

Effects of Substances on Concrete and Guide to Protective Treatments

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Introduction

Portland cement concrete is durable in most natural environments; however, concrete is sometimes used in areas where it is exposed to substances that can attack and deteriorate it. This publication discusses the effects of many substances on concrete and provides guidelines to protective treatments.

The first line of defense against chemical attack is to use quality concrete with maximum chemical resistance. This is enhanced by the application of protective treatments in severe environments to keep corrosive substances from contacting the concrete or to improve the chemical resistance of the concrete surface. Protective surface treatments are not infallible, as they can deteriorate or be damaged during or after construction, leaving the durability of the concrete element up to the chemical resistance of the concrete itself.

Proper maintenance—including regularly scheduled cleaning or sweeping, and immediate removal of spilled materials—is a simple way to maximize the useful service life of both coated and uncoated concrete surfaces.

Improving the Chemical Resistance of Concrete

Quality concrete must be assumed in any discussion on how various substances affect concrete. In general, achievement of adequate strength and sufficiently low permeability to withstand many exposures requires proper proportioning, placing, and curing. Fundamental principles and special techniques that improve the chemical resistance of concrete follow. Refer to *Design and Control of Concrete Mixtures* (Kosmatka et al. 2002) for further information.



Fig. 1. Aggressive substances can compromise the durability of concrete. Shown are concrete beams exposed to high-concentration sulfate soils/solutions. (PCA/CALTRANS test plot, Sacramento, California) (Stark 2002) (IMG12296)



Low water-cement ratio (w/c)—the water-cement ratio or the water-cementitious materials ratio (where applicable) should not exceed 0.45 by weight (0.40 for corrosion protection of embedded metal in reinforced concrete). Water-cement ratios for severe chemical exposures often range from 0.25 to 0.40 to maximize chemical resistance.

Cement content—at least 335 kg/m³ (564 lb/yd³) of cementitious material should be used for concrete exposed to severe freeze-thaw, deicer, and sulfate environments.

Suitable cement type—cement should be suited to the exposure, such as sulfate-resistant cement to help prevent sulfate attack (Table 1). Sulfate-resistant cements, however, like other portland or blended hydraulic cements, are not resistant to most acids or other highly corrosive substances.

Suitable aggregate—quality aggregate is not prone to freeze-thaw deterioration or chemical attack. If an aggregate is shown by field performance (history) or by testing to be susceptible to alkali-aggregate reaction (AAR), appropriate measures should be taken to design a concrete mixture to minimize its susceptibility to AAR. (See Farny and Kerkhoff 2007 and PCA 2007 for further guidance.) Some aggregates may be more suitable than others for certain chemical exposures. (See “Acids” under “Design Considerations.”)

Suitable water—mixing water should not contain impurities that can impair basic concrete properties or reduce chemical resistance. Steinour (1960), and Abrams (1920 and 1924) discuss the effects of impure mixing water.

Chemical admixtures (optional)—dosage varies to achieve desired reduction in permeability and to improve chemical resistance. Water reducers (ASTM C494) and superplasticizers (ASTM C1017) can be used to reduce the water-cement ratio, resulting in reduced permeability and less absorption of corrosive chemicals. Polymer admixtures, such as styrene-butadiene latex, used in the production of polymer-modified concrete, greatly reduce the permeability of concrete to many corrosive chemicals. A typical dosage of latex admixture would be about 15% latex solids by weight of cement. Certain integral water-repelling admixtures, also called hydrophobic pore-blocking or dampproofing admixtures, can slightly improve the chemical resistance of concrete to certain chemicals such as formic acid (Aldred 1988). However, many integral water-repellents offer little to no improvement; therefore tests should be performed to determine the effectiveness of particular admixtures. (See “Evaluating the Effectiveness of Concrete Surface Protection by Testing.”) Admixtures containing chloride should not be used for reinforced concrete. Corrosion inhibitors (ASTM C1582) reduce chloride-induced steel corrosion. (See “Corrosion of Reinforcement” under “Design Considerations.”) Alkali-silica reactivity inhibitors, such as lithium nitrate, can be considered when potentially reactive aggregate is used and when alkali solutions will be in contact with concrete. Shrinkage reducing admixtures can reduce the formation of shrinkage cracks through which aggressive chemicals can penetrate the concrete.

Supplementary cementitious materials (optional)—dosage varies to improve chemical resistance. Supplementary cementitious materials (SCMs) such as fly ash and metakaolin (ASTM C618), slag

Table 1. Requirements for Concrete Exposed to Sulfate-Containing Soils and Solutions

Sulfate exposure	Sulfate (SO ₄) in soil, % by mass	Sulfate (SO ₄) in water, ppm	Cement type*			Maximum water-cementitious material ratio, by mass
			ASTM C150	ASTM C595	ASTM C1157	
Negligible	Less than 0.10	Less than 150	No special type required			—
Moderate**	0.10 to 0.20	150 to 1500	II	IP(MS), IS(<70)(MS)	MS	0.50
Severe	0.20 to 2.00	1500 to 10,000	V	IP(HS) IS(<70)(HS)	HS	0.45
Very severe	Over 2.00	Over 10,000	V	IP(HS) IS(<70)(HS)	HS	0.40

* Pozzolans and slag that have been determined by testing according to ASTM C1012 or by service record to improve sulfate resistance may also be used. Maximum expansions when using ASTM C1012: Moderate exposure—0.10% at 6 months; Severe exposure—0.05% at 6 months or 0.10% at 12 months; Very Severe exposure—0.10% at 18 months. Sulfate resistance of individual pozzolans or slags needs to be established by demonstrating a maximum expansion of 0.10% at 1 year, before a 6 months test duration is acceptable. Refer to ACI 201 (2001) for more guidance.

** Includes seawater.

Test method: ASTM C1580, *Standard Test Method for Water-Soluble Sulfate in Soil*. Source: Adapted from Bureau of Reclamation 1981, ACI 201, and ACI 318.

(ASTM C989), and especially silica fume (ASTM C1240) can improve chemical resistance by reducing the permeability of the concrete and by producing additional cementitious compounds. Dosages by mass of cementitious material often range from 15% to 25% for Class F fly ash, 15% to 40% for Class C fly ash, 35% to 50% or more for slag, and 5% to 10% for silica fume. Dosage is usually proportional to severity of exposure to chemical. Supplementary cementitious materials may not prevent chemical attack but they can slow it down, significantly in some cases. Supplementary cementitious materials can help control alkali-silica reactivity for concretes exposed to high-alkali, high-pH solutions. Unless previous data exist to confirm the beneficial effect of these materials in specific exposures, testing should be performed to substantiate improved chemical resistance. (See "Evaluating the Effectiveness of Concrete Surface Protection by Testing.")

Air entrainment—the proper amount of entrained air is dependent on the exposure condition and on maximum aggregate size (Table 2). Air entrainment makes concrete resistant to freezing and thawing cycles. In addition it improves sulfate and salt resistance, watertightness, and workability.

Table 2. Target Total Air Content for Concrete

Nominal maximum aggregate size, mm (in.)		Air content, percent*	
		Severe exposure**	Moderate exposure**
9.5	(3/8)	7.5	6
12.5	(1/2)	7	5.5
19	(3/4)	6	5
25	(1)	6	4.5
37.5	(1 1/2)	5.5	4.5

* Project specifications often allow the air content of the delivered concrete to be within -1 to +2 percentage points of the table target values.
 ** Severe exposure is an environment in which concrete is exposed to wet freeze-thaw conditions, deicers, or other aggressive agents. Moderate exposure is an environment in which concrete is exposed to freezing but will not be continually moist, not be exposed to water for long periods before freezing, and not be in contact with deicers or aggressive chemicals.
 Adapted from Kosmatka et al. (2002) and ACI 318.

Suitable workability—avoid mixes so harsh and stiff that honeycombing occurs as well as mixes so fluid that excessive water rises to the surface. If necessary, water reducers and superplasticizers can be used to make mixes more workable (higher slump). Supplementary cementitious materials can increase or decrease the workability of fresh concrete, so appropriate mix adjustments should be made.

Thorough mixing—mixing should continue until concrete is uniform, with all materials evenly distributed. Silica fume may require a longer mixing period to become thoroughly distributed throughout a concrete mixture.

Consolidation—concrete should be properly molded into forms and around reinforcement to eliminate stone pockets, honeycomb, and entrapped air.

Finishing—slabs should not be finished while bleedwater is on the surface or, as this will increase the permeability at the surface, decreasing its chemical resistance (and strength). Supplementary cementitious materials or blended cements may affect the bleeding characteristics of concrete. For instance, silica fume mixes tend to bleed very little, and slag or fly ash mixes may bleed longer due to a slower set. Placing concrete at the proper temperature promotes uniform bleeding and setting characteristics and helps control finishing operations.

Proper jointing—isolation, contraction, and construction joints should be used to control cracking. Contraction joints in slabs on ground should be spaced about 24 to 30 times the slab thickness and 36 times the slab thickness for mixtures with low water content and large aggregates (19 mm (3/4 in.) or larger). Joints should be properly sealed with a material capable of enduring the environment. Waterstops, if used, must be properly placed. Construction methods such as the use of heavily reinforced slabs (Farny 2001) or post-tensioned slabs are helpful in reducing the number of joints in areas where joints are undesirable.

Adequate curing—either additional moisture should be supplied to the concrete during the early hardening period or the concrete should be covered with water-retaining materials. In general, curing compounds should not be used on surfaces that are to receive protective surface treatments. If a curing compound is used, it must be completely removed before the surface treatment is applied, or it must be compatible with the surface treatment so as not to impair bond. Concrete should be kept moist and above 10 °C (50 °F) for the first week or until the desired strength is achieved. Longer curing periods increase resistance to corrosive substances by increasing strength and reducing permeability for all concrete mixtures. Concretes made with SCMs may especially benefit from extended curing. Concrete should not be subjected to hydrostatic pressure during the initial curing period. The resistance of air-entrained concrete to freeze-thaw cycles and deicers is greatly enhanced by an air-drying period after initial moist curing. Refer to Kosmatka, et al. 2002 for more information on concrete construction practices.

