International Journal of Adhesion & Adhesives 71 (2016) 10–22

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

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

An anchorage system for CFRP strips bonded to thermally shocked concrete

Rami H. Haddad *, Rajai Z. Al-Rousan

Department of Civil Engineering, Jordan University of Science and Technology (JUST), P.O. Box 3030, 22110 Irbid, Jordan

ARTICLE INFO

Article history:
Accepted 2 August 2016
Available online 20 August 2016

Keywords:
Bond-slip
Anchorage
Fiber reinforced polymer
Strips
Damaged concrete

ABSTRACT

The potential of using CFRP sheet to anchorage CFRP strips, attached to thermally-damaged normal and lightweight concretes (NWAC and LWAC), is investigated. Far-end pull-off specimens were prepared using intact and thermally shocked NWAC and LWAC blocks before tested for evaluating bond behavior. The thermal shock regime, which consisted from heating to 500 °C then cooling suddenly in water, had caused a significant reduction in pull-off force (or bond strength) of as high as 36 and 23% and an increase in slip at failure of as high as 49% and 58%, respectively. The efficiency of anchoring CFRP strips by sheet was more pronounced for LWAC than NWAC and for thermally damaged than control LWAC or NWAC. Furthermore, using higher anchorage length of CFRP sheets along the bond length of the strips contributed to enhancing bond characteristics. The model, proposed in this paper to predict CFRP-concrete bond characteristics, showed excellent fit to present data and promising predictability.

1. Introduction

Normal weight concrete (NWAC) is the most widely used construction material, worldwide, because of its relatively low cost, availability of its ingredients and its satisfactory mechanical properties and durability. Some of the negative aspects relevant to NWAC are its relatively high mass to inertia ratio and poor thermal insulation. As a substitute, lightweight aggregate concrete (LWAC) has been used in several applications where lightweight and insulation are of the major requirements, such as earthquake resisting structures, green house and multistory buildings, and long-span structures such as girders of bridge, and auditoriums. Therefore, the demand for lightweight aggregate has increased, dramatically, over the last decade, which made lightweight natural and artificial aggregates, rather limited in quantities, relatively expensive.

In field, reinforced structures could be subjected to elevated temperatures reaching as high as 500 °C during a period of four hours or more; representing conditions predominate during burning of residential buildings. Previous research revealed that the mechanical properties of both NWAC and LWAC are preserved for exposure temperatures below 300 °C, yet are dramatically reduced upon exposure to temperatures greater than 500 °C due to the decomposition of cementing materials and water vapor pressure as well as the incompatible deformation of aggregates and cement paste, [1]. Of course, water distinguishing of burning concrete structural elements may result in a thermal shock that could aggravate their physical and mechanical status. This is referred to the tensile stresses, generated as a result of the temperature gradient between cool concrete core and hot external surface. It has been stipulated that the magnitude of damage is influenced by many factors such as the size of concrete members, the type of cement and aggregate, the concrete's moisture content and the heat source [2].

In light of the above, it is evident that efficient repair techniques would be needed to regain structural capacity and maintain long-term durability of various structural elements, rather severely damaged by thermal shock. The most recently and widely used repair technique involved using fiber reinforced polymeric (FRP) materials as attachments to concrete elements by special epoxy materials. Although being relatively expensive as compared to traditional repair techniques, such as reinforcing steel jackets and hot rolled steel sections and strips, FRP composites could: (a) impart significant improvements in mechanical properties of repaired concrete elements, without additional dead load, and (b) be easily attached to existing concrete in a relatively short time. Yet, the tendency of FRP composites detachment from concrete surface represents a limitation in using such a technique in repairing highly damaged concrete elements [3,4].

Literature works have reported various CFRP-concrete bond failure modes, at relatively low induced stresses, identified as

* Corresponding author. Fax: +962 27095123/+962 2 7201074.
E-mail address: rhaddad@just.edu.jo (R.H. Haddad).

http://dx.doi.org/10.1016/j.ijadhadh.2016.08.003
0143-7496/

being either interfacial debonding, concrete cover separation, and or end interfacial debonding, triggered by the formation of flexural or flexural-shear cracks [5,6]: the interface bond area had been defined as the interfacial area between concrete and CFRP composites, including a thin layer of the adjacent concrete and the epoxy. Most works acknowledged the use of near and far-end pull-off specimens for the study of bond behavior between CFRP and parent concrete with the aim of determining major CFRP-concrete bond parameters for the development of empirical models for future predictions, [7–9]. Of course, beam and modified beam tests provide the best simulation of actual stresses in concrete under loading as concrete interface with CFRP is being subjected to tensile rather compression stresses as is the case in traditional pull-off bond setups. Yet, beams' large size coupled with the considerable effort and cost required for their preparation and testing limit their use on a wide scale [10].

