Construction and Building Materials 122 (2016) 264–272

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Dimensional factors in oxidation induced fracture in reinforced concrete

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HIGHLIGHTS

- A constant current accelerated corrosion testing program for reinforced concrete was carried out to facilitate modeling of to time to cracking by corrosion.
- The specific aim was to investigate the effect of specimen dimensions, including bar size and concrete sample size.
- A model is proposed that incorporated the size factors and the corrosion current.

ARTICLE INFO

Article history:
Received 25 December 2015
Received in revised form 6 May 2016
Accepted 11 May 2016
Available online 9 July 2016

Keywords:
Concrete
Reinforcing bar
Corrosion
Cracking (fracture)
Durability
Bond
Service life

ABSTRACT

Experiments on reinforced cylindrical concrete elements were carried out studying the influence of specimen size on corrosion of steel reinforcing bars and the extent of cracking of concrete. This work was achieved by accelerated corrosion of reinforced concrete cylinders subject to constant current conditions. Two concrete cylinder and reinforcing bar sizes were used. The effect of cracking on the specimen impedance and corrosion rate was evaluated and a correlation between time to concrete cover cracking and implications on service life was extrapolated. A cracking model as function of time and dimensions of the specimens was developed.

1. Introduction

Fracture of concrete by steel corrosion is known to be the main mechanism of damage in the long term durability of reinforced concrete when exposed to chlorides and acidic environments. The corresponding reduction in the passivation of the steel surface and the reduction in the alkalinity of the concrete pore fluids lead to accelerated corrosion of the reinforcing steel [1,2]. Corrosion of steel by dissolution degrades the composite action in reinforced concrete structural elements, compromising its performance by reducing bond between steel and concrete [3–9,32]. Cracking of concrete in general and by corrosion allows accelerated ingression of water and chlorides and promotes the corrosion and cracking process [31]. It is believed that the appearance of the first crack in reinforced concrete elements is an indicator of the end of its service life [10,11]. Modelling the time to cracking by corrosion is challenging since the corresponding electro-chemo-mechanical processes involve complex interactions and are affected by parameters which vary with time and space across the structure [1,3,10–19].

The modeling of damage by cracking is also challenging. Products of the corrosion process of the reinforcing bar are multi-layered and are composed of several chemical compounds with varying mechanical properties. The exterior layers of oxidized irons have greater access to chloride ions, with high iron to oxygen ratio, and as a result are less expansive [1]. This layer is believed to impede the further ingression of chlorides but not able to impede the ingression of oxygen, creating an inner, more expansive layer of rust, which is caused by a low iron/oxygen ratio. These products of steel corrosion are amorphous, and their bulk properties in the tri-axial state has been difficult to quantify; posing a challenge in the numerical simulation of cracking by corrosion.

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http://dx.doi.org/10.1016/j.conbuildmat.2016.05.077
0950-0618/

Notations

W_{exp}	measured weight loss (g)	D	concrete cylinder diameter
W_{th}	theoretical weight loss (g)	d	reinforcing bar diameter
I	galvanic current (A)	W	original reinforcing bar weight
t	time (s or days)	x_{exp}	measured corrosion penetration
A	atomic weight of iron	x_{th}	theoretical corrosion penetration
Z	valency of the metal	w	measured crack width at the reinforcing bar
F	Faraday constant	$\nu_{r/s}$	ratio of specific volume of rust to steel
i	corrosion current	α	scaling factor

It has been shown that the splitting of concrete and the associated loss of bond strength is not only a function of the degree of corrosion, but is also a function of the size and geometry of the components of the element cross section [10,14,4,20]. Despite significant effort, modeling of expansion forces due to the corrosion process is not fully understood. This report aims to contribute to modeling of corrosion induced cracking in reinforced concrete by subjecting specimens of varying sizes to a constant current accelerated corrosion process.

We have therefore initiated a study in order to investigate: (a) the extent of corrosion as a function of corrosion current, (b) the relation between steel mass loss and cracking of concrete, (c) the effect of size of both concrete cover and reinforcing bar on crack initiation, (d) the effect of cracking on rate of corrosion, (e) the correlation between cover cracking and service life.

