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Influence of construction conditions on strength of post installed bonded anchors

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HIGHLIGHTS

- An experimental campaign of pullout test on 350 post installed bonded anchors.
- Evaluated conditions: drilling machine, filling material, moisture conditions, cleanliness.
- Installation conditions significantly affect the strength of the anchors.
- The most significant variable is the drilling machine.
- Anchors in conventional concrete performed better than in self-compacting concrete.

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ABSTRACT

This paper presents an extensive experimental work on various factors related to the construction conditions that affect the strength of post installed bonded anchors in concrete. The strength of the anchors was evaluated in conventional and self-compacting concrete. Two walls, 2 m high, one of conventional vibrated concrete (VC) and the other of self-compacting concrete (SCC) were built. In each of the walls, 175 anchors of 20 mm rebars were installed. The variables considered for each concrete block were the type of drilling machine used for drilling the hole, type of filling material, moisture conditions of the hole during installation, cleanliness of the hole, and installation direction. A detailed statistical analysis was used to evaluate the influence of the considered variables on the anchors ultimate capacity and slippage of the rebar at service level. The results show that the installation conditions significantly affect the strength of the anchors. The type of drilling machine has a major impact on the anchor strength, while the drill diameter had no significant impact on the results.

1. Introduction

Anchors are commonly used to connect existing cast in place concrete elements to newly cast concrete. Anchors can be either cast with the fresh concrete or post installed in the hardened concrete [1–4]. The post installed anchors can be divided into two main families of anchors: bonded and mechanical anchors [5,6]. Mechanical anchors commonly consist of a metal mechanism, which by an external action expands in the drill hole to develop friction between the two elements which acts as the anchoring resistance. Bonded concrete anchors are post installed anchors in which predrilled holes are filled with a bonding agent, usually epoxy resin or cementitious materials. These anchors are popular because they permit adjustments on site and provide more flexibility [3]. In this system, the overall bond strength of the anchor system depends on the bond between the anchor and the filling material, and the bond between the filling material and the concrete.

The main drawbacks of bonded anchors are that these anchors can only be installed using straight bars, contrary to cast in place anchors where the steel bars can be bent [7], and the high sensibility of adhesive anchors to installation conditions [5].

Anchors with chemical adhesives have progressively replaced cementitious anchors, starting in the 1990a with the development of high resistance adhesives of polyester, vinyl ester and epoxy [4,8,9]. Chemical adhesives consist of a polymer and a filler mixture, commonly a synthetic silica. These adhesives have low shrinkage, they are tougher have a higher resistance to fatigue, provide better protection against corrosion, and their installation is quicker.

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Epoxy adhesives have twice to four times the compressive strength of cement-based mortars, and 10–15 times their tensile strength. Epoxy provides higher toughness and better adhesion to steel and concrete in comparison with polyester, and are more resistant to loss of bond strength in moisture conditions. Chemical adhesives can be found in four different formats: glass capsules, plastic cartridges, tubes or in bulk.

1.1. Design and installation of anchors

The design and installation of post installed anchorage is addressed in ACI 318.14 Appendix D [10] and is based on the use of anchors that have been prequalified for the intended use. The qualification testing and assessment criteria for these anchors are prescribed in ACI 355.4 [11]. The anchor manufacturer is required to test the anchors and provide the data required for design and installation. Prior to the 2011 edition, ACI 318 did not include any provisions for bonded anchors. However, since 2006 most bonded anchors are tested and approved in accordance with the procedures included in ICC Evaluation Service in AC308 [21].

In Europe, the current guidelines for the design of bonded anchors are addressed in various documents: *EN 1992-4 part 5: Post-installed fasteners-chemical systems* [14], *EOTA Technical Report TR029 Design of Bonded Anchors* [12] and the *Guide for good practice fib bulletin 58* [13]. These design guidelines are based on the technical approval of the anchors, as prescribed in the ETAG *001 Guideline for European Technical Approval of Metal Anchors For use in Concrete Part five: Bonded Anchors* [23].

An important aspect that is not clearly addressed by these documents is the requirement of the manufacturer to provide data regarding the sensibility to the various installation factors. Reduction factors due to anchor spacing or edge distance are reported by the manufacturer. However, several installation variables are evaluated in the various sensitive tests, but appropriate reduction factors are not provided. Most manufacturers indicate that the design values provided are only valid for the stated installation conditions.