Nature of Aggressive Chemicals

The rate of attack on concrete may be directly related to the activity of the aggressive chemical. Solutions of high concentration are generally more corrosive than those of low concentration—but in some cases, the reverse is true. The rate of attack may be altered by the solubility of the reaction products of the particular concrete. A lower hydroxide ion concentration generally causes more rapid attack on the concrete surface. Also, since high temperatures usually accelerate chemical attack, better protection is required than for normal temperatures.

Generally there are two ways to mitigate chemical attack, (1) choose the right concrete composition to make it less permeable or isolate it from the environment by using a suitable coating, or (2) modify the environment to make it less aggressive to the concrete (Addis 1994). Kuenning (1966) studied the nature of aggressive chemicals, modes of attack, and reaction products for mortars exposed to acids, aluminates, ammonium salts, borates, carbonates, chlorates, chlorides, chromates, ferrocyanides, fluosilicates, magnesium salts, manganates, molybdates, nitrates, nitrites, phosphates, seawater, stannates, sulfates, alcohols, amino acids, linseed oils, esters, benzene, and sugars. Type I and Type V cements were studied at varying water-cement ratios. He found that resistance of mortar to chemical attack was increased by longer curing time and by a decrease in water-cement ratio. The Type V cement mortar was more resistant to sulfate attack than the other mortars, but not to acidic sulfates or those which contained ammonium or magnesium. The zero-C₃A cement mortar was generally lower in resistance to chemical attack than Type V.

Basson (1989) derives in his publication an aggressiveness index of a water sample, obtained from the chemical analysis of the water and adjusted by factors such as prevailing temperature, flow conditions, or wet and dry cycles of the exposed concrete. Guidelines with protective treatments are given in the final index at the end of this publication.

Salts

Many solutions that have little or no chemical effect on concrete, such as brines and salts, may crystallize upon drying. It is especially important that concrete subject to alternate wetting and drying of such solutions be impervious to them. When free water in concrete is saturated with salts, the salts crystallize in the voids near the surface during drying, sometimes exerting sufficient pressure to cause scaling. Sodium sulfate and sodium carbonate, sometimes present in ground water, are known to cause concrete deterioration from salt crystallization, also called physical salt attack (Haynes et al. 1996, ACI 201 2001, and Stark 2002). Physical attack by sulfate salts can be distinguished from conventional, chemical sulfate attack, for example, by evaluating the sulfate content of the concrete. Chemical sulfate attack increases the sulfate content of the concrete whereas physical salt attack most likely does not. Chemical sulfate attack can be evidenced by significant amounts of ettringite and/or gypsum, as well as the characteristic decalcification of the paste and cracking due to expansion. In physical sulfate attack, damage in the form of scaling is usually limited to the exterior surface of the concrete; the concrete is not affected below the surface. Damage due to salt crystallization can occur with a variety of salts; they need not contain sulfate ions. Concrete structures exposed to salt solutions should have a low water-cement ratio (0.45 maximum) to reduce permeability. A vapor barrier system of clean drain rock and plastic sheeting under slabs should be provided along with proper drainage away from the structure (Fig. 2) (Haynes et al. 1996 and Kanare 2005).

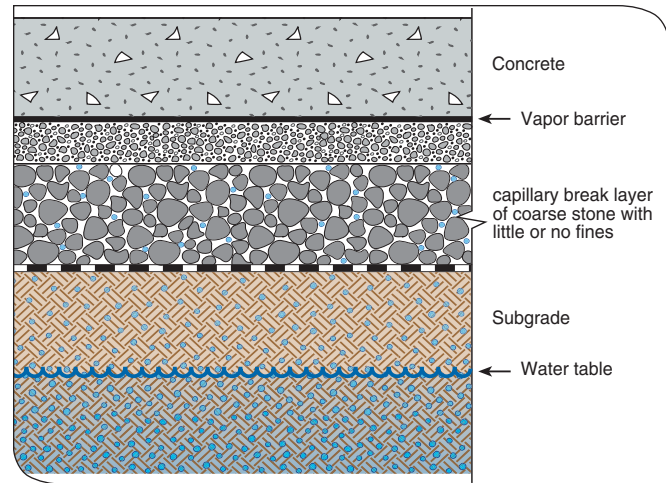


Fig. 2. Low water-cement ratio concrete, a layer of coarse aggregate, and a vapor barrier sheet help prevent concrete deterioration due to salt attack.

Acids

Acids attack concrete by dissolving both hydrated and unhydrated cement compounds as well as calcareous aggregate. Siliceous aggregates are resistant to most acids and other chemicals and are sometimes specified to improve the chemical resistance of concrete, especially with the use of chemically-resistant cement. Siliceous aggregate should be avoided when a strongly basic solution, like sodium hydroxide, is present, as it attacks siliceous aggregate. In certain acidic solutions it may be impossible to apply an adequate protective treatment to the concrete, and the use of a “sacrificial” calcareous aggregate should be considered, particularly in locations where the acidic solution is not flowing. Replacement of siliceous aggregate by limestone or dolomite having a minimum calcium oxide concentration of 50% will aid in neutralizing the acid. The acid will attack the entire exposed surface more uniformly, reducing the rate of attack on the paste and preventing loss of aggregate particles at the surface. The use of calcareous aggregate may also retard expansion resulting from sulfate attack caused by some acid solutions. Within reason, the paste content of the concrete should be minimized—primarily by reducing water content and using a well-graded aggregate—to reduce the area of paste exposed to attack. High cement contents are not necessary for acid resistance. Concrete deterioration increases as the pH of the acid decreases below about 6.5 (Kong 1987 and Fattuhi 1988).

Properly cured concrete with reduced calcium hydroxide contents, such as occur when pozzolans are used, may experience a slightly slower rate of attack from acids. This is because acid resistance is linked to the total quantity of calcium-containing phases, not just the calcium hydroxide content (Matthews 1992). Resistance to acid attack is primarily dependent on the concrete’s permeability and water-cement ratio.

Acid rain (often with a pH of 4 to 4.5) can slightly etch concrete surfaces, usually without affecting the performance of exposed concrete structures. Extreme acid rain or strong acids may warrant special concrete designs or precautions, especially in submerged areas. The American Concrete Pressure Pipe Association (ACPPA 2000) provides guidelines for granular soils with a pH below 5 and the total acidity of the soil exceeding 25 meq/100 gm and requires one of the following precautions to be used.

- Backfill in the pipe zone with consolidated clay material or calcareous material;
- Acid resistant membrane on or around the pipe; or
- 8 to 10% silica fume in the mortar coating.

Where soil pH is below 4, the pipe should be installed in an acid resistant membrane or in an envelope of non-aggressive consolidated clay (ACPPA 2000). Natural waters usually have a pH of more than 7 and seldom less than 6. Waters with a pH greater than 6.5 may be aggressive if they contain bicarbonates.

Water that contains bicarbonates also contains dissolved free carbon dioxide (CO₂) and carbonic acid (H₂CO₃) which can dissolve calcium carbonate unless it is saturated. This “aggressive carbon dioxide” acts by acid reaction and can attack concrete and other portland cement products whether or not they are carbonated. Methods are presented in Steinour (1975) for estimating the amount of aggressive carbon dioxide from an ordinary water analysis when the pH is between 4.5 and 8.6, and the temperature is between 0 °C (32 °F) and 65 °C (145 °F). The German Institute of Standardization Specification DIN 4030-2 includes criteria and a test method for assessing the potential of damage from carbonic acid-bearing water.

Calcium-absorptive acidic soil can attack concrete, especially porous concrete. Even slightly acidic (pH of 5 to 6.9) solutions that are lime deficient can attack concrete by dissolving calcium from the paste, leaving behind a deteriorated paste consisting primarily of silica gel. Langelier Saturation Index values for a water solution and calcium-absorption test data on a soil sample can be used to test for this condition (Hime 1986 and Steinour 1975). Negative Langelier Index values indicate a lime deficiency. Hime noted one project with concrete deterioration had index values of -4.2 to -7.1 in the water, and over 90% calcium absorption in the soil (percent calcium removed from a lime solution by an equal weight of soil). Chemical attack by calcium absorptive soil or water can be reduced by using (1) concrete with low permeability and limestone aggregates; (2) limestone fill around the concrete to help prevent deterioration (Hime 1986); and (3) cement- or lime-stabilized soil, flowable fill, grouting, or other techniques to increase the pH around the concrete.

Steinour (1966[a]) discusses the addition of calcium carbonate to weakly and strongly acidic solutions to minimize low pH conditions. Equations are provided to determine the resultant pH and the potential ability of the solution to attack concrete. Organic acids are discussed in Steinour (1966), who notes that organic acids can be

aggressive at exceedingly small concentrations if there is good flow or replacement of the solution at the concrete surface.

Table 3 shows parameters that influence the rate and extent of acid attack and resistance.

Table 3. Acid Attack and Resistance of Concrete

Acid attack increases with	Acid resistance increases with
<ul style="list-style-type: none"> • increase in acid concentration • continuous and fast renewal of acidic solution at the concrete/liquid interface • higher temperatures • higher pressure 	<ul style="list-style-type: none"> • decrease in permeability of cement paste (low w/cm-ratio) • low proportions of soluble components in concrete • creation of a durable protective layer of reaction products with low diffusion coefficient

Sulfates

Protection against sulfate solutions is usually addressed by a low water-cementitious materials ratio and the proper selection of a portland cement, blended cement, or cement plus pozzolan or slag (see Table 1 and Stark 1989). Fig. 3 illustrates the importance of a low water-cement ratio, regardless of cement type. Fig. 4 demonstrates the visual ratings for concrete beams exhibiting various levels of sulfate deterioration. A high water-cement ratio concrete exposed to severe sulfate solutions will still deteriorate rapidly even if a sulfate-resistant cement (like Type V) is used. The importance of cement type is most significant with moderate water-cement ratios (0.40 to 0.50). The effect of water-cementitious materials ratio is similar to water-cement ratio.

