Quantification of tribological effects in expansion fasteners

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Abstract

Post-installed anchors for civil construction are elements that ensure the integrity of building structures even under the most severe static, seismic and shock loadings. Despite the high popularity of this technology in construction sites all over the world, the current state of knowledge is limited and there is still a great potential for significant improvements.

Specifically, expansion anchors’ mechanism relies purely on friction, therefore being able to manipulate and optimize their tribological behavior is key to meet strict safety regulations and develop outperforming and outlasting design solutions.

This research project, conducted at Hilti Corporation in Schaan (Liechtenstein), presents an investigation of several antifriction coating solutions. Laboratory-scale tests have been performed to quantify the different coefficient of friction while, with full-scale standardized tests (anchor set in concrete), it has been possible to evaluate the overall mechanical performances of the specimens. Afterwards, the obtained data have been analyzed with numerical software and the samples have been further investigated with optical microscopy.

The outcome of this thesis work is crucial for the development of the next generation of expansion fasteners and gives additional insights for a deeper understanding in the tribology of functional coatings.

Keywords: post-installed anchors, civil construction, tribology, antifriction coatings.
**Sammanfattning**

Eftermonterade fästankare i byggnader säkerställer byggnadsstrukturernas integritet, även under de mest allvarliga statiska, seismiska och shockbelastningar. Trots stor användning och popularitet på byggarbetsplatser över hela världen är det nuvarande kunskapsläget av denna teknik begränsat och det finns en stor potential för betydande förbättringar.

Specifikt bygger expansionsankringsmekanismen på ren friktion. Därför är möjligheten att manipulera och optimera fästankarnas tribologiska beteende nyckeln till att uppfylla strikta säkerhetsbestämmelser och kunna utveckla bättre prestanda och designlösningar.

Detta forskningsprojekt har utförts på Hilti Corporation i Schaan (Liechtenstein) och presenterar en undersökning av flera antifriktionsbeläggningslösningar. Laboratorieprov har utförts för att kvantifiera olika friktionskoefficienter, och efter fullskaliga standardiserade tester (med fästankare i betong) har det varit möjligt att utvärdera de övergripande mekaniska prestationerna av dessa. Erhållna data har analyserats numerisk och proverna har undersökt ytterligare med optisk mikroskopi.

Resultatet av detta examensarbete är viktigt för utvecklingen av nästa generation expansionsfästen och ger även ytterligare insikt och en djupare förståelse av tribologin av funktionella beläggningar.
Acknowledgments

First of all, I would like to thank my thesis supervisor, Prof. Joakim Odqvist, for his constant support, availability and constructive suggestions throughout this research project. I also would like to thank Anders Eliasson, coordinator of the Master’s programme, and everyone at KTH for giving me the warmest welcome in the cold Sweden.

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List of abbreviations

CoF = Coefficient of Friction

$h_{\text{eff}}$ = effective depth for anchors' installation

HEA = Hilti’s expansion anchor (non-official name)

SS = stainless steel

CS = Carbon steel

-L (after coating name) = laboratory coating process

-S (after coating name) = serial coating process

Un = uncoated anchor

ETAG = European Technical Approval Guideline

Po = Pullout

Pt = Pullthrough

Cc = Concrete cone
1. Introduction

Fasteners are a versatile means of securing steel elements to concrete and masonry constructions, allowing loads transmission between different components of a structure.

Different fasteners can be classified by their methods of installation:

- *Cast-in-place anchors*, as shown in Figure 1, are embedded in the concrete prior to casting. It is difficult to ensure a proper alignment, but they form a reliable connection with predictable behavior and failure mode.

![Figure 1: Examples of cast-in anchors [1].](image1)

- *Post-installed anchors*, as shown in Figure 1, are secured to the hardened and cured base material via drilling or direct installation. They allow fast and precise positioning and installation, and provide the freedom of adjusting the anchors' layout after concrete pouring. A big disadvantage is that their performances and behavior are much less predictable, it is then a major challenge to acquire additional knowledge for the optimization of this technology.

![Figure 2: Examples of post-installed anchors [1].](image2)

Being able to manipulate one or more variables of the anchor-concrete system is essential to gain additional insights and then produce significant improvements. In particular, the application of antifriction coatings to the functional part of post-installed anchors contributes to control and optimize their tribological behavior. This topic has not been object of in-depth researches yet and so there is a big potential for important outcomes.
1.1 Scope of the thesis

The primary goals of this research project are:

- To present the current state of the art of antifriction coating technology and its application on fastening solutions.
- To characterize different functional coatings through laboratory tests and optical microscopy analysis.
- To investigate experimentally the tribological behavior of expansion anchors quantifying their mechanical performances under standardized dynamic load conditions.
- To explore the correlation between laboratory and real-life conditions through data analysis with statistical methods.

Based on the results of the investigations, recommendations for the development of the next generation of expansion fasteners and methods of applying the proper functional coatings are proposed.
2. State of the Art

2.1 Post-installed anchors technology

2.1.1 Historical overview

The first modern post-installed anchors date back to the beginning of the Twentieth century, when Rawlplug® developed a new technology to secure components to building structures: it consisted of plugs made of wood or lead that were installed in pre-drilled holes and secured through the insertion of nails or screws (FIGURE 3). The rapid growth of the construction industry after the First and Second World War, led the continuous evolution of post-installed anchors, used for the renovation of destroyed buildings. In this period the first mechanical expansion anchors were presented, and powder-actuated fastening systems were developed for reparations in maritime applications [2] [3].

In 1990 the European Organisation for Technical Assessment (EOTA) was established to regulate the performances of construction products, including fastening systems. Nowadays, anchors manufacturers are developing new technologies to meet the implementation of new materials and techniques used in civil construction, while following the strict European Technical Approval Guidelines (ETAGs) [4].
2.1.2 Classification of post-installed fasteners

Nowadays, a wide variety of post-installed fastening systems are available. Each application requires different specifications and having a vast variety of solutions is advantageous but also makes the selection process more complex. In order to simplify the choice of different options, anchors have been classified in different categories.

The first differentiation of post-installed fasteners can be done by the installation mechanism [5]:

- **Drilled-in anchors** are installed in holes drilled into the base material. To ensure proper installation (FIGURE 4) it is important to control the alignment and the diameter of the hole, that must meet the tolerances required by the product selected. In addition, to avoid a significant loss of performances, it is important to properly clean the hole before the insertion of the fastener. Possible applications include the fastening to concrete of structural steel components (i.e. interior or exterior connections) or less critical elements (i.e. suspended lightweight ceilings) [6].

