Assessment of the variability of the pull-off technique for measuring tensile adhesion strength on ceramic tile claddings and mortars

Extended Abstract

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1 INTRODUCTION

The search for a higher level of sustainability in construction, associated with the improvement of building performance, is a topic that society is increasingly focusing on (Flores-Colen, 2009). As such, the goal is for construction elements to have an extended service life and contribute to a good performance of the buildings. Aiming to determine the in-service performance, several assessment methodologies have been developed, including in situ test methods. Therefore, the present dissertation is focused on the knowledge of evaluation techniques for in-service performance and degradation of renders and ceramic tiling claddings.

There are several in situ test methods that can give an important contribution to the study of the in-service evaluation of coating systems, improving the present knowledge of the factors that influence that performance. However, through the analysis of the various standards and technical documents, it is possible to conclude that a consensus has not yet been reached regarding the definition of a procedure for each type of test method, including decision criteria.

Associated with the lack of standardized procedures and evaluation criteria, the in situ test methods present a large variability. In this context, the present dissertation analyses the various factors that influence the variability of a test method to evaluate tensile adhesion strength – the pull-off test. An experimental campaign was developed with the following objectives:

- to analyse the different types of failure obtained from the pull-off test;
- to understand if the results obtained from the tests are within expectations, taking into account the values given by suppliers (when available) and if these comply with the requirements specified in the standards;
- to compare the results obtained from the laboratory campaign with the results obtained from the in situ campaign;
- to study the factors that are expected to influence the result of the pull-off test, namely:
  o the use of metallic discs with different thicknesses;
  o the use of metallic discs with different dimensions;
  o the location of the test (different heights);
  o the use of different dynamometers;
  o different weather conditions (sun, rain);
  o the use of different pre-cuts;
  o the use of metallic discs with different geometries.

2 THE ADHERENCE AND THE PULL-OFF TEST

One of the main performance characteristics that should be guaranteed in ceramic tiling claddings and renders is adherence. This property is fundamental, not only because of the need to guarantee the joining between the coating and the support for safety reasons, but also because of the need for waterproofing or even for aesthetic reasons. Adherence is defined through maximum rupture force per test area and can be measured through the application of a traction force or of a shear force (IPQ, 2008). Adherence measures the adhesive strength of the coating to its substrate through the resistance to perpendicular and tangential tensions that occur in the interface between the coating and the substrate (Maciel et al., 1998). This property essentially depends on the nature of the substrate (surface roughness, initial humidity content and capillary suction), on the type of coating material (materials composition and thickness) and on the weather conditions during application (Gaspar et al., 2011).
The determination of adhesion strength should be carried out at an initial stage, in order to assess if the intended values are met, but also during the service life. Evaluation of the adherence must be performed periodically, for in-service conditions. The main method used to determine adhesion strength is the pull-off test.

The pull-off test is based on the concept that the tensile stress necessary to pull out a metallic disc, with a coat of mortar, from its substrate, is empirically related to the mortar’s tensile adhesion strength. In order to do that, it is necessary to execute a partial cut that penetrates 2mm into the substrate and to glue a metallic disc to the test surface (CEN, 2000). The pre-cut allows the tensions produced to result exclusively from traction and the area upon which the force is exerted to be effectively the area where the metallic disc is glued. The test is illustrated in figures 1 and 2 in the case of tests performed on renders and on ceramic tiles, respectively. The main drawback of the pull-off test is the fact that it is a semi-destructive technique that involves repairs of the tested areas (Gaspar et al., 2011).

![Diagram of pull-off test on rendering mortar](Quintela, 2006)

**Legend:** 1 – metallic disc, 2 – glue layer, 3 – rendering mortar, 3* - mortar (test area), 4 – substrate, $F_u$ – rupture force

![Diagram of pull-off test on ceramic tiling](Figure 2 – Scheme of pull-off test on ceramic tiling)

**Legend:** 1 – metallic disc, 2 – glue layer, 3 – ceramic tiling, 3* - ceramic tiling (test area), 4 – cementitious adhesive, 5 – mortar substrate, 6 – concrete substrate, $F_u$ – rupture force

There are several standards and specifications establishing the procedures for the pull-off test. The European standards regarding the procedure for testing renders and ceramic tiles are the following:


Performance requirements for adhesion strength values are also stipulated by both national and international documents. Generally, these documents stipulate a minimum value of adherence of 0,3 N/mm² for renders. However, for external renders applied on outer walls of old buildings walls, the technical document prepared by Veiga et al. (LNEC, 2004) stipulates a minimum requirement of 0,1 N/mm² or cohesive rupture of the mortar. Regarding ceramic tile claddings, standard NP EN 12004 (IPQ, 2008) establishes a minimum value of 0,5 N/mm² for regular cementitious adhesive and 1,0 N/mm² for improved cementitious adhesive. However, Freitas et al. (2008) studied the durability of cementitious adhesives and concluded that the mortar, which acts as support for ceramic tiles, is the weakest element of the system. In that case, the authors consider that 0,3 N/mm² is the critical value to be established for tensile adherence strength on ceramic tile claddings.
Like all experimental tests, the pull-off test is also susceptible to variability. For that reason, it is advisable to present at least the variation coefficient of the set of tests performed during an experimental campaign. This statistical measure is associated to the relative variability that allows a better view of the scatter of results, both when analysing different parameters of the same test sample and the same parameter for comparable test samples. The variability of the results observed during the analysis of statistical parameters may be due to the properties of the mortar in situ or to the execution of the test (Nepomuceno, 1999).

According to Costa et al. (n.d.), both the intrinsic complexity of adherence in mortar coatings and the test method introduce variability on the results. Some testing factors can influence the variability of the results, such as: type of equipment; pre-cut technique applied; thickness of the metallic disc; thickness of the glue layer between disc and coating surface; geometry and dimension of the test piece; loading rate and its eccentricity; experience of the operators performing the test; environmental conditions during the test (Bai et al., 2009; Vieira, 2009; Costa e Carasek, 2009).

Due to the variation factors inherent to the test itself, Cincotto et al. (1995), as quoted by Costa et al. (2007), refer that tensile adhesion strength can present variation coefficients in the order of 10 to 35%. Soares (2011) reached a similar result, when analysing industrial render and observing that the variation coefficient oscillates between 8,6 e 36,7%. Gonçalves (2010), who studied the mortars used in the joints of shale masonry, also obtained variation coefficients between 7 and 35% in laboratory tests. On the other hand, Ramos et al. (2011) observed higher coefficients of variation (between 40 and 100%) and concluded that the bigger the number of valid pull-off tests, the bigger the probability of a higher variation coefficient. It is also referred that Gonçalves & Bauer (2005) realized that tensile adhesion strength presents an intrinsic variability of 52%, while the test method itself presents an internal variation of 19%.

Due to the fact that the variability of the results of adhesion strength is associated to a multiple in-service factors, which sometimes are difficult to detect and to control, before a pull-off test is initiated as much information as possible must be gathered in order to try to understand which factors may influence the result. Trying to understand these factors will make it easier to pre-establish testing zones with similar characteristics, which is most advantageous for evaluating results.

3 **Description of the Experimental Campaign**

The main experimental campaign was carried out at the manufacturer’s laboratory in Aveiro and on the walls of the natural ageing station at the manufacturer’s facilities in Carregado. Regarding the experimental campaign carried out on building sites, tests were conducted at a building in Restelo and on a wall in Caxias. The experimental campaign carried out on building sites was smaller because the laboratory and the test walls made it possible to carry out a larger number of tests without doing much damage. The campaign was carried out between March and June 2011. Its main objective was to assess the factors that influence the results of the pull-off test. Table 1 shows a summary of the factors studied, respective test site and type of coating analysed.