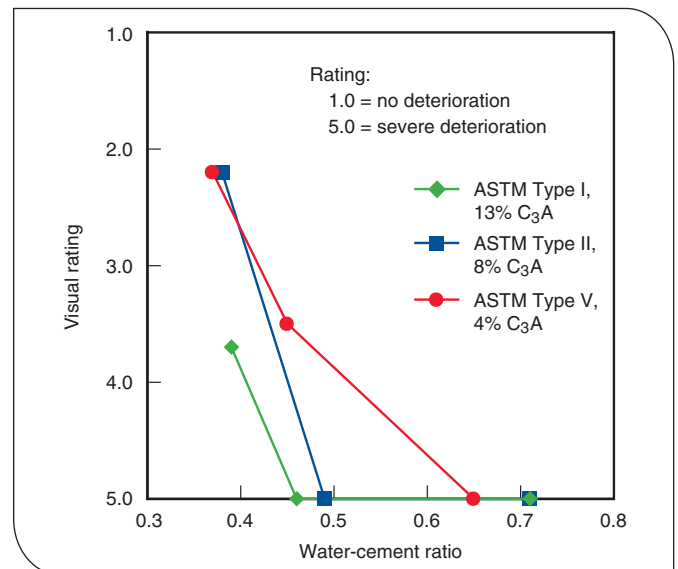


Fig. 3. Average 16-year ratings of concrete beams in sulfate soils for three portland cements at various water-cement ratios (Stark 2002).

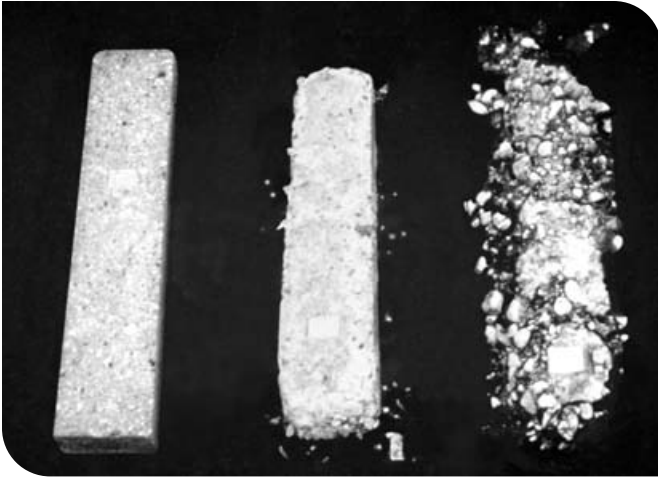


Fig. 4. Illustration of durability range corresponding to visual ratings (left to right) of 1.1, 2.5, and 5.0, respectively. (IMG25531)

Sulfates react with hydrated aluminate phases in concretes to form the expansive compound ettringite, the primary destructive compound in sulfate attack. This is why sulfate-resistant cements have low tricalcium aluminate contents. Sulfate can also react with calcium hydroxide in the paste to form gypsum. The crystallization of sodium sulfate salt due to wetting and drying also attacks concrete and appears as surface scaling (Technology Publishing Company 1992); see also section on “Salts” above.

Some sulfate solutions are more aggressive than others; for example, magnesium sulfate can attack calcium silicate hydrate, the primary component of hydrated cement responsible for strength and other properties of concrete (Kosmatka 1988). Kuenning (1966) studied different sulfate solutions. Silica fume (ASTM C1240), Class F fly ash (ASTM C618), and slag (ASTM C989) can improve sulfate resistance. However, one study (Cohen 1988) illustrated that a high concentration of magnesium sulfate solution damaged silica-fume cement paste much more than Type I or Type V cement paste, whereas the silica fume improved resistance to sodium sulfate solutions.

Environmental conditions also have a great influence on durability. Wet/dry cycling is much more severe than continuously wet conditions for sulfate attack. Therefore, testing of concrete mixtures to determine potential sulfate resistance should simulate the conditions to which the structure will be exposed. The sulfate resistance of concrete materials can be evaluated by using a saturated mortar bar test, ASTM C1012. This test is valuable in assessing the sulfate resistance of concrete that will be continuously wet, but it does not evaluate the more aggressive wet-dry cycling environment. The test can be modified to include wet-dry cycling or the U.S. Bureau of Reclamation’s (1992) wet-dry concrete prism test for sulfate attack can be used. ASTM C1580 (for Soil), ASTM D516 (AASHTO T 290) (for water), or the U.S. Bureau of Reclamation method (1975) can be

used to test soil and/or water for sulfate ion content to determine the severity of the sulfate exposure.

High cement contents, more than 385 kg/m³ (650 lb/yd³), with corresponding low water-cement ratios, are very beneficial to sulfate resistance; however, high cement and high paste contents should be avoided if sulfuric or other acid is present (Kong 1987 and Fattuhi 1988). Coatings can also provide protection against sulfate attack (Fig. 5). Refer to Stark (2002) for more information on the performance of concrete in a sodium sulfate environment.

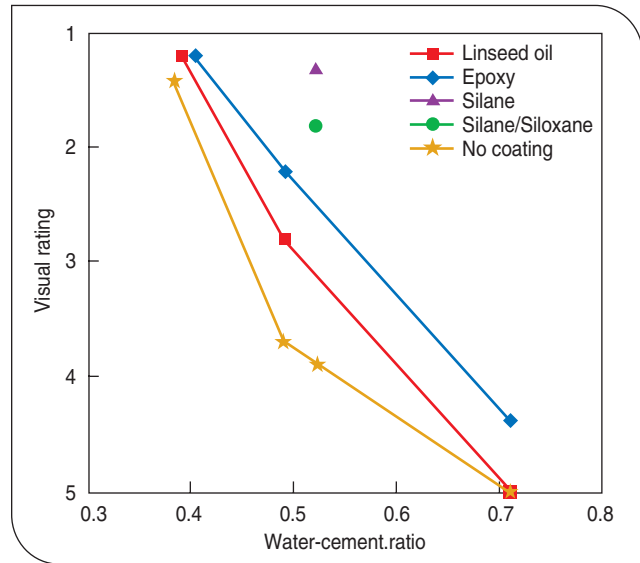


Fig. 5. Effect on sulfate resistance (8 years of very severe exposure) of coatings on concrete. See Fig. 4 for illustration of ratings. (Stark 2002)

Stress Corrosion

Stress corrosion of concrete is a deterioration induced by mechanical stress (load) when concrete is under chemical attack. The flexural strength of concrete or mortar can decrease over 50% due to load applied to concrete when exposed to certain corrosive chemicals, as compared to unloaded samples in the same chemical solution. Stress corrosion occurs only when both chemical attack and load are present simultaneously. The stress accelerates both the dissolving and expansive types of chemical attack. Some substances, such as sodium chloride, that do not attack unstressed concrete, can become destructive when they come in contact with stressed concrete. The amount of stress corrosion increases with the load level and generally increases with the concentration of the corrosive chemical. Substances with which stress corrosion has been observed include ammonium sulfate, ammonium nitrate, sodium sulfate, sodium chloride, magnesium chloride, and magnesium sulfate (Schneider 1987). The chemical resistance of concrete discussed in this publication is aimed at unstressed concrete. More research is needed on stress corrosion of concrete, as little information is available.

Corrosion of Embedded Metals

Corrosion of Reinforcement

The highly basic (alkaline) nature of concrete protects embedded steel from corrosion. The high pH (greater than 12.5) environment provides a protective oxide film on the steel that is passive and non-corrosive. However, carbonation or chloride ions can destroy or penetrate this passive film. Carbonation reduces the pH and allows oxygen access to the steel, thereby developing a potentially corrosive condition. Carbonation is not a problem with good quality concrete. Concrete's resistance to carbonation can be improved by the application of a proper coating. Usually, use of a material having a minimum solids content of 60% and a minimum thickness of 200 micrometers applied in 2 or 3 coats is adequate to resist carbonation (Wei 1990).

Chloride ions aggravate or cause corrosion by (1) reducing resistivity, thereby increasing corrosion currents; (2) increasing the threshold pH required to protect the steel; and (3) penetrating or dispersing the oxide film and combining with iron to form soluble iron chloride that moves iron away from the steel to form expandable iron oxides.

Once chloride ions or carbonation have destroyed or penetrated the passive film and moisture and oxygen are present, an electric cell is formed along the steel or between steel bars and the electrochemical process of corrosion and rust formation begins. Rusting is an expansive process that induces internal stress in the concrete and eventually cracks and spalls the concrete over the reinforcing steel (Fig. 6). Of course, rusting also reduces the cross-sectional area and strength of the reinforcing steel. The rate of corrosion is controlled by the electrical resistivity, chloride-ion concentration, moisture content, and availability of oxygen in the concrete. Conclusions concerning corrosion activity of embedded steel can be made by using the information obtained with ASTM C876, *Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*.



Fig. 6. The damage to this concrete beam, located in a parking structure, resulted from chloride-induced corrosion of steel reinforcement. (IMG25527)

Corrosion of Nonferrous Metals in Contact with Concrete

Nonferrous metals are frequently used in construction in contact with portland cement concrete. Metals such as zinc, aluminum, and lead—and alloys containing these metals—may be subject to corrosion when embedded in, or in surface contact with, concrete.

