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QUANTIFYING SOUND COATING ADHESION

by

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EXECUTIVE SUMMARY

Painting contractors, specification writers, and field inspectors each require singular values for use in quantifying sound coating adhesion. These values would simplify acceptance criteria for new coating systems and, prior to maintenance painting, facilitate identifying sound, but weathered exterior coating systems. To quantify sound coating adhesion, a portable adhesion tester may be used in accordance to several industry standards. This report presents cohesive strengths of substrates and pull-off strengths of coatings; explains how to determine sound initial adhesion; identifies additional parameters which should be quantified prior to maintenance painting; and lists examples of premature failures due to unsound field adhesion.

Findings are as follows:

- Substrate (non-metallic) and coating adhesion may be successfully quantified using a portable adhesion tester.
- Sound initial and weathered coating adhesion, in general, is governed by the material (substrate or coating) having the lowest cohesive strength.
- Coating adhesion ≤ 110 psi is questionable and can, under the right circumstances, lead to premature coating failures.
- A value for sound weathered adhesion is relative and is primarily dependent upon the properties of the selected overcoat(s).
- To prevent overcoat failures, the selected overcoat should display the following properties: A) Glass Transition temperature range ($T_{(g)}$) less than the $T_{(g)}$ of the weathered coating, B) Cohesive strength considerably lower than the weathered coating's adhesion, C) Combined Residual Cure Stress and hygrothermal stress significantly less than the weathered coating's adhesion, and D) Sustainable flexibility.

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Fig. 1 – Portable adhesion testers with pull-off coupons: L) Dyna tester, R) Elcometer™.

Painting contractors, specification writers, and field inspectors each require singular values for use in quantifying sound coating adhesion. These values would simplify acceptance criteria for new coating systems and, prior to maintenance painting, facilitate identifying sound, but weathered exterior coating systems. To quantify sound coating adhesion, a portable adhesion tester (Fig. 1) may be used in accordance to one of the following industry standards: A) ISO 4624 (International Organization for Standardization), or B) ASTM-D-4541 (American Society for Testing and Materials)[1,2]. The ISO standard is designed primarily for laboratory adhesion testing whereas the ASTM standard may be used in either a laboratory or field environment. However, when coating adhesion has been quantified, what values represent sound adhesion? This report presents cohesive strengths of substrates and pull-off strengths of coatings; explains how to determine sound initial adhesion; identifies additional parameters which should be quantified prior to maintenance painting; and lists examples of premature failures due to unsound field adhesion.

COHESIVE STRENGTH

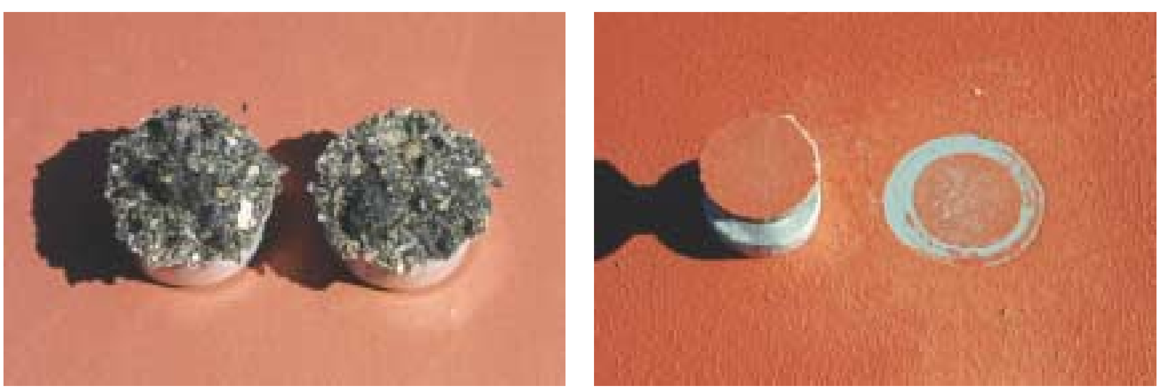

Fig. 2 – Cohesive failures on pull-off coupons: L) Asphaltic concrete attached to a marking paint, R) Acrylic topcoat over epoxy primer.

When a coating is applied to a substrate, adhesion is generally governed by the material (substrate or coating) having the lowest cohesive strength (Fig. 2). For example, when epoxies are applied to metal and tested for adhesion, the epoxy is weaker and fails well before the metal. Conversely, when the same epoxy is applied to concrete, the epoxy is stronger and adhesion testing typically produces a concrete cohesive failure.

