Construction and Building Materials 160 (2018) 450–461

Contents lists available at ScienceDirect

Construction and Building Materials

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

Basic mechanical behaviours and deterioration mechanism of RC beams under chloride-sulphate environment

Jun-hua Wang [a], Gaochuang Cai [b,c,*], Qing Wu [d]

[a] College of Civil Engineering, Nanjing Tech University, Nanjing, Jiangsu 211800, China
[b] Magnel Laboratory for Concrete Research, Ghent University, Technologiepark Zwijnaarde 904, Ghent 9000, Belgium
[c] School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, UK
[d] School of Architecture and Civil Engineering, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu 212003, China

HIGHLIGHTS

- The mechanical behaviors of RC beams under chloride-sulphate ions were experimentally studied.
- The relationship between structural behaviour of RC beams and corrosion degrees of concrete and steel bars was discussed.
- The deterioration mechanism of RC beams under chloride-sulphate ions was discussed.

ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 5 September 2017
Accepted 17 November 2017
Available online 21 November 2017

Keywords:
Chloride–sulphate irons
Corrosion–damaged steel bar
Mechanical behaviour
Deterioration mechanism

ABSTRACT

This paper investigates the basic mechanical behaviour of reinforced concrete (RC) beams using chloride corrosion-damaged steel reinforcements and subjected to sulphate ions environment. To this end, ten RC beams were studied which contained 5% sodium chloride and implemented by a series of drying-immersion cycling (15% sodium sulphate immersion solution). Test results indicated that the flexural capacity, ductility, and stiffness of the beams were improved at early stage of the corrosion. This was attributed to the fact that concrete strength and steel-concrete interfacial bond were enhanced. The former is for the filling effects of micro-expansive Ettringite and gypsum sulphate, while the latter is due to the slight surface corrosion pits of steel bars at the stage. However, the mechanical properties of the beams decreased subsequently for the deteriorations in the concrete strength due to excessive expansion of Ettringite and gypsum sulphate, and the degradation of self-property of reinforcement and its interface bond with the concrete. Based on the study, the deterioration mechanism of RC beams under chloride-sulphate environment was discussed and its main determining factors at different stages were analysed.

1. Introduction

The durability property of concrete structures is of a great major concern for the construction industry worldwide. It is well known that the corrosion of reinforcing steel rebar accelerates the deterioration of durability and mechanical properties of reinforced concrete (RC) structures, which mostly caused by the attack of chlorine ions. Chloride ions in concrete are simply divided into two types depending on how they are introduced into concrete, include (i) mix-in type chloride such as the ones in concrete using chloride-contaminated compositions or admixtures, and (ii) diffusion-in type chloride such as the ones in the concretes exposed under chloride-rich environment. After having entered concrete, chloride ions generally exist in two states, *i.e.,* free chloride ions in internal pore solution and bonded chloride ions in hydration products. The former is one of the main reasons why steel reinforcements deteriorate in concrete for it can easily move to the surface of the reinforcements, while the latter may cause some instable issues of concrete when other aggressive ions appear simultaneously such as sulphate ions. The corrosion rate of steel rebars in concrete is mainly determined by the accumulation concentration of chloride ion in steel surface and the available amount of oxygen and water. The corrosion rate can be described as a function of destroying rate of the surface passive film of steel rebars. The passive film of steel is thin and compact and usually formed in an electrolytic pore solution through releasing iron ions. The destruction of the film could result in an acceleration in corrosion

* Corresponding author at: Ghent University, Technologiepark Zwijnaarde 904, Ghent B-9052, Belgium.
E-mail addresses: wangjunhua@njtech.edu.cn (J.-h. Wang), gaochuang.cai@ugent.be, G.Cai@qub.ac.uk (G. Cai).

https://doi.org/10.1016/j.conbuildmat.2017.11.092
0950-0618/

of steel rebars which then leads to the volumetric increase of steel rebars. This will cause cracking or spalling of concrete surrounding corroded steel and the decrease of the mechanical properties of steel rebar itself which then affects significantly the structural performance of RC elements. Through a series of experimental studies, the mechanical behaviours of corrosion-damaged steel rebars and the structural performances of the concrete members using the corroded rebars have been sufficiently investigated. It was reported an obvious decrease was observed in bond strength between concrete and corrosion-damage steel rebar when the corrosion level of steel reinforcement was in medium range (4–6%, mass loss) [1,2]. Alonso et al. [3] and Castel et al. [4] reported that the corrosion rate of steel reinforcement has a significant influence on the volumetric changes of steel rebars. The degradation in mechanical behaviours of corroded RC beams is determined by the self-strength deterioration of steel reinforcement and steel-concrete interface bond as well as effective cross-section of steel rebars [5,6].

On the other hand, most of the studies on the concrete elements subjected to sulphate environment concerned their material performance such as compressive strength of concrete. In the early stage of corrosion, the sulphate ions diffuse into cover concrete leading generally to an increase in the weight and strength of concrete [7,8], such as the surface hardness of concrete for the enhancement effect of some new productions such as Delayed Ettringite and gypsum [9,10]. Accompanying with further corrosion at later stage, however, the strength degradation of concrete may be induced by the more internal damages such as cracking caused by larger expansion force caused by more Ettringite and gypsum [7–10], which led to more durability issues.

