Madewell Products Corporation Technical Bulletin:

Uniaxial Pull Off (Adhesion) Testing

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Section 1: Introduction

To perform properly, protective coatings and cementitious overlays must be securely bonded to the surfaces to which they are applied. To evaluate the degree to which a protective coating or cementitious overlay is bonded to a substrate, pull off testing (often called adhesion testing) may be performed. This test measures the greatest perpendicular (tensile) force that a given area of the protective coating and/or cementitous overlay can bear before a plug of material is detached from the substrate.

It should be noted that adhesion is sometimes evaluated by cutting with a knife (ASTM D 6677) or through the use of pressure sensitive tape (ASTM D 3359). These test methods are primarily used for coating films less than 20 mils (0.020") thick, and these methods subject the coating to peel and shear forces that cannot be objectively measured. As such, they are somewhat subjective in nature and of little use when evaluating the adhesion of thick film coatings.

Section 2: ASTM D 4541 - Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

This test method is primarily used to evaluate the adhesion of coatings applied to metal substrates. To perform the test, a loading fixture (sometimes called a dolly or a stud) is bonded to the coating surface with a suitable glue. It is often necessary to abrade the coating and loading fixture surfaces with fine sandpaper before the glue is applied to prevent failures at the fixture/coating interface. Also, especially on vertical or overhead surfaces, the fixture must be held in place using a magnet or adhesive tape until the glue has hardened. When the glue has set, a portable adhesion tester is used to measure the force required to pull the fixture from the substrate. This test is normally considered to be destructive because (in most cases) a portion of the finished coating is damaged when the test is performed.

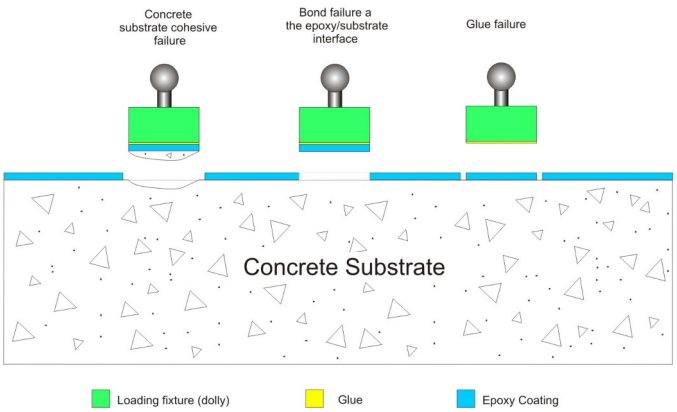
ASTM D 4541 outlines the use of five different instruments. Four of these devices are self-alignment adhesion testers and one is a fixed-alignment instrument. Each instrument type constitutes a different test method and results obtained using one instrument should not be compared to any other. The amount of force required to remove the fixture is divided by the surface area of the fixture to determine pressure and is usually expressed in either megapascals (MPa) or pounds per square inch (psi). Note that ASTM D 4541 specifically states that "scoring around the fixture violates the fundamental in-situ test criterion that an unaltered coating be tested."

Section 3: ASTM D 7234 Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers

ASTM D 7234 is very similar to ASTM D 4541 with the following exception. "Scoring the coating down to the surface of the substrate is required for all coatings thicker than 0.5 mm (20 mils) and for all reinforced or elastomeric coatings. While scoring is recommended for coatings thinner than 0.5 mm (20 mils), the test may be performed without scoring, but the results should note this exception."

When using this test method, scoring should be performed in such a way that microcracks are not formed in the coating material or substrate. This is usually performed with a diamond tipped core bit cooled with water. Note that only the coating film is scored. Scoring is not taken into the coating substrate.

Figure 1: Schematic of Failure Modes (ASTM D 7234)



There are really only three possible failure modes when using ASTM D 7234 as shown in Figure 1. Because the tensile strength of concrete is approximately 8% to 12% of its compressive strength (the rule of thumb is 10%), the adhesion of coatings applied to concrete will typically fall in the range of 250 psi to 600 psi. Because of this, concrete substrate cohesive failure is the best result, especially if the pressure required to remove the dolly is quite high (>250 psi). Bond failure at the coating/substrate interface is less desirable and may be an indicator of poor surface preparation or improper application procedures (e.g., applying a coating to damp or wet concrete). If the resulting adhesion falls in the range of 250 to 600 psi, however, this may provide an acceptable result. Glue failure is usually the result of not preparing the surfaces of the coating to be tested and/or failure to prepare the surface of the test fixture. A glue failure is a failed test. Do not retest a location that has experienced glue failure because the coating, coating/substrate bond line, and the concrete substrate have all been exposed to stress as a result of the failed test. The test should be repeated at another location.