A number of concrete cylinder specimens were subjected to accelerated corrosion process by applying direct constant current. A model for cracking based upon the concrete cover to reinforcing bar diameter ratio is also presented. The validation of the model is demonstrated by comparing the predictions with experimental data obtained from this research and from other studies cited in this paper.

Table 1
Specimen dimensions.

Specimens	Dimensions (mm)				
	Cylinder diameter, D	Steel bar diameter, d	Length, L	C	C/d
C_sR_l	102	19	203	41.5	2.18
C_lR_l	152	19	304	66.5	3.50
C_sR_s	102	9.5	203	46	4.87
C_lR_s	152	9.5	304	71	7.50

C = size of concrete cover (D − d)/2

Table 2
Mixture proportions.

Cement	(kg/m^3)	431
Sand	(kg/m^3)	862
Gravel (maximum size 8 mm)	(kg/m^3)	862
Water	(kg/m^3)	194
W/C		0.45
Unit weight	(kg/m^3)	2349

2. Experiment plan

Four dimensional variations were used; the concrete cylinder specimens were 102 mm and 152 mm in diameter, with 203 mm and 304 mm length respectively, with two reinforcing bar diameters of 9.5 mm and 19 mm (Fig. 1 and Table 1). The specimens were labeled C_sR_s, C_sR_l, C_lR_s, and C_lR_l, where (C) and (R) stand for cylinder and reinforcing bar, and the subscripts (s) and (l) represent the specimen size (small or large).

2.1. Mixing, casting and curing of specimens

The concrete mixture was designed for compressive strength average of 40 MPa in 28 days. Table 2 shows the mixture ingredients. At 28 days, the tested average cylindrical compressive strength of the concrete was 39.08 MPa, the average splitting tensile strength was 4.28 MPa, and the average elastic modulus was 28.34 GPa. Grade 60 reinforcing steel bars were used with a tested average yield strength 413.7 MPa.

The concrete was cast vertically in plastic molds with reinforcing steel positioned as shown in Fig. 1. A table vibrator was used for compaction. Twenty four hours after the casting, the plastic molds were removed and the concrete was cured in a steam room at 20 °C and 95% relative humidity for 28 days. In order to create an axisymmetric condition with respect to mass and ion transport, epoxy resin and silicon adhesive was applied to the end surfaces of the reinforcing bar and concrete cylinders respectively.

2.2. Corrosion test apparatus and galvanic current measurements

Fig. 3 shows the series of electrochemical cells prepared for the accelerated corrosion testing. Four specimens in each size ratio were cast, resulting in total 16 specimens; four each corresponding to four target levels of corrosion of 2.5%, 5%,

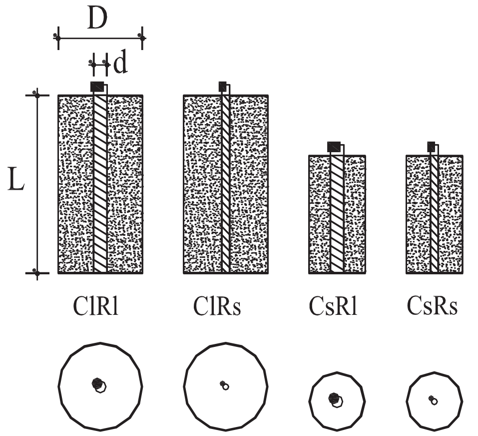

Fig. 1. Specimen name designation.

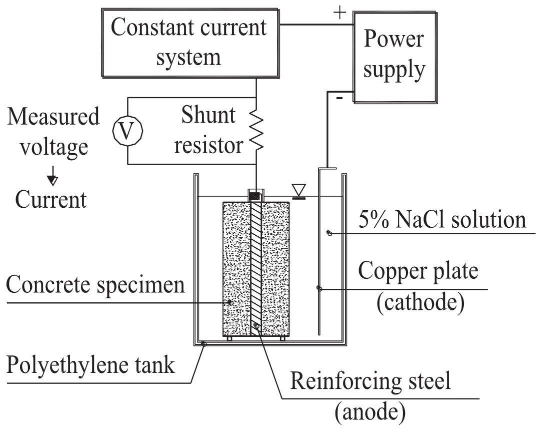

Fig. 2. Accelerated corrosion setup.