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RILEM TECHNICAL COMMITTEE

Recommendation of RILEM TC 246-TDC: test methods to determine durability of concrete under combined environmental actions and mechanical load

Test method to determine the effect of applied stress on chloride diffusion

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Abstract The combination of environmental actions and mechanical load has obvious synergetic effects on the durability of concrete. But these effects have been widely neglected so far. For a realistic service life prediction the effect of an applied mechanical load on chloride penetration has been taken into consideration as a first and important step in RILEM TC 246-TDC since 2011. This recommendation focuses on the test method to determine the effect of applied compressive stress and tensile stress on chloride diffusion. It includes detailed experimental procedure to receive consistent results of chloride profile and the apparent chloride ion diffusion coefficient of concrete under compressive and tensile stress.

Keywords Concrete durability · Compressive stress · Tensile stress · Chloride ion · Diffusion coefficient

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1 Introduction

Several methods to predict durability of reinforced concrete structures exist at present. In most cases, one dominant deteriorating process such as carbonation or chloride penetration is taken into consideration. Experimental results as well as observations in practice show, however, that this is not a realistic and certainly not a conservative approach. The combination of much more severe than the sum of the individual mechanical load and environmental actions may be contributions.

There are obvious synergetic effects which have been widely neglected so far. With the aim of developing more realistic test methods, a first RILEM Technical Committee (RILEM TC 246-TDC) on the determination of durability and service life of concrete under combined environmental actions and mechanical load was set up in 2011.

To establish a solid basis for the following experimental studies, an annotated bibliography containing publications on the durability of reinforced concrete structures exposed to mechanical load and environmental actions was first compiled [1]. This publication presents the state-of-the-art in this specific field. This document is now available for all interested colleagues.

Based on the annotated bibliography and the specific experience of TC members, well-defined comparative test series have been carried out and evaluated. As a first step, the combination of mechanical load and chloride penetration was investigated. It became obvious that for a realistic service life prediction the effect of an applied mechanical load on chloride penetration has to be taken into consideration [2]. Other combinations of mechanical load and environmental actions will be studied in detail in several follow-up technical committees. At a later stage, the results of all follow-up committees will be critically compiled and implemented in national and international codes. In this way, the average service life of the built infrastructure can be extended significantly.

From the wide range of possible combinations of mechanical stress and environmental actions in practice, a few combinations were chosen as a first step. For obvious reasons, this work has to be extended considerably in order to make service life design more reliable in the future.

2 Scope and applications

Among the numerous possible combinations of mechanical load and environmental actions, the effect of compressive load and tensile load on chloride penetration into the pore space of concrete was selected as a first and most important example. This is a simplified case of the many different possible load combinations which may occur in field practice. As expected, a strong effect of an applied mechanical load on chloride penetration was observed. It was found that the chloride penetration is significantly accelerated under an applied tensile stress. The reduction of service life of reinforced concrete structures due to this combination can now be estimated. A more sophisticated method to take combined loads into consideration is being developed. The application of a compressive stress which is higher than half the ultimate strength also accelerates chloride penetration [1–3].

One major aim of RILEM TC 246-TDC was to develop a test method which allows determination of the effect of combined mechanical load and environmental actions. A proposed test method was critically checked by comparative test series run by members of the TC. Up to six laboratories in different countries participated in these comparative test series. The originally proposed test method was developed further and refined based on the first experience with the comparative test methods. Now, the proposed test method can be applied by others based on the detailed recommendation.

3 Equipment, specimens and test procedure

3.1 General

In this section, the principle of the test, the recommended loading rigs, the procedure for preparation, and initial curing of the specimens are described. After preparation, the specimens are mechanically loaded under compression or tension up to a certain stress ratio. During sustained loading the specimens are subjected to chloride ingress. The method for applying the chloride solution to the surface of the specimen is explained. Furthermore, the test procedure and the method for determination of the chloride profiles are given.