An effort was made at every test site to include as much test variations as possible, in order to obtain a large number of values for comparison. In total, 199 tests were performed, of which 107 were conducted in the laboratory, 55 on test walls, 24 at the building in Restelo and 13 on the wall in Caxias. It is important to point out that the tests were not always conducted by the same operator, adding another variation factor to the results.
Table 1 - Summary of influencing factors studied and their test site

<table>
<thead>
<tr>
<th>Test site</th>
<th>Coating system tested</th>
<th>Influencing factors studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>Ceramic tiling glued on concrete slabs with cementitious adhesive normal</td>
<td>Thickness and dimension of the metallic disks; type of dynamometer</td>
</tr>
<tr>
<td></td>
<td>Ceramic tiling glued on concrete slabs with cementitious adhesive L (improved)</td>
<td>Thickness, dimension and geometry of the metallic disks</td>
</tr>
<tr>
<td></td>
<td>Rendering mortar on bricks</td>
<td>Thickness and dimension of the metallic disks</td>
</tr>
<tr>
<td>Test walls</td>
<td>Rendering mortar on wall of brick masonry</td>
<td>Thickness and geometry of the metallic disks; Location of the testing at different heights; weather conditions (dry vs. damped)</td>
</tr>
<tr>
<td></td>
<td>Ceramic tiling with cementitious adhesive L on support of rendering mortars on wall of brick masonry</td>
<td>Thickness of the metallic disks; weather conditions (dry vs. damped)</td>
</tr>
<tr>
<td>Building in Restelo</td>
<td>Ceramic tiling with cementitious adhesive L on support of rendering mortars on wall of brick masonry on level 0 and level 1</td>
<td>Location of the testing at different heights</td>
</tr>
<tr>
<td>Wall in Caxias</td>
<td>Traditional lime based render, with hydraulic properties, based on stone masonry wall</td>
<td>Type of pre-cuts</td>
</tr>
</tbody>
</table>

4 ANALYSES OF THE EXPERIMENTAL RESULTS

Figures 3 and 4 show a summary of all the results obtained from renders and ceramic tiling claddings testing, respectively. The figures mentioned above show the average of the results by type of metallic disc used.

![Pull-off strength - render](image)

**Figure 3 - Values of pull-off strength in renders through several experimental campaigns**
Pull-off strength - ceramic tiling

Legend: □ square discs; ○ circular discs

Figure 4 - Values of pull-off strength in ceramic tile claddings through several experimental campaigns
4.1 Failure modes after pull-off test

The failure mode at pull-off tests is highly variable and its characterization, which should always be presented together with the value of adhesion strength, is indispensable. The study of renders concluded that the most frequent failure mode in the campaign performed on test walls was mortar cohesive rupture (CR-M) with an occurrence of 73%, while in the laboratory campaign the most frequent rupture mode was adhesive rupture (AR-M-sub.C) with an occurrence of 63%. On the other hand, in the campaign performed on the wall in Caxias, cohesive rupture in substrate and adhesive rupture prevailed, with an occurrence of 31% (CR-sub.C – AR-M-sub.S). Within each failure mode, the values for the results obtained in the laboratory and on the test walls are identical, varying between 0,60 and 0,63 N/mm² for mortar cohesive rupture (CR-M) and between 0,52 e 0,56 N/mm² for cohesive rupture in substrate (CR-sub.).

Regarding the tests conducted on ceramic tiling systems, failure occurred in two distinct zones. In the tests conducted on test walls and at the building in Restelo, failure occurred in the more weakened zone, the mortar support (CR-sub.M). On the other hand, in the laboratory campaign (where there is no mortar support) the most frequent failure mode was cohesive rupture in glue, with an occurrence of 93%, while on ceramic tiles glued with regular cementitious adhesive the most frequent failure mode was cohesive rupture in glue and adhesive rupture in the interface between the tiles and the glue, with an occurrence of 76%.

4.2 Analysis in view of adherence requirements

All the tests conducted in the laboratory and on the test walls were carried out on coating systems whose characteristics are known, that is, the technical characteristics of the products used have been declared by the manufacturers. In the pull-off tests performed, the values of average adhesion strength were all above the minimum value stipulated by the manufacturer ((0,5 N/mm² for rendering mortar, 0,5 N/mm² for regular cementitious adhesive, and 1,0 N/mm² for improved cementitious adhesive) and by the applicable standards (0,3 N/mm² or cohesive rupture for render, 0,5 N/mm² for regular cementitious adhesive, and 1,0 N/mm² for improved cementitious adhesive). The following results were the exception: metallic discs with 10 cm side, and circular metallic discs with 4,5 cm diameter and 0,8 cm thickness, in the tests conducted in the laboratory with regular cementitious adhesive.