Since the products of corrosion occupy a greater volume than the metal that has corroded, internal forces of expansion can crack and spall the surrounding concrete. Galvanic corrosion will occur if aluminum and steel or other metals of dissimilar composition are both embedded in concrete and in contact with each other. See PCA (2002) for more information on dissimilar metal corrosion. If aluminum is to be embedded in reinforced concrete, it should be electrically insulated by a permanent coating. Bituminous paint, alkali-resistant lacquer such as methacrylate, or zinc chromate paint can be used. Impervious protective organic coatings such as bitumen, phenolic varnish, chlorinated rubber, or coal-tar epoxies, can also be used on the metal surfaces to prevent galvanic action when it is not possible to separate the metals.

Where it is necessary to embed lead in concrete, protection of the embedded portion with organic coatings is suggested to prevent corrosion of the lead and to prevent galvanic action with reinforcing steel. When copper is used in conjunction with steel, it should be electrically insulated from the steel by means of an impervious organic coating or by use of short lengths of polyethylene tubing slit and slipped over the copper. Copper itself is practically immune to corrosion in chloride-free concrete except where ammonia is present. However, copper, as well as aluminum and lead, should be avoided in concrete containing chlorides. For more information see Woods (1968) and Monfore (1965).

Preventing Reinforcement Corrosion

All concrete structures that will be exposed to a marine environment (saltwater and/or salt air), freezing temperatures, or deicer chemicals require a high-quality air-entrained concrete and ample concrete cover over the reinforcing steel. Concrete cracking should be avoided. Where chlorides and oxygen in the presence of moisture are likely to reach the reinforcing steel, protective treatments are recommended. Chloride-ion-induced corrosion should be of primary concern in bridge decks and parking garages where deicers are used and in marine structures.

The concrete mix design plays an important role in preventing corrosion. In addition to the recommendations for good quality concrete found at the beginning of this document, specific concrete materials and mix proportions should be considered to lower corrosion activity and optimize protection of embedded steel. The first step to maximize chloride (corrosion) resistance is to reduce permeability by specifying a maximum water-cement ratio of 0.40 or less (Stark 1989[a]). Use of fly ash (Class C or Class F), silica fume, water reducers, and high cement contents can lower corrosion activity. These methods can be combined with other corrosion protection methods, including

coatings on the concrete or reinforcement, increasing the cover over the steel, and using corrosion inhibitors. Some additional protective strategies to prevent reinforcement corrosion are discussed below.

Nickel-plated steel will not corrode when embedded in chloride-free concrete. The nickel plate will provide protection to steel as long as no breaks or pinholes are present in the coating. The coating should be about 0.1 mm thick to resist rough handling. Minor breaks in the coating may not be very detrimental in the case of embedment in chloride-free concrete; however, corrosion of the underlying steel could be strongly accelerated in the presence of chloride ions.

Cadmium coatings will satisfactorily protect steel embedded in concrete, even in the presence of moisture and normal chloride concentrations. Stainless steel and galvanized steel reinforcement are also used to reduce corrosion in chloride-free concrete. Galvanized steel should conform to ASTM A767/A767M, *Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*. Chloride ions will cause corrosion of galvanized steel in concrete and may lead to severe cracking and spalling of the surrounding concrete. The use of chloride admixtures should be avoided in concrete containing galvanized steel exposed to corrosive or wet environments. Stark (1989[a]) illustrates the effect of humidity and chloride content on corrosion of black (untreated) and galvanized steel bars. Special stainless steels or monel may be used in concretes containing chloride if test data support their performance.

Fusion-bonded epoxy-coated reinforcing steel is very popular for the construction of marine structures and pavements, bridge decks, and parking garages exposed to deicer chemicals. The epoxy coating prevents chloride ions and other corrosive chemicals, moisture, and oxygen from reaching the steel. If the epoxy coating is damaged during construction, its protection ability is lost, so epoxy repair kits are available to recoat the damaged portion of the bar. Epoxy-coated bars should conform to ASTM A775/A775M, *Specification for Epoxy-Coated Reinforcing Steel Bars*, and to ASTM D3963/D3963M, *Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars*.

Concrete surface sealers, water repellents, surfacings, and overlays stop or reduce chloride-ion or chemical penetration at the concrete surface. Materials commonly used for this include silanes, siloxanes, methyl methacrylates, epoxies, and other compounds.

Latex-modified concrete, low-slump dense concrete, low water-cement ratio superplasticized concrete, silica-fume concrete, and polymer concrete are often used in overlays to reduce chloride-ion or chemical penetration. Concrete with silica fume or super-plasticizers is also used in new and replacement construction monolithically. Impermeable interlayer membranes (primarily used on bridge decks), prestressing for crack control, or polymer impregnation are also available to help protect reinforcement.

Cathodic protection methods may be used to prevent the electrochemical process of corrosion in reinforced concrete. Cathodic

protection reverses the natural electric current flow through concrete and reinforcing steel by inserting a non-structural anode in the concrete, forcing the steel to be the cathode by electrically charging the system. Since corrosion occurs where electric current leaves the steel, reinforcement cannot corrode as it is receiving the electric current.

Corrosion inhibitors such as calcium nitrite are used as an admixture to reduce corrosion. Some calcium nitrite corrosion inhibitors are penetrating formulations applied to the surface of hardened concrete. The protective ions migrate through the pore structure towards the steel. Whether used as an admixture or applied as a surface treatment, calcium nitrite corrosion inhibitors block corrosion by chemically reinforcing and stabilizing the passive film on the reinforcing steel. A certain amount of calcium nitrite can stop corrosion up to a certain threshold level of chloride ion. Therefore, increased chloride levels require increased levels of calcium nitrite to stop corrosion. Organic-based corrosion inhibitors, based on amine and amine and fatty ester derivatives, are also available. (Nmai et al. 1992 and Berke et al. 2003).

The threshold level at which corrosion starts in normal concrete with no inhibiting admixture is about 0.15% water-soluble chloride ion (0.20% acid-soluble) by weight of cement. Admixtures, aggregate, and mixing water containing chlorides should be avoided, but in any case, the total acid-soluble chloride content of the concrete should be limited to a maximum of 0.08% and 0.20% (preferably less) by weight of cement for prestressed and reinforced concrete, respectively (ACI 201.2R and ACI 222R). Acid-soluble chloride content of concrete is measured in accordance with ASTM C1152, *Test Method for Acid-Soluble Chloride in Mortar and Concrete*. ACI 318 bases the chloride limit on water-soluble chlorides, with maximum limits of 0.06% for prestressed concrete and 0.15% for reinforced concrete. Testing to determine water-soluble chloride ion content should be performed in accordance with ASTM C1218, *Test Method for Water-Soluble Chloride in Mortar and Concrete* or ASTM C1524 *Test Method for Water-Extractable Chloride in Aggregate* (Soxhlet Method). ASTM C1524 should be used when the aggregates contain a high amount of naturally occurring chloride.

ASTM G109 can be used to determine the effects of chemical admixtures on the corrosion of embedded steel reinforcement in concrete exposed to chloride environments.

Fiberglass-reinforced plastic (FRP) reinforcement can be used to replace part or all of the steel reinforcement in portland cement or polymer concrete exposed to chemicals that are extremely corrosive to metal. Plastic reinforcing bars are available in most conventional bar sizes. The lightweight, nonmagnetic, nonconductive, high-strength (tensile strength greater than 690 MPa or 100,000 psi) bars are chemically resistant to many acids, salts, and gases and are unaffected by electrochemical attack. Commercially available FRP reinforcement is made of continuous aramid, carbon, or glass fibers embedded in a resin matrix. The resin allows the fibers to work

together as a single element. Resins used in FRP reinforcement include polyester, vinyl ester, nylon, or polyethylene.

Consult ACI 441.1R (2006) for special design considerations. Using more than one protection method simultaneously can result in significant savings in maintenance costs and produce a structure with a long, trouble-free life. For example, the advantages of using epoxy-coated reinforcement are obvious; and epoxy coating stops chloride at the reinforcing steel. However, damaged areas in the coating due to handling during transportation and construction or coating imperfections can be a source of corrosion. An additional protection system, such as a corrosion-inhibitor or silica-fume admixture in the concrete, can be used to further protect the steel at coating-damaged areas. With good design and construction practices and one or more available corrosion protection systems, a concrete structure can be built to endure even the severest environment for many years with little maintenance.

Cover over Steel

Sufficient concrete cover must be provided for reinforcement where the surface is to be exposed to corrosive substances. It is good practice to increase the concrete cover over the reinforcing steel above the normal amount specified in ACI 318 (*Building Code Requirements for Reinforced Concrete and Commentary*). Extra cover slows down the ingress of corrosive chemicals, such as chlorides, that attack reinforcing steel. ACI 201 (2001) recommends a minimum cover of 38 mm (1½ in.) and preferably at least 50 mm (2 in.) for concrete in moderate-to-severe corrosion environments.

Oesterle (1997) and Stark (1989[a]) confirm the need for 65 mm to 75 mm (2½ in. to 3 in.) of cover over reinforcement to provide corrosion protection. Some engineers specify 90 mm (3½ in.) or more of concrete cover over steel in concrete exposed to chlorides or other corrosive solutions. However, large depths of cover on the tension side of concrete members can lead to excessive crack widths. Tolerable crack width for reinforced concrete is 0.41 mm (0.016 in.) with a protective membrane, 0.18 mm (0.007 in.) for deicer exposure, and 0.10 mm (0.004 in.) for water-retaining structures (ACI 224R). Carbon-steel bar supports for reinforcement should not extend to the concrete surface unless noncorrosive plastic-protected bar supports are used. Deep recesses in the concrete (cones) should be provided for form ties, and they should be carefully filled and pointed with mortar or sealed with a plug. In addition to surface treatments, epoxy-coated reinforcing steel, plastic reinforcement, cathodic protection, use of an interlayer membrane, and other techniques should be considered for exposure to chemicals extremely hazardous to reinforcing steel.

Design Considerations

Forms and Curing Membranes

Whenever concrete is to be coated for corrosion protection, the forms should be coated with materials (sealers or form-release agents) that will not impregnate or bond to the concrete after form removal.

