



NACE 6G197

Informational Report and Technology Update

Design, Installation, and Maintenance of Coating Systems for Concrete Used in Secondary Containment

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Approved February 1997

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Printed by NACE International

Foreword

This state-of-the-art report covers the design, installation, and maintenance of polymeric coating systems that are applied and directly bonded to concrete in secondary containment applications. This report is intended to inform manufacturers, specifiers, applicators, and facility owners who are required to contain chemicals and/or protect concrete in these applications.

Concrete is used in secondary containment structures because it is a cost-effective material if properly designed and installed. A chemical-resistant coating is often applied to the concrete to extend the service life of the secondary containment structure and properly contain the chemicals.

Numerous recommended practices, specifications, guides, conference proceedings, books, and technical papers have been published by NACE, SSPC, and other organizations covering the many aspects of coatings for concrete. This report focuses on those aspects of the design, materials, and procedures that are specific to coatings for concrete in secondary containment applications, making refer-

ence to other publications when appropriate. While there are numerous successful commercial products and designs for containment of chemicals, this report focuses on concrete structures that are coated with thermoset polymer coating systems. Other potentially effective containment systems, such as acid-resistant brick and thermoplastic liners, are not described in this report.

Coatings used in secondary containment applications are also called linings, lining systems, or protective barrier systems; however, for simplicity they will be referred to as coatings or coating systems in this report.

This technical committee report was drafted by NACE Task Group T-6H-52, a subcommittee of T-6H on Coating Materials for Atmospheric Service. NACE/SSPC Joint Task Group H* completed the report, which is published by NACE International under the auspices of Group Committee T-6 on Protective Coatings and Linings and by the Steel Structures Painting Council.

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Section 1: Regulations

1.1 The objective of regulations on secondary containment is to prevent migration of hazardous materials into the soil, ground water, and surface water. In the United States numerous federal, state, and local regulations specifically address the containment of hazardous materials.¹⁻⁷ The Resource Conservation and Recovery Act (RCRA)² is a primary example of the applicable regulations that

refer to containment of hazardous wastes.

1.2 Regulations on secondary containment usually require that the systems:³

- (1) prevent migration of hazardous (regulated) materials;
- (2) have a sound substrate;

*Chairman Fred S. Gelfant, Stonhard Inc., Maple Shade, NJ.

- (3) be constructed of or lined with materials that are compatible with the hazardous (regulated) materials;
- (4) be free of cracks or gaps; and
- (5) contain the capacity of the largest tank.

Section 2: Service Conditions

2.1 The exposure of secondary containment systems to various chemicals and physical conditions is usually considered in the selection and design of the system. This section discusses the classification of exposure conditions. Appendices A and B list generic coating systems that have been successfully used in each exposure classification.

2.2 Chemicals

2.2.1 Classification by Type

Most acids and alkalis attack concrete; coatings are used to protect the concrete from attack. Most solvents and hydrocarbons do not attack concrete; however, they are classified as hazardous materials, and existing regulations require that they be contained.³

Chemicals can be classified by specific types and concentrations to rate the resistance of coatings to chemicals. Typically, chemicals within a specific class attack polymers in a similar manner. For acids and alkalis (with some exceptions), the higher the concentration, the more aggressive the attack. With solvents, the closer the solvent is to the solubility parameter of the coating, the more prone that coating is to swelling by permeation of that solvent. In addition, the lower the molecular weight of the solvent, the more rapidly it diffuses into the coating.

Mixing some chemicals reduces their aggressiveness to coatings (e.g., mixing acids with alkalis), assuming that the exotherm from the mixing does not cause thermal damage. (Potential thermal damage from exotherm is ignored.) Mixing other chemicals significantly increases their aggressiveness. For example, mixtures of acids and solvents or mixtures of two or more solvents are commonly used as paint strippers.

2.2.2 The chemical types used in Appendix A include:

- (1) inorganic acids
- (2) organic acids
- (3) oxidizers and oxidizing acids
- (4) alkalis
- (5) chlorinated solvents
- (6) oxygenated solvents
- (7) hydrocarbon solvents

- (8) salt solutions
- (9) pesticides and herbicides

Examples of typical chemicals within each type are given in Appendix C.

2.2.3 Classification by Concentration

2.2.3.1 Most acids and alkalis are further classified by concentration, usually percent by weight in water. When a polymer in a coating is susceptible to attack by a specific chemical, a higher concentration of that chemical is usually more aggressive to the coating (sodium hydroxide is one notable exception). Where a known concentration of a specific chemical is to be contained, compatibility is determined by testing the resistance of the coating to that concentration of the chemical.

2.2.3.2 Evaporation, solidification, and mixing can modify the aggressiveness of a specific chemical. Many acids or alkalis will become more concentrated due to evaporation if they are spilled at a low concentration on a coating and not cleaned immediately. The higher concentrations are potentially more aggressive toward the coating. Some chemicals are spilled in the liquid state but solidify at ambient temperature, thus reducing their mobility and aggressiveness.

2.2.3.3 The concentration classifications used in Appendix A vary depending on the chemical type. For acids and alkalis, Appendix A follows the common practice of listing resistance to a dilute concentration (usually up to 10%, in water), a medium concentration (usually above 10%), and a concentrated level (the highest commonly used concentration). For solvents, Appendix A lists only the resistance to the concentrated (undiluted) level.