A material's cohesive strength is quantified by testing for either tensile strength or pull-off strength and values represent the material's maximum internal strength. Table 1 lists the cohesive strength of substrates commonly painted and Table 2 lists the pull-off strength of various industrial coatings.

Table 1: Cohesive Strength of Substrates

Aluminum	≥ 15,500 psi[(3)]
Asphaltic Concrete @ 63°F	240 psi[(6)]
Concrete	≥ 200 psi[(6)]
Concrete Masonry Unit (CMU)	≥ 180 psi[(6)]
Plywood	≥ 180 psi[(6)]
Polyurethane Foam (PUF)	90 psi[(6)]
Steel	≥ 56,000 psi[(4)]
Stucco	≥ 50 psi[(6)]
Zinc	≥ 33,000 psi[(5)]

Table 2: Pull-Off Strength of Industrial Coatings (ASTM-D-4541)[7]

Acrylic, Direct to Metal	500 psi
Alkyd Primer	300 psi
Alkyd Topcoat	290 psi
Alkyd, Silicone	295 psi
Epoxy, Coal Tar (SSPC Paint 16)	1000 psi
Epoxy Polyamide	750 psi
Epoxy Polyamine	840 psi
Epoxy, Water Based	600 psi
Epoxy, Zinc Rich	1000 psi
Inorganic Zinc	310 psi
Urethane, Aliphatic	600 psi
Urethane, Moisture Cured	600 psi

SOUND INITIAL ADHESION

The following two coating systems illustrate the limiting factor associated with sound initial adhesion: System 1) Silicon alkyd topcoat, alkyd primer, plywood substrate, and System 2) Zinc-rich epoxy primer, epoxy polyamine intermediate coat, moisture cured urethane topcoat, steel substrate. Using Table 1, plywood and steel display minimum cohesive strengths at 180 psi, 56,000 psi, respectively. Using Table 2, the silicone alkyd topcoat is slightly weaker than the alkyd primer (295 psi vs. 300 psi) while the moisture cured urethane is the weakest component of System 2 (600 psi vs. 840 psi, 1000 psi). Consequently, System 1 displays maximum adhesion at ≥ 180 psi (value at which plywood cohesive failures occur) whereas System 2 displays maximum adhesion at 600 psi (value at which moisture cured urethane cohesive/adhesive failures occur). If either System was specified, adhesion values could be used to generate acceptance criteria for sound initial adhesion. However, specifying a value for sound initial adhesion also requires a minimum cure period and a temperature range for performing the adhesion testing. For thermosetting epoxies and urethanes, a cure period of one week is usually sufficient and the temperature for adhesion testing is generally not a concern (≈ 40°F – 90°F). For thermoplastic alkyds and acrylics, a cure period of several weeks may be required and adhesion testing should be performed as close to room temperature as possible (≈ 70°F).

SOUND WEATHERED ADHESION

Fig. 3 – A shim bending technique may be used to Quantify a coating's Residual Cure Stress and Hygrothermal Stress.

In theory if each coat of a weathered coating system's adhesion is ≥ 85 % of its value for initial adhesion, coating adhesion may be classified as sound[8]. Still, a quantitative value for sound adhesion is relative and is primarily dependent upon the properties of the selected overcoat(s). When an overcoat has been selected, certain overcoat stresses should be quantified and used for comparison against the weathered coating's adhesion. For example: 1) Residual Cure Stress (RCS: initial coating stress transferred to a substrate/coating during the paint's cure), and 2) Hygrothermal stress (stress transferred to a substrate/coating from both service temperatures and moisture induced swelling). If the selected overcoat transfers a combination of RCS and hygrothermal stress either exceeding or equal to the weathered coating's adhesion, premature failures from lifting and/or intercoat disbonding may result. The RCS for a common epoxy, as determined by Shimbo et al, ranges from 672 psi to 974 psi (8 mils dry, rm. temp.), whereas hygrothermal stress for an acrylic polyurethane, as determined by Perera et al, ranges from 39 psi (105°F) to 413 psi (72°F)[9,10]. The above epoxy and urethane stress values each exceed alkyd adhesion (Table 2) and, if either paint is applied as an overcoat to an alkyd system, failure may result. To quantify either a singular coating's or coating system's RCS and hygrothermal stress, the CoRI-Stressmeter or an equivalent device may be used[11]. (Fig. 3)