Hence, forms coated with form oils or waxes should not be used against surfaces to be coated. Many curing membranes will also develop little or no bond to coatings applied over them. If form oils, waxes, or curing membranes are present, they should be removed by sandblasting, scarifying, or other processes. Acid etching or washing should be avoided as it may not remove certain curing compounds or form-release agents. Some curing compounds may provide an adequate surface for some surface treatments, and therefore product manufacturers should be consulted as to product compatibility.

Drainage

Where spillage of corrosive substances is likely to occur, a floor should have a slope to drains of at least 2% to facilitate washing.

Finishes

The finish should be compatible with the intended use. Where floors will carry pedestrian or vehicular traffic, some traction should be provided, especially if the floor will be wet in service. Rough surfaces, however, do not repel moisture or facilitate drainage as well as dense, smooth surfaces. They are also more difficult to clean. With adequate drainage and regular cleaning, smooth-finished floors may require no further protection for exposure to mild solutions. One type of smooth floor surface is a burnished floor. This surface is obtained by additional steel trowelling to densify the surface during finishing (PCA 1996.)

Special Applications

Special Concretes

Some environments may be so severe that a special concrete needs to be used. Special concretes can be used as overlay over regular concrete or to construct the entire element, such as a slab on ground. Special chemical-resistant concretes include sulfur concrete, polymer concrete, and many other types. Polymer-concrete binders include epoxy, methyl methacrylate, polyester, furan resin, and other polymer formulations. Consult product manufacturers as to the applicability of specific materials for particular environments.

Dampproofing and Waterproofing

Dampproofing retards the penetration of moisture into a structure above or below grade when slight to no water pressure (hydrostatic head) is involved. Waterproofing makes the structure impermeable to water when a hydrostatic head is present. When correct drainage has been provided, the groundwater table is low, and no hydrostatic head exists, dampproofing may be adequate. In general, concrete's permeability decreases as its strength increases. Very little water vapor will pass through a high-strength, dense concrete, but concrete of low strength that is poorly consolidated can be quite permeable. Therefore, the first line of defense against water problems is the use of high quality concrete mixtures and good construction practices.

Dampproofing generally consists of spraying or brushing a specified bituminous material on the outside of walls below grade. While many specifications call for only one coat of material, two lighter applications, made at right angles to each other, are recommended.

For floors on ground, roofing felts, plastic films, or rubber-sheet membranes can be used as vapor retarders or barriers. Polyethylene film is low in cost and easily installed, but it is also easily punctured and difficult to seal at the edges. More durable products are polyethylene-coated kraft paper and glass-reinforced waterproof paper, extrusion coated on both sides with polyethylene.

A waterproofing membrane must be impervious to liquid water and have high resistance to the passage of water vapor. Waterproofing materials (Table 4) are brushed, troweled, sprayed, or otherwise applied to a smooth concrete surface. When correctly applied with skill and care, these products can be impervious to water and water vapor. ASTM D6489-99(2006) *Test Method for Determining the Water Absorption of Hardened Concrete Treated With a Water Repellent Coating* provides a procedure for the determination of the water absorption by a core of concrete taken from a surface treated with a water repellent.

Table 4. Materials Used for Moisture Barriers*

Mineral bentonite panels, granules, spray, trowel
Urethane bitumen membranes
Butyl (rubber) sheet membranes
Neoprene membranes
Fabric-reinforced bitumens
Polyurethane-rubber-coated polyethylene sheets
Polyvinyl chloride sheets
Liquid polymers
Hot-applied bitumen (the original waterproofing coating)
Elastomeric chlorosulfonated polyethylene

* An integral waterproofer incorporated in the concrete mixture is not a satisfactory alternative to waterproofing membrane.

In view of the diversity of moisture-barrier products, the best available advice of the manufacturers and waterproofing contractors should be obtained whenever any major waterproofing is needed.

Joints in walls and floors must be sealed to prevent the passage of water or other unwanted substances into or through them. The American Concrete Institute (ACI) Committee 504 Report, *Guide to Joint Sealants for Concrete Structures*, recommends polysulfides, polysulfide coal tars, polyurethanes, rubber asphalts, low-melting-point asphalts, and hot-applied PVC coal tar as suitable field-applied sealants for water-excluding structures. Waterstops also may be used in the joints, or for even more positive protection, both a waterstop

and joint sealant may be used. Refer to Kanare (2005) for more information on dampproofing and waterproofing concrete floors.

Architectural Concrete

Many specifiers require that precast and cast-in-place architectural concrete surfaces be protected by a water-repellent coating. Such coatings serve to (1) prevent deterioration of concrete surfaces by industrial airborne chemicals, (2) inhibit soiling of surfaces, (3) facilitate cleaning of surfaces, (4) accentuate the color of aggregate and mortar in exposed-aggregate architectural concrete, and (5) avoid color change of surfaces when wet.

Ideally such coating materials should be water-clear, capable of being absorbed into the concrete surface, long lasting, and not impart a glossy coating effect or discolor on exposure to sunlight or atmospheric contaminants. A great number of products of varied chemical composition are sold for this use.

Laboratory research and analysis of the coatings indicate that low-viscosity acrylic resins based on methyl methacrylate generally offer the best protection for exposed-aggregate surfaces. Silanes and siloxanes are also often used as water repellents on architectural concrete.

Paint

Paints are commonly used for the protection and decoration of concrete surfaces. Paint is formulated to give certain performance under specified conditions. Since there is a vast difference in paint types, brands, prices, and performances, knowledge of composition and performance standards is necessary for obtaining satisfactory concrete paint. The quality of paint for concrete is not solely determined by the merits of any one raw material used in its manufacture. Many low-cost paints with marginal durability are on the market. In order to select proper paints, the user should deal with manufacturers supplying products of known durability and obtain from them, if possible, technical data explaining the chemical composition and types of paints suitable for the specific job at hand.

A clean, dry surface is a prerequisite for the success of most applied decorative or protective coatings. Concrete should be effectively moist cured, and then it should be allowed to air dry before application of a paint. Moisture remaining in the concrete can cause blistering and peeling of some paints.

Many types of paint are used on concrete surfaces. These include portland cement-based paint; emulsions consisting of alkyd and latex; latexes such as acrylics, polyvinyl acetate, and styrene butadiene; and solvent paints consisting of the oil vehicles, styrene butadiene, chlorinated rubber, vinyl, catalyzed epoxies, polyesters, and urethanes. Some are more suitable than others for exterior surfaces.

Portland cement-based paints can be used on either interior or exterior exposures. The surface of the concrete should be damp at the time of application and each coat should be cured by dampening

as soon as possible without disturbing the paint. Damp curing of portland cement paint is essential. On open-textured surfaces the paint should be applied with stiff-bristle brushes such as scrub brushes. Paint should be worked well into the surface. For concrete of smooth or sandy surface, whitewash or Dutch-type calcimine brushes work best.

Latex materials are used in some modified portland cement paints to retard evaporation, thereby retaining the necessary water for hydration of the portland cement. Moist curing is unnecessary with latex-modified cement-based paint and, in fact, may be undesirable.

Latex paints are resistant to alkali and may generally be applied to new concrete after 10 days of good drying weather. The preferred method of application is by long-fiber, tapered nylon brushes 100 mm to 150 mm (4 in. to 6 in.) wide. However, application may also be made by roller or spray. Latex paints may be applied to damp, but not wet, surfaces; if the surface is moderately porous or extremely dry conditions prevail, prewetting of the surface is advisable. Use of a primer, if available, is recommended.

Portland cement paints and latex paints are commonly used for interior or exterior concrete walls in normal climates. Wet environments or sanitary structures may require a polymer paint. Floors require an abrasion-resistant polymer paint (ACI 515.1R and PCA 1992). Refer to ASTM D6237 *Guide for Painting Inspectors (Concrete and Masonry Substrates)* for key elements of surface preparation and coatings application.

Maintenance

Not all exposures are so severe that a barrier system is required. Proper maintenance such as routine sweeping and washing along with wiping up spills immediately can minimize chemical attack from liquids or abrasion from fine materials. For floors, a periodic waxing helps keep materials from being absorbed into the concrete, and proper drainage and joint maintenance can direct these materials off the concrete surface (Mailvaganam 1991).

Cleaning and Surface Preparation

Proper preparation of the concrete surface and good workmanship are essential for the successful application of any protective treatment that must bond to, or be absorbed into, a concrete surface. It is important to have a firm base free of grease, oil, efflorescence, laitance, dirt, and loose particles.

Surface preparation and cleaning are distinct steps in readying a surface for coating or sealing. The first step should be initial cleaning, which removes heavy deposits of oil and grease or other dirt and contaminants. The second step in preparing a surface for coating removes weakened surface layers or laitance, provides a surface profile (roughness), and removes additional contaminants that cleaning does not. A final cleaning should be performed again after

surface preparation, immediately before coating or sealing, to remove airborne contaminants and dust. This can be done by vacuuming or blowing down with oil-free compressed air. The best methods of cleaning and preparing the concrete surface depend on job conditions and should be performed only when appropriate safety precautions have been taken.

Surface preparation should be performed in accordance with the guides and standards from the American Society for Testing and Materials (ASTM), American Concrete Institute (ACI), National Association of Corrosion Engineers (NACE), the International Concrete Repair Institute (ICRI), and the Society for Protective Coatings (SSPC), some of which are discussed below.

Concrete should normally be well cured (7 days) and dry before protective treatments are applied. Moisture in the concrete may cause excessive internal vapor pressure that can cause blistering and peeling of certain coatings. However, some sealers, such as certain silanes, actually require some moisture in the slab upon application. The coating manufacturer should be consulted for recommendations. Drying time of concrete varies, and new concrete should dry for at least 30 days before coatings are applied, but longer periods are typically better.