3.2 Test equipment

The applied load may be either compressive or tensile. The specimens for both loading cases are different as well as the loading rigs. The specimen geometry and preparation are discussed in Sect. 3.3. The principle of the loading rig for compression is shown in Fig. 1. The compressive load is applied on a prismatic concrete specimen using a test rig similar to test rigs used for creep loading and described in RILEM recommendation of TC 107-CSP [4]. Different loading rigs are used for the creep tests. The hydro-pneumatic accumulator shown in Fig. 1 is recommended.

Test rigs, which have the same principle and function and fulfil the requirements of RILEM recommendation of TC 107-CSP can be used as well. All the test rigs shall be mechanically stable during the entire loading period. A test rig with a fixed container for the chloride solution is shown in Fig. 2a. The method of fixing the container to the test specimens is shown in detail in Fig. 2b.

The test rig shown in Fig. 3 is recommended for tensile loading. Two plates attach the four bolts on each end face of the dumbbell tension specimens (Fig. 4) to the spherical hinges which are employed to minimize the uniaxial eccentricity of the tension specimen. Any other test rig based on the same principle may also be used. Strain gauges with an accuracy of ± 1 μm should be glued to the steel frame for monitoring the applied load. They can be mounted on the steel bars connecting the two end plates or on the steel pins connected to the spherical hinges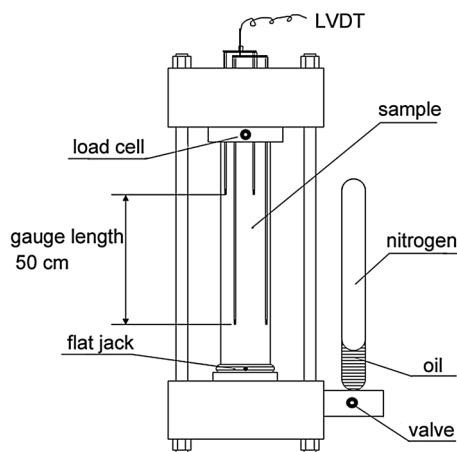. The strain gauges attached to the frame should be calibrated using dead loads or a loading frame equipped with load cells to convert the measured strain into stress.

To apply the chloride solution to the surface of the loaded specimen, a plastic container shall be used as shown in Figs. 2 and 3. The container shall have an inner dimension of $80 \times 160 \times 50$ mm^3; the

Fig. 2 Details of test equipment: **a** example of test rig with specimens including attached container for chloride solution, and **b** container and principle for fixation of container
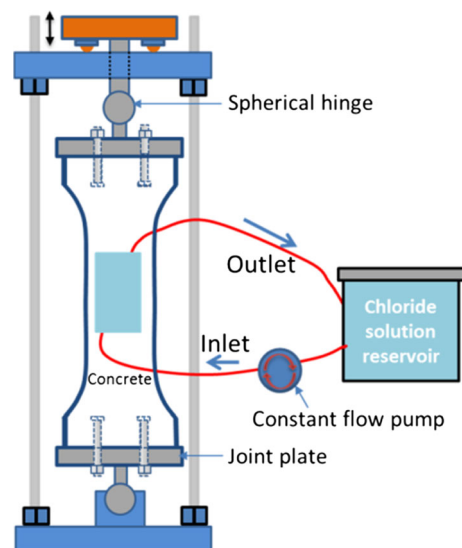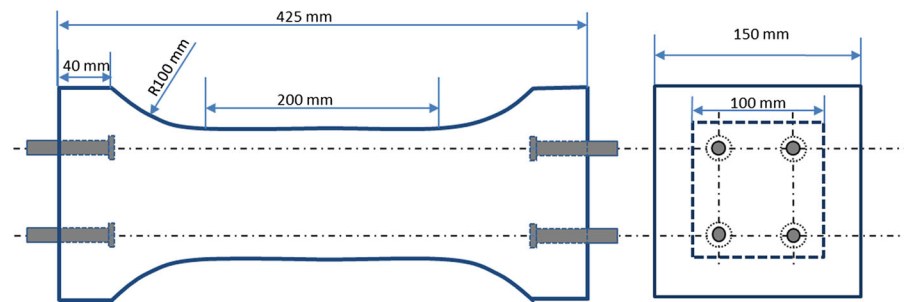

