Cement & Concrete Composites 60 (2015) 34–43

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Development length of steel reinforcement with corrosion protection cementitious coatings

Xiaofei Pei, Martin Noël*, Amir Fam, Mark Green

Department of Civil Engineering, Queen's University, 58 University Ave., Kingston, ON K7L 3N6, Canada

ARTICLE INFO

Article history:
Received 20 January 2015
Accepted 5 April 2015
Available online 9 April 2015

Keywords:
Concrete
Corrosion
Coating
Reinforcement
Bond
Development length

ABSTRACT

The bond strength and development length of steel reinforcing bars coated with cementitious capillary crystalline waterproofing materials were evaluated using a modified pull-out test method. The coatings possess self-healing capabilities and are characterized by a novel eka-molecular sieve type structure to prevent moisture penetration. Following a study on corrosion protection, in which the coating showed a great promise, it was decided to investigate the effect of the coating on bond strength. A self-reacting inverted T-shaped beam was designed to simulate the stress conditions of flexural structural members. Six T-beams were fabricated, each of which contained eight rebar test samples. Tests were conducted at approximately seven days and at three months after casting to investigate curing effect on bond. Although the bond strength of the coated samples were reduced compared with the uncoated bars, theoretical development lengths obtained from current concrete design code equations were sufficient to reach the yield strength of the bars.

1. Introduction

The deterioration of concrete structures due to the corrosion of reinforcing steel is currently a major concern in North America. A recent report indicates that about 11% of bridges in the USA are structurally deficient and need repair [1]. In Canada, more than 40% of bridges are over 40 years old and the total maintenance or rehabilitation cost is estimated at $10 billion [2]. Corrosion-resistant alternatives to conventional steel reinforcement such as epoxy-coated reinforcing steel, stainless steel and MMFX steel, have been used to varying levels of success and each possess their own set of drawbacks.

Epoxy-coated reinforcement was developed in the early 1970s in North America. Epoxy resin works as a protective film and electrical insulator coating the surface of reinforcing steel. One of the main difficulties associated with the application of epoxy-coated reinforcement is the cracking of the coating at bends in the bar and damage during transportation and handling [3]. Localized pitting corrosion at the location of damage or defects in the coating layer can cause a significant reduction in strength; damage to the coating layer comprising less than 2% of the rebar surface area has been reported to greatly detriment structural performance compared with uncoated bars [4]. Research studies have also indicated that perfect coating is not achievable in practice [3].

In addition to durability issues, approximately 35% and 25% reductions in bond strength compared with uncoated bars have been reported for splitting failure and pullout failure modes, respectively [5]. The CSA A23.3 Concrete Design Code increases the design development length by a factor of up to 1.5 for epoxy-coated reinforcing steel [6].

Unlike epoxy, the cementitious capillary crystalline waterproofing (CCCW) material used in this study (CN2000 B) has demonstrated self-healing capabilities [7] and therefore may not be susceptible to similar durability issues. In the presence of moisture, the coating material may be able to engage in a continuous hydration reaction and propagate into the concrete matrix [8,9]. A previous study has demonstrated the excellent corrosion protection provided by these coating materials, which can be applied either to the interior or exterior concrete surface or directly onto the rebar [10]. Fig. 1 shows the variation of half-cell potential with time which reflects the probability of corrosion activity, for the case of coating applied directly to the bars, compared to uncoated control steel bars. The behaviour shows the enhanced corrosion protection provided by the coatings, which delayed the time to reach the active corrosion limit by approximately 50–150%. Based on the success achieved with respect to corrosion protection, it was natural to investigate the effect of rebar coating on bond strength.

---

* Corresponding author. Tel.: +1 519 588 3124.
E-mail addresses: martin.noel@queensu.ca (M. Noël), fam@civil.queensu.ca (A. Fam), greenm@civil.queensu.ca (M. Green).

http://dx.doi.org/10.1016/j.cemconcomp.2015.04.003
0958-9465/

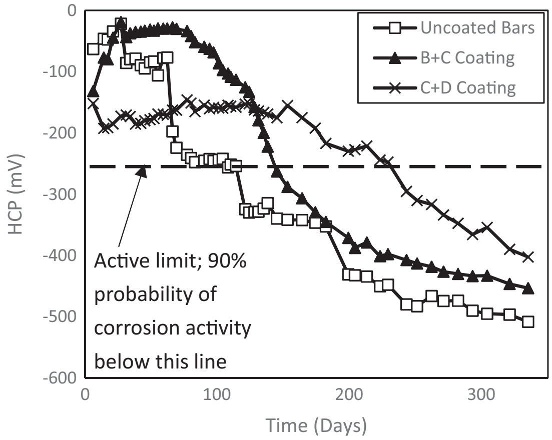

Fig. 1. Average half-cell potential indicating time to corrosion activity for coated reinforcing bars.