Depending on service conditions and coatings used, concrete is considered dry enough for many coatings when no moisture is indicated for example by test method ASTM D4263, *Test Method for Indicating Moisture in Concrete by the Plastic-Sheet Method*. Kanare (2005) provides extensive information on moisture tests and concerns.

Surface Repair: Patching, Removal of Protrusions

On both new and old concrete, surfaces to be treated should not only be clean and dry, they should be uniform, and have no protrusions or holes—to enable the coating or sealer to achieve optimum performance. Precautions should be taken to eliminate objectionable voids in the surface that might cause pinholes in the protective treatment. Good vibration and placing techniques will reduce the number of surface imperfections in concrete. The concrete surface should be smoothed immediately after removal of forms by applying grout or by grinding the surface and then working grout into it. Protrusions on the concrete surface should be removed by chipping, and the area smoothed with an abrasive material such as a grinding stone. Large voids should be filled or patched. Other surface treatments that have good adhesion to cured concrete, such as latex-modified grouts or mortars, epoxy, or other synthetic resin formulations, can also be used to produce a smooth surface. *The Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces* (International Concrete Repair Institute 1996) can be consulted for additional information.

Patch materials should be suited to the application. Sometimes, the patch itself is the protective treatment. Very low permeability, dense patches, for example, have been used to limit chloride ion ingress

and protect steel reinforcement. However, one study found that this led to increased reinforcement corrosion as a result of differences in chloride and oxygen diffusion rates between the old concrete and the new patch material (PCA 1994). The corrosion then led to spalled patch areas. The study recommends matching the patch material as closely as possible to the existing substrate. This approach minimizes differential chloride ion ingress and oxygen diffusion, and reduces the possibility of spalled patches. If required, the entire surface can then be coated to provide uniform protection and appearance.

Cleaning Methods

Initial cleaning can be done with chemicals, steam, and sometimes, solvents. Chemical cleaning with hot water and TSP (trisodium phosphate) or commercial detergents removes contaminants from the surface. This solution should be thoroughly rinsed to remove residues of the cleaning chemicals. Steam cleaning effectively removes water-soluble contaminants from the surface of concrete; detergents or degreasers added to the water can increase the effectiveness of steam cleaning. De-greasing, if needed, is accomplished by applying a mixture consisting of a cleaner, curing compound remover (a chlorinated, emulsifiable solvent), an industrial grease remover (a highly alkaline, low-phosphate, biodegradable detergent), and liberal amounts of water. The mixture is scrubbed into the concrete surface, repeatedly, if necessary. The surface finally is rinsed, scrubbed with water, and vacuumed to a damp condition. Chemical stripping softens or dissolves cured coatings, but is only for small areas that cannot be prepared more effectively by other means. Additional cleaning or surface preparations must follow chemical stripping to remove contaminants from the chemical cleaning process. Hydrocarbon solvents are not recommended for general cleaning because they dissolve the contaminant, possibly spreading it and carrying it deeper into the concrete pores. (See Holl 1997 for further information on cleaning and preparing the surface.)

Acid treatment is not recommended. It may not provide a proper surface for mechanical bond and may even impair good bond with the coating or sealer if all of the acid is not removed. The acids themselves are hazardous materials. However, acid treatment may be the only option for surface preparation on some jobs, such as sites with limited access to machinery. If acid treatment of the surface is performed, it should be in accordance with ASTM C811 and D4260, and the acid must be thoroughly removed and neutralized so that good bond between the concrete and coating is possible. ASTM D4262 can be used to test the pH of the cleaned surface, which should be around 7 (neutral).

Surface preparation is achieved by scarifying, grinding, shot-blasting, waterblasting, abrasive blasting, or flame cleaning. Grinders or scabblers can be used to remove weak concrete, friable laitance, high spots, and finishing defects. Diamond grinding can improve smoothness and wear resistance of floors. Scarifiers can remove laitance, paint marks, pitch adhesives, and thermoplastic adhesives, level the concrete, and produce nonskid surfaces. The machines have hard-

ened-steel cutting wheels that hammer off the surface. Shotblasting or abrasive blasting removes surface contaminants. Machines with vacuum bags make the operation almost dust-free.

Concrete can also be treated by flame cleaning. An oxyacetylene blowpipe is passed over the surface of concrete, followed by a mechanical after-treatment using rotary brushes or vibratory machines such as scalers. The flame reaches a temperature of about 3100 °C (5600 °F), which is hot enough to damage the top layer of concrete, about 1 mm to 4 mm (0.04 in. to 0.16 in.). This material is then removed by brushing, and the surface is swept or vacuumed to remove the dust. Thoroughly prewetting the slab ensures uniform concrete removal. Materials such as rubber streaks, oil, gasoline, grease, and deicing chemicals can be removed with this method. Flame cleaning is very effective on oil-stained floors, because it does not promote migration of deep-seated oil to the surface. An added benefit of flame cleaning is that it restores alkalinity to the concrete. See Mailvaganam (1991) and Beilner (1990) for further information. Flame-cleaned surfaces should be coated immediately after cleaning.

In some cases, mechanical methods of cleaning have led to poor bond due to a cracked substrate. When mechanical (impact) methods are used, a follow-up with waterblasting can remove any cracked or loose surface material. Waterblasting and flame cleaning, unlike the mechanical methods, minimize cracking of the concrete substrate (Fig. 7). After a concrete surface is cleaned and dried, all residue must be removed. Industrial vacuum machines, air pressure, and water washing are used to remove dust particles from a prepared surface.



Fig. 7. Waterblasting equipment can prepare horizontal surfaces without damaging the concrete substrate. (IMG25539)

Concrete cast against forms is sometimes too smooth for adequate adhesion of protective coatings. Such surfaces should be lightly sand-blasted or ground with silicon carbide stones to obtain a slightly roughened surface. See PCA's *Removing Stains and Cleaning Concrete Surfaces* (PCA 1988) for more information.

ASTM International¹ documents on cleaning concrete are listed as follows:

- C811, *Practice for Surface Preparation of Concrete for Application of Chemical-Resistant Resin Monolithic Surfacing*
- D4258, *Practice for Surface Cleaning Concrete for Coating*
- D4259, *Practice for Abrading Concrete*
- D4260, *Practice for Liquid and Gelled Acid Etching Concrete*
- D4261, *Practice for Surface Cleaning Concrete Unit Masonry for Coating*
- D4262, *Test Method for pH of Chemically Cleaned or Etched Concrete Surfaces*

ASTM D7234 *Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers* can be used to determine if a concrete surface is properly cleaned and adequate for a particular coating. ASTM D7234 can also be used as a quality control test to assure that particular coatings meet specified bond-strength requirements.

ACI 515.1R and ACI 503R provide information on surface evaluation including methods, where applicable, to test the bond of the surface treatment to the concrete. Treatment manufacturers' recommendations for surface preparation should be properly executed.

Concrete Protection in Europe

The European concrete standard EN 206-1 classifies exposure classes related to environmental actions such as "chemical attack" and "corrosion induced by chlorides." Based on severity of an exposure condition, types and amount of cementitious materials and maximum water-to-cementitious materials ratio are specified. The European Standard EN 1504 covers *Products and Systems for the Protection and Repair of Concrete Structures*. The 10-part document provides guidelines for maintenance and protection of concrete components. Coatings to be considered as "surface protection systems for concrete" must comply with EN 1504-2. Part 9, contains comprehensive information on the assessment of the actual conditions and on planning the work. Also included are classification of repair methods, how to choose appropriate materials, and how to specify the implementation.

Choosing the Treatment

Protective treatments for concrete are available for almost any degree of protection required (Fig. 8). A "monolithic surfacing" generally means a continuous coating with a thickness of 1 mm (40 mil) or more (National Association of Corrosion Engineers 1991). Coatings vary widely in composition and performance, and some of

the generic classifications given here are so broad that they can serve only as a guide. The reader is advised to seek further, more detailed recommendations from the manufacturer, formulator, producer, or material supplier.²

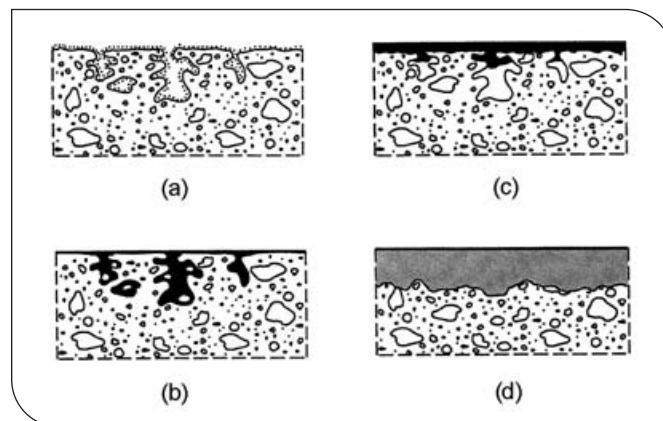


Fig. 8. Four different types of protective treatments for concrete are: (a) hydrophobic (water repelling), (b) sealers, which fill the pores at the surface and can partly be membrane-building, (c) membrane-building coatings, and (d) mortar and concrete coatings.

Every coating is formulated to render a certain performance under specified conditions. Its quality should not be determined solely by the merits of any of its components since the proportioning of ingredients also is very important in determining performance. Coating performance depends as well upon the quality of surface preparation, method and quality of coating application, ambient air conditions during application, and film thickness. Coating failures are most often caused by improper material selection and surface preparation (ICRI 1997). Other reasons for poor performance include inadequacies in film thickness, drying times between coats, curing regimes, and exposure to harsh unsuitable environmental conditions.

Most coatings will perform well if they are placed at mild ambient temperatures, between about 10 °C and 30 °C (about 50 °F and 90 °F). The concrete itself should be above 10 °C (50 °F) when it is being treated. Some treatments such as urethanes and epoxies can be applied at temperatures down to -7 °C (18 °F). Any general discussion of chemical resistance and other properties of coatings must assume optimum formulation, proper methods of applying the coating, and materials suited to the exposure.