1.2. Failure modes of bonded anchors

There are five main failure modes of post installed anchors in uncracked concrete, as shown in Fig. 1: steel failure, pull-out failure, concrete cone failure, concrete splitting failure, space and edge cone failure.

In the case of bonded anchors, for embedment depths up to about nine anchor diameters, the pullout capacity increases when increasing the embedment depth. Minimum edge distance and minimum spacing between anchors are required to avoid splitting during installation and space and edge cone failure [2].

1.3. Factors affecting adhesive anchors

There are numerous factors that affect the behavior and performance of bonded anchors [1,2,5,8,18,19]. These can be grouped into four main groups: installation factors, service factors, characteristics of the adhesive and characteristics of the concrete. The installation factors include: hole orientation, type of drilling machine, moisture conditions of the hole, installation temperature, embedment depth, anchor diameter. The service factors include: temperature variation during the life of the structure, exposure to extreme temperature, moisture conditions, freeze-thaw cycles, and exposure to chemical and physical hazards [7,8]. The characteristics of the bonded factors include: type of adhesive material used, method used to insert the adhesive, initial and final strength of the adhesive material. Factors related to the characteristics of the concrete include: strength of the concrete, age of concrete, type of concrete, humidity conditions, and cracking state.

The effect of these variables is considered in the technical approvals of the anchors and the various design guidelines. However, in our opinion some of them are not adequately addressed.

For example, ACI 318.14 [10] provides mean values of bond strength for normal conditions, and only indicates that other parameters such as the drilling equipment, hole diameter, concrete age and temperature, and moisture content may affect the bond between adhesive and substrate. The document does not provide the designer with additional information regarding the effect of these variables on the anchor performance.

TR029 [12] includes partial safety factors to account for low, normal, or high installation safety conditions, however, in does not differentiate between the specific conditions. Fib bulletin 58 [13] addresses the effect of various installation conditions (ambient and concrete temperatures, installation parameters) and refers to manufacturer's instructions.

The three documents that address the testing and evaluation of the anchors, ACI 318, ICC308 and the ETAG 001, include testing requirements in various installation conditions. However, the three documents do not address the same variables, and in some cases, there is disagreement regarding the effect on the anchor performance. Also, the influence of each of the installation variables is not clearly manifested in the design guidelines.

For example, in section 2.1.1 of the ETAG 001 part 5, two drilling machines techniques are listed: rotary hammer and diamond drilling. The use of a pneumatic hammer is not contemplated. In section 5.1.2.1 of the same document, it is indicated that "the test conditions are defined for electric hammer drilling machine, and that in general these conditions are also valid for other drilling techniques".

The ACI 355.4 addresses the drilling method in more detail. According to Section 3.2.1, "the default drilling method uses a rotary hammer drill with carbide bit. Optional drilling methods for assessment includes core drilling and rock drilling." In addition, in Section 3.5, it is stated that "hammer drilling and rock drilling are assumed to produce similar hole wall characteristics for the standpoint of bond strength development. Drilling with diamond core bits, dry or wet, produces a smoother hole wall with a layer of drilling slurry or dust that can impair bond development."

Another example is the effect of the drilling diameter. According to Section 5.1.2.1 e) of the ETAG 001 part 5, the drilling tolerance of the hole does not have to be considered since "this variable does not adversely affect the performance" of the anchor system. According to ACI 355.4-11, the drill hole shall be with a diameter that is less than or equal to 1.5 the nominal anchor diameter. There is also a comment that hole diameters greater than 1.5 d_a require separate considerations of bond stresses developed along the anchor element/grout interface, as well as between the grout and the concrete.

The use of bonded anchors in self-compacting concrete, is an additional variable on which there are very few studies. Self-compacting concrete (SCC) is a flowable concrete that can consolidate under its own weight. It is a relatively new material, that is, commonly used in construction today.

Typical SCC mixtures have higher powder content and lower aggregates content than conventional concrete. Self-compacting concrete offers significant advantages over conventional concrete, such as its high fluidity, ease of passage through dense reinforcement, no need for vibration, and better surface finish. There are numerous studies on the concrete-to-steel reinforcement bond in self-compacting concrete [15,16,17]. However, the performance of post installed anchors in this material, has been little studied. The design criteria for post installed anchors is mainly based on extensive experimental background [14], done mainly on vibrated,