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Influence of long-term chloride diffusion in concrete and the resulting corrosion of reinforcement on the serviceability of RC beams

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ABSTRACT

This paper presents the chloride penetration and the effect of chloride ingress on the serviceability of reinforced concrete (RC) beams. A series of experimental studies were carried out on beams with various corroded ages up to 28 years. The chloride content in different locations were tested during various periods. Different states influencing the serviceability of the corroded beams were investigated, including the maximum width of the corrosion-induced cracks of the concrete cover, the mid-span deflection of the beams under the service load and their load-bearing capacity. Based on the results available from this programme, the service life of corroded beams was predicted by the corrosion process of the reinforcement. The results showed that the chloride corrosion could significantly deteriorate the serviceability of the beams. The current criteria concerning the chloride content at the level of the reinforcement of the concrete beams and the maximum width of the corrosion-induced cracks appear to be very conservative.

1. Introduction

The serviceability limit state (SLS), which refers to user comfort, functionality and aesthetic aspects, is defined as the limit between the state where the performance of the structure is acceptable and the state where the structure is no longer serviceable according to DuraCrete [1]. The identification of the service life of a reinforced concrete structure usually includes the following three events: (1) the depassivation of reinforcement - for RC constructions exposed to a chloride environment, this limit state corresponds to the chloride concentration at the reinforcement reaching a critical threshold; (2) the criterion of maximum corrosion-induced crack width, which is limited to 0.3 mm; (3) the spalling of the concrete cover, which may endanger human life. Spalling is assumed to occur when the width of a corrosion-induced crack reaches 1.0 mm.

Chloride corrosion is considered as one of the principal factors that reduce the SLS of RC constructions exposed to a marine environment or de-icing conditions [2–4]. Corrosion of the reinforcement in RC constructions leads to loss of cross-section in the steel bars [5], cracking of the concrete cover [6,7], and reduction of the bond between the steel bar and the concrete [8]. All of these states inevitably result in a reduction of the serviceability of RC constructions.

The threshold values of corrosion initiation in the reinforcement for RILEM [9] and ACI [10] are different at present. The relationship between chloride content and the initiation of reinforcement corrosion remains to be clarified. Indeed, Angst et al. [11] showed a high scatter on the relationships between chloride content and corrosion onset.

A remarkable point is that most standards limit the maximum width of load-induced cracks to a value close to 0.3 mm and that 0.3 mm is also an SLS criterion concerning corrosion-induced cracks. The criterion of crack width for the SLS is also an empirical value. Sakai et al. [14] stated that a limit of 0.8 mm was appreciated for aesthetic requirements, which is different from the value proposed by DuraCrete [1].

Nevertheless, it is worth noting that the notion of limiting load-induced cracks to a given threshold, such as 0.3 mm, to avoid corrosion development is still under debate. A series of research works have been conducted on the states mentioned above, which are related to the SLS of the RC elements. Gowripalan et al. [12] and Win et al. [13] have investigated the influence of load-induced cracking behaviour on the process of chloride penetration into

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concrete. Yoon et al. [15] found that loading history and loading level had significant effects on both corrosion initiation and the process of corrosion propagation. However, Ababneh et al. [16] hold that the pre-exposure to a mechanical load has no influence on corrosion initiation or the corrosion rate thereafter, unless the load reaches some limit where connected cracks develop, through which chloride ions flow and depassivate the steel bars.

In addition to the differences in research conclusions, there are some other drawbacks for most laboratory investigations. For example, the corrosion process is very often accelerated by an impressed current. So it would be interesting to attempt to clarify the influence of chloride-induced corrosion on the serviceability of RC constructions in conditions of natural corrosion, such as the maximum corrosion cracks, the stiffness of the RC constructions under service load in corroded state as a function of time.

François et al. [17] have been conducting a long-term programme to investigate the corrosion process of RC beams in a chloride environment under service load since 1984. During the last three decades, corroded RC beams have been studied continually and research has included the corrosion process [18], cracking propagation [19] and residual ultimate mechanical structural behaviour [20,21]. For the previous published materials in this program, most of the publications were only fixed on the residual ultimate capacity. This paper is also based on this long-term programme, the results of the beams from the same group during different periods were collected and discussed so as to make clear the parameters affecting the chloride diffusion and the serviceability of corroded beams, including the chloride content, the cracking process and the mechanical performance under the service load, which were recorded after different durations of corrosion.