Safety is an important consideration in any concrete coating application. Many coatings contain solvents that are fire, explosion, toxic, or environmental hazards. Some materials become volatile only after mixing, so proper handling is very important. In enclosed areas, ventilation should be planned to minimize effects to workers or the public.

¹ ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, Tel. 610.832.9585; Fax 610.832.9555; e-mail: service@astm.org; Website: <http://www.astm.org>.

² These four terms are used interchangeably in this publication.

Application should be planned. All employees should be made aware of proper first aid treatment before working with new materials. The producers of the various coatings can provide valuable information—manufacturer literature, Material Safety Data Sheets—on the merits of their products for a particular use and on the proper and safe procedure for application.

Certain materials (thermoplastics) soften at elevated temperatures and may even melt or become ineffective. Various grades of coatings are available for use over a fairly wide temperature range. For concrete coatings, where flavor or odor is important, the U.S. Food and Drug Administration or the Food Directorate of Health and Welfare Canada should be consulted regarding restrictions for materials in contact with food ingredients.

The coating thickness required depends on (1) the exposure, whether continuous or intermittent, (2) the resistance of the material to the chemicals involved, and (3) the ability to form a continuous, pinhole-free surface. As a rule, thin coatings are not as durable as heavier coatings and, hence, are less suitable where there is considerable abrasion. Coating thickness can be measured while the coating is still wet or after it has dried. The following test methods can be used to check coating thickness.

- ASTM C1005, *Measurement of Dry-Film Thickness of Organic Coatings Using Micrometers*
- ASTM D1212, *Measurement of Wet Film Thickness of Organic Coatings*
- ASTM D4138, *Measurement of Dry Film Thickness of Protective Coating Systems by Destructive, Cross-Sectioning Means*
- ASTM D4414, *Measurement of Wet Film Thickness by Notch Gages*
- ASTM D4787, *Practice for Continuity Verification of Liquid or Sheet Linings Applied to Concrete Substrates*
- ASTM D6132, *Nondestructive Measurement of Dry Film Thickness of Applied Organic Coatings Using an Ultrasonic Gage*

Along with listing the test method for measuring thickness, acceptance criteria should be provided with the procedures. The coating manufacturer/supplier should be able to supply guidance in this area.

The more common protective treatments are listed in the table starting on page 15; the numbers and letters correspond to the descriptions given below in the discussion of “Protective Treatments.” For most substances, several treatments are suggested, any of which will provide sufficient protection in most cases. When choosing a type of protection, consider the chemical environment, service condition (that is, splash and spill or immersion), and any mechanical requirements, keeping in mind the consequences of failure and ease of repair.

The information in the guide table is only for determining when to consider various coatings for chemical resistance. Where more

specific information is required, particularly to determine whether protection is required for large installations, small mortar prisms representative of the concrete to be used can be immersed in the corrosive liquid and evaluated for resistance as discussed in Kuenning (1966). (See also “Evaluating the Effectiveness of Concrete Surface Protection by Testing.”) ASTM C267, *Test Method for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacing and Polymer Concretes*, can be used to determine the chemical resistance of protective surface treatments when exposed to particular chemicals. ASTM C267 can also be used to determine the relative improvement provided by admixtures.

Where applicable, resin surfacings, especially epoxy, urethane, polyester, and vinyl ester, should meet the requirements of ASTM C722, *Specification for Chemical-Resistant Resin Monolithic Surfacing*. ASTM C722 materials are usually resin-and-filler (fine-aggregate) systems trowel or spray applied to a minimum thickness of 1.5 mm (0.06 in.). ASTM C722 has two types of surfacings—Type A for chemical resistance and moderate-to-heavy traffic, and Type B for mild chemical resistance and severe thermal shock.

Where continuous service over long periods is desirable, it may be more economical to use the higher quality means of protection rather than a lower-first-cost treatment that may be less permanent.

Evaluating the Effectiveness of Concrete Surface Protection by Testing

Surface treatments generally are one of two types: sealers or barriers. A sealer limits the amount of moisture, chlorides, sulfates, or other material that can enter the concrete pores; a barrier provides complete isolation between the concrete and the substance. It may be necessary to test a surface treatment to confirm its ability to protect concrete in a given application. Comparing differences in properties of protected and unprotected concrete allows evaluation of the coating or sealer.

Testing of the concrete could involve the following measurements:

- length change
- weight change
- moisture absorption
- freeze thaw resistance
- chemical ingress
- surface scaling
- bond between coating and substrate
- abrasion

It is also possible to compare concrete properties, such as strength and modulus of elasticity, before and after exposure.

Kuenning (1966) can be used as a guide for developing a test program for concrete protection treatments. In that study, prisms of mortar 15 mm x 15 mm x 100 mm (0.6 in. x 0.6 in. x 3.9 in.) were made at water-cement ratios to represent concrete paste in permeability and strength. Variables in the study included cement type, length and type of curing, and strength and type of exposure solution. Specimens were made in accordance with ASTM C305, and moist cured 3 or 28 days. The initial length, weight, compressive

strength (ASTM C39), and dynamic modulus of elasticity (ASTM C215) were measured. Additional conclusions about the attack mechanisms can be obtained with chemical, X-ray, and petrographic studies of the deteriorated mortars.

Results of a test program might aim to explain the mechanism of attack, the relative resistance to attack, or to predict the resistance to other concentrations of the same chemical or other chemicals.

Suggestions for test variations include different strengths of exposure solution, continuous immersion or alternate wet and dry exposure, and increasing, decreasing, or cycling the storage temperature.

What the Tests Can Reveal

Physical results need interpretation to give meaning to the data. Weight gain or increase in length of the concrete specimen can mean water (or other liquid) absorption or crystal formation. Weight loss or loss in length can mean that compounds are being leached out of the cement paste (binder is dissolving), or water is being replaced by a less dense liquid. An increase in the transverse frequency could mean continued hydration or deposit of crystals within the specimen. A decrease in frequency can mean microcracking or loss of binder or mortar by solution.

The Alberta DOT, Transportation and Utilities, tests sealers using a performance-based procedure (Carter 1994). Six companion cubes are made with concrete representative of field concrete: 300 kg/m³ (505 lb/yd³) cement content, 0.5 water-cement ratio, and 6% air content. The cubes, measuring 100 mm (4 in.) on each side, and weighing 2400 g (5.3 lb), are allowed to dry, then three are sealed and three left unsealed before immersion in water for 5 days. After weighing the specimens, results are reported as a reduction in absorption, then 70 g (0.15 lb) of the surface is abraded, and the sample is re-immersed. This cycle of abrading/re-immersing allows determination of effective penetration depth, which also influences sealer effectiveness.

Protective Treatments

A large number of chemical formulations (not listed here) are also available as sealers and coatings to protect concrete from a variety of environments. Product manufacturers should be consulted in the use of these and other protective treatments.

The Society for Protective Coatings (SSPC) and the National Association of Corrosion Engineers offer detailed listings of U.S. Standards and Guides for the use of Protective Coatings on Concrete as well as Coating and Corrosion links to be found on their Internet pages: www.sspc.org, www.paintsquare.com, and www.nace.org. For additional information about the chemical resistance of some concrete surface protection systems, see McGovern (1998).

When applying a coating or lining to concrete, it is best performed when concrete is in a cooling cycle, usually late afternoon or early evening hours. This is when concrete tends to draw air into itself, which helps the coating to penetrate the surface rather than be pushed out of it by warm vapors trying to escape (National Association of Corrosion Engineers 1991).

1. Magnesium Fluosilicate or Zinc Fluosilicate

These chemicals are commonly sold as floor hardeners. The treatment consists generally of three applications.

Either of the fluosilicates may be used separately, but many of the products sold are a mixture; solutions of 20% zinc fluosilicate and 80% magnesium fluosilicate appear to give the best results. For the first application, 0.5 kg (1 lb) of the fluosilicate crystals should be dissolved in 4 l (1 gal) of water; about 1 kg (2 lb) of crystals per 4 l (1 gal) of water are used for subsequent applications.

The solution may be applied efficiently with large brushes for vertical surfaces and mops for horizontal surfaces. The surfaces should be allowed to dry between applications (about 3 or 4 hours are generally required for absorption, reaction, and drying). Brush and wash the surface with water shortly after the last application has dried to remove encrusted salts that may cause white stains.

Treatment with fluosilicates reduces dusting and hardens the surface by chemical action. It increases resistance to attack from some substances but does not prevent such attack. With poor-quality concrete, the treatment is not effective.

Concrete surfaces to be treated with fluosilicates should not contain integral water-repellent agents because these compounds will prevent penetration of the solution. Fluosilicate hardeners should not be used when paints are to be applied because they result in poor adhesion of many coatings. Also, hardened surfaces are difficult to etch properly.

2. Sodium Silicate (Water Glass)

Also sold as a floor hardener, commercial sodium silicate is about a 40% solution. It is quite viscous and must be diluted with water to

secure penetration; the amount of dilution depends on the quality of the silicate and permeability of the concrete. Silicate of about 42.5 degrees Baumé diluted in proportions of 1 part silicate to 4 parts water by volume makes a good solution. Two or three coats should be used. For tanks and similar structures, progressively stronger solutions are often used for the succeeding coats.

Each coat should be allowed to dry thoroughly before the next one is applied. On horizontal surfaces the solution may be liberally poured on and then spread evenly with mops, brooms, or brushes. Scrubbing each coat with stiff fiber brushes or with scrubbing machines and water after it has hardened will assist penetration of the succeeding application. The treatment increases resistance to attack from some substances but does not prevent such attack.