Section 4: ASTM C 1583 Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)

ASTM C 1583 was not written to address the adhesion of coatings applied to concrete. However, this test method may be used to evaluate the bond of the Mainstay Composite Liner where the adhesion of both the restoration mortar and the epoxy corrosion barrier are important. The method of performing the test is very similar to ASTM D 7234 in that both the epoxy corrosion barrier and the restoration mortar are scored using a diamond tipped hole saw cooled with water. Using this test method, however, scoring is continued 1/2" into the concrete substrate (see figure 2).

When using this test to evaluate the adhesion of the Mainstay Composite Liner, coring the epoxy corrosion barrier, restoration mortar, and concrete substrate must be done very carefully so as not to bind or damage the plug that remains after coring. This plug, when subjected to direct tensile force, can be quite strong. However, this plug can be easily damaged by any lateral force. See figure 2.

Figure 2

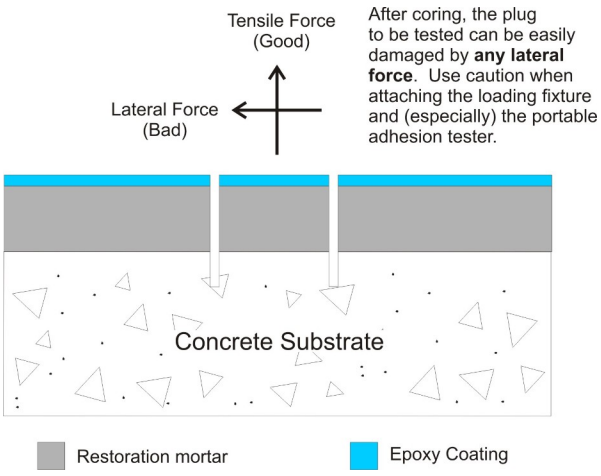
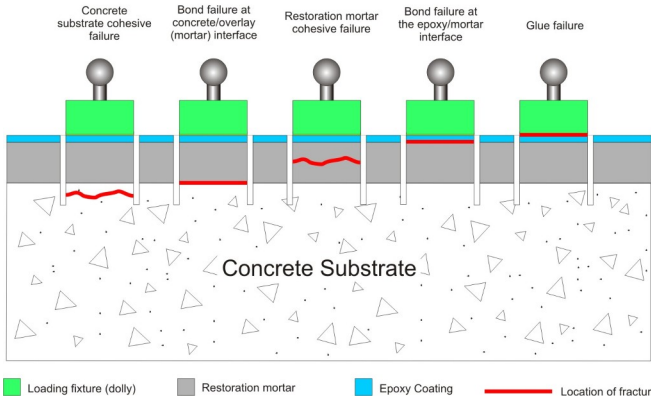


Figure 3: Schematic of Failure Modes (ASTM C 1583)



The International Concrete Restoration Institute (ICRI) Guideline No. 320-2R recognizes ASTM C 1583 as an important quality control test for bond strength of overlay materials and recommends a minimum requirement of 250 psi (1.71 Mpa). However, the guideline acknowledges that some specifiers use an acceptance criteria less than this.

When testing adhesion in accordance with ASTM C 1583, there are five different failure modes to be considered. The first, concrete substrate cohesive failure is the most desirable result if the minimum requirement of 250 psi is also obtained. If concrete substrate cohesive failure, occurs at a pressure less than 250 psi, this is an indicator of poor substrate strength, and little can be done to improve this result other than to replace the substrate concrete.

Bond failure at the mortar/substrate interface is a less desirable result and may be an indication of poor surface preparation or improper application techniques (e.g. applying the mortar to concrete that is not saturated surface dry). If this result occurs at a pressure greater than 250 psi, this may not be cause for rejection of the work. However, this result could probably be improved if the underlying reasons for this failure mode were understood and corrected.

Restoration mortar cohesive failure is an indication of low restoration mortar strength. This may be the result of adding too much water when the mortar was mixed, or it may be the result of the mortar freezing before it has developed significant strength. This also may simply be the result of not allowing the mortar to fully cure prior to performing the test. If this result occurs at a pressure greater than 250 psi, this may not be cause for rejection of the work. However, this result could probably be improved if the underlying reasons for this failure mode were understood and corrected.

Bond failure at the coating/mortar interface is the worst of all possible failure modes. In regards to the Mainstay Composite Liner, the bond between the epoxy coating and the restoration mortar should be greater than the cohesive strength of the mortar, the bond between the mortar and substrate, and even the tensile strength of the concrete itself. Even if this result occurs at a pressure greater than 250 psi, this result is not acceptable. Causes for this type of failure include not allowing the

mortar and coating sufficient time to cure, allowing the mortar to become too hard before application of the epoxy, or contamination of the mortar surface before the epoxy is applied.

