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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,

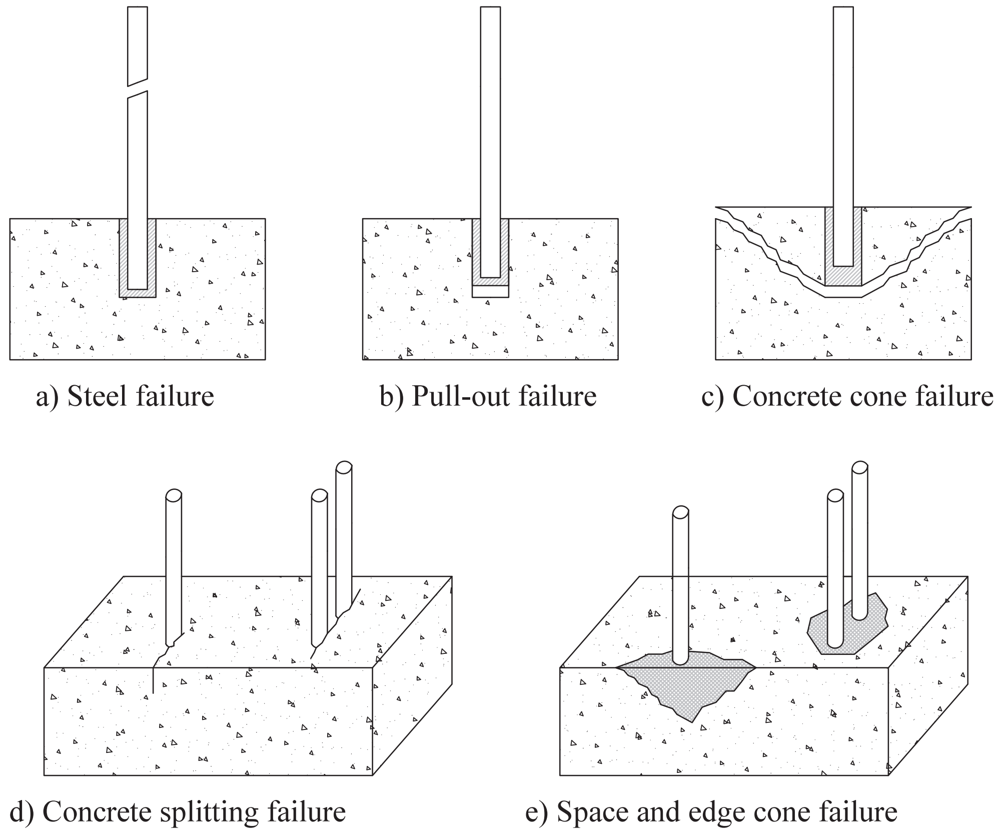

Fig. 1. Failure modes of adhesive anchors.

normal strength concrete. Given the extensive use of SCC in the precast industry and its progressive incorporation into the ready-mix industry, it is definitively necessary to study the behavior of adhesive anchors in hardened self-compacting concrete to establish whether the guidelines applied to anchors installed in conventional concrete are also applicable to SCC. A main concern is the possible higher sensitivity to installation conditions of the anchors, due to the higher powder content and less contact surface with aggregates.

2. Scope of research

This work provides new insights to various installation related factors that affect the strength capacity of post installed bonded anchors, and offers new data regarding the behavior of these anchors in vibrated concrete and self-compacting concrete. The study includes an extensive experimental campaign of 348 anchors, that are used to quantify the sensitivity of post-installed adhesive and grouted anchors to installation conditions. Statistical analysis procedures are used to evaluate the effect of each of the variables on the strength of the anchors. The results show that it is imperative for anchorage systems manufacturers to address these aspects in more detail in their installation procedure manuals.

3. Experimental program

The experimental program consisted of the installation and pullout test of horizontal and vertical bonded anchors in two concrete blocks, one made of conventional vibrated concrete and the other of self-compacting concrete. The experimental work was divided into various phases: fabrication of the concrete walls, drilling the holes with the different drilling machines, cleaning and wetting the drill holes for the specific test conditions, injecting the adhesive, installing the anchors, performing the pull to failure tests, and statistical analysis of the results. There are numerous variables that affect the strength of adhesive anchors, and it is impossible to include them all in the experimental program. In this study, the following variables were evaluated:

1. Type of concrete (conventionally vibrated concrete and self-compacting concrete)
2. Direction of drilling (horizontal and vertical. The vertical holes were drilled vertically downwards)
3. Filling material (epoxy resins, epoxy-acrylate resin, cementitious grout)
4. Drilling machine (pneumatic hammer with compressed air, electrical hammer, and diamond core drilling).
5. Drilled hole condition (clean and dirty). The cleaning of the hole consisted of two brushing with a round steel hair brush and three blows with compressed air, from the inside towards the opening of the hole. For the dirty hole condition, no cleaning was performed. The dust and debris from the drilling was left inside the hole.
6. Humidity conditions (humid and dry).
7. Drilling diameter (24 mm, 28 mm, 32 mm).
8. Height of the drilling (for horizontal anchors).

The installation of the anchors was a complex process due to the numerous variables that had to be considered for each drill. The installation conditions for each anchor were determined in such a way to assure that all the variables analyzed were covered. We first distinguished between vertical and horizontal anchors, considering them different families.

The first group comprised only of horizontal anchors. The different diameters, drilling machines, dry and humid, and clean and dirty conditions were studied only for the resin type adhesives (epoxy and epoxy-acrylate), resulting in 72 anchors for each concrete type. In addition, horizontal anchors with cementitious grout were installed for the following conditions: one size of drilling diameter (28 mm), one cleanliness condition (clean), two humidity conditions, and three drilling machines. This results in 6 additional anchors for each support type. In addition, two anchors were installed for each configuration. The total number of horizontal anchors installed in each concrete block was 156.

For the vertical condition, the 3 types of drilling machines were considered, one diameter size and two types of adhesives (epoxy resin and cementitious grout). Regarding the cleanliness, in the case of the epoxy resin, only the dry condition was considered, whereas for the cementitious grout, the two humidity conditions were considered, but only for the clean holes. This resulted in 18 vertical anchors for each concrete type, with two anchors for each configuration. In total, 174 anchors were installed in each block; 156 horizontal and 18 vertical.

The complete matrix with all the installation variables are included in Tables 1 and 2, in the following section, which include the mean value results for all the pull-out test.

The following variables were fixed and considered of a constant value for all the anchors.

A. Diameter of the bar – a 20-mm bar diameter was considered. In the construction industry, the bar diameters used can vary from 6 to 32 mm. A 20-mm bar was taken as a mean value within this range, as it is also the most commonly used diameter.
B. Type of steel of the bar – all the bars were GEWI® fully threaded corrugated B 500S steel bars.
C. Distance of the anchors from the borders and anchor spacing – The anchors were separated from the border and from each other sufficient distance so that the pull-out strength will not be affected by this distance preventing undesirable failure modes. A minimum edge distance and anchor spacing of 250 mm was used.
D. Depth of the anchor – An embedment depth of 250 mm was used for all anchors.
E. Cracking of the concrete – It was considered that the concrete is uncracked. A steel mesh reinforcement was provided to guarantee the fulfillment of this requirement. The rein-

Table 1
Ultimate load (kN)/displacement at service load (mm) for horizontal anchors in VC.

