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Mathematical relation of steel thickness loss with time related to reinforced concrete contaminated by chlorides

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HIGHLIGHTS

- Intensive and long term experimental program on corrosion of reinforced concrete in its propagation phase.
- Controlled and outdoor environmental conditions.
- Database for further numerical studies.
- Mathematical relation of cumulative steel thickness loss with time.
- Reliability in simulating/predicting the corrosion of reinforced concrete and its durability.

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ABSTRACT

Corrosion of chloride contaminated reinforced concretes exposed to outdoor conditions and to six controlled environmental conditions was followed within a five year study. Corrosion was evaluated four times a year performing visual observations (rust, cracks, delamination) and electrochemical measurements from which corrosion rates were calculated. These latter values were converted in cumulative steel thickness loss versus cumulative time in order to propose a mathematical relation for simulating corrosion in the propagation phase. It was found that a mathematical power relation fitted the experimental data better than a linear relation.

1. Introduction

Reinforced concrete is a composite engineering material widely used in the construction industry (buildings, bridges, tunnels, nuclear plants, historical monuments, etc.). One of the major factors responsible for the deterioration of these structures is the corrosion of the reinforcement [1–6] which may result in damages in the form of rust spots, cracking and even delamination of the concrete cover (risk for end-users). In addition, the structural damage may consist in loss of a reinforcement cross-sectional area and loss of bond between reinforcement and concrete, resulting in loss of serviceability and structure safety.

Experimental study of the rebar's corrosion in concrete is a difficult task because of the high number of parameters that are involved [7]. They can be gathered in three interactive groups: (i) concrete states, (ii) environmental conditions and (iii) corrosion tests. Concerning the concrete states, the presence of chloride ions has been extensively studied [8–10] for the determination of the chloride level threshold that initiates corrosion and this is still in discussion today. The concrete formulation also interacts with the corrosion process: Bouteiller have studied the corrosion initiation due to chloride ions on pre-cast components made with either ordinary Portland cement or Portland cement with 70% blast furnace slag [11]. Reinforced concrete specimen size is another relevant parameter [12]. The influence of the environmental conditions (controlled temperature and relative humidity or natural

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weathering) has been studied [13–19]. Moreover, under laboratory control, different authors have studied the corrosion process related to the oxygen content [20–22]. At last, depending on the investigation method, the testing device, the experimental condition (laboratory or in situ), corrosion results can also be difficult to compare [23–29].

Studying the corrosion of rebar in concrete requires electrochemical characterizations that rely upon half-cell potential, resistance or resistivity and linear polarization resistance. For several decades, the civil engineering diagnosis has relied upon half-cell potential mapping [30]. With some care this technique can be used quite successfully to identify areas of the structure which may be suffering from corrosion attack. However it gives no information about the rate at which corrosion may be occurring. The measurement of concrete resistivity is also a qualitative technique [31]. It has been suggested that the presence of a low concrete resistivity in the regions indicated as being actively corroding by half-cell potential mapping can be used as an indicator that the rate of corrosion in probably quite high. The linear polarization resistance (LPR) technique can provide quantitative information on the corrosion rate of reinforcing steel [27]. This technique has seen a growth in popularity in recent years and is beginning to see more widespread use as an effective non-destructive test for the evaluation of reinforced concrete structures at risk for corrosion attack [18,23,25–28,32–38]. When the technique is to be used in situ, there is concern about the variability of measurements and the influence of fluctuations due to environmental conditions.

As reported in the literature [39,40], modelling and/or predicting the durability of reinforced structures highlight the lack of experimental studies dealing with the corrosion in its propagation phase.

The aim of this paper is to propose a mathematical relationship between cumulative steel thickness loss and time, in the propagation phase of the corrosion. Therefore reinforced concretes contaminated by chloride ions (in the mix or by wetting/drying cycles) were exposed to different environmental conditions (controlled and outdoor) and their corrosion was studied during a five year period.