Fig. 3 Test rig for tension and dumbbell specimen with chloride solution container and reservoir for chloride solution

Fig. 1 Schematic representation of test rig for compression [4]

Fig. 4 Geometry and dimensions of dumbbell specimens for tension tests

minimum thickness of the container shall be 5 mm. The container is transparent in order to enable continuous observation of the circulation of the chloride solution. To connect the container with the specimen, a clamping system as shown in Fig. 2b is used. The container shall be connected to a reservoir by an inlet and an outlet hose. The volume of the reservoir should be at least 25 l. It must be resistant to the aqueous chloride solution. A pump with a small capacity should be used to circulate the solution at a constant flow rate of 5 $\pm$ 1 ml/s. The flow rate shall be checked regularly.

3.3 Preparation of concrete specimens

For the preparation of the specimens, the internal dimensions of the steel moulds are required with a tolerance of ± 1 mm. For the compression tests the concrete shall be cast into $100 \times 100 \times 400$ mm^3 prisms. Dumbbell specimens for tension tests shall be cast with the dimensions given in Fig. 4. To connect the specimen with the tensile testing rig, four bolts shall be embedded at each end of the mould for dumbbell specimens before pouring. The raw materials and mix composition of the concrete are chosen for each specific project and should be similar to the mix used on site or as prescribed in the project specifications. Concrete with a slump between 12 and 15 cm is recommended for easy casting. The specimens shall be cast according to EN 206 [5].

A thin film or foil of Teflon shall be applied to all internal faces of each mould in order to avoid the disturbing effects of demoulding oil. The fresh concrete shall be cast in two layers. After spreading each layer of concrete uniformly, each layer shall be compacted on a vibration table.

After casting, the specimens shall be stored in a room maintained at 20 °C and not <95% relative humidity (RH) for 24 h. Afterwards, the samples shall be demoulded. For further curing two alternative procedures are available:

- *Procedure A* immersion the specimens in tap water saturated with Ca(OH)$_2$ at a temperature of 20 °C.
- *Procedure B* placement of the specimens in a moist curing chamber at a temperature of 20 $\pm$ 2 °C and a relative humidity not <95%.

After curing, specimens shall be removed from the curing procedure for testing at an age of 28 days.

All specimens shall be vacuum saturated with Ca(OH)$_2$ solution before the application of the mechanical load and beginning the chloride diffusion test. The vacuum apparatus shall consist of the following.

(a)   A container with a capacity for at least three specimens.
(b)   A pump that is capable of maintaining an absolute pressure of <50 mbar (5 kPa) in the container.

The prisms shall be placed under vacuum ($p < 5$ kPa) for 2.5 h. Then the pressure shall be gradually increased to atmospheric pressure as water is let in and the samples left in the container for another 24 h.

After vacuum saturation, the water on the surfaces of the specimens shall be removed with a dry towel. Then the surface shall be immediately sealed with two layers of self-adhesive aluminium foil. The chloride container should also be attached immediately on a window with dimensions 80×160 mm^2 left open on one moulded surface with the following.

The preparation of specimens for compression and tension tests shall be identical.

3.4 Test procedure

A flow chart of the test procedure is shown in Fig. 5.

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┌─────────────────────────────────────┐
│ Determination at age of 28 d         │
│ 1. Compressive strength or tensile   │
│    strength                          │
│ 2. Initial chloride content          │
└─────────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────────┐
│ Chloride diffusion under applied     │
│ stress for 2, 6, 18 and 36 weeks.    │
│ 1. Application of compression or     │
│    tension                           │
│ 2. Circulation of chloride solution  │
└─────────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────────┐
│ Determination of chloride profile    │
└─────────────────────────────────────┘
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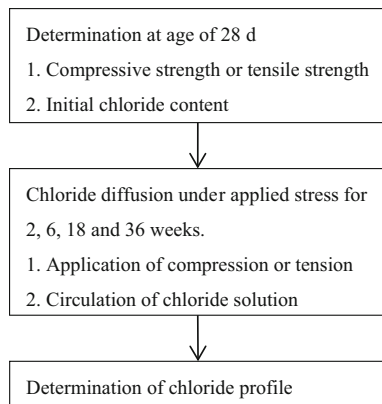
Fig. 5 Flow chart of the test procedure