Drilling machine	Drilling diameter(mm)	Drilled hole condition	Epoxy resin		Epoxy-acrylate		Cementitious grout	
			Dry	Humid	Dry	Humid	Dry	Humid
Pneumatic hammer	24	Clean	197/0.25	202/0.01	205/0.05	196/0.33		
		Dirty	197/0.05	202/0.04	195/0.06	213/0.29		
	28	Clean	203/0.11	202/0.10	189/0.04	194/0.52	211/0.04	194/0.26
		Dirty	207/0.04	213/0.01	186/0.11	201/1.42		
	34	Clean	210/1.08	195/0.05	175/0.00	199/4.20		
		Dirty	196/0.03	193/0.01	203/0.01	194/1.47		
Electrical hammer	24	Clean	197/0.09	210/0.11	180/0.55	186/1.05		
		Dirty	200/0.02	76/12.40	175/1.32	73/11.12		
	28	Clean	215/0.04	203/0.18	182/0.52	186/1.98	185/0.02	200/0.01
		Dirty	199/0.01	168/3.19	103/7.02	119/12.69		
	32	Clean	207/0.06	196/0.13	185/0.54	147/3.26		
		Dirty	215/0.02	155/5.90	121/10.58	89/9.47		
Diamond core	24	Clean	205/0.00	148/2.04	161/0.01	131/7.52		
		Dirty	200/0.00	163/0.64	163/0.01	136/10.51		
	28	Clean	203/0.01	196/1.52	195/0.01	101/17.57	204/0.03	128/0.06
		Dirty	200/0.01	171/1.41	184/0.01	60/5.49		
	32	Clean	208/0.03	202/1.93	132/1.79	73/15.72		
		Dirty	189/0.00	110/8.00	146/2.30	42/18.15		

Table 2
Ultimate load (kN)/displacement at service load (mm) for horizontally in SCC.

Drilling machine	Drilling diameter (mm)	Drilled hole condition	Epoxy resin		Epoxy-acrylate		Cementitious grout	
			Dry	Humid	Dry	Humid	Dry	Humid
Pneumatic hammer	24	Clean	200/0.11	199/0.18	200/0.03	199/0.36		
		Dirty	204/0.02	216/0.05	196/0.14	199/0.44		
	28	Clean	198/0.04	202/0.08	197/0.18	196/1.72	210/0.01	187/0.16
		Dirty	190/0.24	202/0.01	195/0.25	181/0.89		
	34	Clean	215/0.01	195/0.07	215/0.17	135/8.33		
		Dirty	200/0.02	176/0.41	200/0.04	173/2.99		
Electrical hammer	24	Clean	158/0.72	168/0.62	104/3.01	184/0.57		
		Dirty	196/0.08	81/15.76	137/2.40	49/7.88		
	28	Clean	198/0.08	157/1.99	152/5.08	140/4.95	207/0.11	105/0.29
		Dirty	171/0.75	150/2.87	139/5.24	81/10.42		
	32	Clean	197/0.07	147/5.47	144/4.28	140/4.52		
		Dirty	175/0.20	174/2.38	111/9.38	75/14.94		
Diamond core	24	Clean	197/0.04	141/0.04	143/0.16	119/8.27		
		Dirty	201/0.01	162/2.52	190/0.44	68/9.93		
	28	Clean	202/0.01	172/2.07	52/7.96	49/17.00	198/0.01	154/0.05
		Dirty	204/0.00	92/11.24	109/0.03	61/5.76		
	32	Clean	216/0.05	172/0.09	86/10.10	23/6.91		
		Dirty	215/0.02	174/1.83	63/10.52	40/14.68		

forcement consisted of a 250 × 250 mm reinforcement mesh with a10 mm bar diameter.

F. Tensional state of the concrete – unloaded.
G. Qualifications of the person installing the anchor – The people who performed the anchored are qualified for the task, received the necessary formation, and are experienced with this work.
H. Age of anchors at pullout – the anchors were tested after the adhesives have fully cured and reached the full capacity. The minimum age at pull out was 28 days both for the cementitious grout and the resins. The maximum time of testing after anchor installation was 90 days. The anchors were installed during the months of May and June when the ambient temperature was about 20–25 degrees Celsius.
I. Age of concrete – pull-out tests were conducted on a concrete of no less than 3 months, to assure that its properties have been stabilized.

Fig. 2 shows one of the walls with all the anchors installed, after the pull-out tests. There was no premature failure due to interaction between the different anchors, and that the resulting concrete cones are do not overlap.

The following sections include a description of the different phases of the experimental campaign.

3.1. The concrete walls

Two walls 3.00 m wide, thickness of 0.60 m thick and 2.00 m high were built. One was cast with conventional concrete (VC) and the other with self-compacting concrete (SCC). The blocks included minimal reinforcement, which was installed in such a way as to not affect the pull-out tests.

The design strength for both concrete blocks was C-40 (characteristic compressive strength of 40 MPa) and the concrete was provided by a commercial ready-mix plant. It was important to have a concrete with sufficient strength, to avoid failure of the concrete during the pull-out test of the anchors. However, the supplied concrete had a mean 28-day compressive strength of 54 MPa (corresponding to European strength class C50/60) and 73 MPa (corresponding to European strength class C70/85) for the VC and SCC, respectively, obtained as the average of two 15 × 30 cm cylinder specimens.

Even though the objective was to have concrete blocks of similar strengths, the compressive strength of self-compacting concrete was almost 20% higher than that of the conventional concrete. The higher strength of the self-compacting concrete was a result of the higher cement content and lower water/cement ratio [20]. Since both concretes were of sufficient strength, failure of the concrete was not expected. Cement typeCEMI-52.5R was used for both concretes. VC had a water-to-cement ratio of 0.43 and a cement content of 400 kg/m^3, whereas SCC has a water-to-cement ratio of 0.36 and a cement content of 450 kg/m^3. The maximum aggregate size was 12.5 mm. The gravel-to-sand ratio was 1.14 for the VC and 0.76 for the SCC. The SCC mixture also included 120 kg of limestone filler.

Fig. 2. The anchors drilled in one of the walls.

3.2. Drilling technique

Three different drilling machines were considered, each with a different type of drill. The machines used were: pneumatic hammer with compressed air, electrical hammer, and diamond core drilling. Fig. 3 shows the different drilling machines used.

The compressed air hammer with integral drill is a machine that is fed on compressed air, supplied by a compressor, in this case, with a pressure of 8 bars. The advantage of this tool is that it is very robust and powerful. Also, the compressed air that is blown into the hole during the drilling continuously blows the debris out of the hole, providing effective cleaning. The disadvantage of compressed air hammer is that it can cause cracking around the anchor.

