Construction and Building Materials 105 (2016) 113–122

Contents lists available at ScienceDirect

Construction and Building Materials

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

Residual performance of concrete–adhesive interface at elevated temperatures

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HIGHLIGHTS

- The interfacial behavior of adhesive–concrete members is examined when exposed to elevated temperatures.
- Residual thermal-responses are characterized at material- and structure-levels.
- Performance-based design of concrete–adhesive interface subjected to thermal loading is proposed.

ARTICLE INFO

Article history:
Received 18 April 2015
Received in revised form 4 September 2015
Accepted 5 December 2015
Available online 17 December 2015

Keywords:
Bond
Degradation
Elevated temperature
Interface
Performance-based design
Thermal

ABSTRACT

This paper presents a two-phase experimental program to evaluate the performance of concrete–adhesive interface subjected to thermally-induced distress, including material- and interface-level investigations. Elevated temperatures ranging from 25 °C to 200 °C are applied to three adhesive types (i.e., low viscosity, high viscosity, and high temperature epoxies). The residual thermal behavior of these epoxies and corresponding concrete–adhesive interface is characterized by various test methods such as dynamic mechanical analysis (ASTM D7028), dynamic elastic modulus test (ASTM C215), and bending test (ASTM C78). With an increasing temperature, the resonant frequency and dynamic modulus of the concrete–adhesive interface decrease due to the physical softening of the adhesive layer. Strength recovery is observed with a change in adhesive-morphology when the applied thermal load disappears, while such an effect is not pronounced for the high temperature adhesive. Thermomechanical observations indicate that the deformability and stiffness-softening of the concrete–adhesive interface tend to augment at elevated temperatures, and the failure of the interface is controlled by material cohesion rather than adhesion. Technical recommendations are proposed towards the performance-based design of concrete–adhesive interface subjected to temperature load.

1. Introduction

Fire hazards are one of the most important issues for constructed facilities. A recent statistical survey reports that there were 1.4 million fire cases in the United States in 2011, entailing an estimated loss of $11.7 billion in property and over 17,500 injuries [1]. The majority of design codes are based on prescriptive language to warrant the stability of structural members in fire, while an alternative approach called performance-based design has been emerging to overcome the limitation of the conventional design approach [2]. Numerous research programs have been carried out on the behavior of reinforced concrete members exposed to fire and literature-survey papers were reported [2–4]. The post-fire behavior of structural members is as crucial as their during-fire behavior in many aspects. The reason is that a structural system having experienced moderate fire damage can continuously be used with necessary technical action, thereby avoiding costly demolition and reconstruction. It is accordingly imperative to understand the residual performance of structural components subjected to thermally-induced distress.

Structural adhesives are frequently used for concrete structures. Chemical and physical compositions of polymeric adhesives are vital considerations, provided that they influence rheological and temperature-dependent responses [5,6]. The integrity of concrete–adhesive interface needs particular attention when subjected to elevated temperatures because the adhesive material may experience significant changes in mechanical properties and hence the degradation of the interface performance is accompanied. Tu and Kruger [7] examined the effect of temperature on the performance

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http://dx.doi.org/10.1016/j.conbuildmat.2015.12.014
0950-0618/

of structural adhesives bonded to concrete. Adequately cured adhesives showed good creep resistance due to rigid molecular chains; however, temperature exposure altered their long-term behavior. Two types of failure modes were noticed depending upon substrate conditions: (i) cohesion failure within the adhesive layer when bonded to fully cured concrete and (ii) adhesion failure along the bond line when bonded to uncured concrete. Moussa et al. [8] studied the thermomechanical recovery of an epoxy exposed to elevated temperatures up to 150 °C. Adhesive coupons were made and thermally conditioned. After achieving predefined temperature levels, the specimens cooled down for a tension test. Experimental observations encompassed that the residual mechanical properties of the conditioned adhesives were similar to those of control specimens and some post-curing effects were noticed. Despite these research endeavors, limited information is available in published literature as to the effect of adhesive characteristics on the thermal response of the concrete–adhesive interface and corresponding design guidelines. A systematic study is required to shift prescriptive design approaches towards performance-based design, including refined design parameters. This paper presents an experimental study examining the residual behavior of concrete–adhesive interface subjected to elevated temperatures along with various polymeric adhesive characteristics. The research was comprised of two segments: material characterization and interfacial performance, leading to the development of design recommendations.

2. Research significance

The vulnerability of concrete–adhesive interface subjected to a fire is a critical factor in many circumstances such as epoxy-based anchoring to concrete and plate-bonding for structural rehabilitation. The physicochemical behavior of adhesives is complex and especially challenging at elevated temperatures because of changes in their microstructural properties (e.g., polymer cross-links). Fire is a potential hazard to all existing structures whose integrity needs to be maintained in any cases without collapse. It is, therefore, important to consider acceptable structural performance for pre-, during- and post-fire events when structural members are designed. Fundamental fire protection is provided by an insulation material that will retard heat transfer for a reasonable time period within the range of design fire (e.g., ISO/TE-16733 [9]) and thus the structural member in a fire may not experience as high temperature as its surrounding environment. Various insulation systems are available for fire protection, including non-combustible and non-flammable materials [10]. In this paper, the effect of elevated temperatures from a material-level perspective was first evaluated to understand the residual behavior of various types of structural adhesives frequently used for concrete application. An interface-level investigation was then conducted to study the thermal behavior of concrete–adhesive interface, including interfacial capacity and failure mode which would then be employed for proposing performance-based design factors.