The compressive strength of the concrete prisms and the tensile strength of the dumbbell specimens at an age of 28 days shall be determined on specimens with the same dimensions as those used for the chloride diffusion test. The average value based on at least three specimens shall be considered to be the reference strength. For the determination of the reference compressive strength, a servo-controlled testing machine with an accuracy of ±0.1 kN shall be used. For the reference tensile strength, it is recommended to use the same test rig as used for the tests under sustained load.

The initial chloride content of the concrete shall be determined by chemical analysis on cubes prepared from the same fresh concrete as used for the compression or tension specimens and cured in an identical way. The test procedures shall be in accordance with EN 14629 [6]. The powder required for chemical analysis can be obtained by drilling or by milling starting at a side surface of the cubes. Milling is recommended. In the case of drilling, at least three points on one side surface shall be selected. The average value as obtained from the three points shall be considered to be the initial chloride content C_i.

Compressive stress shall be applied on the prismatic concrete specimens. Tensile stress shall be applied on the dumbbell specimens. The applied stress shall be controlled regularly and kept constant for the entire duration of the test.

The stress ratio is the ratio of applied stress and the reference strength. For compression tests, the three following stress ratios shall be used: 0, 30 and 60%. For tension tests, the following stress ratios shall be used: 0, 50 and 80%.

After a particular stress is applied, the container shall be fixed immediately onto a side surface of the specimens and connected with the reservoir by the inlet and outlet hoses. The reservoir should contain at least 25 l of aqueous salt solution (3 wt% NaCl) or sea water. Then the pump to circulate the solution is started.

The concentration of the solution should be checked regularly, at least once a week during the whole exposure period and corrected if necessary. The chloride solution in the reservoir must be isolated from the atmosphere by a lid to avoid evaporation and contamination.

The specimens shall be unloaded after an exposure time of 2, 6, 18 and 36 weeks, or any other predetermined duration. The solution tank is then removed from the specimens. The specimens are then ready for the determination of the corresponding chloride profile. The scheme of the procedure for chloride profile is shown in Fig. 6.

Sampling for the determination of chloride profiles must start immediately after removal of the solution tank from the unloaded specimen. Sampling of the material for the chloride analysis can be performed in three different ways namely, (a) milling, (b) drilling or (c) cutting and subsequent crushing. The procedures for each method shall be in accordance with Ref. [7]. The recommended procedure is milling. Powder from the exposed surface of all specimens shall be obtained stepwise by milling layers with a thickness of 1–2 mm. Do not sieve the powder obtained after milling to avoid any change in the material to be analysed. The thickness of the layers should be adjusted to the expected depth of the chloride profile so that a minimum of eight points can be obtained for each profile between the exposed surface and the depth
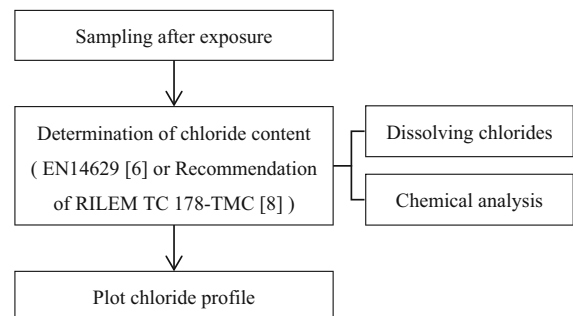
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┌─────────────────────────────────┐
│ Sampling after exposure          │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐        ┌──────────────────────┐
│ Determination of chloride content│────────│ Dissolving chlorides  │
│ ( EN14629 [6] or Recommendation  │        └──────────────────────┘
│   of RILEM TC 178-TMC [8] )      │────────┌──────────────────────┐
└─────────────────────────────────┘        │ Chemical analysis     │
                 │                           └──────────────────────┘
                 ▼
┌─────────────────────────────────┐
│ Plot chloride profile            │
└─────────────────────────────────┘
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Fig. 6 The scheme of the procedure for chloride profile

where the initial chloride content is reached. Each layer should produce at least 5 g of powder. The sampling area shall not exceed 60×140 mm^2 in the centre of the exposed surface area in order to avoid the edge effects and disturbances by the adhesive on the aluminium foil.