![FIGURE 4: Example of installation procedure for drilled-in anchors](image)
- *Direct-installation anchors* comprise studs or nails that are directly driven into the hardened base material by means of compressed air or explosive charge. This mechanism is versatile and fast, but the fasteners can be deflected by harder aggregates, decreasing the load capacity. Common lightweight applications include components for insulation, decking and grating [6].

Another possible classification for post-installed anchors, can depend on how the load is transferred to the base material ([Figure 5] [5]):

- *Mechanical interlock* involves transfer if load by means of a bearing interlock between the fastener and the base material. Fasteners that rely on this mechanism are headed anchors, anchor channels, screw anchors and undercut anchors.

- *Friction* is the load-transfer mechanism employed by expansion anchors. During the installation process, an expansion force is generated which gives to a friction force between the anchor and the sides of the drilled hole. This friction force is in equilibrium with the external tensile force.

- *Chemical bonding* transfers the tension load to the base material by means of adhesion and micro-keying. Bonded anchors employ this mechanism.

It is important noting that most of the anchors’ functionality relies on a combination of the previously presented mechanisms.

![Figure 5: Type of load transfer in different post-installed anchors](image.png)
2.1.3 Base materials

In the construction industry, a wide variety of material is used in order to meet the design and cost efficiency requirements of the project. The selection of a proper fastening solution is significantly influenced by the base material, which usually represents the weakest element of the connection. Reinforced concrete allows a reliable anchorage, but other base materials, such as hollow bricks, can reduce substantially the fasteners’ mechanical performances. An overview of the most common base materials for fastening applications in civil constructions is now presented, including a focus on their effects on anchors performances [8].

Reinforced concrete

Concrete has been the most utilized material in the construction industry since the first applications in the ancient Roman Empire age. It is a composite material consisting of a mixture of cement, coarse and fine aggregates, water and various additives. After a proper mixing, the material is cured and hardens in molds where the final form is produced [9] [10].

One of the most distinctive features of concrete is its high compressive resistance but this is combined with a poor tensile strength. This limitation can be overcome by introducing steel bars (reinforcing bars or rebars) before the hardening of the mixture: the obtained composite is called reinforced cement concrete. When compressive loads are applied to the structure, the concrete part is involved in keeping the integrity of the material, while the rebars get in actions during tensile loads [10].

It is typical for this material that cracks occur just after the hardening process or during the service life of the structure. In case of seismic events or other phenomena, the movement of cracks influence negatively the performances of the anchor-concrete connection. This is the reason why high-performances fastening solutions must be tested also in cracked concrete conditions to prevent failures [11].
Masonry materials

Masonry materials are the group of base materials employed in the fabrication of individual blocks for the construction of walls and building structures. These elements are joined together by means of workable pastes, called mortars, and the most common is the Portland cement [12].

Compared to reinforced concrete, masonry structures are characterized by inferior strength and form a less reliable connection with fasteners. One of the most critical factor affecting the fasteners effectiveness, is the masonry elements’ structure:

- Solid blocks are characterized by a dense structure with a high compressive strength. Some examples include bricks (such as clinker bricks and sand-lime bricks) building stones (such as marble, granite, travertine and limestone), cast stones, concrete blocks and many others. In comparison with reinforced concrete structures, it is not necessary to employ special solutions [3].
- Perforated hollow blocks are made from the same dense material of solid blocks, but are characterized by a perforated hollow structure. The cross-sectional area of these blocks is less than 75% of the gross area of the block measured in the same plane. In this case, the employment of proper fastening solutions is necessary: anchors with injection systems are the most common and reliable, but special expansion anchors can also be used [3].
2.1.4 Expansion anchors

Working principles

Mechanical expansion anchors are post-installed fasteners that transfer tension load to the concrete by friction and slightly by mechanical interlock (FIGURE 6). Its distinctive feature is the expansion that occurs when a tensile pre-stress is applied: the bolt is drawn into the metal sleeve and the local deformation in the concrete walls generates friction [5].

![FIGURE 6: Forces involved in fastening through expansion anchors [5].](image)

Depending on the way the expansion force is produced, mechanical expansion anchors can be classified into two categories:

- Torque-controlled: the pre-stressing force is generated by the application of torque to the bolt head or nut. They can be further differentiated into two types: bolt-type are characterized by a conic end of the bolts that accommodates the expansion of the sleeve, sleeve-type are characterized by the sleeve that encases the bolt and its design reaches the surface of the concrete. Some examples of torque-controlled expansion anchors include single-cone, double-cone, taper-bolt, wedge and bolts with internally threatened cone.

- Displacement- or deformation-controlled: the pre-stressing force is generated by the application of an impact force applied by hammering. This type of anchors is more sensitive to bad tolerances of the drilled hole.

![FIGURE 7: Some varieties of torque-controlled expansion anchors [5].](image)
**Failure mechanisms**

Expansion fasteners' technology is well established, and the concrete-steel connection is usually reliable in standard conditions. However, the anchorage effectiveness is influenced by many factors that most of the time are not easily controlled, like the base material strength and environmental conditions. In addition, the selection of a proper design and a correct installation are very important: the embedment depth (commonly indicated as $h_{eff}$), the anchor spacing, and the anchors dimensions are other crucial factors affecting their functionality [5].

In case of failure caused by critical tensile and shear loads, different scenarios can occur [5], [13]:

- Anchor failure: the bolt breaks because the loads overcame the material’s (usually steel) tensile strength. This type of failure is the least common and it is usually caused by the inappropriate selection of the anchor or by some defects in the material.
- Pull-out failure: the entire anchor slips out of the drilled hole without breaking. It is caused by inadequate expansion force applied against the walls (insufficient pre-stress applied or too wide drilled hole).
- Pull-through failure: the bolt slips out of the drilled hole leaving the sleeve inside. It is caused by insufficient internal friction between the two elements of the anchors.
- Concrete cone failure: the concrete breaks with a cone form, with the vertex coinciding with the embedment depth. This is the optimal failure mode because it means that anchor worked properly, and the load applied was fully transferred to the base material. It is also possible to get a partial concrete cone failure when the cone’s vertex is closer to the concrete surface.