2.2.4 Frequency and Duration of Contact

2.2.4.1 For coatings that are suitable for continuous and long-term exposure to a chemical (i.e., suitable for immer-

sion exposure or primary containment), frequency and duration of contact with the chemical is not a concern; however, for aggressive chemicals that will degrade a specific coating system, determining the frequency and duration of contact is important. Many factors can affect the actual exposure of the coating to the chemicals that are to be contained. These include spill frequency, spill amount, time until dilution or clean-up, effectiveness of dilution or clean-up, and temperature of the spill (see 2.2.5).

2.2.4.2 The exposure classifications used in Appendix A are 72 hours and continuous. The 72-hour classification applies to secondary containment areas subject to spills that are cleaned as soon as they are detected. The 72-hour chemical resistance requirement is often adopted for areas where spills may not be detected until after one whole weekend. The 72-hour classification is also applied to areas that are not subject to spills but are designed to contain chemicals after catastrophic failure of a primary containment tank. The continuous classification is for areas that are subject to continuous spills or areas where spills are not cleaned.

2.2.5 Surface Temperatures

2.2.5.1 Although spills from process chemicals may initially be at temperatures above ambient, these spills usually cool to ambient conditions in a relatively short period of time. Catastrophic tank failure for a chemical stored above ambient temperature is one exception. Increases in temperature caused by diluting and/or neutralizing concentrated acids and alkalis could affect the maximum temperature to which the coating is exposed.

2.2.5.2 The surface temperature classifications used in Appendix A include ambient temperatures (up to 40°C [104°F]), elevated temperatures (40°C to 70°C [104°F to 158°F]), and high

temperatures (70°C to 100°C [158°F to 212°F]). These classifications are important because coatings used in secondary containment may deteriorate rapidly when exposed to chemicals at elevated or high temperatures.

2.3 Physical Conditions

2.3.1 Ambient Environment

2.3.1.1 When classifying the ambient environment to determine the exposure and suitability of a coating system, important factors include the temperature range (maximum and minimum surface temperature), the rate of temperature changes (i.e., daily due to ambient temperature swings or sudden due to thermal shock from chemical spills), and sunlight exposure.

2.3.1.2 The ambient temperature ranges used in Appendix B are as follows: low-temperature range (22°C ± 10°C [72°F ± 50°F]), which includes most indoor and controlled environments; medium-temperature range (22°C ± 20°C [72°F ± 68°F]), which includes most indoor areas without temperature control and some outdoor, covered areas; wider-temperature range (22°C ± 30°C [72°F ± 86°F]), which includes most outdoor environments; and extreme-temperature range (22°C more than ± 30°C [72°F more than ± 86°F]), which includes severe hot or cold outdoor environments.

2.3.2 Traffic Conditions

The traffic condition classifications used in Appendix B include:

- (1) occasional foot traffic
- (2) constant foot traffic
- (3) fork lift
- (4) drum storage
- (5) process area
- (6) tank storage
- (7) heavy traffic (tanker trucks, steel-wheeled vehicles)

Section 3: Concrete

3.1 Concrete Design for New Structures⁸⁻¹¹

Proper concrete design and installation practices are required to ensure the performance and success of

the concrete as the substrate of the secondary containment system.

3.1.1 Concrete Properties

Describing specific raw materials and mix designs for concrete is beyond the scope of this report. These topics are adequately covered in numerous American Concrete Institute documents.⁽¹⁾ It is important to know the desired properties of the finished concrete structure and concrete surface and how they affect the coating to be applied. The properties of concern, the factors that affect these properties, and common specifications are given in the following paragraphs.

3.1.1.1 Strength

3.1.1.1.1 Compressive strength provides a rigid structural base for the coating. Tensile strength provides adequate adhesion between the coating system and the concrete. Tensile and shear strength ensure the concrete survives the stresses applied by the curing coating on the concrete. Tensile and flexural strength resist cracking in the concrete during curing and drying of the concrete and during thermal cycling.

3.1.1.1.2 In addition to installation, finishing, and curing practices, the strength of concrete is affected by the type of cement, the amount of cement in the mix, the water-to-cement ratio, and the air content. According to ACI 209,¹² the tensile strength of concrete ranges from 6 to 8% of the compressive strength. For secondary containment, ACI 350.2R¹⁰ recommends a minimum of 28 MPa (4,000 psi) compressive strength and 1.7 MPa (250 psi) tensile strength at 28 days after concrete placement. The following mix design is typical for achieving these values:

- (1) cement content: 200 kg/m³ (600 lb./yd) minimum,
- (2) water-to-cement ratio: 0.45 maximum,
- (3) air content (depends on geographical location): 4 to 8%.

3.1.1.2 Strength Development

The rate at which concrete develops

strength is important for scheduling coating application. According to ACI 209, strength development is a function of cement type, 28-day design compressive strength, temperature, and time. As described in ACI 305R¹³ and ACI 306R,¹⁴ the early rate of strength development increases with increased temperature; however, the ultimate strength achieved is lower for concrete that is placed at elevated temperatures. ASTM⁽²⁾ C 150¹⁵ Type III cement or accelerators are used where rapid strength development is required, but often at the unwanted expense of increased shrinkage. Strength development is slower for ASTM C 150 Type II and Type V cements.