The chloride content of each sample shall be determined by chemical analysis according to EN 14629 [6] or the Ref. [8]. Longer time shall be needed for chloride extraction when there are particles with a diameter larger than 1 mm in the powder.

All tests shall be run at least in triplicate. The apparent chloride ion diffusion coefficient for each specimen shall be calculated by fitting the error function obtained as a solution of Fick's 2nd law. An average value of the apparent chloride ion diffusion coefficient shall be determined from at least three specimens.

4 Presentation and evaluation of test results

The chloride surface concentration and the apparent diffusion coefficient shall be determined according to Annex F of EN12390-11: 2015 [9]. Test results shall be presented in Tables 1, 2 and 3 and as graphical representation as shown below.

In particular, it has been observed that for applied compressive stress ratios higher than 50% and after longer exposure times, the obtained values of the chloride profile do not agree well with values predicted by Fick's 2nd law of diffusion. This is a clear indication that chloride penetration into concrete is a complex process in which diffusion combines with chemical reactions, interactions of the dissolved ions with the porous material (filter effect), and the effect of capillary forces. Fick's 2nd law is considered to be an approximation which describes the combined effect of the different processes. In view of this problem it is usually recommended to neglect the values obtained near the surface. It is recommended to use this approach until a more realistic model is available. A

Table 2 Parameters for chloride profiles for each concrete specimen

C_s or $C_{S,\Delta x}$
D_a
R^2
Δx
Number of layers
Number of neglected layers near the surface

The number of neglected layers near the surface shall be indicated

Table 1 Input data for chloride profiles

Test duration, t			
Initial chloride ion content, % m/m concrete			
Stress category			
Stress ratio			
Layer	Beginning of layer, mm, from exposed layer	End of layer, mm, from exposed surface	Average depth of layer, mm, from exposed surface	Average chloride ion content of layer, % by weight of concrete
L01				
L02				
L03				
L04				
L05				
L06				
L07				
L08				
L09				
L…				

Table 3 Chloride profiles as affected by stress ratio and exposure time

Stress category	Stress ratio	Exposure time, w	C_s or $C_{s\Delta x}$, wt.%	D_a,×10^{-12}m²/s	R^2
Compression	0	2			
		6			
		18			
		36			
	30%	2			
		6			
		18			
		36			
	60%	2			
		6			
		18			
		36			
Tension	0	2			
		6			
		18			
		36			
	50%	2			
		6			
		18			
		36			
	80%	2			
		6			
		18			
		36			

typical example is given in Figs. 5 and 6. Values near the surface can be higher or lower than predicted by diffusion alone and therefore may be neglected in the data fitting process. An apparent diffusion coefficient can be determined by fitting the descending branch of the chloride profile with the error function.

The regression analyses are performed on the measured chloride profiles using the error-function solution to Fick's 2nd law as expressed by Eq. (1):

$$C_x = C_i + (C_s - C_i) \cdot \left(1 - \mathrm{erf}\frac{x}{2\sqrt{D_a \cdot t}}\right) \qquad (1)$$

The initial chloride content, C_i, is determined according to Sect. 3.4. Then Eq. (1) still contains two unknown parameters, i.e. C_s and D_a. These parameters are to be determined by fitting Eq. (1) to measured chloride profiles.

The output of the regression analysis is provided in terms of C_s, D_a and the correlation coefficient, R^2.

The calculated set of apparent diffusion coefficient, D_a, and the surface concentration, C_s, as determined on load-free and loaded samples shall be evaluated to determine the effect of the external load as well as the exposure time.