The electrical hammer is a handheld rotary drill with a hammering action with a carbide tipped bits. The drilling is achieved by the spinning of the bit. The hammering action further enhances the drilling and breaks up the concrete pieces into fine powder, so that it can be removed from the hole by the rotation action of the drill bit. The disadvantage of this drilling method is that the debris material is not evacuated efficiently. This is the most commonly used method to drill anchor hole, and is the drill method indicated in the installation manual of various manufacturers.

The diamond core drilling differs completely from the other two systems described above. In this method, the drilling equipment must be anchored to the concrete by means of mechanical fasteners. The drilling is done by the diamond crown which grinds through the concrete in a circular motion. During the drilling, water is injected into the drill hole. The water mixes with the dust to form a slurry which helps the grinding process and keeps the core bit cool. The concrete core is broken and extracted as a full piece. It is recommended to clean the hole with abundant water immediately after the drilling, to avoid the debris from drying inside the hole. One of the advantages of this method, is that the drilling can easily cut through the reinforcement, and that it does not induce cracking around the anchor hole. On the other hand, the inside of the drill hole is very smooth, and this affects the bonding capacity of the anchor, and the hole is in wet conditions due to the use of water during the drilling.

3.2.1. Drill diameter

The difference between drill diameter and anchor diameter, usually referred to as hole clearance, is somewhat addressed with approximate values in current standards [22]. The installation instructions of the manufacturer include the drill bit diameter to be used with each anchor diameter. However, sometimes on site a larger or smaller drill diameter bits is used. It is for this reason that the sensitivity of the anchor performance due to drilling diameter tolerances of should be evaluated. A 20 mm GEWI anchor bar used for all the anchors. Three drilling diameters were considered in this study: 24, 28, and 32 mm, for. According to the manufacturer data, for a nominal diameter of 20 mm the maximum diameter over threads is 23 mm. For this anchor diameter, the standard hole clearance should be 2–3 mm. Therefore, a 24-mm drill is the minimum size possible, 28 mm is the recommended size, and 32 mm would be an oversize diameter.

Fig. 3. The drilling machines used: pneumatic rock drill with compressed air, electrical hammer drill, and diamond core drilling.

3.2.2. Filling material

Three types of filling material were evaluated: epoxy resin, epoxy-acrylate resin and a cementitious grout. The epoxy resins are characterized by strong adhesion to all types of surfaces, high mechanical resistance and fast curing, making them the most common adhesive material for anchors. Even though the epoxy-acrylate has poorer performance than the epoxy resins, it is still quite in use because of its good application properties, and therefore was also considered in this study. The main differences between the epoxy resin and the epoxy-acrylate resin are that the epoxy resin presents greater adhesion with the concrete, it can adhere to wet supports and has greater mechanical resistance, less shrinkage and slower setting. On the other hand, the advantages of the epoxy-acrylate resin are that it can be used at lower temperatures and is easier to extrude. Overall, it can be considered that the epoxy-acrylate resin is of lower quality than epoxy resin, with lower performance, but easier to apply and faster. In this study the epoxy resin SIKA ANCHOR FIX 3® and the epoxy-acrylate SIKA ANCHOR FIX 2® were used.

The cementitious grout used in this study is a self levelling and shrinkage compensating grout, with a 24-hour compressive strength of 24–36 MPa and a 28-day strength of 57–64 MPa, depending on the water content of the mixture. It is difficult to ensure adequate filling of the anchors holes with cementitious grouts, as they are self levelling, and subsequently these adhesive filling is not recommended for horizontal anchors. Nevertheless, horizontal anchors with cementitious grout were included in the experimental campaign for comparison with other filling materials.

3.2.3. Cleanliness of the hole

The cleanliness of the hole affects the performance of the anchor. Dirty holes can result in poor adhesion as loose particles obstruct direct contact between the adhesive and the support material. For anchors installed in holes drilled with the rotary hammer or the pneumatic hammer, the cleaning consists of radially brushing with a steel brush (diameter equal to 32 mm) and two blowing with compressed air. Special attention should be given in the case of diamond core drilling. In this case, since water is used as part of the drilling process, the hole was cleaned washed immediately after drilling with water, to prevent the fine powder from drying inside the hole. After the hole has dried, the same cleaning procedure was adopted, that is, one brushing and two blows.

The "dirty" condition included no cleaning of the anchor hole. In the case of the diamond core drilling, the hole was not cleaned with water immediately after the drilling, and the fine powder was left to dry inside the hole.

3.2.4. Humidity of the concrete

This parameter is measured in terms of the relative humidity. The condition of dry support is defined for a relative humidity below to 5%, which normally corresponds to normal drying conditions of several days. The wet condition refers to near 100% of relative humidity. This condition is obtained by filling the drill hole with water for ten days. For horizontal drillings, this was done by installing a special recipient that ensured that the hole was continuously filled with water. For vertical drillings, the hole was directly filled with water. Prior to the installation of the anchors, the water was completely sucked out. For vertical anchors, the water was removed using a pressurized gun, to ensure that there was no free water in the drill hole. For the dirty condition, no additional cleaning was performed.

3.3. Pullout test

Confined pull-out tests were performed at least one month after the installation of the anchors, to ensure complete curing of the adhesive material. For the pull-out test, a 60-ton hydraulic power jack, with a step controlled loading speed and digital measurement of the sliding action of the rod, was used. In the confined test configuration, a concrete cone failure does not occur [23]. There was continuous reading of the applied load and sliding of the bars. A hydraulic power jack with a maximum capacity of 60 tons was used. A special metallic bridge was built so that the jack will to push directly against the concrete adjacent to the anchor. The distance between the inner edge of the bridge and the anchor axis was 15 mm in both directions. The test set up is show in Fig. 4.

Fig. 4. Test setup.

The load was applied at a maximum rate of 96 kN/min, in accordance with UNE-EN 1881 [24]. Each of the pull-out test continued either until failure or up to a displacement of 20 mm.

4. Results and analysis

The experimental campaign included the pullout of 348 anchorage bars. For each test, the load deformation curve was recorded by electronic means. The values of interest include the maximum load (the value at which test was stopped after reaching the elastic limit, C_{els} = 195 kN, or the one that caused adherence failure at lower load than the elastic limit) and the displacement of the bar at service load. The service load considered was 91.07 KN, which corresponds to an elastic limit of 195 kN for a B500S 20 mm bar, considering a reduction coefficient of 1.15 for the yield strength of the material and an amplification coefficient of 1.5 for the load. Measurements of the bar displacement were used to calculate the displacement of the anchor.

Tables 1 and 2 include a summary of the results for the anchors in the horizontal direction for VC and SCC, respectively. In each case, the average of the two test values is shown.

Tables 3 and 4 include the results for the anchors in the vertical direction for VC and SCC, respectively.

The different load vs displacement curves can be classified into three groups: displacement of the anchor at service loads, displacement of the anchor at service load with an increase in load, and failure of the anchor bar without displacement (Fig. 5).