2. Materials and methods

2.1. Concrete states

Reinforced concrete slabs (300 × 300 × 50 mm with 5 parallel rebars) which concrete composition is given in Table 1 had a 30 MPa compressive strength. Water to cement ratio was chosen equal to 0.7 which is of course very high for new constructions but that was usually used decades ago in structures from historical monuments or civil engineering. These ancient structures are the ones that are corroding today. Slabs were casted and/or aged to study three different states. Slabs "T" were sound reinforced concrete (used as reference). Slabs "G" were contaminated with 5% of NaCl by weight of cement added in the mix. Slabs "I" contained chlorides that have penetrated by wetting and drying cycles (salted pond NaCl 35 g/L, during 12 months).

2.2. Reinforced concrete prisms

Specimens of the study were reinforced concrete prisms that were sawed from the slabs described previously (10 prisms per slab). The prisms T, G and I (which dimensions were 150 × 50 × 50 mm) contained a central rebar with an uninsulated steel surface area equal to 18.85 cm^2 (length 100 mm and diameter 6 mm). More details for describing the specimens can be found in [17]. Total [41] and free [42] chloride contents (in g% by weight of cement) were respectively equal to 2.7 and 1.4 for prism n°639-G and to 4.8 and 3.1 for prism n°664-I. For both chloride contaminations, the chloride content was higher than 0.4% by weight of cement (this ratio usually refers to a condition for which corrosion is likely to occur [43]) and therefore rebar's corrosion was considered to be in the propagation phase. Five reinforced concrete prisms per state were exposed to seven environmental conditions meaning a total of 105 studied specimens.

2.3. Environmental conditions

Six controlled environmental conditions were considered based on two temperatures (20 °C and 45 °C) and three relative humidities (60%, 80% and 92%). The outdoor condition consisted in the suburb of Paris where temperature and relative humidity recorded from September 2008 to January 2014 respectively varied within a

Table 1
Concrete composition (kg/m^3).

Cement (CEM I 52.5N CE CP2 NF)								275
Water								192
Palvadeau aggregates	149	277	180	170	57	324	265	473
(size mm)	0/0.315	0.315/1	0.5/1	1/4	2/4	4/8	8/12	12.5/16

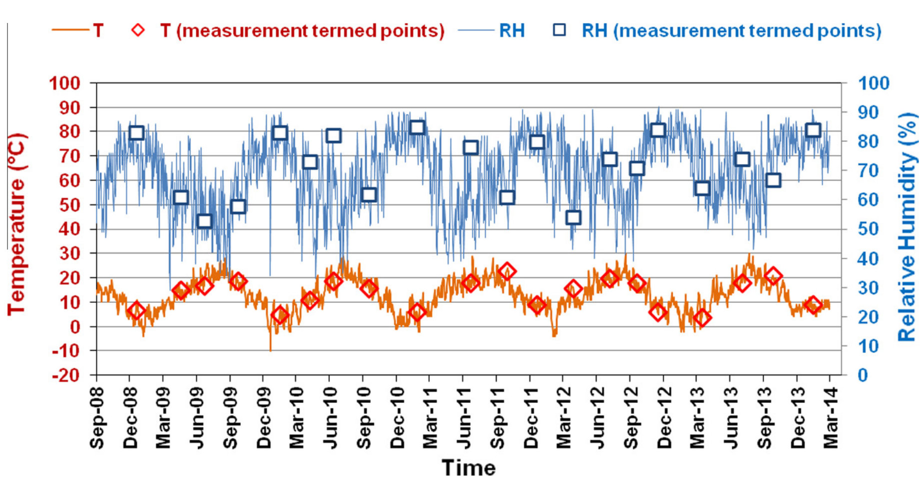

Fig. 1. Temperature and relative humidity values from September 2008 to January 2014 in the suburb of Paris. Temperature and relative humidity at the measurement termed points are also indicated.