In addition, in case that RC structures are under more aggressive environment, the combined attack action of chloride irons and sulphate ions may happen as well. For example, some marine RC structures such as bay bridges or the structures near salt lake which has high consternation chloride ions and sulphate ions both. Furthermore, it was reported that the variations in temperature and humidity also influence the deterioration process of the structures which results in severe durability issue only after few years [11]. In the marine environment, the concentration of sulphate ion varies from 2800 mg/L to 3000 mg/L [14] which is a moderate corrosion degree to concrete structures per Chinese code [12]. When sulphate ions penetrate into concrete, they reacted with the solution of calcium hydroxide to form a micro-expansive Delayed Ettringite [13]. If the expansive Delayed Ettringite extends to the boundaries of internal voids, an expansion force may occur to its surrounding cement paste which then leads to an increasing growth of micro-cracks. The micro-cracks accelerate certainly the diffusion rate of chloride ions in concrete resulting in a faster corrosion of reinforcing steel rebars [14].

Even although a number of studies have been performed regarding concrete deterioration caused by sulphate irons or reinforcement corrosion induced by chloride ions, the deterioration mechanism of RC elements in the combined corrosion actions is more complex, compared to the cases under a single corrosion ion environment. For instance, several experimental studies [15–19] demonstrated that the diffusion of sulphate ions in concrete is reduced when chloride ions appear in the concrete.

However, up to now limited studies have been published to research the mechanical performance of RC structural members attacked by chloride irons and sulphate irons both. Therefore, this study aims to investigate the influence of corrosion-damaged reinforcements and corroded concrete on mechanical behaviours of RC beams due to the combined attacks of chloride and sulphate irons. The failure mode of test beams, the stiffness, ductility and bearing capacity of the beam are investigated in detail with different corrosion ratio of steel reinforcement and concrete.

2. Test program

In order to investigate the mechanical behaviours of RC beams with corrosion-damage steel reinforcement caused by chloride ions in sulphate solution environment, ten RC beams were constructed containing 5% sodium chloride which was to introduce the corrosion of steel rebars. The different corrosion ratio of concrete was attained by drying and immersion cycles in 15% sodium sulphate solution, which was to simulate the corrosion of concrete subjected to sulphate ions.

2.1. Details of specimens

Fig. 1 illustrates the reinforcement arrangement and dimension of representative specimens, while Table 1 lists the details of all test specimens. The corrosion of concrete was simulated by a series of drying-immersing cycles in sodium sulphate solution up to 150 days. The overall depth (H) and width (B) of cross sections of all beams were 200 mm and 150 mm respectively, and the length of the beams was 1500 mm. Two deformed steel rebars (HRB 335) with a diameter of 20 mm (D20) were used as the longitudinal tensile steel rebars of the specimens, while two HRB 335 steel rebars with a diameter of 10 mm (D10) were applied as top longitudinal reinforcing rebars. Deformed steel rebars (HRB235, Diameter = 6 mm) were used as transverse stirrups in the beams with a spacing of 150 mm. All test beams were divided into two series named A-x and B-x respectively depending on shear span ratio. There were five test beams with five corrosion levels according to their different drying-immersion corrosion days in each series.

2.2. Materials and specimen manufacture

The concretes of all specimens were supplied by a local ready-mix concrete plant. The water content and cement content per unit volume of the concretes were 340 kg/m^3 and 763 kg/m^3 respectively. The amount of coarse aggregates (maximum gross diameter of 30 mm) and fine aggregates in the concrete were 2140 kg/m^3 and 763 kg/m^3, respectively. According to previous research conducted by one of the authors [20], the corrosion damage of steel reinforcement of concrete member immersed in sodium chloride solution was similar to the ones in the case that the reinforcements in concrete beams mixed with sodium chloride and implemented by drying-wetting cycles. Therefore, 38 kg/m^3 sodium chloride was used in the concretes as the test beams were cast. The beam specimens and three concrete cubes (100 mm × 100 mm × 100 mm) were cast simultaneously and cured covering wet burlaps for a week and then were cured in a natural environment. The 28-day compressive strength of concretes without corrosion was 28.3 MPa which was the average value of measured strengths of three concrete cubes.

The yielding and ultimate strengths of the used HRB335 steel rebars (D20) are 391 MPa and 435 MPa, respectively. The applied HRB 235 steel rebars (diameter = 6 mm) have a yielding strength of 246 MPa and an ultimate tensile strength of 304 MPa. According to current Chinese code [21] and sectional analysis of the specimens A-0 and B-0, the design flexural/shear strength ratios of the beams are 1.22 and 1.75, respectively, meaning that the design failure mode of the test beams without corrosion was shear failure.

2.3. Accelerated corrosion method

In order to simulate the corrosion process of concrete beams under the combined action of chloride and sulphate ions, all beams containing 5% sodium chloride were subjected to a series of