Table 1 contains the basic input information on the depth intervals of the concrete layers, the measured chloride content C_m of each layer, as well as the initial chloride content, C_i, and the duration of the test, t.

The parameters can be calculated by fitting the experimental data with the following slightly modified equation.

$$C(x,t) = C_i + (C_{s\Delta x} - C_i)\left(1 - \mathrm{erf}\left[\frac{x - \Delta x}{\sqrt{4D_a t}}\right]\right) \qquad (2)$$

Here $C(x,t)$, is the chloride content measured at average depth x and exposure time t for $x > \Delta x$, % by mass of concrete; C_i, is the initial chloride content, % by mass of concrete; $C_{s\Delta x}$, is the calculated surface chloride content at the convection zone (surface region in which capillary suction and drying affect the chloride profile), % by mass of concrete; Δx, is the depth of the convection zone; D_a, is the apparent chloride diffusion coefficient, $m^2 \, s^{-1}$; x, is the depth below the exposed surface to the mid-point of the milled layer, m; t, is the exposure time, s.

A typical example for the measured and fitted chloride profiles as function of depth is presented in Fig. 7 where the values measured near the surface is neglected by the fitting process. Another example is shown in Fig. 8. In this case the values determined near the surface are lower than predicted by simple diffusion. These values are neglected for the determination of an apparent diffusion coefficient.

For the application and interpretation of results obtained by means of this recommendation it must be kept in mind that all tests are performed using water
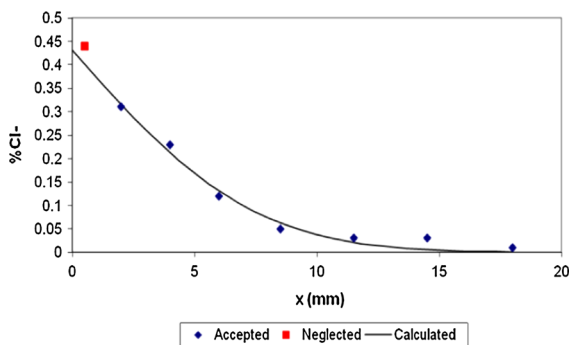

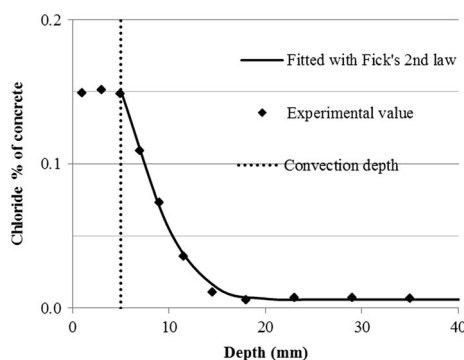**Fig. 7** Measured and fitted chloride profiles, an example

Fig. 8 Measured and fitted chloride profiles with "convection"

saturated specimens. This condition was chosen in order to provide a well-defined situation in which chloride diffusion dominates all other transport mechanisms such as capillary absorption and intermediate drying. Under these conditions the effect of an applied load on chloride penetration can be determined. The test results obtained under well-defined conditions can be considered to be a reliable indication of the durability of reinforced concrete structures in aggressive environments. In practice, however, the real situation is more complex. For realistic service-life prediction the results obtained following this recommendation have to be corrected with respect to the real conditions of exposure.

In Table 2, the output of the regression analysis is provided in terms of the fitted chloride content of exposed concrete surfaces C_s, the apparent diffusion coefficient D_a and the correlation coefficient R^2, and Δx the depth of the convection zone.

In Table 3, results obtained on all concrete specimens are summarized.

5 Test report

The test report shall contain at least the following information.

(a) Reference to the method as described here
(b) Brief description of the test rig
(c) Composition of the concrete
(d) Selected stress ratios
(e) Concentration of the chloride solution
(f) Test results showing as Tables 1, 2 and 3 and Figs. 7 or 8, rounded to the nearest 0.001% for chloride content
(g) Any deviation from the procedure described in this method
(h) Evaluation of test results with respect to specific applications.

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