In addition to the above stresses, the selected overcoat's glass transition temperature range ($T_{(g)}$) should be significantly lower than the $T_{(g)}$ of the weathered coating. A material's $T_{(g)}$, according to Pappas et al., is defined as the temperature at which there is an increase in the thermal expansion coefficient[12]. As a coating weathers, the $T_{(g)}$ becomes elevated and internal stress can increase[13]. Consequently, using an overcoat with a $T_{(g)}$ lower than the weathered coating generally minimizes intercoat stress through increased flexibility, decreased hardness, decreased cohesion, and decreased tensile strength[14]. In the field, a coating's $T_{(g)}$ may be quantified by extracting a 1/4" to 1/2" paint chip and sending it to a laboratory employing a Differential Scanning Calorimetry (DSC: ASTM-E-1356).

Using coating System 2 as an example, sound weathered adhesion is displayed at ≥ 510 psi (600 psi initial urethane adhesion x 0.85) and overcoating with a flexible paint having a cohesive strength << 500 psi should not present a problem. When viewing Table 2, the silicone alkyd and alkyd topcoat meet the above cohesive strength requirement with values at 295 psi and 290 psi, respectively. These values are well below System 2 weathered adhesion and, if applied as an overcoat, represent the maximum Residual Cure Stress (RCS) transferred to a coating system[15]. Although the alkyds satisfy the cohesive strength requirement, sustainable flexibility is also required of the overcoat. Alkyd coatings, in general, initially display moderate flexibility, whereas over time flexibility decreases and internal stress increases. This effect is undesirable and, for weathered coating System 2, a more appropriate overcoat selection may be an elastomeric acrylic displaying a cohesive strength of 300 psi and a percent elongation from 150 % to 350 %.

EXAMPLES OF UNSOUND FIELD ADHESION

The three examples presented below show that coating adhesion ≤ 110 psi is questionable and can, under the right circumstances, lead to premature coating failures.

Air Force Base, Louisiana

A "dry fall" alkyd coating was applied to the underside of a sheet metal roof at three times the manufacturer's recommended thickness and displayed an adhesive strength ≤ 100 psi[16]. Due to the synergistic effects of high humidity, significant thermal loading/sheet metal expansion, and excessive thickness, the alkyd coating was lifting from the roof in sheets. The alkyd coating was 100 % removed and reworked using two coats of an elastomeric acrylic.

Reserve Center, Washington

Two coats of a Direct to Metal (DTM) acrylic were applied to a weathered alkyd system over galvanized sheet metal and displayed an average DTM/alkyd intercoat adhesive strength of 90 psi[17]. Due to the DTM acrylic's high cohesive strength (> 500 psi), the alkyd's low/weathered cohesive strength and thermal loading effects, the DTM acrylic exhibited various degrees of intercoat lifting and peeling. The coating system was allowed to continue failing until it became aesthetically displeasing and was to be 100 % removed and reworked with an epoxy primer followed by a topcoat of aliphatic urethane.

Naval Air Station, Texas

A four-coat, 20 mils dry, hangar floor coating system was applied to shot-blasted concrete and displayed on average an unsound adhesive strength of 110 psi[18]. Due to the combined effects of the excessively thick topcoat applications (solvent entrapment) and incomplete intercoat mixing, the primer was transformed back into its uncured state (chemical incompatibility) and exhibited numerous spot failures. The coating system was spot repaired and has provided somewhat acceptable performance.

SUMMARY

- Substrate (non-metallic) and coating adhesion may be successfully quantified using a portable adhesion tester (ASTM-D-4541 or equivalent).
- Sound initial and weathered coating adhesion, in general, is governed by the material (substrate or coating) having the lowest cohesive strength.
- Coating adhesion ≤ 110 psi is questionable and can, under the right circumstances, lead to premature coating failures.
- A value for sound weathered adhesion is relative and is primarily dependent upon the properties of the selected overcoat(s).
- To prevent overcoat failures, the selected overcoat should display the following properties: A) Glass Transition temperature range ($T_{(g)}$) less than the $T_{(g)}$ of the weathered coating, B) Cohesive strength considerably lower than the weathered coating's adhesion, C) Combined Residual Cure Stress and hygrothermal stress significantly less than the weathered coating's adhesion, and D) Sustainable flexibility.

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