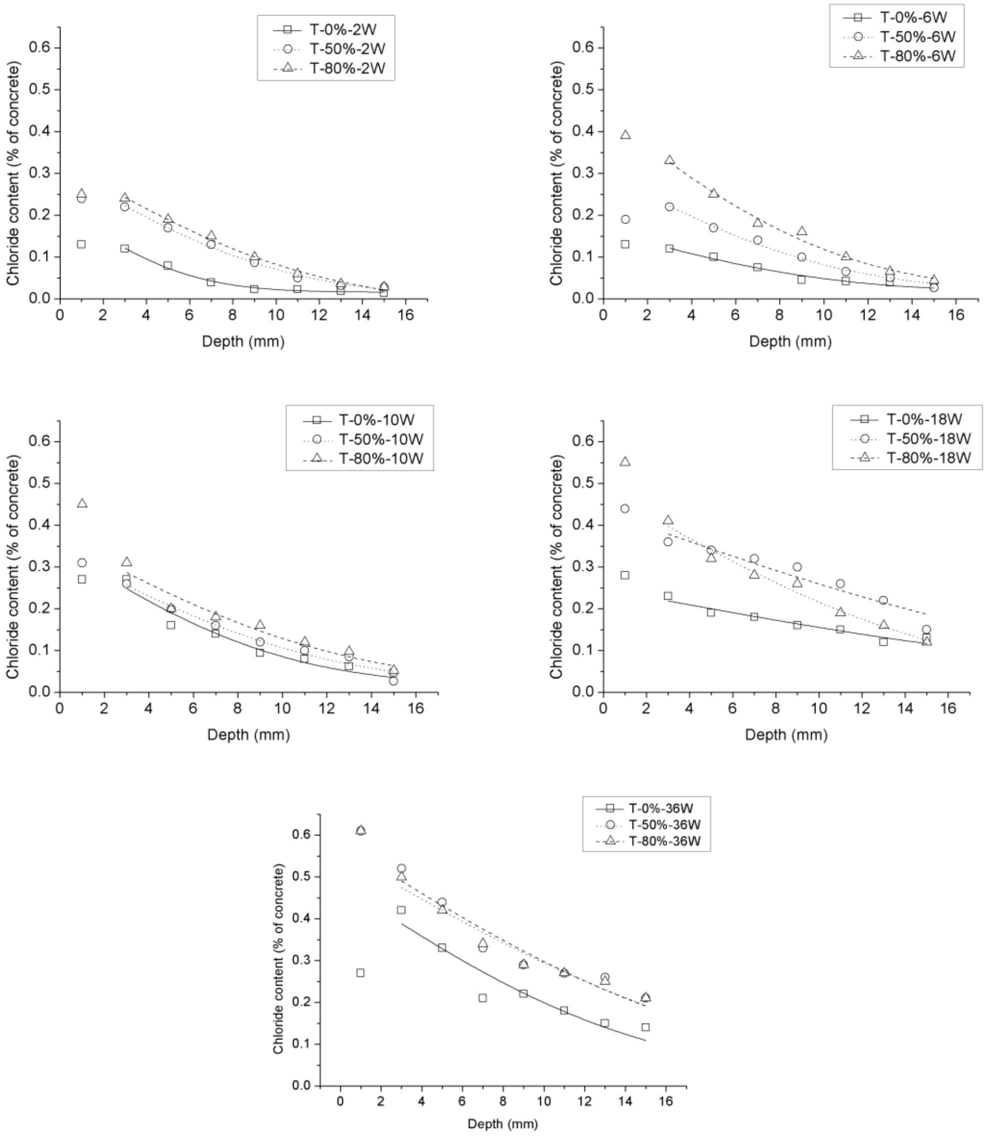

Fig. 11 Chloride profiles determined after 2, 6, 10, 18 and 36 weeks with 0, 50 % and 80 % tensile stress ratio

3.2.2 Typical chloride surface concentration and diffusion coefficient

The migration of chloride into concrete is a complex process which finally may be simulated by reactive diffusion. Diffusion coefficients and modelled surface concentrations determined by curve fitting according to EN 12390-11: 2015 Annex F [15] are shown in Figure 12.