As with ASTM D 7234, a glue failure is a failed test. Do not retest a location that has experienced glue failure because the coating, mortar and concrete substrate (and the bond lines between these layers) have all been exposed to stress as a result of the failed test. The test must be repeated in another location.

Section 5: Loading Fixture (Dolly) Size

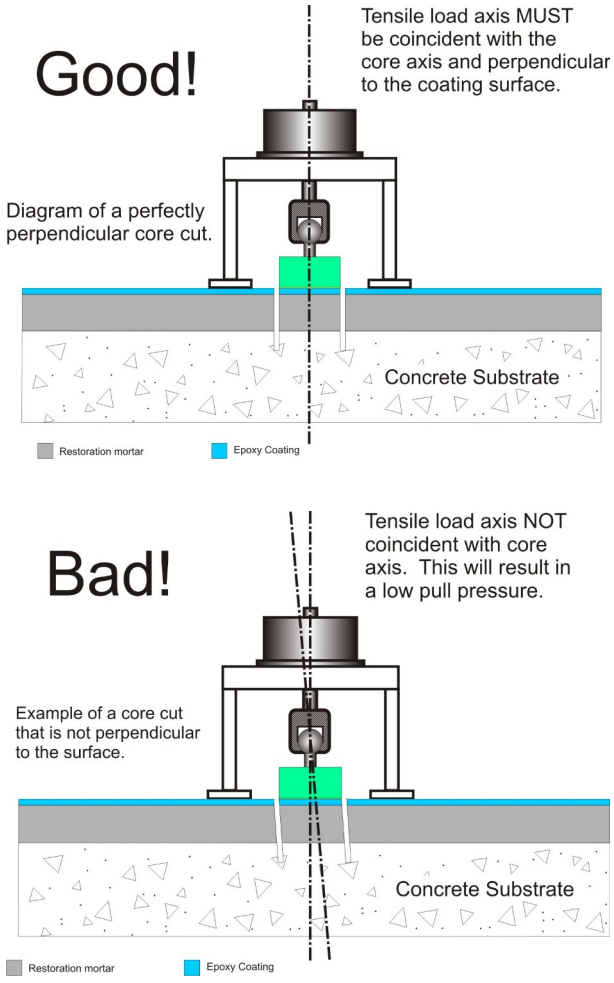
Loading fixtures come in a variety of diameters from 10 mm to 50 mm (.394" to 1.97"). Because of the irregular nature of concrete (e.g., presence or absence of large aggregate near the surface), larger 50 mm diameter loading fixtures are recommended when testing the adhesion of the Mainstay Composite Liner.

Photo 1

Section 6: Coring Around the Loading Fixture (Dolly)

Coring must take place before the loading fixture is installed. It is imperative that the axis of the core is perfectly aligned with the tensile load axis. Pulling pressure will be significantly reduced if these two axes are not coincident (the same).

Figure 4



Coring the pulloff location is complicated significantly when the surface to be tested is curved (for example, on the interior walls of a manhole). Interesting fact. both ASTM D 4541 and ASTM D 7234 require that the "test area must be a flat surface large enough to accommodate the specified number of replicate tests.. ASTM C 1583 does not mention the word "flat".