Throughout the whole campaign, the square discs with 10 cm side always presented values below all the other discs (square and circular discs with approximately 5 cm side and diameter, respectively). This fact may be related to two possible causes, namely: i) the high tensions that concentrate on the corners of the test sample when using large dimension metallic discs and ii) the smaller amount of pressure applied when gluing larger dimension ceramic tiles.

Regarding the fact that the pull-off tests performed in the laboratory with regular cementitious adhesive and circular metallic discs with 4,5 cm diameter resulted in values below the minimum requirements, it is believed to be associated with the proven fact that discs with a smaller thickness tend to present lower results for adhesion strength. These results reinforce the instructions given by European standards that advise the use of metallic discs with a thickness higher than 10 mm.

In the tests conducted on ceramic tiling systems, on test walls and on the building in Restelo, it was not possible to determine if cementitious adhesive reached the minimum values, given that the failure occurred in the most weakened zone, the rendering mortars. However, the render does meet the requirements, seeing that it has an average adherence of 0,47 N/mm².

On the wall in Caxias, the average value of adherence was 0,22 N/mm², within the minimum requirements anticipated by LNEC for mortars applied on the exterior surfaces of old buildings.
4.3 Tests conducted in laboratory versus on site environments

It is confirmed that tests conducted at building sites present a scattering of results substantially higher than tests conducted in the laboratory. At the building sites, the coefficient of variation for tests carried out on render(s) remained in the order of 79%, while in the laboratory and on the test walls it varied between 12% and 35%. On the other hand, the tests conducted on ceramic tiling systems presented a variation coefficient between 29 and 56% at building sites and between 8 and 26% on test walls and in the laboratory.

These results are essentially due to the controlled conditions of application provided by the manufacturer, both in the laboratory and on test walls, as regards the products used for the execution and application of the coatings, and also the conduction of the tests. Therefore, it can be stated that the greater the control in executing a coating system, the higher its homogeneity and therefore the smaller the variability of the results. Besides the control of coating execution, its in-service degradation, which usually is not uniform, may result in very high values for the variation coefficients (depending on the type and extension of the existing anomalies), as shown by the results obtained from the tests conducted at the wall in Caxias.

4.4 Factors influencing the test method

4.4.1 Influence of metallic disc thickness

This study concludes that the use of metallic discs with different thicknesses directly influences the results. In most of the comparisons accomplished, it was observed that the values of average adhesion strength increased when the thickness of the metallic disc was augmented. Figure 5 shows one of the comparisons where this happened. Authors Bungey and Madandoust (1992), as quoted by Bai et al. (2009), observed the same fact for tests performed on concrete. The rise in percentage terms is variable and was different for each type of metallic discs. The variation average was about 3% for each millimeter of thickness increase, for variations between 4 and 6 mm of thickness. It is necessary to mention that European standards 1015-12 (CEN, 2000) and 1348 (CEN, 2007) recommend the use of metallic discs with thickness higher than 10 mm.

4.4.2 Influence of metallic disc dimension

It became evident from this analysis that the use of large dimension metallic discs (10 cm side) resulted in substantially lower values for adhesion strength. However, this analysis must be studied in depth, since the
square ceramic tiles with 10 cm side suffered a smaller amount of pressure when glued. However, the analysis of this type of metallic discs carried out in the laboratory on render also resulted in substantially lower values (a 60% decrease). Combining the fact that the values obtained diverge from the average of the remaining metallic discs with the fact that large dimension discs cause bigger damage on the coating testing zone, it is considered that the use of this type of metallic discs should be avoided.

On the other hand, Flores-Colen (2009) studied the influence of metallic disc dimensions with tests performed on square metallic discs with 50 mm or 100 mm side. The author could not come to a definitive conclusion since, although she verified that in most cases the tests with larger metallic discs resulted in smaller values, she also observed results with a different tendency. Soares (2011) came to the same conclusion when he studied square metallic discs with 40 mm and 50 mm side and found no variation pattern.