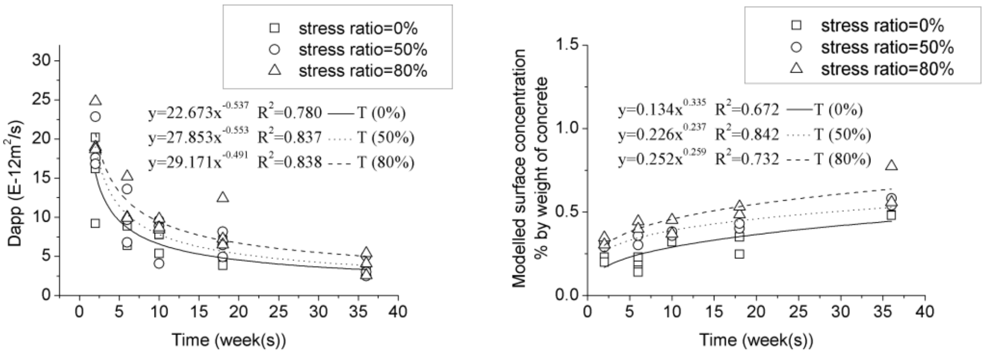

Fig. 12 Chloride ion diffusion coefficients and modelled surface concentrations of concrete under tension

Figure 12 shows that the diffusion coefficient of concrete under tension increases with the stress ratio at the same exposure time. The application of tensile stress speeds up chloride diffusion in concrete. In the meanwhile, the diffusion coefficient decreases with the exposure time, no matter whether an external tensile stress is applied or not.

Due to the limited number of samples, the modelled surface concentrations of concrete under different stress ratios scatter over a relatively wide range but tend to increase with exposure time and stabilize at values approaching 0.6 % for 36 weeks. The chloride profiles and the results of modelled surface concentrations also show the existence of the convection zone, but not very obvious. To get more reliable information on this, more tests need to be carried out.

The chloride content at the concrete surface depends on material properties and on geometrical and environmental conditions, and may largely differ from the modelled surface concentration derived from regression analysis using the diffusion law. When a considerable convection zone is found, more points near the surface should be eliminated, thus deeper layers should be sampled. Accordingly, for the service life predictions, the content of chlorides at the substitute surface $C_{s,\Delta x}$ should be considered instead (with Δx the depth of the convection zone).

3.2.3 Discussion on the diffusion coefficient of concrete under tension

It was found from the comparative test that the test under uniaxial tensile stress is more difficult to conduct than that under compressive stress due to the uniaxial eccentricity of specimen under tension. Cautions shall be taken to avoid uniaxial eccentricity and stress relaxation when carrying out tensile stress, especially at the higher stress ratio. The eccentricity may influence the stress distribution and correspondingly influence the chloride penetration inside the concrete.

Another key factor is to keep the diffusion of chloride ions stable in long test durations, such as those exceeding 36 weeks. In other word, the flow rate and the chloride gradient shall be constant during the whole tests.

In summary, eccentric stress and unstable chloride diffusion in concrete may be the reasons causing the wide variation in the critical stress ratio in existing literature. The innovative designed test rig of RILEM TC 246-TDC, which consists of the loading control unit and the chloride medium circulation unit, solved several of the mentioned problems which are likely to appear under high tensile stress.

4. Modelling and prediction

4.1 Modelling

Reinforced concrete structures which are exposed to de-icing salt or seawater could be damaged by chloride induced reinforcement corrosion. The fib Model Code for Service Life Design, fib bulletin 34 [5], provides a transport model for predicting the time-dependent probability that reinforcement corrosion is initiated. The transport model considers when a critical corrosion inducing chloride content at the depth of the reinforcement is reached in dependence of the concrete characteristics and chloride impact. Further explanations, further information on relevant input data and example calculations are given in fib bulletin 76 [16]. According to [5] and [16], transport of chlorides into concrete can be modelled utilizing Equations 1, 2 and 3, cp. [16]. Equation 2 was extended by a so-called stress factor k_l, which takes stress condition of the structural member into account.

$$C(c_{nom}, t_{SL}) = C_i + (C_s - C_i) \cdot \left[\operatorname{erf}\left(\frac{c}{\sqrt{D_{app,A}(t_0) \cdot t}} \right) \right] \tag{1}$$

$$D_{app,A}(t) = k_e \cdot k_l \cdot D_{app}(t_0) \cdot \left(\frac{t_0}{t} \right)^{\alpha_A} \tag{2}$$

$$k_e = \exp\left(b_e \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T_{real}} \right) \right) \tag{3}$$

In the following study the influence on the service life of unloaded compared to loaded concrete (compression and tension) is presented.