![Failure modes for mechanical expansion anchors.](image)
**Hilti HEA anchors**

The object of study of the present research work is the Hilti expansion anchor HEA (Figure 9). Hilti HEA is a product designed to meet specific safety requirements for both cracked and uncracked concrete under static and seismic loadings.

**Figure 9:** Example of Hilti expansion anchor.

The version utilized in anchor tests is the M10 diameter and below, in **Table 1**, a short overview of the product specifications is presented. Detailed descriptions of the full range of Hilti’s expansion anchors can be found in the official Hilti catalogue [14].

**Table 1:** Extract of Hilti HEA technical datasheet.

<table>
<thead>
<tr>
<th>Material</th>
<th>Stainless steel, A4 (SS316)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating</td>
<td>Antifriction coating</td>
</tr>
<tr>
<td>Dimensions</td>
<td>M10 x 130 mm length</td>
</tr>
<tr>
<td>Approvals</td>
<td>ETA-98/0001 / 2018-02-09</td>
</tr>
<tr>
<td></td>
<td>- ETA C1-C2 (seismic)</td>
</tr>
<tr>
<td></td>
<td>- Fire resistance</td>
</tr>
<tr>
<td></td>
<td>BZS D 08-602 / 2016-08-17 (Shock)</td>
</tr>
<tr>
<td>Application examples</td>
<td>Structural steel</td>
</tr>
<tr>
<td></td>
<td>Façade</td>
</tr>
<tr>
<td></td>
<td>Mechanical equipment</td>
</tr>
<tr>
<td></td>
<td>Racks</td>
</tr>
<tr>
<td></td>
<td>Hand rails</td>
</tr>
</tbody>
</table>
2.2 Tribology of Coated Expansion Anchors

Tribology comprises the study of friction, wear and lubrication of interacting surfaces in relative motion: wear is defined as the material consumption and loss of mechanical performances caused by friction, while lubrication is a method to control wear and reducing the friction [15].

Even early civilizations invented techniques to control this phenomenon, such as simple lubricants, low friction surfaces and rudimental bearings; however, the lack of a solid theoretical knowledge compromised the development of truly optimized solutions and only after World War II this science began to be deepened [16].

2.2.1 Tribological behavior of expansion anchors

As previously introduced, expansions anchors’ functionality relies almost purely on friction. When installed in concrete, they represent a complex tribological system, where different elements of different materials and surface properties are in contact, with the presence of a variety of loads.

There are three main systems that can be described in the expansion anchor – concrete system: threat-nut friction system, external friction system and internal friction system.

Thread-nut friction system

As the name suggests, this system is represented by the friction occurring between the threaded part of the bolt and nut, a connection that is required for the support of steel elements to the base concrete. Its tribology is important to regulate this joining: a low friction would result in a loose connection between the two elements, while a high friction would not permit an easy insertion of the nut into the threaded bolt.

This tribological system has not been investigated in the present research project, but a deeper study can be very useful to have a better understanding and control of the prestress applied during torquing.
**External friction system**

The external friction system in expansion fasteners is the tribological system that describes the behavior of the external part of the sleeve and the base material (concrete). The friction occurring between these two elements is essential to ensure a solid fastening.

The force generated by the sleeve during expansion is transferred to the concrete which generates an opposite friction force that avoid the slippage of the anchor.

This is a complex tribological system because it is common that the sleeve does not expand homogeneously, creating not uniform contact areas, and also the concrete is not a homogeneous material.

**Inner friction system**

The object of the study of the present research project is the tribological system that includes the sleeve and the expansion cone of the bolt. For the correct functionality of expansion anchors, the sleeve must slide along the bolt, but the resistance of the concrete and the rigidity of the sleeve generate a normal force that create a friction force opposed to the sliding direction.

Being able to control through a proper coefficient of friction, is crucial to obtain the desired functionality: having a too high coefficient of friction between the parts would prevent the expansion, while a too small coefficient of friction would allow the sleeve to slip from the cone. The application of functional coatings, in particular antifriction coatings, permit a better control of this parameter.
2.2.2 Anti-friction coatings

Oil-based lubrication is the most traditional and common method to reduce the friction between of moving parts. This technique is very efficient, but it does not allow to work in clean conditions. In recent years new technologies are being developed to overcome this limitation and solid lubricants are evolving rapidly [17].

Anti-friction coatings, also known as bonded coatings, are products similar to paints. They are based on a resin matrix and a solvent where small particles of solid lubricants are dispersed. The most common fillers for this kind of coatings are polytetrafluoroethylene (PTFE), waxes, Molybdenum disulphide (MoS₂) and graphite [17], [18].

Application methods

Anti-friction coatings can be applied in several methods but two are the most common techniques currently utilized [19]:

- Spraying: with this technique an extremely thin and uniform coating is achieved. The process can be performed with compressed air or, less commonly, through electrostatic adhesion.
- Dipping: with this technique a thicker and less homogeneous coating is obtained. This process is suitable for large lots of products of small dimensions, such as bolts and screws. The coating thickness can be controlled regulating the centrifugal speed of the machine.

Anti-friction coating variants

In the table below, **TABLE 2**, a short description of the coating variants employed in the research project is presented. Considering these compounds are commercial products bought from third-party companies, it is not possible to know the exact components and mixture percentages.
**TABLE 2: Specifications of functional coating variants.**

<table>
<thead>
<tr>
<th>Coating 1</th>
<th>Coating 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matrix</strong></td>
<td>Alkyd polyester resin</td>
</tr>
<tr>
<td><strong>Additives</strong></td>
<td>Zinc oxides, Waxes, PTFE</td>
</tr>
<tr>
<td><strong>Solvent</strong></td>
<td>Water</td>
</tr>
<tr>
<td><strong>Properties</strong></td>
<td>Anti-friction effect</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coating 3</th>
<th>Coating 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matrix</strong></td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Additives</strong></td>
<td>Lubricant (unknown type)</td>
</tr>
<tr>
<td><strong>Solvent</strong></td>
<td>Water, amino ethanol</td>
</tr>
<tr>
<td><strong>Properties</strong></td>
<td>Anti-friction effect</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coating 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matrix</strong></td>
</tr>
<tr>
<td><strong>Additives</strong></td>
</tr>
<tr>
<td><strong>Solvent</strong></td>
</tr>
<tr>
<td><strong>Properties</strong></td>
</tr>
</tbody>
</table>
3. Experimental

3.1 Samples preparation

The samples preparation procedure consists of applying the functional coating to the proper uncoated samples. For the present research project, two methods have been used: laboratory and serial coating processes.