The displacements curves in Fig. 5 correspond to the following three cases: *displacement failure at service load* corresponds to an anchor installed in the following conditions: in dirty, wet SCC concrete, with epoxy-acrylate resin, electrical hammer, horizontal 34 mm drilling. The displacement *at service load with an increase in load*, corresponds to an anchor installed on clean, dry SCC concrete, with epoxy-acrylate resin, electrical hammer, horizontal 28 mm drilling. And, the *No displacement-steel reach yielding* corresponds to an anchor installed on dirty, dry SCC concrete, with epoxy resin, pneumatic hammer, and horizontal 28 mm drilling.

4.1. Method of analysis

The objective of the analysis was to study the effect of the different variables on the horizontal and vertical anchors. Due to the complexity of handling many variable combinations, the statistics program SPSS was used. The statistical analysis of the results included multiple stepwise regression analysis and dispersion diagrams. The variable of interest is the ratio between the ultimate pull out load, C_{max}, and the load corresponding to the elastic limit of the rebar C_{ELS}. The value of C_{ELS} is the elastic limit of the anchor, and is the limit value used in the design of anchors. The higher the value of this ratio, the better the performance of the anchor.

The influence of the different independent variables on the ratio $C_{MAX}/C_{ELASTIC}$, was evaluated using a backward stepwise regression analysis. In this analysis, all the variables are inputted into the model, and based on statistical criterion, they are assessed one by one to see whether they should be removed.

In a backward stepwise regression analysis, the variables that are less significant are eliminated in a progressive process from the model. These variables are selected based on the p-value of the t-statistic. A maximum p-value of 5% was chosen, meaning that variables with a p-value greater than this value were removed from the model. This is an iterative calculation process that continues until all the variables are considered significant.

The following is the initial equation used for analysis:

$$C_{MAX}/C_{ELS} = \beta_1 + \beta_2(CON) + \beta_3(MACH) + \beta_4(DIAM) + \beta_5(MAT) + \beta_6(CL) + \beta_7(HUM) + \beta_8(HEIG) + u \quad (1)$$

where the dependent variable, C_{MAX}/C_{ELS}, is expressed in terms of the different variables analyzed.

β_{1-8} are the unknown coefficients associated with each of the independent variables, which are calculated using the regression analysis. In this type of analysis, the objective is to find

Table 3
Ultimate load (kN)/displacement at service load (mm) for vertical anchors installed in VC.

Drilling machine	Drilling diameter (mm)	Drilled hole condition	Epoxy resin	Cementitious grout	
			Dry	Dry	Humid
Pneumatic hammer	28	Clean	198/0.01	204/0.41	210/0.01
Electrical hammer			196/0.01	188/1.23	196/0.02
Diamond core			200/0.01	215/0.22	192/0.04

Table 4
Ultimate load (kN)/displacement at service load (mm) for vertical anchors in SCC.

Drilling machine	Drilling diameter (mm)	Drilled hole condition	Epoxy resin	Cementitious grout	
			Dry	Dry	Humid
Pneumatic hammer	28	Clean	209/0.07	210/0.06	207/0.10
Electrical hammer			196/0.02	209/0.07	190/0.22
Diamond core			212/0.10	209/0.35	205/0.08

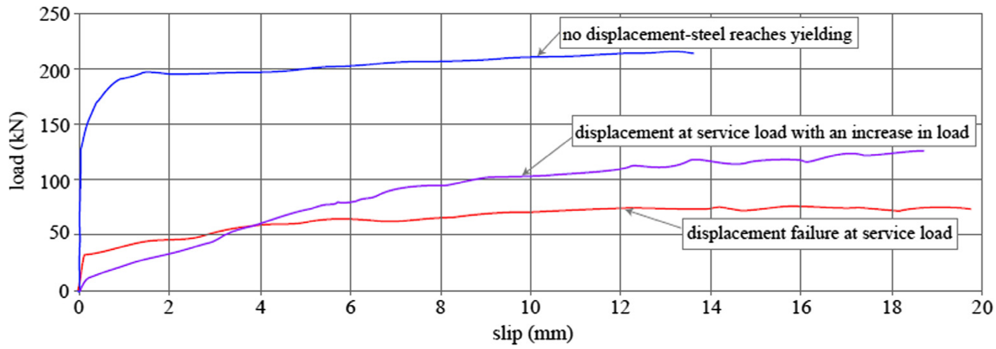

Fig. 5. Different load vs displacement curves. 1.

the combination of independent variables that correlate maximally with the dependent variable.
u is the standard residual of the regression analysis (see Eq. (2)). The residual is the difference between the predicted value and the observed value. A low error value means that the model fits better the data. In this type of analysis, it is more common to use the standard residual, which is the residual divided by an estimate of their standard deviation.

The independent variables considered in the analysis are:

- Type of concrete (CON): O for conventional (VC), 1 for self-compacting (SCC).
- Direction of the anchor (DIR): horizontal and vertical
- Type of drilling machine (MACH): 1 (pneumatic hammer), 2 (electrical hammer), 3 (diamond drill).
- Drill diameter (DIAM): 24, 28, 34 mm.
- Filling material: (MAT): 1 (epoxy resin), 2 (epoxy-acrylate resin), 3 grout
- Cleanliness (CLN): 0 (clean), 1 (dirty).
- Humidity (HUM): 0 (dry), 1 (wet).
- Height of the drill (HEIG): 0.250, 0.375, 0.500, 0.625, 0.750, 0.875, 1.000, 1.125, 1.250, 1.375, 1.500, 1.625 and 1.750 m.

4.2. Effect of the different variables on the maximum load/elastic limit of the rebar

In the first part of the analysis, the anchors were divided into two groups. The first group included only the horizontal anchors with epoxy resin and epoxy-acrylate. This means that a comparison was done between the two filling materials and considering cleanliness and humidity of the hole, diameter of the drilling and drilling machine. The second group included the vertical anchors and the corresponding horizontal anchors installed in equivalent conditions. This second group included the holes filled with epoxy resin and with cementitious grout. The backward stepwise regression analysis for the first group resulted in the following reduced model:

$$C_{MAX}/C_{ELS} = 1.56 - 0.09\ (CON) - 0.14\ (MACH) - 0.21\ (MAT) - 0.08\ (CLN) - 0.15\ (HUM) + u \qquad (2)$$

The statistical analysis showed that the diameter and height of the drill are not significant, and these were therefore eliminated from the model. Figs. 6–10 include the effect of each of the variables on the mean predicted value of C_{MAX}/C_{ELS}, according to the reduced regression model. It should be noted that these bar graphs show the mean value of all the evaluated conditions in each of the groups. These results are an interesting comparison between different conditions, however, specific combinations can have an

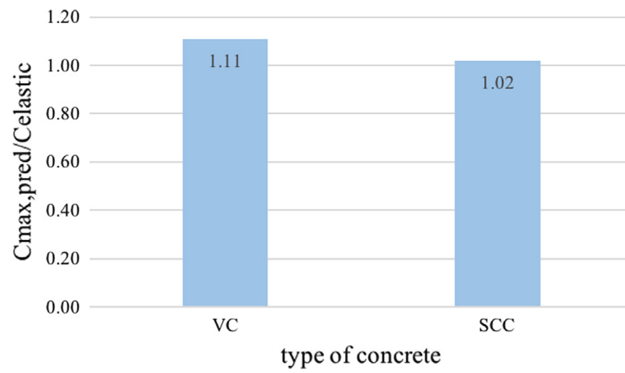

Fig. 6. Effect of type of concrete on C_{MAX}/C_{ELS}.