In an event of a major fire that is followed by water distinguishing, structural concrete elements made with NWAC and LWAC would be subjected to thermal shock, which results in reductions in their compressive and tensile strengths with possible surface deterioration [11]. Consequently, the efficiency of repairing these elements with CFRP composites would be dependent upon their damage extent and the repair configuration, proposed. Since limited studies (if none) have addressed this subject, an in-depth investigation to quantify bond characteristics between NWAC or LWAC and CFRP strips with and without CFRP sheet anchorage was carried out. Far-end pull-off specimens were prepared by bonding CFRP strips to NWAC and LWAC blocks ($150 \times 150 \times 100$ mm^3) before and after thermally-damaged at bond lengths from 50 to 125 mm, and a constant width of 50 mm. Two different anchorage systems using CFRP sheets were applied to two sets of far-end pull-off specimens with CFRP strips. Either CFRP sheets (100×50 mm^2 and 100×100 mm^2) were adhered to the free-end of the CFRP strips and surrounding concrete or attached at a constant width of 100 mm along the entire bond length of the CFRP strips: detailing of the testing program is summarized in Table 1. The findings of this work may aid in determining optimal bond lengths and/or anchorage configuration for best resistance against early debonding of CFRP strips from thermally shocked concrete.

2. Research significance

As well stipulated, efficient bond stress transfer from concrete to CFRP composites is fundamental in regaining the original load capacity of deteriorated concrete elements, while straining the CFRP composite to their ultimate practical limits. This is highly dependent upon the damage extent of the exterior concrete surface as well as the mechanical and geometric properties of the repair material and companion epoxy. Of course, the causative factor and/or the severity of damage determines the extent and form of concrete's surface deterioration hence bond to CFRP attached composites. Thermal shock of heated NWAC or LWAC generates two forms of degradation, physical and chemical. A lack of literature regarding bond behavior between CFRP and thermally damaged NWAC and LWAC necessitated conducting the present investigation.

3. Experimental program

3.1. Concrete mixture

Type I ordinary cement that complies with ASTM specifications C150 was used in the preparation of NWAC and LWAC mixtures along with silica fume (with 90% silicon dioxide) at contents of 10–15% (by wt). Coarse and fine limestone aggregate were used in preparation of one grade of NWAC, whereas coarse and fine tuff aggregates were used in the preparation of one grade of lightweight aggregate concrete (LWAC) mixture. The tuff is a volcanic lightweight small rocks, rich with silica and calcium oxides and spread in the eastern Jordanian desert. Both types of aggregate (having maximum aggregate size of 19 mm) comply with the gradation recommended by ASTM C33 [12] for structural concrete. Their physical properties were obtained and are listed in Table 2.

3.2. CFRP strips/sheet and bonding resin

Unidirectional CFRP strips, manufactured by BASF, were attached to the concrete blocks before and after being exposed to thermal shock, The 50 mm-wide strips have a tensile strength and a strain at failure of 2.7 GPa, and 1.4%, respectively. Sika manufactured CFRP sheets were used for anchoring CFRP strips with typical width and thickness of 300 and 0.17 mm, respectively. Its tensile strength and strain at failure, as provided the manufacturer, indicated 3.9 GPa and 1.5%, respectively.

BASF epoxies of two parts were used to attach both CFRP strips and sheets. The epoxy, specified for strips processes a density of 1.7 g/cm^3 and a compressive strength of 60 MPa, and was applied to concrete at thickness of 1 mm. The epoxy for the tensile was applied at a thickness of approximately 2 mm. Its strain at breaking, tensile elastic modulus, and tensile strength are 0.9%, 4.5 GPa, and 30 MPa, respectively.

Table 1
Detailing of testing program for the present study including number of test specimens.

CFRP strip length (mm)	Pull-off anchorage by CFRP sheets			Concrete type	Number of Specimens		
	Reference	End (mm)	Full-Length (mm)		PT	CS	SS
50	Without	100 × 50	100 × 50	NWAC	6	3	3
				LWAC	6	3	3
75	Without	100 × 50	100 × 75	NWAC	6	3	3
				LWAC	6	3	3
100	Without	100 × 50	100 × 100	NWAC	6	3	3
				LWAC	6	3	3
125	Without	100 × 50	100 × 125	NWAC	6	3	3
				LWAC	6	3	3

PT, Pull-off test; CS, Compressive strength; SS, Splitting strength; NWAC, Normal weight aggregate concrete; LWAC, Lightweight aggregate concrete.