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Effect of heating rate on bond failure of rebars into concrete using polymer adhesives to simulate exposure to fire

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ABSTRACT

The high bonding capacity of polymer adhesives has encouraged their application for anchoring steel bars into concrete for structural purposes. However, high temperatures have the effect of weakening the bond and endangering the construction under a fire situation. This paper evaluates bond resistance to temperature by means of pull-out tests performed with a constant tensile load on the steel bar and a progressive temperature increase of the bond throughout the test until a failure temperature is reached. Two testing programs were performed using separate heating technologies: electric oven and gas furnace, which mainly differ by their heating speed, in order to assess the influence on bond failure at high temperature. The study describes thermal characteristics and phenomena such as vaporization in different concrete zones near the anchor in both of the testing devices (electric and gas).

1. Introduction

Polymer adhesives are increasingly used as bonding materials for structural elements in construction. Epoxy resins were developed in the 1940s [1] and early research was performed in the 1960s on the load bearing capacity of these resins in order to provide engineering data for construction guides for structural applications [2] by studying deformation under static load, behavior under cyclical stressing and the effect of environmental factors such as moisture and limited thermal variations (0–50 °C) [3]. Among many applications such as joining of precast concrete elements, bonding of old and new concrete, polymer resins are used to bond steel rods into already existing reinforced concrete slabs for reparation or renovation purposes. Design documentation has been established in order to reach the same level of safety between cast-in rebars and post-installed rebars at a service temperature of 23 °C[4]. Previous tests have shown that concrete/steel bonds using adhesives such as epoxy resin tend to have larger bond strength than mechanical anchors (concrete/steel bond) at a service temperature of 23 °C [5].

Different tests (such as Fourier transform infrared spectroscopy, differential scanning calorimetry, thermo gravimetric analysis, moisture sorption analysis and dynamic mechanical thermal analysis) have been performed on epoxy resin products to assess their thermal, hygroscopic and mechanical characteristics [6]. Tests generally show a decrease of the polymer's modulus with an increase of temperature during the glass transition. This evolution of mechanical properties of the resin itself leads to a decrease in the load bearing capacity of the bond. Studies performed on bond strength after exposing the specimen to high temperatures and cooling it back to laboratory temperature before performing a pull out test show that the residual bond strength decreases when the temperature and exposure time increase and is influenced by parameters such as the cooling speed, resin components or the type of concrete [7–8]. Spalling of concrete at high temperatures and thermal expansion between bonded materials also contribute to bond weakening after heating [9]. The temperature increase rate in these tests is between 10 and 30 °C/min with exposure temperatures reaching 700 °C. Yet, a lack of testing campaigns with both thermal loading and pull-out being performed simultaneously remains today. Residual tests do not describe the load bearing capacity in a fire situation mainly due to the significant variations of the resin's mechanical proprieties with temperature increase. Little technical documentation and regulation exists concerning the assessment of a chemical anchor's load bearing capacity in a simulated fire situation. Thus, a testing procedure in a heated environment must be established in order to describe a resin's behavior along a bond presenting a temperature gradient to evaluate its mechanical capacities and establish anchor sizing to ensure the structural integrity of the bond in a burning construction for a given time before collapse. The testing procedure's representative character regarding fire

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simulation must be questioned; particularly the influence of heating rate, technology and thermal flux direction for heating the bond must be studied.

The goal of this paper is to study the influence of heating technology on the results of pull-out tests performed at high temperature on specimens including a steel rod anchored in a concrete cylinder with epoxy and vinyl resins. Two series of tests were carried out using on one hand an electric oven with a heating rate close to the ones used in the residual tests above: (of about 10 °C/min) and on the other hand, a gas furnace with a much faster heating rate following the ISO-834 [10] curve (of about 300 °C/min at the beginning) which is normally used for fire simulation tests. Experimentation was performed to evaluate how each heating technology affects bond failure results and to assess the thermal loading differences.