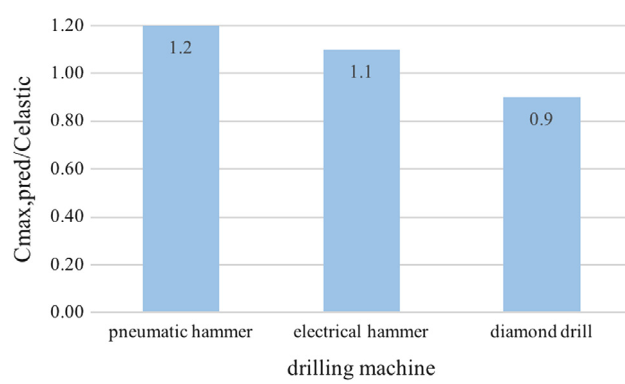

Fig. 7. Effect of the drilling machine on C_{MAX}/C_{ELS}.

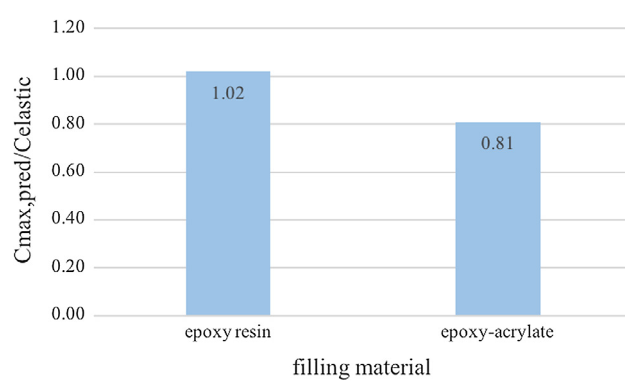

Fig. 8. Effect of filling material on C_{MAX}/C_{ELS}.

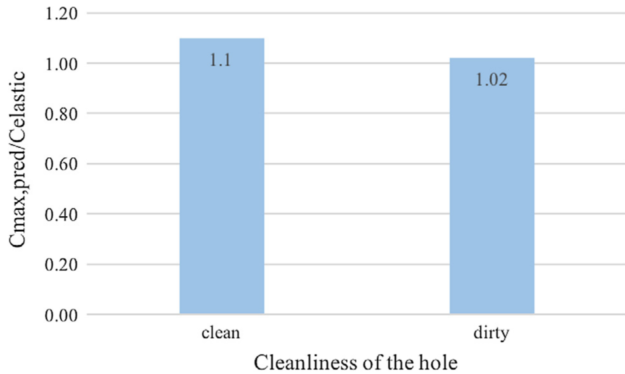

Fig. 9. Effect of cleanliness of the hole on C_{MAX}/C_{ELS}.

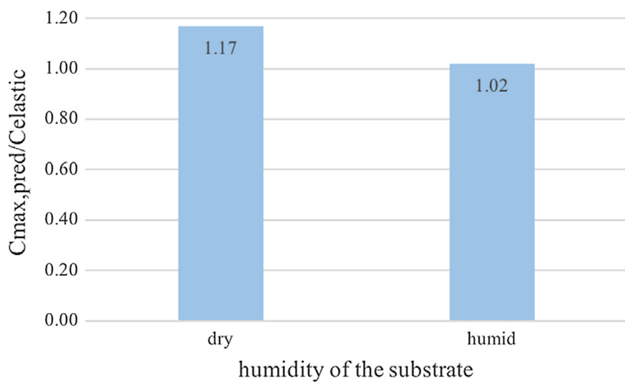

Fig. 10. Effect of the humidity conditions on C_{MAX}/C_{ELS} of horizontal anchors with epoxy and epoxy-acrylate fillings.

effect that is different or opposite from the mean effect. It is important to evaluate these mean results and compare them with the error bar graphs in Fig. 13.

Fig. 6 includes a comparison between the anchors installed in the conventional vibrated concrete block and the anchors installed in the self-compacting concrete block. It is interesting to note that even though the compressive strength of the SCC was higher, the anchors installed in the conventional concrete performed better, with a 9% higher relative capacity. SCC is characterized with a higher paste volume than conventional concrete, which may be the cause for this difference in results.

The effect of the drilling method, filling material type, cleanliness of the hole and the humidity condition of the concrete also have a significant effect on the strength capacity of the anchor.

In Fig. 7 the influence of the type of drilling machine is shown. The anchors installed using the electric hammer drill have a relative capacity (CMAX/C_{ELS}) 13% greater than the those installed with the diamond drill, and a 12% lower relative capacity than the anchors installed an air hammer. The anchors installed using the air hammer performed the best of the three drilling machines used.

The type of drilling machine significantly affects the frictional finish of the drilling hole, which directly influences the relative capacity of the anchor. The smooth surface that is obtained from drilling with a diamond core machine results in a lower bonding strength between the surface of the concrete and the adhesive material, and a lower relative capacity of the anchor. Both the electrical drill and the pneumatic air hammer improve the roughness of the hole surface and therefore result in a better relative anchor capacity. The additional increase in capacity of the pneumatic air hammer is largely attributed to the additional cleaning effect which occurs during drilling, minimizing the effect of cleanliness variable, as will be discussed further ahead.

In Fig. 8 the influence of the adhesive material is compared. This group includes only the horizontal anchors, and does not include the grout, which was included only in the vertical anchors. Comparing the two materials, anchors with epoxy resins have 26% higher relative capacity than epoxy-acrylate resins.

In Fig. 9 the influence of cleaning drill is shown. As expected, the drills that did not include any type of cleaning obtained a relative capacity 8% lower than those that underwent proper cleaning.

Regarding the humidity conditions of the drilled hole, as represented in Fig. 10, in dry substrates the relative capacity of the anchor is 15% higher than in a wet substrate.

The second group of anchors included the vertical anchors and the horizontal anchors executed in equivalent conditions. In this group, the drill diameter (28 mm) and the cleanliness (clean conditions) were a constant for all the drills. The resulting equation from the backward stepwise regression analysis is the following:

$$C_{MAX}/C_{ELS} = 1.01 + 0.07(\mathrm{DIR}) - 0.12(\mathrm{HUM}) + u \quad (3)$$

In the analysis of the second group, it was found that the direction of the drilling is extremely significant, up to the point of minimizing the effect of the type of concrete, filling material and drilling machine which were eliminated in the consecutive steps. It should be noted, that the type of drilling machine was less significant in the second group because the parameter of cleanliness of the hole was not considered and all holes were clean. Consequently, the resulting model considers only the direction of the drilling and the humidity conditions.