3.1.1 Laboratory coating process

Two types of samples (FIGURE 12) have been utilized for different tests: full M10 bolts have been used for anchor tests in concrete, while machined parts of M16 bolts (SRV samples) have been used for friction measurements.

![Figure 12: Representation of the inner friction system in expansion anchors.](image)

3.1.2 Laboratory coating process

Laboratory coating is the process utilized for the application of new coatings that are still under development and don’t have an approved composition.

In the table below, TABLE 3, an outline of the benefits and the limitations of this process is presented.
**Table 3: Advantages and disadvantages of laboratory coating process.**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous coating</td>
<td>Different from standard process</td>
</tr>
<tr>
<td>Rapid in-house process</td>
<td>Not suitable for large lots of samples</td>
</tr>
<tr>
<td>Little amount of substances</td>
<td></td>
</tr>
<tr>
<td>required</td>
<td></td>
</tr>
<tr>
<td>Controlled conditions</td>
<td></td>
</tr>
</tbody>
</table>

The coating procedure has been conducted utilizing the QPI-168 dip coater by Qualtech Products Industry Co. Ltd. The following steps have been followed [20]:

1. Dilution of the concentrated solution to the desired solid content;
2. Stirring of the solution using a magnetic stir plate;
3. Cleaning of uncoated samples in ultrasound with diluted ethanol for 10 minutes;
4. Attachment of samples to the dip coater machine;
5. Dip coating of the samples into the coating solution; Machine settings in Appendix
6. Drying of the samples into a furnace at 80 °C for 3 hours.

### 3.1.3 Serial coating process

Serial coating is the process employed by Hilti for coating of standard anchors currently on the market, and it has been utilized for standard or soon-to-be-approved coatings.

In the table below, **Table 4**, an outline of the benefits and the limitations of this process is presented.

**Table 4: Advantages and disadvantages of serial coating process.**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same process utilized for standard products</td>
<td>Inhomogeneous coating</td>
</tr>
<tr>
<td>(easy comparison)</td>
<td>Time-consuming process (need to wait for production schedules)</td>
</tr>
<tr>
<td>Suitable for large lots of samples</td>
<td>Large amount of substances required</td>
</tr>
<tr>
<td></td>
<td>Not perfectly controlled conditions</td>
</tr>
</tbody>
</table>
The coating procedure is conducted utilizing a centrifuge, represented in Figure 13. The machine can host several hundreds of samples at the same time, but the resulting coating is not uniform: this inhomogeneity is caused by bolt-bolt or bolt-wall contact points.

**Figure 13:** Centrifuge used for standard coating process.

### 3.2 Tribology tests

The most important parameter for the characterization of antifriction coatings is the measurement of the coefficient of friction. These measurements have been obtained through tribology tests conducted in laboratory conditions using a tailored test-rig following standard procedures [21] [22].

The aim of these tests is to simulate the tribological behavior of bolt and sleeve in expansion anchors. Friction between these elements occurs during installation and throughout the whole life of the anchor.

#### 3.1.1 Materials

<table>
<thead>
<tr>
<th>Test-rig</th>
<th>Hilti SRV custom test-rig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>“Hitman” custom software.</td>
</tr>
<tr>
<td>Samples</td>
<td>SRV sample: portion of M16 standard stainless steel HEA bolts obtained through machining. It represents the cone of the bolt where the sleeve slides during expansion. These samples have been coated with different functional coatings.</td>
</tr>
</tbody>
</table>
- Counterpart sample: parallelepipedal block of stainless steel representing the sleeve of the expansion anchor.

Coatings
- Coating 1L (laboratory-coated anchor with Coating 1)
- Coating 1S (serial-coated anchor with Coating 1)
- Coating 2L (laboratory-coated anchor with Coating 2)
- Coating 2S (serial-coated anchor with Coating 2)
- Coating 3
- Coating 4
- Coating 5
- (Uncoated)

3.2.2 Procedures

During the tribology test, the two samples are put in relative motion against each other while a constant normal load is applied. The SRV samples is set in motion through a reciprocating drive and the counterpart sample is held still [21].

The procedure below has been followed:

7. Start up of the test-rig;
8. Start up of Hitman software;
9. Configuration of test parameters in Hitman software;
10. Cleaning of the samples using diluted ethanol;
11. Fixing the SRV samples to its sample holder (carrell);
12. Check of the horizontal alignment of the SRV sample;
13. Fix of the counterpart sample to its sample holder;
14. Attachment of the carrell holding the SRV sample to the Hilti SRV piston;
15. Start of the testing program;
16. Removal of the samples from the holders.

3.2.3 Input and output parameters

All the tests were conducted with a normal load set to 500 N, a value that has previously been proven to be realistic during the installation and working life of an expansion anchor. Only half a cycle has been set to simulate the tribological behavior of the first expansion of the sleeve on the bolt’s cone (TABLE 5).
The coefficient of friction (CoF) is defined as the absolute value of friction force curve divided by the normal load curve measured by the machine, it is then an indirect output.

**TABLE 5: Input and output parameters of tribology tests.**

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Normal load value</td>
<td>- Actual normal load curve</td>
</tr>
<tr>
<td>- Normal load curve</td>
<td>- Friction force curve</td>
</tr>
<tr>
<td>- Number of cycles</td>
<td>- Coefficient of friction curve (indirect)</td>
</tr>
<tr>
<td>- Amplitude of cycles</td>
<td>- Static coefficient of friction</td>
</tr>
<tr>
<td>- Test duration</td>
<td>- Dynamic coefficient of friction</td>
</tr>
<tr>
<td>- Frequency of data recording</td>
<td>- Delta(Static, Dynamic CoF)</td>
</tr>
<tr>
<td></td>
<td>- Scuffing effect</td>
</tr>
</tbody>
</table>

Before getting the information from the coefficient of friction curve, it is important to check that the normal load imposed was constant. If the alignment of the sample is not appropriate, a fluctuation of the load curve might occur (GRAPH 1).