The study corresponds to a case study already presented in [16], Table A.2-15 which has been considered due to its similarity in concrete material (CEM I-concrete of w/c = 0.45, unloaded). The case study of fib bulletin 76, which is re-calculated here for loaded concrete members, represents a typical XS2-exposure (member immersed in seawater) in Portugal (Europe). Most of model input parameters, especially the variables characterizing the environmental load, were taken from the aforementioned Table A.2-15 of fib bulletin 76. However, input variables which do characterize the concrete material ($D_{app}(t)$) were derived from the aforementioned experiments. Material data used in the re-calculation was data of all 5 labs (CBMA, GHENT U., TU DELFT, TUM and DALIAN U.) participated in the experimental program. Diffusion coefficients determined after 6 weeks (t_0 = 0.115 years) of unloaded exposure were considered to be the (unloaded) reference value (mean was 6.52 x 10^{-12} m^2/s, standard deviation was 2.88 x 10^{-12} m^2/s), Table 2. All other load conditions were referenced with a stress factor k_l, which was $k_l = 1$ for the reference, $k_l = 0.80$ for stress ratio 0.3 (compression), $k_l = 1.17$ for stress ratio 0.6 (compression), $k_l = 1.25$ for stress ratio 0.5 (tension) and $k_l = 1.53$ for stress ratio 0.8 (tension),

For the determination of an age exponent, the exposure time should be as large as possible (minimum 2 years). In this study, the maximum exposure time was only 36 weeks. In total 15 series were investigated (5 labs, 3 different stress levels), consequently 15 “short term” age exponents, cp. Figure 10, could be calculated according to [16], approach A. Table 2 contains not only information on α_A but also shows the general input parameters in accordance with [5].

Table 2 Input parameters for the service life prediction

Parameter	Unit	Distribution type	Mean	Standard deviation	a	b
$D_{app}(t_0)$	$\cdot 10^{-12}$ m^2/s	Normal	6.52	2.88	-	-
α_A	-	Beta	0.39	0.18	0	1
t_0	years	Constant	0.115	-	-	-
t	years	Constant	50	-	-	-
T_{ref}	K	Constant	293	-	-	-
T_{real}	K	Normal	288	5.0	-	-
b_e	K	Normal	4800	700	-	-
$C_{S,\Delta}$	M.-%/c	Lognormal	3.0	1.0	-	-
Δx	mm	Constant	0	-	-	-
C_{Crit}	M.-%/c	Beta	0.6	0.15	0.2	2.0
c	mm	Normal	50	6	-	-

4.2 Prediction

The service life prediction for 100 years unloaded, under compressive stress and under tensile stress respectively, is given in Figure 13. All calculations are performed by utilizing the software STRUREL [17].

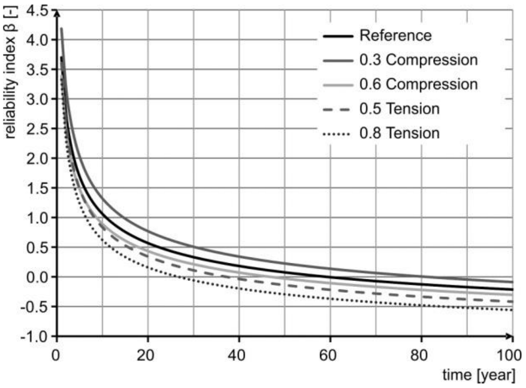

Fig. 13 Calculated reliability of chloride exposed concrete members, unloaded, compression and tension stress (two different ratios)

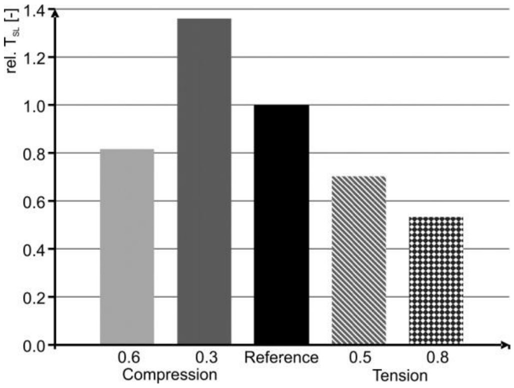

Fig. 14 Relative service life (rel. T_{SL}) of chloride exposed concrete members, unloaded (reference), compression and tension loaded (two different ratios)