2. Materials and experimental procedure

2.1. Specimen

A 12 mm diameter Diwidag type rebar was anchored in a concrete cylinder (16 cm diameter, 25 cm height) bordered by a 2 mm thick steel layer to avoid cracks on the exterior lateral side of the cylinder (Fig. 1). The concrete specimens had a compressive strength that ranged between 20 and 24 MPa throughout the testing campaign; each strength was determined by averaging three compressive tests performed on the cylinders. The cylinders used for testing had been cured several months in laboratory conditions (after a curing of 28 days at ambient temperature and moisture). The anchor hole was drilled in the hardened concrete a few days before the pull-out test and cleaned according to the resin supplier's indications. The resin was then injected in order to bond the rebar. The anchor was 12 cm deep in the axial direction with a diameter of 16 mm. Two thermocouples were placed on the rebar in the embedded part: at the deepest part of the anchor (TC1) and at 1 cm from the concrete surface (TC2).

Table 1 presents the general information given by the manufacturers on the four resins.

2.2. Pull-out test

The pull-out tests were performed in a heated environment by applying a tensile load to the rebar with a hollow jack while maintaining the concrete cylinder in the electric oven or gas furnace. The tensile load was applied before heating and kept constant throughout the test while the specimen was progressively heated

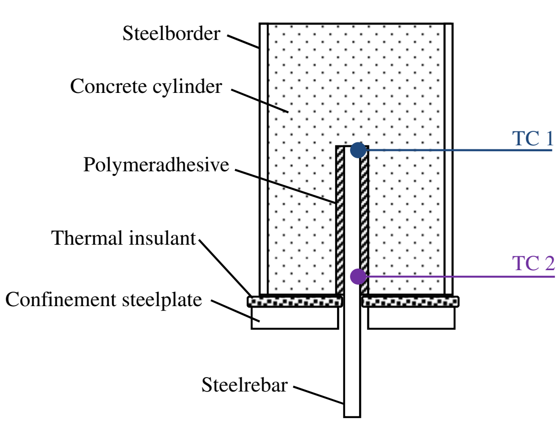

Fig. 1. Test specimen.

Table 1
Resin information.

Resin	Type	Full cure time at 20 °C	Bond strength at 20 °C
R1	Vinyl ester	110 mins	18 MPa
R2	Epoxy	16 h	20 MPa
R3	Epoxy	12 h	
R4	Urethane methacrylate	90 mins	

up to a failure point determined by the debonding of the steel bar. A load cell and displacement sensor were situated on the jack in order to check that the load remained constant and to identify the precise pull-out time. The resin temperatures (given by TC1 and TC2) were measured throughout the test in addition to the oven/furnace temperatures given by thermocouples placed in the heating devices and for which the positions are presented on Figs. 2 and 3. For a given applied tensile load, the pull-out failure load was associated to TCm (mean value of TC1 and TC2 temperatures). For each resin, tests were performed at different loads (ranging from 4 to 60 kN) in order to evaluate bond failure temperatures for different levels of loads.

2.3. Heating device and procedure

A cylindrical electric oven has first been used (Fig. 2). This oven is equipped with 3 rings of resistance element heaters on its lateral sides. The difference between bottom and top temperatures given by the oven thermocouples next to the resistances was less than 5 °C. The thermal loading applied with this oven consisted of a regular heating at a slow rate (generally 20 °C/min, unless mentioned in the text) up to 750 °C after which the target temperature was maintained until failure of the bond.

A rectangular shaped gas furnace has also been used (Fig. 3). It is equipped with 8 gas burners located four by four at mid height on two lateral faces of the furnace. In this case the temperature distribution is much heterogeneous than with the electric oven. The temperature difference between the thermocouples placed on the lateral faces inside the furnace, at the same height, can reach 100 °C. Only one half of the furnace was used to test a specimen. This furnace allows the application of a much higher heating rate than the electric oven (about 300 °C/min at the beginning of the heating process). A heating curve following the ISO 834 [10] curve used in normalized tests to simulate fires in buildings has been applied with this device.

For practical reasons, the anchor is oriented downwards in the electric heating test with the jack located beneath the oven. In the gas heating device, the specimen is placed in the opposite direction and the anchor is oriented upwards with the pull out jack on top of the furnace.

2.4. Control and acquisition

In the electric device, the jack was regulated automatically to maintain the tensile load. The acquisition of temperatures and jack displacement were performed every 5 s giving a relatively precise time and temperature interval in which the bond failure occurred.

In the gas device, the jack and the temperature were regulated manually and the acquisition of temperatures and displacement was performed every 30 s. Due to the higher acquisition interval and to the faster temperature increase on the anchor, the uncertainty on the failure temperature was much higher with the gas furnace. The jack's displacement curves varied in a greater manner from one test to another; sometimes the rebar progressively slipped by about