3.1.1.3 Surface Strength

Surface strength enables the concrete to remain intact during surface preparation. It also helps to maintain adequate adhesion between the coating system and the concrete when subjected to stress from curing of the coating, thermal movement, and physical abuse. Surface strength is a function of the concrete design strength, segregation, and the cure at the surface. Segregation reduces surface strength and can be caused by too much vibration during placement or excessive finishing and can result in a high water-to-cement ratio or an excess of fine aggregate at the surface. Surface strength depends on the normal concrete cure parameters described in Paragraph 3.1.1.1, plus the added variable of how long the surface is kept moist. Concrete based on ASTM C 150 Type I cement reaches 50% of 28-day strength if the surface is not kept moist, 80% if the surface is kept moist for three days, and full 28-day strength if the surface is kept moist for seven days. Concrete based on ASTM C 150 Type III cement reaches full 28-day strength if kept moist for three days.¹⁶

3.1.1.4 Surface Imperfections and Porosity

Defects such as surface voids, tieholes, bugholes, pinholes, and excess porosity may affect the application or performance of the coating. Protrusions such as

⁽¹⁾ American Concrete Institute (ACI), 38800 International Way, Country Club Drive, Farmington Hills, MI 48331.

⁽²⁾ American Society for Testing and Materials (ASTM), 100 Barr Harbor, West Conshohocken, PA 19428-2959.

form lines, fins, sharp edges, and spatter may cause holidays or thin sections in the coating if they are not removed. Most defects are caused by placement and finishing techniques, although excess porosity is usually the result of excess moisture or insufficient surface curing. Most defects and deficiencies can be avoided by proper mix design, installation procedures, and curing. Surface deficiencies are usually addressed during surface preparation or when patching the surface prior to coating (see Paragraphs 3.2.3, 3.3.2, and 6.2).

3.1.1.5 Uniformity

Concrete uniformity depends on correct mixing, placing, and finishing. Defects such as honeycombs and rock pockets, usually caused by insufficient vibration or insufficient fluidity to the mix, do not provide a sound substrate for coatings. Segregation may result in surface cracking (see Paragraph 3.1.1.3).

3.1.1.6 Shrinkage

3.1.1.6.1 Shrinkage can cause cracking, curling, and excessive joint movement in a concrete structure and can cause plastic shrinkage cracking at the surface of a slab. Predicting and controlling shrinkage is important, particularly if the coating is applied soon after placement. According to ACI 209, shrinkage in concrete using Type I cement that is kept moist for seven days can range from 415 to 1,070 x 10⁻⁶ m/m (in/in). Approximately 40% of the shrinkage occurs in the first 28 days and 90% in the first year.

3.1.1.6.2 Shrinkage can be affected by:

- (1) cement type (The cement types, listed in order from the most shrinkage to the least shrinkage, are as follows: ASTM C 150 Type III; ASTM C 150 Type I; ASTM C 150 Type II; and ASTM C 845¹⁷ Type K);
- (2) aggregate type, size, and shape (smaller aggregates may increase shrinkage);
- (3) mix and cure temperature (higher temperature increases shrinkage);

- (4) cure accelerators (may increase shrinkage); and
- (5) water content (more water increases shrinkage).

3.1.1.6.3 Water content is the most important factor. Curling, plastic shrinkage cracking, and low surface strength occur when the surface dries too rapidly. Common practices for reducing problems due to shrinkage include minimizing water levels in the concrete mix, ensuring sufficient moisture levels at the surface during cure, and placing joints correctly. Coating applicators can expect additional movement at the joints when they are coating a concrete substrate early in its shrinkage history.

3.1.1.6.4 ACI 223¹⁸ describes the use of ASTM C 845 Type K cement. Type K cement reduces shrinkage during cure, but it also reduces strength and slows strength development.

3.1.2 Structure Design

Any coating system that is bonded to a concrete substrate depends on the concrete for its structural integrity. Details concerning the design of concrete structures are beyond the scope of this report; they are addressed in numerous ACI reports, including ACI 302.1R,⁸ ACI 350R,⁹ and ACI 350.2R¹⁰. The range of service conditions and exposures in secondary containment areas varies widely, affecting the priority of specific design considerations. Design guidelines range from standard floor construction for light service conditions (ACI 302) to specialized design for primary containment (ACI 350). The effects of shrinkage, loading, and thermal movement are considered and accommodated in the design of the joints, reinforcement, slab thickness, and concrete mix. The size of the containment structure, which is usually governed by regulations, and the proper slope to facilitate drainage are also important design considerations.

3.1.3 Joints

3.1.3.1 ACI 302, ACI 350, ACI 504R¹⁹ and ACI 224R²⁰⁻²² give recommendations on the location and design of joints for concrete structures. Joints are usually categorized as either contraction (control) joints or isolation (expansion)

joints. Contraction joints are designed to accommodate in-plane drying shrinkage and thermal movement. Isolation joints are designed to isolate abutting but separate structural sections, such as supporting walls, tank pads, and columns. Good concrete design practice includes cutting the contraction joints in square patterns early in the cure—before random shrinkage cracking—to a depth of at least one-fourth of the slab thickness.