2. Experimental context

A long-term programme was set up in 1984 at Laboratoire de Matériaux et Durabilité des Constructions (L. M. D. C.) in Toulouse, France [17]. The intention was to investigate the corrosion process of the reinforcement and the influence of chloride corrosion on the mechanical performance of the corroded beams.

In this programme, 36 RC beams were cast with dimensions of 3000 mm × 280 mm × 150 mm, which was a popular size in the construction industry at the time of casting (1984). Two different diameters of reinforcement and two different concrete cover depths were used. As a result, the 36 beams were separated into two groups: A and B. The beams were loaded by coupling a beam from Group A and a beam from Group B with a loading system. Two load levels were used as the service load of the beams, which were consequently classified as A1, A2, B1 and B2. The beams were kept in a chloride environment under sustained loading. It should be noted that another 36 beams, cast in the same conditions and having the same composition, were stored in the normal laboratory environment to serve as control beams. Various investigations were conducted at different stages.

This paper deals with the beams in Group B. Detailed information about the beams is shown in Table 1. B1, B2 is the classification of the type and the service load of the beams; Cl is short for chloride corrosion, and T indicates control (non-corroded) beams; the last figure in the label is the beam number within each group. For example, B1Cl1 means the corroded beam with sequence number 1 in Group B under a service load of level 1. It is worth noting that the age in the table is the age at which the beams broke. However, some investigations were carried out at different stages before the beams were broken. It should be pointed out that not all the beams in Group B are presented here, as some of them were used at early age, for which few results are available, and some are still stored in the corrosion room for further research.

Table 1
Detailed information on the beams.

Label	Mser (kN m)	Type	Final age (years)
B1Cl1	13.5	Corroded beam	14
B1Cl2	13.5	Corroded beam	23
B1Cl3	13.5	Corroded beam	23
B1T1	13.5	Control beam	14
B2Cl1	21.2	Corroded beam	23
B2Cl2	21.2	Corroded beam	26
B2Cl3	21.1	Corroded beam	28
B2T2	21.2	Control beam	26
B2T3	21.2	Control beam	28

*Mser: bending moment applied at the mid-span of the beams.

2.1. Material composition and properties

The concrete and the cement compositions are shown in Table 2. The ratio of water to cement was designed to be 0.5. Nevertheless, the water content may have been readjusted in the casting process in order to achieve a constant workability of 70 mm in the slump test. The mechanical properties of the concrete were also checked. The average compressive strength was 45 MPa and the elastic modulus was 32 GPa, based on mechanical tests on cylindrical specimens of 110 mm × 220 mm at 28 days. The nominal yield strength for the reinforcement was 500 MPa.

2.2. Reinforced concrete specimens

The layout of the beams in Group B is shown in Fig. 1. It is necessary to point out that the concrete cover was only 10 mm, which corresponded to the minimum depth required by French regulations [22] for a non-aggressive environment in1984. It corresponds to a concrete cover of 16 mm for the longitudinal reinforcing steel bars. But the minimum depth should be increased to 20 mm according to the current Eurocode 2 standard [23].

2.3. Loading systems and conservation

A three-point loading system was used on all the beams by coupling a Group A beam with a Group B beam as shown in Fig. 2. The moment at the mid-span of the beam is shown in Table 1. Once the beams were loaded, they were transferred to a sealed room with four spray nozzles, located one in each upper corner and spraying a saline fog of 35 g/L, which corresponds to the salt concentration of sea water. Fig. 2 shows a diagram of the set-up.

After the beams had been stored in the constant fog environment for the first 6 years, the spraying system was changed to wetting-drying cycles in order to accelerate the corrosion process. Detailed information about the spraying cycles is given in Table 3.

It should be pointed out that the corrosion adopted in this program was considered as climate accelerated corrosion (no impressed current but accelerated chloride ingress) which was similar to natural corrosion. Moreover, no more chlorides came from the outside environment during the 7 years (from 19 to 26 years). Nevertheless, the chloride content in concrete beams was already very important and the corrosion process was continuous during these 7 years. One beam was fully tested B2Cl1 at 23 years), including chloride content, cracking map, and mechanical behaviour. The influence of non-continuous chloride regime was not taken into account but it seemed that beams were sufficiently contaminated by chlorides to have a continuous corrosion process.