Figure 5

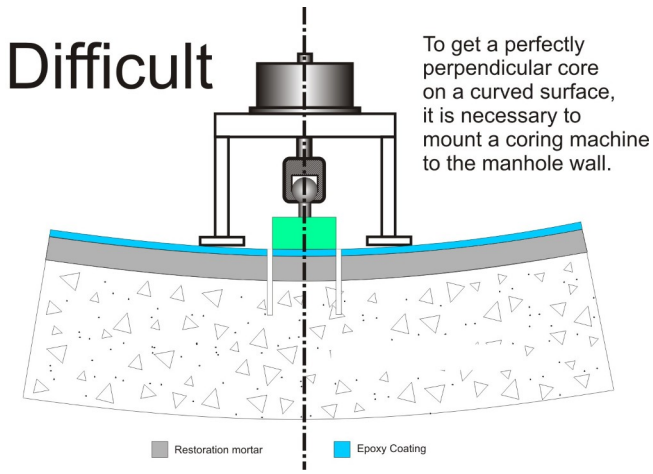


Photo 2

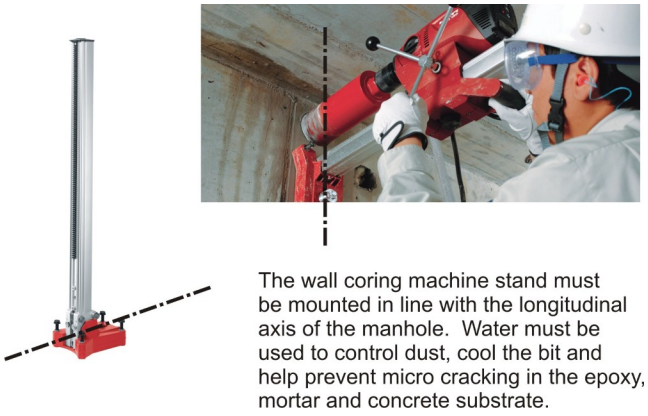


Photo 2 gives an example of a Hilti® coring machine attached to a concrete wall with a single bolt. When using a machine like this, the base of the machine should be checked with a level and adjusted so that it is perfectly perpendicular (aligned with the longitudinal axis of the manhole). Water should always be used to cool the diamond bit while coring. Note that diamond core bits are generally sized based on the hole they create as opposed to creating a plug of a specific diameter. For example, McMaster-Carr sells a 2.25" core bit (part number 2872A34) that claims to have a 2" ID. Because large format adhesion load fixtures are typically 50 mm, this theoretically leaves a plug about 0.030" larger than the dolly.

ASTM C 1583 requires the user to "Measure the diameter of the test specimen in two directions at right angles to each other. Record the average diameter to the nearest 0.2 mm [0.01 in.]". Use the diameter of the specimen to calculate the area using the equation Pi (usually rounded off to 3.1416) times the radius (one half of the diameter) squared (R2). The results of this measurement are used to "calculate the bond strength or tensile strength by dividing the tensile load at failure by the area of the test specimen".

Bond strength (pressure) is calculated using the following equation:

$$\text{Bond Strength} = \frac{\text{Tensile Load}}{\text{Area of the Specimen}}$$

If you want the bond strength to be expressed in MPa (megapascals), the tensile load must be expressed in Newtons, and the area of the specimen must be expressed in square millimeters (mm^2).

If you want bond strength to be expressed in psi (pounds per square inch), the tensile load must be expressed in pounds of force, and the area of the specimen must be expressed in square inches (in^2).

Section 7: A Note About Pull Rate

ASTM D 4541 advises that the load be applied to the test fixture at a rate of 150 psi per second so that the test is performed in about 100 seconds or less (oddly, the instrument described in Annex A3 suggests 100 psi/second). ASTM D 7234 requires a pull rate of 30 psi/second and the test must be performed within 30 seconds. ASTM C 1583 calls for a pull rate of 5 psi/second (+/- 2 psi) and does not require a maximum time to

perform the test. From a practical standpoint, many adhesion testers on the market do not offer the user a method to accurately control the rate at which load is applied to the test fixture. When using an instrument such as this, nothing can be done except to apply the load as uniformly as possible within the maximum time outlined.

A couple of newer instruments, such as the PosiTest AT-A Automatic and the Proseq DY-2 Family of testers, DO allow the user to set the rate at which load is applied to the test fixture. When using this type of tester, set the loading rate according to the standard being used. Note: There is really no way to perform pull testing per ASTM C 1583 without the use of an automatic instrument.

Section 8: "How Can I Be Sure to Achieve Good Adhesion Results?"

First, download and read the Mainstay Composite Liner Application Guide available at www.madewell.net. This guide outlines methods for preparing concrete surfaces prior to application of the Mainstay Composite Liner. In addition to surface preparation, this guide contains information regarding wetting the concrete surfaces and testing pH prior to application of the mortar. Second, mix the mortar using as little water as possible and shoot or spin the mortar onto the concrete substrate with as much force as possible. Finally, be sure to apply the epoxy topcoat to the freshly applied mortar while it is still soft enough to easily push a screwdriver through the mortar to the substrate.

Section 9: Is There Any Other Way To Determine Adhesion?

This question is often asked because uniaxial pull testing is difficult to perform in the field and, if performed improperly, the results can be bad news. One of the arguments against pull-off testing in general is that it only tells you that the system or coating is bonded at a single, specific location. Also, after testing, that location no longer exists because the test is destructive (usually).

An alternative way to test the bond of a cementitious overlay such as the Mainstay Composite Liner is to "sound" the surface of the liner with a round stone or hammer in accordance with the principles outlined in ASTM D 4580 Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding. When sounded with a stone or hammer, a tightly bonded liner will ring with a high pitched tone, and any disbonded area will sound with a low pitch tone. The advantage of sounding is that the entire surface of the liner can be tested for soundness as opposed to a single point.

ASTM D 4580 Procedure C – Rotary Percussion outlines the use of a rotary device that makes performing the test quick and simple. If you would like to view a video that describes this test, go to YouTube.com and search for "sounding concrete".

Photo 3