3.1.3.2 For floors, ACI recommends that the maximum distance in meters between joints be equal to 24 to 36 times the slab thickness in meters (the maximum distance in feet between joints would be equal to two to three times the slab thickness in inches). To minimize stress on the coating, shorter distances between joints (as low as 4 m [12 ft]), in conjunction with placing or cutting joints where stresses are anticipated (e.g., at corners, around tank foundations, and at slab intersections), have been used. Alternatively, highly reinforced structure designs have been used that reduce the reliance on joints.⁹

3.1.4 Hydraulic and Hydrostatic Pressures

The movement of moisture in concrete throughout the curing process and after application of the coating is an important design consideration. Pressure due to moisture from drying of the concrete or from ground water may be substantial; in some instances, the pressure may be sufficient to disbond barrier coating systems that appear to be well bonded. These pressures are commonly referred to as hydrostatic, capillary, and osmotic pressures.²³⁻²⁵ Hydrostatic forces through structures may affect bonded coating systems at cracks or joints in the concrete. Capillary and osmotic forces are difficult to predict and are potentially significantly higher than hydrostatic forces. In most cases, a vapor barrier (or positive-side waterproofing) is installed under the concrete slab to prevent subsurface moisture from permeating the slab.

The inherent free moisture content of concrete is 3 to 6%. Moisture in excess of this level evaporates from the concrete. Concrete is usually placed with more water than is needed to completely hydrate the cement. One reason for waiting 28 days prior to coating concrete with a barrier system is to allow this excess moisture to evaporate (see Paragraph 6.1). This waiting period is especially important if a

vapor barrier (or positive-side waterproofing) is installed because the barrier does not allow moisture to exit into the ground.

3.1.5 Concrete Finishing and Surface Characteristics

3.1.5.1 In addition to mix design, surface cure, and surface preparation, the method used to finish concrete surfaces has a significant effect on the properties of the concrete surface. The typical profile, porosity, and strength of various finished concrete surfaces are shown in Table 1. The coating system depends on these surface characteristics for adhesion.

3.1.5.2 No preferred method for finishing concrete to accept coatings has been established by the concrete coatings industry. The surface cure, surface preparation method, and type of coating system to be applied can greatly influence the effectiveness of a concrete finishing method. For example, broom finishing is sometimes used because it gives a profile for the coating; however, most of the profile may be removed during surface preparation. When sacking (grout rubbing) is used to fill voids in formed concrete surfaces, subsurface voids are created; the added cement is usually removed during surface preparation due to improper cure of the added cement paste. Using a metal-trowel is gaining acceptance as the preferred finishing method for horizontal surfaces, providing the surface is not excessively trowelled, the concrete is properly cured, and the laitance is removed prior to coating.

3.1.6 Concrete Cure

3.1.6.1 Maintaining sufficient moisture and proper temperature in concrete in the early stages of cure is important to ensure development of the designed strength. Keeping the surface moist until sufficient strength has developed at the surface is important to ensure development of sufficient surface strength, to reduce curling, and to reduce surface cracking.^{11,13,14,16,27,28}

3.1.6.2 ACI 308¹⁶ recommends seven days of moist curing for ASTM C 150 Type I portland cement-based concrete and three days for ASTM C 150 Type III portland cement-based concrete, if the temperature is above 10°C (50°F). ACI

308 also describes numerous methods to properly cure concrete, including the

use of sealing materials and other methods to keep concrete moist.

TABLE 1
Typical Surface Properties of Finished Concrete²⁶

Method	Profile	Porosity ^(A)	Strength ^(A)	Problems
Formed concrete	Smooth to medium	Low to medium	Medium	Voids, protrusions, release agents
Wood float	Medium	Medium	Medium	
Metal trowel	Smooth	Low	High	
Power trowel	Smooth	Very low	High	Very dense
Broom finish	Coarse to very coarse	Medium	Medium	
Sacking	Smooth	Low to medium	Low to high ^(B)	Weak layer if not properly cured
Stoning	Smooth to medium	Low to medium	Low to high ^(B)	Weak layer if not properly cured
Concrete block	Coarse to very coarse	Very high	Medium	Pinholes
Shotcrete ^(C)	Very coarse	Medium	Medium	Too rough for thin coatings

^(A) These surface properties are based on similar concrete mix, placement, and vibration, and are prior to surface preparation.

^(B) Strength depends on application and cure.

^(C) Shotcrete may be refinished after placement, which would change the surface properties shown in this table.

3.1.6.3 ACI 305 and ACI 306 describe the effects of hot and cold temperatures on concrete curing. Knowing the time required for adequate surface cure is essential for determining when coating application may begin (see Paragraph 6.1).

3.1.7 Sealers and Curing Membrane Compounds

Sealers and curing membrane compounds are commonly used to improve surface cure and to reduce moisture loss immediately after placement and finishing of concrete surfaces. Materials and practices are described in ACI 308 and ASTM C 309.²⁹ Commonly used curing membrane compounds (some of which also perform as sealers after the concrete has cured) include synthetic resins, waxes, and acrylic-based materials. Many of these materials are incompatible with thermoset coatings and are difficult to remove. Paragraph 3.2.6 describes a method for testing sealers for compatibility with coating materials and ease of removal.