The research program described herein focused on the bond strength of reinforcing steel coated with CCCW materials commercially known as CN2000. CCCW coating B is a rigid cementitious coating material with breathing and waterproofing abilities which could react with moisture to penetrate into the concrete matrix [7]. CCCW coating C is a polymer/latex material with a high elastic range that provides some flexibility to the coating. CCCW coating D is a cement-based material which reacts with CCCW coating C to form a flexible membrane [11]. Based on the results of previous research investigating the corrosion mitigation capabilities of various coatings [10], two combinations of coating material were selected for use in this study, namely CCCW coatings B+C and C+D. Both short term (7 days) and long term (3 months) effects of exposure to moisture on the bond behaviour of the coatings were investigated in these tests. A total of 48 pull-out tests were conducted.

CCCW coating materials have been used in a variety of projects around the world and have demonstrated excellent sealing and anti-corrosion capabilities. One of the most important characteristics of CN2000 coating materials is their self-healing ability [7–9]. Compared with other coating materials, such as epoxy, this characteristic could eliminate durability issues associated with improper application or damage during construction. Previous research has shown that CCCW coating B+C and CCCW coating C+D can mitigate corrosion of steel reinforcement when applied either on the exterior concrete surface or directly on the reinforcing steel bars [10]. The primary objective of this paper then is to investigate the effect of coating the bars on the bond strength between the rebar and concrete and on the development length.

2. Experimental program

2.1. Specimen design and fabrication

The most popular and commonly used test methods to assess the bond strength of internal reinforcement are beam-end tests and pull-out tests. Beam-end tests have the advantage of realistically simulating the stress distribution in a reinforced concrete flexural member, yet they require a complex test setup and are relatively expensive to conduct. Conventional pull-out tests, on the other hand, are simple to conduct but misrepresent realistic conditions by inducing compressive stresses in the concrete surrounding the bars which artificially enhance the bond strength, leading to unconservative results.

A modified pull-out test was employed for this project which combines the advantages of both beam-end and conventional pull-out tests. This test was designed to simulate the bond failure mode of the tensile reinforcing steel in flexural members and to eliminate compressive stresses in the concrete in the vicinity of the reinforcing bar being tested. Self-reacting inverted T-shaped concrete beams were designed to satisfy the test requirements so that the steel test frame would bear directly against the bottom flange of the concrete beam placing the entire web of the T-beam in tension (Figs. 2 and 3). This ensures that the concrete around the reinforcing bar is in tension as is the case in practice.

The design concrete strength, f_c', in this test was 40 MPa and the design yield strength of the reinforcing steel, f_y, was 400 MPa. High-early strength cement was used for the concrete. Two different diameter reinforcing bars were tested which were CSA 15M and 25M. The bars to be tested were embedded in the vertical webs of the T-beams at various embedment lengths (Fig. 2). In total, six T-shaped beams were fabricated and each one contained eight test samples.

Prior to the fabrication of the T-beams, one end of each rebar sample was sand blasted to white metal and coated with CCCW coating material (Fig. 4). For coating CCCW coating B+C, the mix quantities were 500 ml water and 1 kg CCCW coating B for every 1.5 kg of CCCW coating C. Coating type C+D used a mix ratio of 1 kg CCCW coating C for every 1 kg of CCCW coating D. The coatings were applied in a single layer by dipping the bars in the coating material and then shaking 20 times to obtain a uniformly distributed film.

The concrete forms were made from plywood with vertical stiffeners to prevent bulging. The concrete pour was completed in two phases to simplify the design of the formwork. Nominal 30 MPa concrete was used for the base portion of the beams poured during the first phase. The web portions of the beams were poured one month later; nominal 40 MPa concrete was used for the second phase and the slump before the pour was approximately 200 mm. To ensure proper consolidation, the concrete was poured only halfway to the height of the web portion and then vibrated using an electric vibrator. Following vibration of the first lift, the second half of the concrete was poured and vibrated.

The web portion of the T-beams had a height of either 1300 mm or 500 mm to accommodate the various embedment lengths. The web width of the T-beams was 200 mm and was reinforced with 15M vertical stirrups at a spacing of 90 mm to prevent the formation of wide horizontal concrete cracks during testing. The reinforcing test bars were placed near one face of the web of the T-section with a clear cover of 38 mm similar to the provisions of the ASTM A944 standard test method for beam-end bond tests [12]; the eccentric loading creates a slight stress gradient in the web similar to a flexural member in bending while the limited cover allows the bond strength to be governed by splitting of the concrete cover as is typically the case in beams. The reinforcing steel bars were staggered from side to side along the web at a horizontal spacing of 300 mm to prevent any interactive effects between consecutive tests (Fig. 2). The orientation and cover of the reinforcing bars were carefully controlled to minimize any misalignment or variation in the concrete cover. Bond breakers consisting of PVC tubes were used to debond a 50 mm length at the loaded end of each pullout bar (Fig. 2).

A steel frame was designed to complete the self-reacting test setup. A hydraulic cylinder was placed on top of the steel frame to apply the load and a steel coupler was used as a gripping device for the steel bars (Fig. 3). Thirty-two pullout tests from four T-beams were conducted after one week of curing. The remaining two beams, which consisted of a total of 16 test samples (15M bars), were covered with plastic film and water cured continuously for three months prior to testing.