**GRAPH 1: Example of fluctuations of the constant normal load applied.**

From the coefficient of friction curve, it is possible to obtain the static and dynamic coefficient of friction of the system (GRAPH 2), essential values for the tribological characterization of the coating variants.
3.2.3 Test rejection criteria

The tribology tests conducted with the Hilti SRV test-rig have been rejected if the alignment of the samples was not optimal:

- The SRV samples alignment has been checked carefully before the test with a displacement measuring device. In case a good alignment could not be found (SRV sample not well-machined), the SRV sample was discarded prior the testing.
- The countersample alignment was not easily controllable because of the sample holder design. It was only possible to see if the alignment was appropriate by checking the contact line after the test has been performed. In Figure X an example of good and bad contact line is shown. In case of a bad contact line, the test has been rejected because the actual pressure applied can differ significantly (same load, minor contact area) and additional wear occurs, altering the friction behavior of the system.
**Figure 14**: Example of the acceptable (a) and non-acceptable (b) contact lines in the countersamples.
3.3 Dynamic Tests

The mechanical performances of the anchors were tested in concrete, simulating the real-life behavior of the products with different coating variants under static and dynamic loadings.

The employed test evaluates the long-term mechanical performances of expansion anchors under significant normal load applied. The base material is low strength reinforced concrete with 0.1 mm cracks that are opened to 0.3 mm on every cycle.

The main parameters utilized for the quantification of the performances of the anchors are the vertical displacement (the minor displacement the better) and the pullout force (residual force required for pullout at the end of the 1000 cycles).

3.3.1 Materials

**Machines**
- Cracked concrete test rig (for crack cycling)
- Tension test rig (*FIGURE 15*)

**Tools**
- Drilling machine and de-duster
- Hammer
- Torque

**Measuring devices**
- Displacement transducer
- Prestress measuring device
- Crack amplitude sensors

**Base material**
- Concrete C20/25
- Cracked (0.1 mm cracks):
- Reinforcement bars (“H disposition”)

**Samples**
- HEA M10 (130 mm length) full anchor bolts coated with different functional coatings.

**Coatings**
- Coating 1L (laboratory-coated anchor with Coating 1)
- Coating 1S (serial-coated anchor with Coating 1)
- Coating 2L (laboratory-coated anchor with Coating 2)
- Coating 2S (serial-coated anchor with Coating 2)
- (Uncoated)
3.3.1 Testing protocol

All the tests performed were regulated by the European Technical Approval Guidelines (ETAGs), and the testing procedures are described on the ETAG 001. The present test is referred in the Annex A 04/2013 [23].

Each test was performed individually:

1. Drilling hole along the crack (deeper than $h_{eff}$)
2. Removal of dust and cleaning of the hole
3. Measuring of the diameter of the drilled hole at depth = $h_{eff}$
4. Check of the quality of the crack along the drilled hole
5. Hammering of the anchor until $h_{eff}$
6. Insertion of washer and nuts
7. Securing anchor to measuring devices
8. Application of prestressing force $F_{DT1}$ through manual torque
9. Wait of 10 minutes for relaxation
10. Unloading
11. Application of $F_{DT2}$ (half $F_{DT1}$) through manual torque
12. Wait for concrete relaxation
13. Partial unloading through torqueing
14. Start of the test with the application of constant normal force
15. Start of cracks opening cycles (0.1 mm – 0.3 mm)
16. End of 1000 cycles
17. Application of increasing normal load until pullout

The quality of the crack along the drilled is checked at the functional depth of the anchor ($h_{eff}$). The hole is discarded if the crack is not centered (does not pass through one of the diameters of the drilled hole).

The protocol gives some limitations to define if the test passed or failed: the vertical displacement of the anchor at 20 cycles must not exceed 2 mm and not exceed 3 mm at the end of the test (after 1000 cycles).

### 3.2.3 Input and output parameters

**TABLE 6** summarizes the input and output parameters for the Dynamic Tests.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Prestress applied</td>
<td>- Vertical displacement curve</td>
</tr>
<tr>
<td>- Crack opening amplitude</td>
<td>- Displacement @1, 20, 1000 cycles</td>
</tr>
<tr>
<td>- Constant normal load applied</td>
<td>- Pumping effect</td>
</tr>
<tr>
<td>- Number of cycles</td>
<td>- Load curve</td>
</tr>
<tr>
<td></td>
<td>- Load applied after prestress</td>
</tr>
<tr>
<td></td>
<td>- Pullout force</td>
</tr>
<tr>
<td></td>
<td>- Failure mode</td>
</tr>
</tbody>
</table>
The crack movement is represented by a sinusoidal curve whose amplitude varies between 0.1-0.3 mm for 1000 cycles.

In **GRAPH 3**, the tensile loads applied to the tested anchor is shown. Through this plot it is possible to visualize the three main sections of the test:

- Section 1 comprises the application of prestress and the relaxation that occurs.
- Section 2 represents the 1000 cycles of the crack opening, when a constant load is applied.
- Section 3 shows the pullout test conducted after the cycling test.

**GRAPH 3**: Tensile load during Dynamic Test.
3.4 Static Tests

The Static Tests evaluate the normal load required for pullout of the expansion anchors in low strength reinforced concrete with 0.3 mm cracks. The test is conducted in confined conditions, which means that a cylindric metallic component is set around the anchor avoiding the concrete cone failure mode.

The main parameter utilized for the quantification of the performances of the anchors is the force required to obtain failure.

3.4.1 Materials

Machines - Cracked concrete test rig
- Tension test rig

Tools - Drilling machine and de-duster
- Hammer
- Torque
- Contain cylinder

Measuring devices - Displacement transducer
- Prestress measuring device

Base material - Concrete C20/25
- Cracked (0.1 mm cracks):
  - Reinforcement bars ("H disposition")

Samples - HEA M10 (130 mm length) full anchor bolts coated with different functional coatings.

Variants - Coating 1L (laboratory-coated anchor with Coating 1)
- Coating 1S (serial-coated anchor with Coating 1)
- Coating 2L (laboratory-coated anchor with Coating 2)
- Coating 2S (serial-coated anchor with Coating 2)
- Coating 3
- Coating 4
- Coating 5
- (Uncoated)
3.4.1 Testing protocol

All the tests performed were regulated by the European Technical Approval Guidelines (ETAGs), and the testing procedures are described on the ETAG 001. The present test is referred in the Annex A 04/2013 [23].