3.2 Existing Concrete Structures

Concrete structures more than one year old can be characterized more easily than new concrete structures because strength, surface strength, shrinkage, and moisture content have stabilized. After one year—with the exception of years with mild winters—the structure has been exposed to a complete thermal range. Other than structural problems (which are beyond the scope of this report), after one year most movement and cracking from shrinkage and thermal cycling is evident and can be treated appropriately in the coating system design. However, existing structures may have been subjected to physical abuse or chemical contamination that needs assessment and repair prior to application of a coating.^{30,31}

3.2.1 Surface Strength

3.2.1.1 Requirements

The minimum requirement for surface strength depends on the service conditions and coating system (see Sections 2.3 and 5.2). As stated in Paragraph 3.1.1.3, adequate surface strength ensures that the concrete structure remains intact during surface preparation.

and ensures that the bond to the coating is sufficient to survive stresses from curing and thermal cycling. Many coating manufacturers and designers typically specify minimum bond strength between 1.4 and 2.1 MPa (200 to 300 psi), depending on the coating and the service conditions.

3.2.1.2 Test Methods³²

3.2.1.2.1 ASTM D 4541³³ is typically used to test for surface strength.

3.2.1.2.2 ACI 503R, Appendix A,³⁴ uses a larger test area than ASTM D 4541.

3.2.1.2.3 The patch test involves applying the coating to a 100- to 150-mm (4- to 6-in.)-diameter area of the concrete after surface preparation, typically by the same application method as will be used to coat the entire structure. After 24 hours, the concrete/coating interface is tested by striking the side of the patch with a hammer or a hammer and chisel. Although the patch test is not quantitative, it is simple and easy, requires no special equipment or adhesives, shows potential adhesion of the specific coating to be used, and tests surface strength in a shear mode.

3.2.2 Physical and Chemical Damage

Existing concrete structures that have been subjected to mechanical damage (due to impact or abrasion), chemical attack, or rebar corrosion are restored to provide a uniform, sound substrate for coating. In cases of severe damage, the concrete may need to be completely removed and replaced. It is important to remove all deteriorated concrete and to cut the surrounding sound concrete using the procedures described in ICRI⁽³⁾ 03730³⁵ in order to best receive and hold the patching material. Some contaminants may have a detrimental effect on the rebar or the applied coating if they are not completely removed.

Methods for detecting and treating residual chemical contamination are discussed in Paragraph 3.3.1. Cementitious repairs are treated as new concrete (see Paragraph 3.1). Polymeric grouts and patching materials are often used, especially when the coating is to be applied immediately after the repair. It is important that these materials be compatible with the coating to be applied. Selection and application of these materials is described in Paragraph 6.2.

3.2.3 Other Defects and Imperfections

3.2.3.1 Defects such as honeycombs, scaling, and spalling do not provide a sound, uniform substrate for the coating. Defects are usually removed and patched prior to surface preparation (see Paragraph 6.2).

3.2.3.2 Surface voids, tieholes, bug-holes, pinholes, and excess porosity may affect the application and performance of the coating. The maximum substrate void size or porosity that can be tolerated depends on the type of coating. These voids typically are filled prior to coating application (see Paragraph 6.2). If voids are not filled and the coating is applied, the trapped air vapor expands and contracts and may affect the cure or the film integrity and performance of the coating. Excessive porosity in the concrete surface may result in pinholes.

3.2.3.3 Protrusions such as form lines, fins, sharp edges, and spatter may cause holidays or thin sections in the coating if they are not removed. Protrusions and rough edges typically are removed during surface preparation.

3.2.4 Joints and Cracks

Many coatings are rigid and are prone to reflective cracking (see Paragraph 4.7.1). Therefore, it is important to identify existing joints and cracks and quantify the maximum expected movement prior to coating selection. Movement at joints or cracks is due to shrinkage, thermal cycling, settling, or load; however, in existing structures no significant movement is expected due to shrinkage.²⁰⁻²² Additional information about the identification of joints and their expected movement is given in ACI 302, ACI 504, and in Paragraph 3.1.3 of

⁽³⁾ International Concrete Repair Institute (ICRI), 1323 Shepard Dr., Ste. D, Sterling, VA 22170.

this report. Monitoring joints and cracks over 24 hours helps to determine whether they are static or dynamic. Some cracks are invisible in warm conditions when the concrete is expanded, but they may be visible when temperatures are lower, when the concrete is drying (because the crack dries slower), or when a dye method is used to identify cracks. Joints and cracks that are identified as dynamic are usually treated as described in Paragraph 4.7.1 to prevent reflective cracking in the coating.

Plastic shrinkage cracking is common in concrete when the surface is not cured properly. On existing concrete structures, these cracks can be treated as static cracks; however, the surface strength is probably low due to the improper surface cure (see Paragraph 3.2.1).

3.2.5 Hydraulic and Hydrostatic Pressures

The importance of moisture migration and the effects of ground water and vapor barriers are described in Paragraph 3.1.4. In existing concrete structures, unless the concrete structure has been continuously wet, moisture migration due to drying is not a concern. However, all other issues discussed in Paragraph 3.1.4 apply to both new and existing concrete. It is important to determine whether a vapor barrier is under the existing concrete structure. If no vapor barrier is present, a moisture migration or moisture test can be used to determine whether a moisture problem exists.