In Fig. 11 the influence of the direction of the anchorage is shown. The vertical anchors presented a relative capacity which is 8% higher than the horizontal anchors. This can be attributed to the better filling of the vertical drills.

Quite interestingly, the influence of the humidity conditions differs in the second model, in which the vertical direction is included. This can be explained by the higher sensibility of the cementitious grout to the humidity condition of the hole, and considering that the cleanliness of the hole was a constant in this second model. Influence of the moisture conditions for grout anchors is shown in Fig. 12**.**

4.3. Analysis of the effect of different parameters through error bars

The analysis presented above is complemented with a graphical analysis of the 95% confidence interval error bars. This format allows to identify the variables that have higher and lower scatter, and those of greatest influence on C_{MAX}/C_{ELS}.

Fig. 13 shows the grouped graphs of error bars including the drilling machine, the humidity conditions, the type of concrete and the cleanliness of the hole.

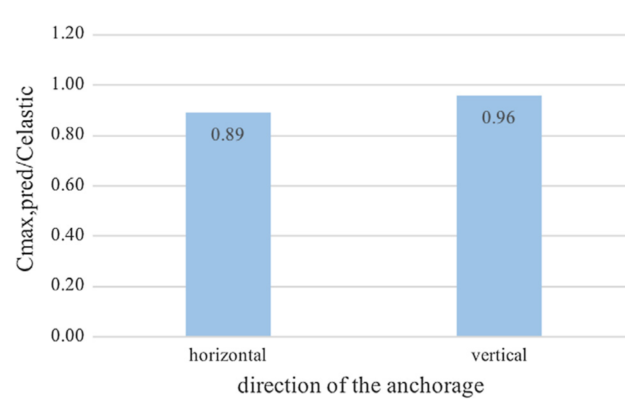

Fig. 11. Effect of the direction of the anchorage on C_{MAX}/C_{ELS}.

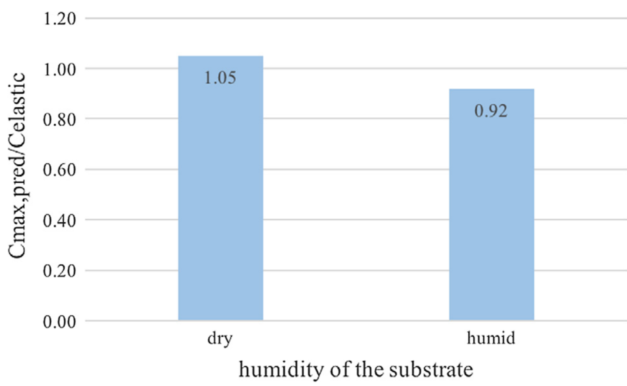

Fig. 12. Effect of the humidity conditions on C_{MAX}/C_{ELS} of anchors with grout.

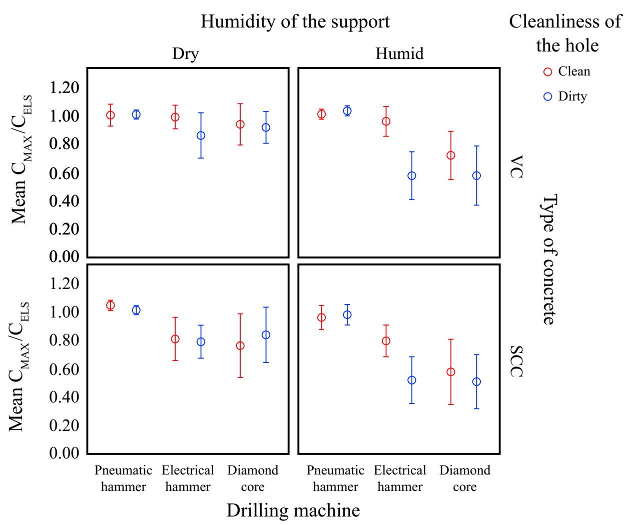

Fig. 13. 95% confidence interval error bars for groups of variables.

In Fig. 13, the use of pneumatic hammer virtually eliminates the effect of the other variables due to its cleaning action and its rough finish. The mean values are practically equal, regardless of the humidity and cleanliness of the hole and the concrete type. In general, the use of a pneumatic hammer results in low scatter, even though it is a little higher in the case of the wet SCC.

The electrical hammer is more sensible to the cleanliness of the hole, but this sensibility is more relevant in the case of wet supports, with a similar trend for VC and SCC. In the case of clean holes, the improvement is 33% with respect to the dirty holes in wet supports (with electric hammer).

On the other hand, the diamond core drilling is less influenced by the cleanliness, and is more affected by the humidity condition, than the other drilling techniques. It is affected by the type of concrete, in a similar way that the electrical hammer, for dry support; for wet support, similar results were obtained for VC and SCC. In general, the results with diamond core are worse, and present higher scatter, than the other drilling techniques. Nevertheless, it is worth noting that the results for the dry vibrated concrete are like those of the pneumatic hammer, being little influenced by the cleanliness.

4.4. Effect of the different variables on the displacement at service load

The second part of the analysis includes an evaluation of the effect of the different variables on the maximum displacement of the anchor bar (in mm) under service loads. The service load considered was 91.07 KN, which corresponded to an elastic limit of 195 kN for a B500S 20 mm bar, considering a reduction coefficient of 1.15 for the yield strength of the material and an amplification coefficient of 1.5 for the load.

Like in the regression analysis of the maximum load, two approaches were considered: one including the horizontal anchors with epoxy resin and epoxy-acrylate fillings, and another with all the vertical tests and their horizontal counterparts.

For the first group, the following is the initial model used:

$$DIS_{service\ loads} = \beta 1 + \beta 2(HOR) + \beta 3(MAQ) + \beta 4(DIAM) + \beta 5(MAT) + \beta 6(LIM) + \beta 7(HUM) + u \quad (4)$$

The results of the backward regression analysis indicate that the concrete type is statistically not significant, and this variable was, therefore, eliminated from the model. The following is the resulting model:

$$DIS_{service\ loads} = -12.91 + 1.858\ (MAQ) + 0.17(DIAM) + 3.32\ (MAT) + 1.40\ (LIM) + 3.34\ (HUM) + u \quad (5)$$

Figs. 14–18 show the estimated mean displacement of the horizontal anchors under service load, as a function of different variables. Each graph represents the grouped effect of one variable.

From Fig. 14, it can be observed that the largest displacements are obtained when using the diamond core machine, with displacement values of about 3 times the displacement obtained with air hammer drilling. It can be observed that the drilling machine affects the displacement of the anchor in the same way the anchor capacity, but the effect is stronger in the case of the displacements.