4.4.3 Influence of test site

The analysis performed on the test wall in Carregado allowed the conclusion that the average adhesion strength for the pull off tests has a tendency to decrease as height increases (Figure 6). This fact has already been proven by other authors (Gonçalves and Bauer (2005)), and is mainly related to the ergonomic position necessary for the human body to execute the application of the coating, namely the amount of force and the level of spreading that can be applied on the render. At the building in Restelo there was a decrease of adhesion strength values in tests conducted at first floor level, which may be related to the lack of comfort of the operator, when standing on top of a scaffold and/or suffering higher exposure to sun and rain in areas situated on a higher level.

![Figure 6 - Correlation between pull-off strength and the height of the test area in the wall](image)

4.4.4 Influence of type of dynamometer

One of the factors that the present dissertation intended to study was the influence of using different types of dynamometers. However, despite the fact that three different dynamometers were used throughout the whole experimental campaign, only the tests performed in the manufacturer’s laboratory in Aveiro made it possible to compare two different dynamometers on identical metallic discs.

For square metallic discs with 5 cm side and 0,8 cm thickness, there were five tests performed with the 500 daN (D1) dynamometer and another five tests with the 1000 daN (D2) dynamometer. The values obtained when using the higher range dynamometer (D2) were lower. However, and given that only one case study was carried out, the results must be cautiously interpreted and may serve as a starting point for future developments, which evaluate identical dynamometers with different powers.
Additionally, when using different dynamometers, there are other factors related to its use that may influence adhesion strength values, such as the loading rate. By using an automatic dynamometer this factor is, in principle, under control. On the experimental campaigns carried out for this dissertation the test operator controlled the dynamometer’s loading rate, that is, it may have varied with each test.

4.4.5 INFLUENCE OF WEATHER CONDITIONS (DRY/DAMPED)

The purpose of studying the influence of atmospheric conditions is to investigate the difference in the results obtained when the pull-off test is performed after a period of time during which the coating system has been exposed to rain. In this dissertation the method chosen to saturate the surface was to wet it for about three minutes with a hose. In order for the moistening of the surface to be more effective, the coating was wet after the pre-cuts had been carried out.

However, it was difficult to come to a conclusion, given that in the case of render coating systems the average adhesion strength increased and in the case of ceramic tiling systems it was the opposite. Quintela (2006) came to the same conclusion when analysing a one-coat pigmented render. Despite the fact that, in most cases studied, the author found no variations between the dry render and the wet render, she also obtained results where there was a decrease and results where there was an increase of the average adhesion strength.

Although the manufacturer’s technical specifications indicate that immersion into water causes a decrease of the average adhesion strength, it is necessary to take notice that the moistening that was carried out is a completely different procedure. Further research should be carried out, given that this type of analysis may help to understand the results of a pull-off test performed on an exterior coating after long periods of rain.

4.4.6 INFLUENCE OF PRE-CUT TYPE

The analysis of the influence of the type of pre-cut was carried out at the tests conducted on the wall in Caxias, since this was the only location of the experimental campaign where the circular metallic disc was glued on top of a circular pre-cut. The results have shown that the use of square metallic discs presented an average adhesion strength about 87% higher than the circular metallic discs, which is a conclusion opposed to the one obtained by Costa et. al. (n.d.) and by Gonçalves (2004). However, these results may be due to the high vibration that the circular drilling system caused on the applied coating, which was very degraded, contrary to the coating tested by the above mentioned authors, that was prepared and tested in the lab conditions. The same happened in the study carried out by Flores-Colen (2009), where the use of the diamond disc trimmer was more appropriate to less compact mortars than the use of the core drilling machine. Therefore, it is not advisable to use the results obtained from the wall in Caxias for comparison purposes because they represent only one study case and had a very high variation coefficient (about 77%), due to the different conditions of the wall and to its state of degradation. Thus, it is considered that more studies are needed to come to a more reliable conclusion.

4.4.7 INFLUENCE OF METALLIC DISC GEOMETRY

In the study carried out to assess the influence of the type of geometry of the metallic disc used on the pull off tests it is necessary to point out that the tests with circular metallic discs were performed using a square-shaped pre-cut. By using a circular metallic disc on top of a square-shaped pre-cut an irregular force was exerted on the coating system, that is, the corners of the square are not subject to traction only. Figure 7 shows the results that allowed the analysis of the influence of the metallic disc geometry.
In the case of ceramic tiles, the results show a tendency for an increase in the values of the average adhesion strength between circular metallic discs and square metallic discs (a variation of about 49 and 24% for the G.1 and G.2 cases, respectively). The tests performed on test walls (G.3 case) show the opposite, with a small negative variation of about 7%.