3.2.5.1 Moisture Test Methods

The following are some of the common methods used to identify or quantify the free moisture in concrete prior to the application of coatings.^{36,37}

- (1) ASTM D 4263,³⁸ Plastic Sheet Method.
- (2) RMA Test Method,³⁹ Calcium Chloride Absorption Rate (RMA test).⁽⁴⁾
- (3) BS 5325,⁴⁰ Appendix A.1, Hygrometer Test (Relative Humidity Method).⁽⁵⁾
- (4) BS 5325, Appendix A.2, Conductivity Test (Gel Bridge Method).
- (5) Calcium Carbide Method.³⁶
- (6) Capacitance-Impedance Method.³⁶

3.2.5.2 Use and Interpretation of Moisture Test Methods

3.2.5.2.1 ASTM D 4263 and the RMA test are commonly used and accepted in the United States. The hygrometer and conductivity tests are cited in numerous British standards and are accepted in the United Kingdom, while the carbide method is accepted in other parts of Europe.

3.2.5.2.2 All of these methods are quantitative except for ASTM D 4263. The plastic sheet, RMA, and capacitance-impedance methods are nondestructive, while the hygrometer, conductivity, and calcium carbide methods involve drilling into the concrete.

3.2.5.2.3 Testing duration is 16+ hours for ASTM D 4263, 72 hours for the RMA method, and from 4 to 72 hours for the hygrometer test. The other methods give results immediately if the testing equipment has been calibrated.

3.2.5.2.4 The plastic sheet method may indicate if excess moisture is present at the time of the test. However, because the method depends on a moisture differential—a higher relative humidity in the concrete than in the air above the concrete surface—during the test span, potential problems are not always evident at the time the test is performed.

3.2.5.2.5 The coating manufacturer can provide information on the tolerance of a specific coating system for free water or moisture migration. A free water content of less than 5% by weight is acceptable for most coatings. Alternatively, concrete relative humidity of less than 80% or moisture transmission rates of less than 15 g/24 hr/m² (3 lb/24 h/1,000 ft²) have proved acceptable for most coatings.³⁶

⁽⁴⁾ Rubber Manufacturers Association (RMA), 1400 K St. NW, Ste. 900, Washington, DC 20005.

⁽⁵⁾ British Standards Institution (BSI), Two Park St., London, W1A 2BS, United Kingdom.

3.2.5.2.6 Occasionally, despite moisture testing, a problem is not identified until after an impermeable coating is applied.

3.2.5.3 Retrofit Repair

Negative-side barrier systems, grouting with high-density cementitious products, and penetrating sodium or potassium silicate sealers have been used successfully under coatings in some installations, although using a negative-side barrier system is not usually effective. Where practical, well points have been used to relieve the source of hydrostatic pressure.

3.2.6 Existing Sealers and Coatings

Maintaining an adequate bond between the concrete substrate and the coating is important. Existing sealers or coatings on the concrete are tested for compatibility with the coating to be applied. If they are not compatible, the sealers or coatings are removed. Even if the existing coating is found to be compatible by adhesion testing, the surface of the existing coating is abraded to provide adequate surface profile for the coating to be applied.

3.2.6.1 Sealers and Curing Membrane Compounds

Curing membrane compounds (ASTM C 309), sealers, and hardeners (sodium silicate) are often encountered in existing concrete structures. The methods in Paragraph 3.2.1.2 are useful in determining whether the existing material is compatible with the coating to be applied. Sodium silicate can be removed only by abrasive blasting or water blasting, whereas the wax, resin, and acrylic materials can be removed by abrasive blasting, flame blasting, or the use of paint strippers (see Paragraph 3.3).

3.2.6.2 Existing Coatings

The methods in Paragraph 3.2.1.2 are useful in determining whether the existing coating is compatible with the coating to be applied. Procedures for removing existing coatings are discussed in Paragraph 3.3.1.3.

3.3 Surface Preparation

Surface preparation of concrete is covered in documents published by NACE (6F163,⁴¹ 6G166,⁴² 6H175,⁴³ and 6G191⁴⁴), ASTM (C 811⁴⁵), ICRI (Guide No. 03732⁴⁶), NACE/SSPC (work in progress²⁶), ACI (515.1R⁴⁷), and in technical articles.^{28,48,49}

3.3.1 Contamination

Visible and nonvisible contaminants on new and existing concrete surfaces often impede coating adhesion. Problems caused by surface contaminants that are not removed during surface preparation or by contaminants migrating to the concrete/coating interface could become evident some time after the coating application. Identification and removal of contaminants is covered in detail in NACE 6G191, ASTM D 4258,⁵⁰ PCA⁽⁶⁾ IS214.02T,⁵¹ and in technical articles.^{30,31,52,53}

3.3.1.1 Types of Contamination

3.3.1.1.1 Hydrophobic Materials

- (1) Form-release agents, including oils, wax, grease, and silicone
- (2) Curing membrane compounds and sealers, including waxes and resins
- (3) Existing incompatible coatings and adhesives

3.3.1.1.2 Salts and Reactive Materials

- (1) Chemicals, including acids, alkalis, and salts
- (2) Laitance and efflorescence
- (3) Concrete admixtures

3.3.1.1.3 Microorganisms

- (1) Fungus, moss, mildew, algae, and other organic growths
- (2) Decomposing foods that produce organic acids

3.3.1.2 Tests for Contamination

3.3.1.2.1 Hydrophobic Materials

Hydrophobic materials can be detected by a water drop test.⁵³

3.3.1.2.2 Salts and Reactive Materials

⁽⁶⁾ Portland Cement Association (PCA), 5420 Old Orchard Rd., Skokie, IL 60077-1083.