Each test was performed individually:

1. Drilling hole along the crack (deeper than \( h_{\text{eff}} \))
2. Removal of dust and cleaning of the hole
3. Measuring of the diameter of the drilled hole at depth = \( h_{\text{eff}} \)
4. Check of the quality of the crack along the drilled hole
5. Hammering of the anchor until \( h_{\text{eff}} \)
6. Insertion of washer and nuts
7. Securing anchor to measuring devices
8. Application of torque \( \tau_{\text{ST1}} \)
9. Wait of 10 minutes for relaxation
10. Application of torque \( \tau_{\text{ST2}} \) (half \( \tau_{\text{ST1}} \))
11. Crack opening to 0.3 mm
12. Insertion of the Pullout machine
13. Application of increasing normal load until failure occurs

As for the Dynamic Test, the quality of the crack along the drilled is checked at the functional depth of the anchor (\( h_{\text{eff}} \)). The hole is discarded if the crack is not centered (does not pass through one of the diameters of the drilled hole).

3.4.3 Input and output parameters

**TABLE 7** summarizes the input and output parameters for the Static Tests.

<table>
<thead>
<tr>
<th><strong>Input parameters</strong></th>
<th><strong>Output parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Prestress applied</td>
<td>- Load curve</td>
</tr>
<tr>
<td>- Crack opening</td>
<td>- Pullout force</td>
</tr>
<tr>
<td>- Increasing normal load</td>
<td>- Load vs displacement</td>
</tr>
<tr>
<td></td>
<td>- Failure mode (Po, Pt)</td>
</tr>
</tbody>
</table>
In **GRAPH 4**, an example of the resulting load-displacement curve is presented: the pullout force is defined as the maximum of this plot and gives the load capacity of the tested anchor.

**GRAPH 4:** Load-displacement curve obtained with Static Test.
4. Results

4.1 Tribology tests

GRAPH 5 represents the coefficient of friction against time curves for the variant coated with Coating 5, obtained during tribology tests.

GRAPH 5: Tribology tests of the variant coated with Coating 5.

From the above graph, several information can be obtained: the static and dynamic coefficient of friction, the delta between the two values and a quantification of the scuffing effect. In the next paragraphs, all the obtain results are presented.
4.1.1 Static coefficient of friction

The static coefficient of friction value is represented by the peak of the static region (highlighted in **GRAPH 6**) in the CoF-time curve [24].

**GRAPH 6**: Static coefficient of friction in the CoF-time graph.

Below, in **GRAPH 7**, all the values obtained by variants are plotted. The boxplot shows the median value and the interquartile range of the results.

**GRAPH 7**: Static coefficient of friction values obtained.
4.1.2 Dynamic coefficient of friction

The dynamic coefficient of friction is given by the first value obtained in the dynamic region (highlighted in GRAPH 8) in the CoF-time curve [24].

**GRAPH 8:** Dynamic coefficient of friction in the CoF-time graph.

Below, in GRAPH 9, all the values obtained by variants are plotted. The boxplot shows the median value and the interquartile range of the results.

**GRAPH 9:** Dynamic coefficient of friction values obtained.
4.1.3 Delta (Static, Dynamic CoF)

The difference between the static and dynamic coefficient of friction value is shown in **GRAPH 10**. A high value indicates a sudden change from static to dynamic behavior.

**GRAPH 10**: *Delta between static and dynamic coefficient of friction in the CoF-time graph.*

Below, in **GRAPH 11**, all the values divided by variants are plotted. The boxplot shows the median value and the interquartile range of the results.

**GRAPH 11**: *Delta between static and dynamic coefficient of friction values obtained.*
4.1.4 Scuffing

The scuffing effect is a type of adhesive wear occurring in highly loaded systems and can significantly affect the dynamic CoF. It has been quantified by calculating the angular coefficient of the trendline of the dynamic region (GRAPH 12) [22], [25].

**GRAPH 12**: Quantification of scuffing in the CoF-time graph.

Below, in **GRAPH 13**, all the values divided by variants are plotted. The boxplot shows the median value and the interquartile range of the results.

**GRAPH 13**: Scuffing values obtained.
4.2 Dynamic Tests

4.2.1 Displacement

The vertical displacement when a normal load is applied is the main criteria to quantify the mechanical performances of expansion anchors during dynamic testing. In GRAPH 14 an example of displacement behavior is presented, while the results at 1 cycle (GRAPH 15), 20 cycles (GRAPH 16) and 1000 cycles (GRAPH 17) are displayed for each variant.

GRAPH 14: Example of Displacement vs Cycles curve in Dynamic Test.

GRAPH 15: Displacement at 1 cycle results.
**GRAPH 16:** Displacement at 20 cycles results.

**GRAPH 17:** Displacement at 1000 cycles results.
4.2.2 Pullout Force

The pullout test is performed at the end of the crack opening cycles and it consists of an increasing normal load until failure of the concrete-anchor system occurs. The pullout force is defined as the maximum of the load curve obtained (GRAPH 18).

**GRAPH 18:** Example of Load vs Displacement curve in Dynamic Test.

Below, the boxplot of the obtained results for each variant is presented (GRAPH 19).

**GRAPH 19:** Pullout resistance results in Dynamic Test.
4.3 Static Tests

4.3.1 Pullout Force

The pullout force is the main criteria to quantify the mechanical performances of expansion anchors during Static Tests. In GRAPH 20 an example of pullout behavior is presented, while the boxplot of the obtained results for each variant is shown in GRAPH 21.

GRAPH 20: Example of Load vs Displacement curve in Static Test.

GRAPH 21: Pullout resistance results in Static Test.
5. Discussions

5.1 Coefficient of friction

5.1.1 Test rig set-up

*Calibration*

The friction tests were supposed to be performed on a different test-rig, Bruker® UMT Tribolab, but some problems with the calibration occurred: as shown in **GRAPH 22**, the measured friction force had negative values at the beginning of the test. At that point, since the reciprocating movement has not started yet, the friction force is expected to be zero. This is probably caused by some bending occurring at the moment of the two samples getting in contact.