The tests performed and the results obtained are not comparable with the bibliography analysed, given that in this particular comparison, only the geometry of the metallic disc is variable while the type of pre-cut remains the same. However, although the results obtained present two tendencies, it may be considered that the tests conducted on ceramic tiles in the laboratory are the most suitable to come to a conclusion, given that they present less variation factors inherent to the execution of the test. An example would be the fact that they did not need a pre-cut. In that case, it may be concluded that the results obtained from tests carried out on ceramic tiles using square metallic discs with about 5 cm side tend to be 24 to 43% higher than the ones obtained with circular metallic discs with about 5 cm diameter.

5 CONCLUSIONS

The methodology of the test method for measuring tensile adhesion strength has several variants given that, although there are standards establishing a procedure, in practice the existence of several accessories and testing equipment leads to different testing procedures.

This dissertation was essentially focused on the assessment of the influence that average adhesion strength has on results, due to various factors inherent to the testing procedure. In order to achieve that goal, a wide-ranging type of metallic discs was used during the whole experimental campaign to obtain a large variety of cases available for study. However, although results were available for different types of metallic discs they were not entirely comparable at the end of the experimental campaign. In fact, when comparing the influence of a variation factor only that same factor should vary, which was not always possible during the present dissertation. An example is that, most of the time, there are two variation factors present: the influencing factor being studied and the thickness or the dimensions, among other factors. This is why it is suggested that, for future studies on the influence of variation factors, a set of metallic discs permitting a more rigorous comparative study should be available.

Regarding the factors that would predictably influence the pull-off test, it is possible to verify that the conclusions obtained through the present dissertation do not always coincide with the conclusions obtained
through the bibliography that was analysed, and that in some cases opposite conclusions were reached. An example is the influencing factor represented by the use of circular metallic discs versus square metallic discs. On the one hand, authors Costa et al. (n.d) and Gonçalves (2004) obtained higher results for average adhesion strength using circular metallic discs but, on the other hand, the present dissertation obtained lower values. However, Costa et al. (n.d.) obtained higher values for circular metallic discs with 5 cm diameter when compared with metallic discs square with 10 cm side, while in this study it was compared metallic discs with identical area. Thus, if a comparison is made identical to the prepared by Costa et al. (n.d.), it will arrive at the same conclusion, since the metallic discs square of 10 cm side always resulted in substantially lower values.

Another influencing factor that did not allow a reliable conclusion was the damped coating, since both studies performed obtained opposite results, just as the conclusions presented by LNEC (1996), that admit that the values of adherence to the substrate may decrease after saturate the exterior coatings, and by Quintela (2006) where most of the cases analysed showed no difference between the results obtained with dry coatings and damped coatings. Thus, it is considered that the influencing factors mentioned above should be investigated further.

It was possible to conclude that the failure mode in pull-off tests must always be characterized and presented together with the results of tensile adhesion strength, given that the conclusions obtained from results analysis vary according to the type of failure. Understanding the weakness zones of a coating system allows the minimization of the factors that promote in-service loss of adherence.

Regarding the fulfillment of the requirements imposed by standards, in most of the pull-off tests performed the values for average adhesion strength were above the minimum stipulated by the manufacturer and defined by valid standards.

It is important to mention that the variability of this technique was quite different for tests performed at building sites and for tests performed in the laboratory and on test walls. Due to the fact that conditions of application were controlled by the manufacturer for coating systems tested in the laboratory and on test walls, it was expectable that test results at building sites showed greater variability.

Finally, although in this dissertation the proposed goals were achieved and understanding of the adherence measuring technique was broadened, there were aspects for improvement in order to have a follow-up and deepen knowledge. One of the aspects suggested, that was not approached in the present dissertation, is the analysis of pull-off test reproducibility. Therefore, it is proposed that laboratory tests be performed, either by different operators on distinct dates or in various operational conditions, applying the same test method, in order to evaluate the variation in results.

**References**