Acid, alkali, and sulfate attack leaves a weak surface layer that can be detected using the surface sometimes be detected by testing the pH of the concrete surface. Normal fresh concrete has a pH of 12 to 13, but aged concrete can have a pH at the surface as low as 7 before surface preparation. Salts, including efflorescence, are often visible as a white bloom, colored deposit, or weak surface layer. Salts can be identified by analytical methods, e.g., atomic absorption. Efflorescence is a sign that water is transporting salts from the ground or the concrete to the surface. This problem of moisture migration is discussed in Paragraph 3.2.5. Removal of efflorescence does not solve the moisture migration problem.

3.3.1.2.3 Microorganisms

Organic growths are visible on concrete surfaces. Decomposing foods that produce organic acids can deteriorate concrete.

3.3.1.3 Treatment and Removal

3.3.1.3.1 Hydrophobic Materials

Steam cleaning, flame blasting, and degreasers and absorbents are used to remove oil and grease. The method chosen to remove a coating is usually the least destructive method that is successful. In increasing order of aggressiveness, the methods are: (1) using paint strippers, (2) grinding, (3) wet abrasive blasting, dry abrasive blasting, or high-pressure water cleaning, and (4) water jetting, scarifying, or flame blasting. These methods are discussed in Paragraph 3.3.2.

3.3.1.3.2 Salts and Reactive Materials

Salts and efflorescence can be removed by abrasive blasting, water blasting, or applying a weak acid solution and then water cleaning.⁵¹ Residual acids and alkalis are first neutralized and then removed by water cleaning. If the concrete is deteriorated down to the rebar, see the ICRI Guide.³⁵

strength test methods in Paragraph 3.2.1.2 or by various analytical methods. Acidic materials can

3.3.1.3.3 Microorganisms

Fungus, moss, mildew, algae, and other microorganisms are removed by washing with sodium hypochlorite (household bleach) and rinsing with water.⁵¹ High-pressure water cleaning or abrasive blasting may also be used.

3.3.2 Surface Preparation Methods

Table 2 lists typical surface preparation methods with their intended use, profile created, typical problems encountered, and solutions to those problems. Acid etching, which used to be common practice, is now infrequently specified, primarily due to environmental considerations and lack of consistent results.

3.3.3 Quantifying Prepared Concrete Surfaces

The degree of surface preparation needed to achieve good adhesion depends on the requirements of the coating system (see Section 5). The following tests are typically used to determine the properties of prepared concrete surfaces.

3.3.3.1 Surface strength³² (see Paragraph 3.2.1)

3.3.3.2 Surface profile²⁶

Surface profile is quantified by equivalent graded abrasive paper sizes, or, for coarse profiles, by measuring the surface profile in millimeters (mils).

3.3.3.3 Surface cleanliness (see Paragraph 3.3.1)

- (1) ASTM D 4258
- (2) Dust: black cloth test

3.3.3.4 pH

pH testing is performed to ensure neutralization after surface preparation by acid etching. pH testing has also been used to help detect the presence of acidic or alkaline contaminants.⁵³

ASTM D 4260⁵⁸

3.3.3.5 Moisture content^{36,37} (see Paragraph 3.2.5.1)

3.3.3.6 The 28-day waiting period (see Paragraph 6.1)

TABLE 2
Surface Preparation Methods²⁶

Preparation Method	When Used	Profile Created ^(A)	Problems	Solutions
Dry abrasive blasting ⁵⁴	Removal, profile, cleaning	Fine (150) to extra coarse (40)	-Dust on surface -Airborne dust -Noise	-Vacuum cleaning -Vacuum attachments -None
Wet abrasive blasting	Removal, profile, cleaning	Fine (150) to extra coarse (40)	-Wets concrete -Creates sludge	-Let concrete dry -Cleaning
High-pressure water cleaning ^{55,56}	Removal, cleaning	Fine (150) to extra coarse (40)	-Wets concrete -Creates sludge	-Let concrete dry -Cleaning
Water Jetting ^{55,56}	Removal	Rougher than extra coarse	-Creates sludge -Wets concrete -Coarse profile	-Cleaning -Let concrete dry -None ^(B)
Impact tools	Removal, profile, cleaning	Rougher than extra coarse	-Airborne dust -Fracturing -Coarse profile	-Vacuum attachments -Other methods -None ^(B)
Power tools	Removal	Smooth (no grit equivalent)	-Airborne dust -Fine profile	-Vacuum attachments -Other methods
Flame blasting ⁵⁷	Removal, profile, cleaning	Rougher than extra coarse	-Excess removal -Damages concrete	-Experience ^(B) -Remove damaged concrete
Acid etching ⁵⁸	Profile, cleaning	Fine (150) to medium (100)	-HCl is hazardous -Not for vertical or overhead surfaces -Neutralization -Wets concrete -Curing membrane	-Other acids -Other methods -pH testing -Let concrete dry -Other methods

^(A) Profile is described using standard classifications and screen grit sizes for coated abrasive products. These are typical surface profile values only. Results may vary significantly due to concrete properties and surface preparation practices.