![Graph 22: Calibration issues occurred with the first friction tests.](image)

Several modifications of the Bruker® UMT Tribolab sample holders were performed in order to better control the samples alignment and securing, but only minor improvements were obtained.
Because of this calibration issues, the Hilti SRV test-rig was utilized for the friction tests, give more reliable and consistent results. In some cases negative values for the friction force were also measured at the beginning of the tests, but of minor magnitude.

*Modification of sample holders*

The two test-rigs, Bruker® UMT Tribolab and Hilti SRV, are both employing SRV bolts (see Chapter 4) as the main sample, but the geometry of the cylinders for the securing slightly differs, as illustrated in Figure 16.

![Figure 16: Geometry of the two SRV samples.](image)

In order to use both them with Hilti SRV test-rig, a modification of its original sample holder was necessary: in Figure 17, the two variants of samples holder used with Hilti SRV test-rig are presented.

![Figure 17: Samples holder used for the two variants of SRV samples.](image)
5.1.2 Coefficient of friction curves

Determination of Static and Dynamic CoF

As showed in the previous chapter, the static and dynamic coefficients of friction can be easily evaluated observing the curve shape, however, in some cases, the determination of their values can be ambiguous.

**GRAPH 23** shows two cases were the determination of the static coefficient of friction is unclear. When a distinct peak is not present, probably due to high scuffing in that test, the point in correspondence of the change of slope has been selected.

![Graph 23: Example of unclear static coefficient of friction.](image)

The evaluation of the dynamic coefficient of friction can be ambiguous too: in **GRAPH X**, an example of unusual dynamic friction behavior is presented. In general, the lowest value close to the peak of the static CoF has been used to determine the dynamic CoF.
Scatter in results

The boxplots of the obtained values for the static and dynamic coefficient of friction (see Chapter 4) present a relevant scatter but still in the expected range. Tribology is not a property of a material that can be easily measured through proper machines, but rather a property of a system, so more variables are present and can influence significantly the results.

In the present research work, using the methodology described in Chapter 3, there are several factors that can cause a scatter in the results, as presented in Table 8.

**Table 8: Factors influencing the scatter of the results.**

| Coating adhesion | If the coating is easily removed by scratching, the measured coefficient of friction is influenced by the base material (stainless steel). The coating adhesion could be improved by changing the chemical composition of the substance or manipulating some parameters (i.e. drying time and temperature) of the coating process. |

**Graph 24: Example of unclear dynamic coefficient of friction.**
<table>
<thead>
<tr>
<th>Coating homogeneity</th>
<th>Portions of areas with no or very thin coating (more common in serial-coated samples) can influence the friction measurements. Optimizing the centrifuge design and number of bolts employed could improve the homogeneity of serial coated samples.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface roughness</td>
<td>Surface roughness influences the adhesion of the two samples in contact, the and the abrasion of the system. This behavior can promote scuffing and then an irregular and ambiguous dynamic coefficient of friction.</td>
</tr>
<tr>
<td>SRV sample alignment</td>
<td>A tilted sample generates a height change in the direction of load during the test, causing an alteration of the applied normal force. This happens because the machine is not able to calibrate the load quickly enough to the new height during the reciprocating movement.</td>
</tr>
<tr>
<td>Countersample alignment</td>
<td>If the samples are not perfectly aligned, the contact line can be only partial and so a higher pressure is applied (less area, constant normal load). Higher pressure can promote scuffing and the coating is more easily removed, altering the results of the dynamic behavior.</td>
</tr>
</tbody>
</table>

5.1.2 Scuffing effect and optical microscopy

One of the main reasons why coating on expansion anchors was introduced, was to reduce the scuffing effect. The mechanical performances of anchors with high scuffing is less predictable, something that absolutely needs to be avoided in structural engineering.

This factor has also been investigated with optical microscopy: it is easily noticeable the difference between a sample coated with a low friction coating (FIGURE 18, Coating 5) when compared to the evident wear of an uncoated sample (FIGURE 19).
**Figure 18:** Scuffing of Coating 5 sample.

**Figure 19:** Scuffing of uncoated sample.
5.2 Dynamic Tests

5.2.1 Displacement

*Displacement @1 cycle*

One of the first parameters that has been investigated is the vertical displacement of the anchor after 1 cycle of crack opening: this value was expected to be similar for each variant, but it has been found that it is independent by the coating type and the scatter of results is significant.

It has been hypothesized that the factors that might influence the first displacement are included in the initial conditions. Since the base material used for all the samples is the same (reinforced concrete C20/25) and the crack has been checked carefully before each test, the prestressing conditions were evaluated: for the investigation, the actual load to reach the constant testing load was quantified referring to the load-time plot (GRAPH 24).

![GRAPH 24: Determination of actual load applied to reach testing load.](image)

The different values are caused by the unspecified instructions in the testing protocol for the second unloading phase. It is then clear that having a different final prestress applied, the load required to reach the normal load during crack opening cycles differs from test to test.

Comparing the obtained values with the vertical displacement of the anchor at 1 cycle, a strong correlation has been found, as shown in GRAPH 25.
**Graph 25:** Correlation between load applied to reach testing load and displacement at 1 cycle.

**Displacement @20 and @1000 cycles**

As presented in the testing protocol (Chapter 3), the displacements at 20 and 1000 cycles are important to evaluate the performances of the anchor: if the displacement at 20 and 1000 cycle is below, respectively, 2 and 3 mm, the anchor successfully passed the test.

Directly comparing these two values, a strong linear correlation has been found as shown in **Graph 26**.

**Graph 26:** Correlation between displacement at 20 cycle and final displacement (1000 cycles)
This correlation is very important for the prediction of the final displacement just after a few cycles: it has been found that the vertical displacement at 1000 is equal to about 1.5 times the displacement at 20 cycles.

5.2.2 Sample size

The results for the pullout tests at the end of the 1000 cycles, show that all the variants behaved similarly. Only the uncoated samples show an indication of better performances, about 15-20% better than the other variants.

However, it is important to consider that for the coated variants 5 tests have been performed, while for the uncoated variants only two tests have been performed. This is due to the high cost of each individual test and the unpredictable behavior of the concrete slab (some drilled holes might not be usable if the crack is not located correctly.)
5.3 Static Tests

5.3.1 Pullout Force

Pullout Force

Taking into considerations all the values of the pullout force, it is hard to draw conclusions since the scatter is significant. However, if the results for the Coating 1S variants are divided by the slab utilized, as presented in GRAPH 27, it becomes clear that this factor plays a crucial role, and in this case the scatter is in the expected range.