In the case of the drill diameter, this variable did not have a significant effect on the relative capacity of the anchor, while its effect

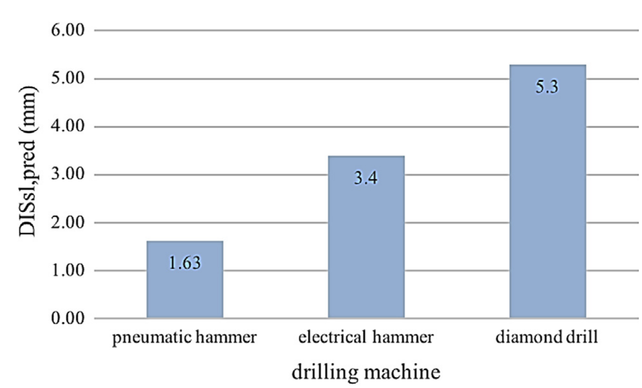

Fig. 14. Effect of drilling machine on displacement of the anchors.

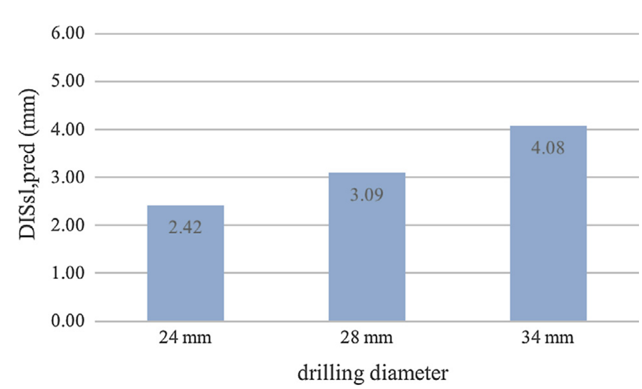

Fig. 15. Effect of drilling diameter on the displacement of anchors at service loads.

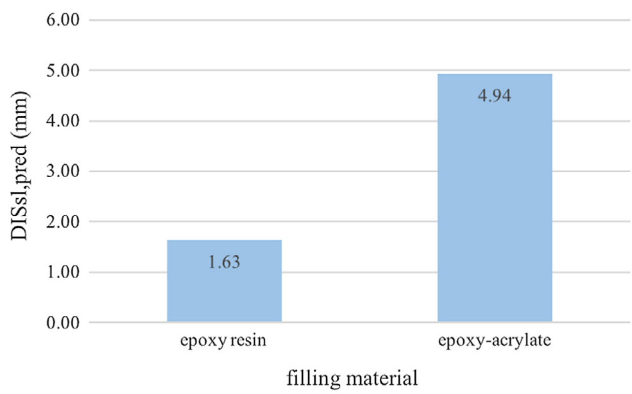

Fig. 16. Effect of filling material on the displacement of anchors at service loads.

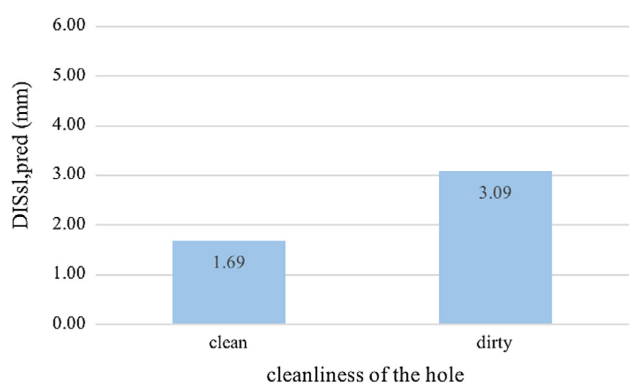

Fig. 17. Effect of cleanliness of the hole on the displacement of anchors at service loads.

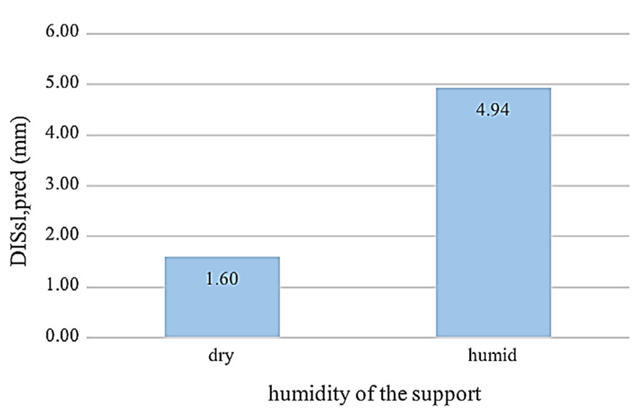

Fig. 18. Effect of moisture content on the displacement of anchors at service loads.

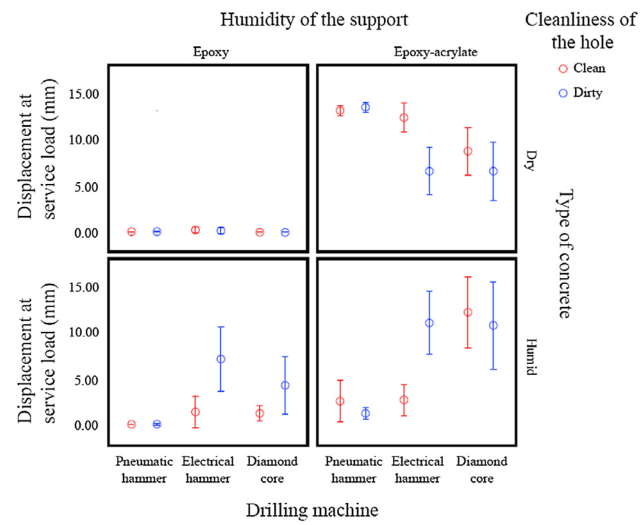

Fig. 19. 95% confidence interval error bars for groups of variables.

on the anchor displacement is significant. As shown in Fig. 15, as the diameter of drill increases, the displacement of the anchor also increases. The displacement for 34 mm drills is 1.68 times the displacement of the 24 mm drills. The drill diameter should be the minimum required to install the anchor correctly, as larger diameters have a negative influence on the anchor's response.

In the case of the adhesives, as shown in Fig. 16, the epoxy acrylate resin has a mean displacement that is three times the displacement obtained with the epoxy resin. A similar tendency was also observed in the relative capacity results of the anchor.

In Fig. 17, the effect of the cleanliness of the drill hole is shown. As expected, the anchors that were installed without any cleaning of the drill hole showed higher displacements than the anchor holes that were properly cleaned. Similar behavior was observed in the anchor capacity results.

The moisture content is one of the most important variables affecting the displacement of the anchor bars at service loads. The displacements of the anchors installed in a wet substrate were around 3 times larger than the displacements of the anchors installed in dry conditions, as can be observed in Fig. 18**.**

For the second group of tests, regression analysis revealed that none of the variables is statistically significant in terms of the displacement at service loads.

4.5. Analysis of the effect of different parameters through error bars

The analysis presented above is complemented with a graphical analysis of the 95% confidence interval error bars. This format allows to identify the variables that have higher and lower scatter, and those of greatest influence on the displacement at service load.

Fig. 19 shows the grouped graphs of error bars including the drilling machine, the humidity conditions, the type of concrete cleanliness of the hole, and filling material.