^(B) May be acceptable for thick coating systems; otherwise, the surface can be patched prior to coating application.

Section 4: Coating System Design Requirements

4.1 General information on design requirements for coating systems is contained in various ASTM, ACI, and NACE publications^{47,59-67} as well as in technical articles.⁶⁸⁻⁸⁷ Paragraphs 4.2 to 4.8 discuss coating system properties, the importance of these properties, and the variables that affect these properties. Paragraph 4.9 lists the test methods commonly used to quantify coating properties.

4.2 Chemical Resistance

A coating system is designed to survive the anticipated chemical exposure for its entire design life (see Paragraph 2.2). The chemical resistance of a coating depends on the polymer type, cross-link density, cure time and temperature, filler type and amount, coating thickness, and reinforcement.

4.3 System Physical Properties and Stress Considerations

4.3.1 Ignoring stress concentrations at joints, cracks, and corners, continued coating performance depends on many factors, including concrete surface strength, concrete surface profile, coating system strength, coating system elasticity, coating system thickness, coating shrinkage during application, thermal exposure conditions, chemical exposure conditions, and thermal expansion of the concrete and coating.

4.3.2 Structural integrity of the coating and coating adhesion depend on the tensile, flexural, and compressive strength of the coating. Flexibility and toughness enable the coating to withstand strain and forces due to impact or substrate movement. In most thermoset polymer systems there is a direct trade-off between cross-link density, which gives increased strength and chemical resistance, and flexibility, which gives increased ability to bridge cracks. Flexibility and strength are balanced to give optimum performance.

4.4 Permeability

4.4.1 Low water vapor transmission (WVT) of coatings applied to steel in primary containment is critical in preventing corrosion of the steel substrate. However, concrete substrates do not corrode from water vapor. The WVT of a coating for concrete is simply an indicator—not always a good one—of the coating's ability to protect the concrete from corrosive materials and to protect the environment from hazardous materials.

4.4.2 Results of WVT tests do not correspond to the transmission resistance of the coating to solvents or solvent vapors. The permeability of a coating when exposed to a specific solvent is a function of the solubility parameters of the solvent and the coating, the molecular size of the solvent, the cross-link density of the polymer, and the type and amount of filler in the coating. The coating can be tested for weight gain after immersion in a solvent to indicate the relative permeability of the coating in that specific solvent. The WVT and permeability of coatings are reduced by increased film thicknesses, increased cross-link densities in the polymer, and the use of fillers.

4.4.3 One U.S. federal regulation has specified a maximum WVT of 1×10^{-7} cm/s (3.4 g/h-m²) (4.9 grains/h-ft²) for secondary containment systems.⁸⁸ This level is based on 15 L (4 gal) of water per day for an uncoated 200-m² (2,000-ft²) concrete slab with all cracks sealed. Most coating systems, depending on their thickness, meet this criterion, even when the

WVT of the concrete is ignored. While a coating system may meet the WVT criterion, the amount of water that passes through the coating during WVT lab testing may be insignificant when compared to the relative effect of pinholes and cracks in the field-applied coating system (see Paragraph 4.7.1). New York state regulations specify a maximum transmission level of 1×10^{-6} cm/s (34 g/h-m²) (49 grains/h-ft²) for the chemical to be contained.⁸⁹ However, no approved test method currently exists for measuring the transmission of various chemicals through coating systems.

4.5 Adhesion

Most coating systems depend on the concrete substrate for structural integrity; therefore, maintaining good adhesion to that substrate—even after weathering and chemical exposure—is critical to coating performance. Maintaining intercoat adhesion in multilayer coating systems and patching materials is equally important. Properties of the concrete substrate that affect adhesion include surface strength, profile, cleanliness, porosity, and moisture content. Properties of the primer of the coating system that affect adhesion include viscosity, surface tension, physical strength, chemical affinity for the concrete, and resistance to alkalis and hydrolysis. For multilayer systems, properties that may affect adhesion include blush in epoxies, wax in unsaturated polyesters and vinyl esters, and numerous application-related phenomena (see Paragraphs 6.4.4 and 6.4.5). To ensure good adhesion, all the above properties are specified, inspected, and/or tested prior to and during coating application. The minimum requirement for adhesion, as tested by the methods in Paragraph 4.9.3, typically ranges from 1.4 to 2.1 MPa (200 to 300 psi). However, the mode of failure is as important as the adhesion value. Any failure mode other than cohesive failure in the concrete indicates potential adhesion problems.

4.6 Thermal Effects

4.6.1 Shrinkage from Cure and Aging

Polymers and coatings often shrink volumetrically due to cross-linking or solvent evaporation. The thermoset coatings described in Paragraph 5.2 range in potential shrinkage from less than 1% to more than 10%, depending on the type of polymer, amount of filler, amount of solvent, and extent of cure. The amount of shrinkage affects the adhesive bond between the coating and the concrete. The stress due to shrinkage can range from insignificant in low-shrink, highly elastic coatings systems, to catastrophic in high-shrink, rigid coatings. Stress due to shrinkage can intensify adhesion problems,