3. Experimental program

The experimental program of the present research encompassed 21 concrete cylinders, 70 epoxy coupons, and 72 interface test specimens bonded with three different types of adhesives subjected to elevated temperatures. Following is a description of materials, specimen preparation, thermal exposure, and test approaches.

3.1. Materials

Concrete was designed to have a specified compressive strength of 40 MPa, while cylinder tests at 28 days revealed an average strength of 42 MPa. Three kinds of epoxy adhesives were selected: low viscosity (LV), high viscosity (HV), and high temperature (HT) epoxies. It is worth noting that low- and high-viscosity adhesives are frequently used in practice, while high temperature epoxies are limitedly used (but still promising) and hence comparative investigations are needed from thermomechanical standpoints. The LV adhesive is a two-part product consisting of a resin and a hardener to be mixed at 100:34 by weight, respectively, and stirred until a homogeneous mixture is obtained. According to the manufacturer, the following properties are available: viscosity at 25 °C = 1350 cps, ultimate strength in tension = 55.2 MPa, elastic modulus = 3034 MPa, Poisson's ratio = 0.4, and glass transition temperature = 71 °C. The HV epoxy is solvent-free and also mixed with two components. Unlike the previous adhesive, it is contained in a special plastic cartridge with a mixing nozzle and hence a mixture is spontaneously acquired when squeezing the cartridge with a dedicated caulking gun. Typical curing time is 24 h at room temperature. Because this adhesive has been developed for steel anchors embedded inside concrete, specific material properties of the adhesive itself are not reported by the manufacturer (only anchorage strength is available in the manufacturer's document). The HT adhesive is suitable to structural bonding for high temperature application. It includes a high temperature service hardener and is stirred with two parts as in the case of other epoxies at a ratio of 100:22 (resin and hardener) by weight. Typical material properties are: viscosity at 25 °C = 500 cps, laminate tensile strength = 213 MPa, tensile modulus = 374 MPa, and glass transition temperature = 170 °C. For material characterization at elevated temperatures, dog-bone coupons were made with individual adhesives: 100 mm long × 5 mm wide × 10 mm thick, as shown in Fig. 1.

3.2. Test specimens and thermal exposure

Concrete blocks were cast for interface testing, including dimensions of approximately 400 mm long × 100 mm wide × 80 mm thick per specimen (two blocks) as shown in Fig. 2(a). Upon curing of the concrete after 28 days of casting, each specimen was bonded with the foregoing adhesives and cured as per the manufacturers' recommendations. It should be noted that the surface of the adherend

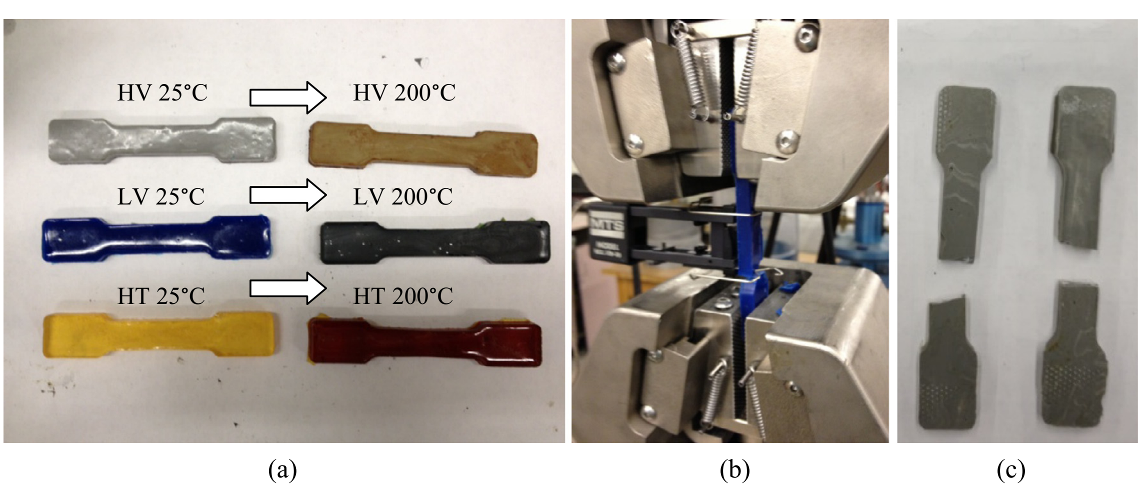

Fig. 1. Adhesive test: (a) adhesive coupons before and after thermal exposure; (b) tension test; (c) failure of HV epoxy coupons exposed to 100 °C.