In Fig. 19, the use epoxy in a dry support practically eliminates the effect of all other variables, including the drilling machine. The behavior of the pneumatic hammer is always better, even with epoxy-acrylate and humid support. The electric hammer and diamond core are more sensitive to the cleanliness than the diamond core. The worse conditions are obtained for the epoxy filling in humid and dirty conditions, and for the epoxy-acrylate in both the humid and dry conditions.

5. Conclusions

In this study the influence of some construction related variables on the strength of post installed adhesive anchors in concrete was analyzed. These variables have considerable influence on the maximum capacity of the anchor and its displacement under service loads. The following conclusions can be drawn:

- The installation conditions that lead to higher ultimate capacity of the anchors, also resulted in lower displacements. The variable combinations that had less scattering of results, also gave rise to higher anchor capacities.
- The most significant variable affecting the ultimate capacity is the drilling machine, which interestingly, is one of the less studied parameter in the literature. Considering the mean values of

all test parameters, the results of the pneumatic hammer were 28% higher than with the diamond core and 14% higher than the electrical hammer. The pneumatic hammer also has the effect of minimizing the effect of the other installation variables. The anchors installed using the other two machines are greatly affected by the rest of the installation variables. It is noteworthy that most manufacturers recommend the use of the electrical hammer, which was found not to be the best option.

The European technical approval document does not contemplate the use of a pneumatic hammer. We recommend including this machine. In addition, the various testing protocols refer to the electrical hammer as the default drilling machine. We recommend the pneumatic drilling machine as the default drilling machine, given the superior results obtained in present research.

- The humidity condition and cleanliness affect the strength capacity of the anchors to a greater or lesser extent depending on the drilling method and filling material employed. The humidity condition of the hole is of more significance than the cleanliness condition of the hole.
- Results were better for anchors installed in conventional concrete than in self-compacting concrete, and this even though the compressive strength of the SCC block was higher than that of the VC Block. This can be explained by the higher aggregate content of conventional concrete, resulting in larger bond surface between filling material and aggregate. It should be noted, however, that further investigation is needed on this variable.
- based on these results, we recommend that for use in specially concretes, for sensitive testing to be included in the qualification testing programs for anchors.
- The epoxy resin performs better than the epoxy-acrylate, in terms of ultimate capacity and slippage of the anchor. The scatter of the results was also lower for this adhesive. The epoxy resin performs better than cementitious grout, especially on horizontal drills.
- The vertical drills behave better than the horizontal ones due to better filling and compacting conditions (the mean C_{MAX}/C_{ELS} was 8% higher), being this effect more significant in wet conditions.
- In regard to cementitious grout, this material is highly affected by the humidity condition of the concrete. Considering the maximum load, the lowest results were obtained in the for horizontal drillings in SCC, wet conditions, and diamond core drilling.
- The drill diameter did not significantly affect the maximum capacity of the anchors, but strongly affected the displacement at service loads. aa significant variable factor.

The authors wish to point out that the conclusions of the study are based on the results of this experimental campaign only, and should not be extrapolated to other commercially available products. Installation should only be performed according to the manufacturer instructions.

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References

[1] R.A. Cook, Behavior of chemically bonded anchors, J. Struct. Eng. 119 (9) (1993) 2744–2762.
[2] R. Eligehausen, R. Mallée, J.F. Silva, Anchorage in Concrete Construction, John Wiley & Sons, 2006.
[3] P. Upadhyaya, S. Kumar, Pull-out capacity of adhesive anchors: an analytical solution, Int. J. Adhes. Adhes. 60 (2015) 54–62.
[4] Ö. Çalışkan, S. Yılmaz, H. Kaplan, N. Kıraç, Shear strength of epoxy anchors embedded into low strength concrete, Constr. Build. Mater. 38 (2013) 723–730.
[5] R. Eligehausen, R.A. Cook, J. Appl, Behavior and design of adhesive bonded anchors, ACI Struct. J. 103 (6) (2006) 822.
[6] M. Gesoğlu, E.M. Güneyisi, E. Güneyisi, M.E. Yılmaz, K. Mermerdaş, Modeling and analysis of the shear capacity of adhesive anchors post-installed into uncracked concrete, Compos. B Eng. 60 (2014) 716–724.
[7] B.S. Hamad, R. Al Hammoud, J. Kunz, Evaluation of bond strength of bonded-in or post-installed reinforcement, ACI Struct. J. 103 (2) (2006) 207.
[8] R.A. Cook, R.C. Konz, Factors influencing bond strength of adhesive anchors, ACI Struct. J. 98 (2001) 76–86.
[9] M. McVay, R.A. Cook, K. Krishnamurthy, Pullout simulation of postinstalled chemically bonded anchors, J. Struct. Eng. 122 (9) (1996) 1016–1024.
[10] ACI 318-14, Building Code Requirements for Structural Concrete, American Concrete Institute, 2014.
[11] ACI 355.4-11, Qualification of Post-installed Adhesive Anchors in Concrete and Commentary, American Concrete Institute, 2011.
[12] TR029. EOTA (2007). Design of bonded anchors.
[13] FibBulletin 58 (2011). Design of anchorages in concrete. Guide to good practice.
[14] EN 1992-4 (2009). Eurocode 2: Design of concrete structures – Part 4: Design of fastenings for use in concrete, European Committee for Standardization.
[15] H. Okamura, M. Ouchi, Self-compacting concrete, J. Adv. Concr. Technol. 1 (1) (2003) 5–15.
[16] I.P. Sfikas, K.G. Trezos, Effect of composition variations on bond properties of self-compacting concrete specimens, Constr. Build. Mater. 41 (2013) 252–262.
[17] P. Helincks, V. Boel, W. De Corte, G. De Schutter, P. Desnerck, Structural behaviour of powder-type self-compacting concrete: bond performance and shear capacity, Eng. Struct. 48 (2013) 121–132.
[18] S. Yilmaz, M.A. Özen, Y. Yardim, Tensile behavior of post-installed chemical anchors embedded to low strength concrete, Constr. Build. Mater. 47 (2013) 861–866.
[19] A. El Menoufy, K. Soudki, Effects of various environmental exposures and sustained load levels on the service life of postinstalled adhesive anchors, J. Mater. Civ. Eng. 26 (5) (2013) 863–871.
[20] S. Cattaneo, F. Mola, Assessing the quality control of self consolidating concrete properties, J. Constr. Eng. Manage. ASCE 138 (2012) 2.
[21] ICC-es AC 308 (2012) Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements. Concrete and Masonry anchor manufacturers association.
[22] P. Spyridis, K. Bergmeister, Effects of assembly tolerances on bolted anchorages in concrete, J. Struct. Eng. 140 (1) (2012) 04013024.
[23] ETAG 001 part five (2002). Guideline for European technical approval of metal anchors for use in concrete. Bonded anchors.
[24] UNE-EN 1881. Products and systems for the protection and repair of concrete structures – Test methods – Testing of anchoring products by the pull-out method.