GRAPH 27: Pullout Static Tests for Coating 1S divided by plate.

If this division is applied to all the sample variants (GRAPH 28), a clearer overview of the result can be observed. In particular, if the comparison of the pullout force values is only made within the same slab, some interesting conclusions can be drawn:

- Slab 1: The serial-coated variants (Coating 1S and Coating 2S) had about 20% higher pullout force then the only laboratory-coated variant (Coating 1L).
- Slab 2: All the variants are laboratory-coated and the results are similar.
- Slab 3: the Coating 1S variant is 27% less performant than compared to the uncoated variant (median values are compared).
**GRAPH 28:** Results of static *Pullout tests divided by plate.*
5.4 Correlations between tests

5.4.1 Static CoF vs Dynamic Test Pullout Force

An insight of a very important correlation can be found while comparing the static coefficient of friction obtained with the tribology tests (GRAPH 29) and the pullout force values of the Dynamic Test (GRAPH 30). In fact, developing a coating with an appropriate static coefficient of friction, would optimize the pullout resistance of the anchor.

**GRAPH 29: Static coefficient of friction values in tribology tests.**

**GRAPH 30: Pullout resistance results in Dynamic Test.**
5.4.2 Scuffing vs Dynamic Test Pullout Force

The uncoated variant in the Dynamic Test has been the one that has had the better performances: in fact, it has had the highest pullout resistance (see Graph 30 in the previous page) but also a very good final displacement (Graph 31). Since the uncoated has a very high scuffing (Graph 32) compared to the other variants, this might be the factor that has influenced the most its mechanical performances.

Graph 31: Scuffing values in tribology tests

Graph 32: Displacement at 1000 cycles results in Dynamic Test.
5.5 Social Implications

5.5.1 Safety in building constructions

Hilti’s expansion anchors are employed to ensure a correct installation of structural and non-structural elements to cracked and non-cracked concrete and are certified to withstand strong seismic events. Even in advanced European countries such as Italy, where the earthquake hazard is significant, most buildings are not complying with the safety regulations and it is common that a moderate seismic activity is causing severe damages to buildings and people [14] [26] [27].

Improving safety measures in building constructions is the main motivation for this scientific investigation. In fact, controlling expansion anchors’ tribological behavior is a key step to increase their mechanical performances, and designing an optimized friction system would bring several benefits:

- **Installation reliability.** Installation is crucial phase to guarantee a proper bond with the base material and it is highly correlated by the friction of the bolt-sleeve system. Once the fastener has been hammered into the concrete, it is challenging for the worker to assess if the expansion of the sleeve has occurred properly. Having more reliable friction performances would lower the chances of improper installations that might cause hazardous failures.

- **Safety in standard conditions.** In standard operating conditions, Hilti’s expansion anchors are designed to support structural and non-structural elements such as structural steel components, façades, mechanical equipment, racks and hand rails. Optimizing the friction of the steel-concrete and sleeve-cone systems would prevent the bolt to slide off the original position or, in more critical cases where severe loadings are involved, a controlled displacement of the bolt would facilitate the detection of a possible imminent failure.

- **Safety in extreme conditions.** Hilti’s expansion anchors are approved for C1 and C2 seismic categories and during these events the sleeve is in relative motion to the bolt while keeping a strong bond with the concrete. This mechanism can be substantially improved by optimizing the anchor’s tribology, resulting in even more effective seismic resistance.
6. Conclusions and Future Works

6.1 Conclusions

In Table 9, a summary of all the findings for each test are presented:

**Table 9: Conclusions for each test.**

<table>
<thead>
<tr>
<th>Tribology tests</th>
<th>Dynamic tests</th>
<th>Static Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Built expertise in Hilti SRV test-rig calibration and control of parameters.</td>
<td>• It is possible to predict the final displacement after only 20 cycles</td>
<td>• Slab plays a significant role in the results of the pullout force. Only results from same slab should be compared.</td>
</tr>
<tr>
<td>• New insights on possible influencing factors in friction tests for further investigations.</td>
<td>• The application of a consistent prestress is key to control the initial displacement</td>
<td>• A relevant difference between serial- and laboratory-coated samples has been found.</td>
</tr>
<tr>
<td>• Scuffing seems a very interesting parameter for further studies.</td>
<td>• First insights on correlation between static CoF and pullout force</td>
<td>• In the same slab Uncoated was ~30% more performant than standard Coating 1S.</td>
</tr>
</tbody>
</table>

It has been hard to find a direct correlation between the values obtained through characterization of coatings and anchor tests. This is probably caused by the complexity of the systems involved that include multiple variables that are not completely possible to control.

However, the outcome of this research project can be considered positive because some important clues regarding this correlation has been found (i.e. static CoF and Dynamic Test pullout force). In addition, very significant results in the anchor tests lead to relevant results:
- The uncoated variant seems to be the most performant, which is surprising because the application of functional coating was expected not only to make the results more stable but also increasing the performances.
- In Static Tests an important difference in pullout force has been found in serial-coated variants against laboratory-coated variants. This proves that for these tests the coating process influence the results in higher scale compared to the coating composition.
- Even if the differences in the functional coating fillers can be observed during the tribological characterization, this parameter does not influence evidently the results in anchor tests.

6.2 Future works

Thanks to the obtained results, some future works could be recommended:

- Additional coating characterization: the quantification of additional parameters of the functional coating applied (roughness, coating thickness...) might help finding new correlations with anchor tests. This investigation is also helpful to better understand the differences between the laboratory and serial-coating process.
- Confirm the correlation between static coefficient of friction and pullout force in Dynamic Tests: additional tests on different variant using the Dynamic Test protocol might confirm or reject the possible link between these two parameters. Testing coatings with extremely high and low static coefficient of friction should support the interpretation of the results.

Additionally, the testing methodology needs some adjustments in order to obtain more consistent and valid results:

- In Dynamic Tests the protocol for the prestressing region should be more detailed in order to have a consistent load applied to reach the normal constant load during test and control the first displacement.
- In Static Tests only tests conducted in the same slab should be compared. Otherwise normalization to the concrete strength must be performed (the concrete strength of the slabs utilized is within the range C20 and C25, but no additional detail is known).
7. References