In order to give numbers on the influence of loading on service life the end of service life was defined to be reached when reliability drops below the defined minimum of $\beta = 0.5$. Based on this definition, service life was determined for each of the five presented calculations and referenced on the unloaded case respectively, cp. Figures 13 and 14. Figure 14 shows that the service life of members loaded by 30 % of ultimate compressive stress was prolonged by a factor of 1.36 compared to the reference; the service life of members loaded by 60 % of ultimate stress was shortened by the factor of 0.82 in comparison to unloaded member.

If tensile stress is applied, service life decreased compared to the reference. Service life was shortened by the factor of 0.70 (tension, 50 % of ultimate stress) and 0.53 (tension, 80 % of ultimate stress), respectively.

It is obvious that the concrete loading condition has an influence on the service life time.

5. Conclusions and outlook

The main task of RILEM TC 246-TDC was to study the influence of applied compressive and tensile stresses on the rate of chloride penetration. Results obtained are presented and discussed in this report. These results show that the state of stress should be taken into consideration to make durability and service life design more reliable. In the future, more work will be necessary in order to investigate the influence of an applied stress, for instance on the rate of carbonation and on frost resistance. Results described in the final report of RILEM TC 246-TDC clearly show the need for follow-up investigations. Future technical committees could have the common task to establish a solid basis for taking the influence of an applied stress on durability and service life into consideration. Then only the actual situation of the built infrastructure in many countries can be substantially improved in a systematic way.

As mentioned in the introduction to this report already, RILEM TC 246-TDC opened a new field of research, with the major aim to make design for durability and service life of reinforced concrete structures more realistic and more reliable by taking combinations of applied mechanical stress and environmental loads into consideration. It was initially clear that this task could not be finished within the duration of a single RILEM TC. Yet a beginning was made, which now asks for well-structured continuation. The influence of an applied stress on chloride migration was measured and a recommendation on the test method was formulated. Results obtained already allow an estimation of the influence of an applied stress on durability and service life of reinforced concrete structures exposed to a chloride containing environment. If the recommended test method is applied, specific behaviour of different types of concrete under stress can be taken into consideration.

The next step should be to run similar test series on concrete exposed to carbonation and to formulate a standard method that will allow determining the influence of an applied tensile or compressive stress on the rate of carbonation. First tests have shown that there is a dramatic influence of an applied stress on rate of the carbonation [7]. It may be expected that application of a moderate compressive stress slightly reduces the rate of carbonation, hence service life will increase. But at an applied stress higher than half of the ultimate stress could induce damage into the composite structure of concrete and thus may lead to progressive reduction of service life. Under the influence of an applied tensile stress, however, the rate of carbonation will continuously increase. This means that structural elements under permanent tensile stress will need a thicker cover to reach the same service life under given environmental conditions. Detailed investigations are still needed to obtain quantitative results to support these hypotheses for different types of concrete.

For a realistic and reliable service life prediction the influence of an applied cyclic stress has to be taken into consideration too. So far, however, only very limited data exist [9].

It may be anticipated that durability and service life of reinforced concrete structures also depends on combinations of applied stress, carbonation and chloride penetration with freeze-thaw cycles. Frost action has been studied recently in detail by two RILEM TCs, TC 176-IDC [18] and TC 117-FDC [19]. These two RILEM TCs published recommendations were based on a series of comparative test series, which were run and results were evaluated according to ISO 5725 [20]. Now the essential results of these two TCs are part of European standardization. Cracks formed during freeze-thaw cycles and frost suction in particular will have to be taken into consideration in future tests of combined environmental and mechanical loading [21].

In order to achieve a better understanding and a systematic description of the influence of combined mechanical load with environmental actions on durability and service life of reinforced concrete structures, a numerical model of damage processes in the composite structure of concrete has to be developed. This model can be tested by comparison with measured data and it can be helpful to predict the behaviour under different load combinations.

In parallel to the experimental test series and numerical simulations, the actual method to predict durability and service life has to be further developed in order to enable easy use of the experimental data obtained for realistic service life prediction.

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