3. Drying Oils

Two or three coats of linseed oil may be used as a protective treatment; boiled linseed oil dries faster than raw oil and is used more commonly. Soybean oil and tung (China wood) oil can also be used. The treatment increases resistance to attack from some substances but does not prevent such attack.

The concrete should be well cured and at least 14 days old before the first application of a drying oil. If this is not possible, the concrete should be neutralized by applying a solution consisting of 24 parts of zinc chloride and 40 parts of orthophosphoric acid (85% phosphoric acid) to 1000 parts of water (24 ml; 40 ml; 1 l or 3 oz; 5 oz; 1 gal). After it is brushed on the concrete, the solution should be allowed to dry for 48 hours. Any crystals that have formed on the surface should then be removed by light brushing. This solution should not be used on prestressed concrete. Sometimes a magnesium fluosilicate treatment is also applied to harden the surface before the oil treatment.

The oil treatment may be applied with mops, brushes, or spray and the excess removed with a squeegee before the oil gets tacky. It is not wise to build up a heavy surface coating, as penetration of the oil into the surface is desirable. Diluting the oil with turpentine or mineral spirits to obtain a mixture of equal parts gives better penetration for the first coat; subsequent coatings may be diluted less. Careful heating of the oil to about 65 °C (150 °F) and hot application to a warm surface also help achieve better penetration. Each coat must dry thoroughly for at least 24 hours before the next application. Drying oils tend to darken concrete.

4. Coumarone-Indene

Available in grades from dark brown to colorless, this synthetic resin is soluble in xylol and similar hydrocarbon solvents and should be powdered to aid dissolving. A solution consisting of about 3 kg coumarone-indene per 1 l xylol plus 20 ml boiled linseed oil (6 lb of coumarone-indene per gal of xylol with 1/2 pt of boiled linseed oil) makes a good coating. Two or more coats should be applied to fairly dry concrete. The coatings have a tendency to yellow with exposure to sunlight but the yellowing does not seem to affect the protective properties.

Coumarone-indene availability has been decreasing for many years, and current substitutes include hydrocarbon resin polymers (hydrocarbon resins) and rosin-based resins.

5. Styrene-Butadiene

Styrene-butadiene copolymer resins are available in various medium-strength solvents, some faster drying than others. Three coats are generally recommended, with the first coat thinned for better penetration. Twenty-four hours should elapse between coats, and a delay of 7 days is necessary for thorough drying before the coated surface is placed in service. These coatings tend to yellow with exposure to sunlight.

Because this coating is solvent-borne, however, it usually is high in volatile organic compounds (VOC) and less and less available, due to state and local VOC content limits.

6. Chlorinated Rubber

Chlorinated rubber cures by solvent evaporation. Chlorinated rubber surface treatment consists of a trowel-applied mastic of heavy consistency up to 3 mm (1/8 in.) thick, or multiple coats of specially formulated lower-viscosity types can be brushed or sprayed on to a maximum thickness of 0.25 mm (10 mils). An absolute minimum of 0.1 mm (5 mils) (applied in two coats) is recommended for chemical exposure.

In general, concrete should age for two months before this treatment. The concrete may be damp but not wet, as excessive moisture may prevent adequate bonding. It is advisable to thin the first coat, using only the producer's recommended thinner (other thinners may be incompatible). A coating dries tack-free in an hour, but a 24-hour interval is recommended between coats.

The applied coating is odorless, tasteless, and nontoxic after it dries. Because it is solvent-borne, however, it usually is high in volatile organic compounds (VOC). It is difficult formulating coatings that are based chlorinated rubber resins and that comply with state and local VOC content limits. Also, its strong solvents, may lift and destroy previously painted and aged coatings of oil or alkyd base. The use of newer surface coating materials has rendered this treatment less and less common.

7. Chlorosulfonated Polyethylene (Hypalon)

Four coats of about 0.05 mm (2 mils) each and an appropriate primer are normally recommended to eliminate pinholes. Thinning is not usually required, but to reduce viscosity for spray application, the producer's recommended thinner should be used up to a limit of 10% of the amount of coating used. Each coat dries dust-free within 10 to 20 minutes, and the treatment cures completely in 30 days at 21 °C (70 °F) and 50% relative humidity. A fill coat of grout or mortar is required since the paint film will not bridge voids in the concrete surface. Moisture on the surface may prevent good adhesion.

These coatings are expensive and must be applied by trained personnel. They are not used where less costly coatings are adequate.

8. Vinyls

Of the vinyls available, polyvinyl chloride, polyvinyl chloride acetate, and polyvinylidene chloride are the ones used extensively in corrosion control. The resins are soluble only in strong solvents. Due to the high viscosity of the resins, only solutions of low solids content can be made. Multiple coats are therefore required for adequate film thickness. Vinyls should generally be sprayed onto dry surfaces, as their fast drying (30 minutes) makes brush application difficult.

Vinyl chloride coatings make good top coatings for vinyl chloride acetate and others, but do not themselves adhere well directly to concrete.

Polyvinyl acetate latex (waterborne) copolymers are widely available as decorative coatings, but like other latexes, they are usually inferior to solvent-system coatings for chemical resistance. In addition, the vinyl acetate latexes (waterborne emulsions) are sensitive to the free alkalinity of concrete and eventually break down.

9. Bituminous Paints, Mastics, and Enamels

Asphalt or coal-tar coatings may be applied cold (paints and mastics in cutback or emulsion form) or hot (mastics and enamels). Two coats are usually applied to surface-dry concrete: a thin priming coat to ensure bond and a thicker finish coat. The priming solution is of thin brushing consistency and should be applied to cover the surface completely; any uncoated spots should be touched up. When the primer has dried to a tacky state, it is ready for the finish coat. Multiple coats should be applied at right angles to each other to ensure continuity and avoid pinholes.

Emulsions are slower drying, more permeable, and less protective than the other coatings. Cutbacks and emulsions, if not completely cured, can impart odor or flavor to materials with which they are in contact. The producer's recommendations on service and application temperatures should be strictly observed.

Bituminous mastics may be applied cold or heated until fluid. Cold mastics are cutbacks or emulsions containing finely powdered siliceous mineral fillers or bitumen-coated fabrics to form a very thick, pasty, fibrous mass. This mass increases the coating's resistance to flowing and sagging at elevated temperatures and to abrasion. Thin mastic layers, about 1 mm ($\frac{1}{32}$ in.) thick, are troweled on and allowed to dry until the required thickness has been obtained. Hot mastics usually consist of about 15% asphaltic binder, 20% powdered filler, and the remainder sand, graded up to 6-mm ($\frac{1}{4}$ -in.) maximum size. They should be poured and troweled into place in layers 16 mm to 25 mm thick ($\frac{5}{8}$ in. to 1 in.).

Enamels should be melted, stirred, and carefully heated until they reach the required application temperature. If an enamel is heated above the producer's recommended temperature, it should be discarded. If application is delayed, the pot temperature should not be allowed to exceed 190 °C (375 °F). When fluid, the enamel should be applied quickly over tacky cutback primer, since it sets and hardens rapidly.

10. Polyester

These resin coatings are two- and three-part systems consisting of polyester, peroxide catalyst, and sometimes a promoter. The amount of catalyst must be carefully controlled because it affects the rate of hardening. The catalyst and promoter are mixed separately into the polyester. Fillers, glass fabrics, or fibers used to reduce shrinkage and coefficient of expansion compensate for the brittleness of resin and increase strength. Polyesters are usually silica filled except for hydrofluoric acid service, which requires non-siliceous fillers such as carbon. (National Association of Corrosion Engineers 1991).

Coatings with a 2- to 3-hour pot life generally cure in 24 to 36 hours at 24 °C (75 °F). Shorter curing periods require reduced pot life because of high heats of reaction. Coatings are sensitive to changes in temperature and humidity during the curing period. Some coatings can be applied to damp surfaces at temperatures as low as 10 °C (50 °F). The alkali resistance of some polyesters is limited. It is recommended that trained personnel apply the coatings. Polyester-and-filler surfacings should conform to ASTM C722.

11. Urethane

These coatings may be one- or two-part systems. A one-part system may be moisture cured or oil modified. The coatings that cure by reacting with moisture in the air must be used on dry surfaces to prevent blistering during the curing period. Oil-modified coatings dry by air oxidation and generally have the lowest chemical resistance of the urethane coatings.

Two types of the two-part system are also available: catalyzed and polyol cured. Catalyzed coatings have limited pot life after mixing and cure rapidly. Elastomeric urethane topcoats have a very quick chemical cure, so they can be exposed to fog, rain, chemical splash, or immersion almost immediately after application. Overnight curing is recommended if the coating will be exposed to traffic in service; several days of curing are needed for high-impact or abrasive applications (National Association of Corrosion Engineers 1991). For polyol-cured coatings, the mixture is stirred well and allowed to stand for about one-half hour before use; it should have a pot life of about 8 to 12 hours. Polyol-cured coatings are the most chemically resistant of the polyurethane coatings but require the greatest care in application.

Polyurethane elastomers are two-component elastomeric coatings that have distinct advantages over rigid floor surfacings: they adhere well to concrete, and are flexible and nonshrink, so they are able to bridge small cracks in the surface.

A newer type of coating, polyurea, normally uses polyamines as coreactants to react with isocyanates and does not require a catalyst. Polyurea is distinguished by its extremely fast gel time (as low as three seconds for a "quick set" polyurea). As a result of the rapid set time, polyurea coatings are not sensitive to moisture and humidity and can be applied in conditions of high ambient humidity. Polyurea should not be applied on wet concrete. Trapped moisture will not

react with the coating as it sets, but it will impair adhesion and ultimately lead to coating failure. Polyurea coatings tend to have a very limited pot life and their recoat time becomes a problem in cases when multiple coats occur (Kenworthy 2003).

All urethane coatings are easily applied by brush, spray, or roller. Rough or porous surfaces may require two coats. For immersion service in water and aqueous solutions, it may be necessary to use a primer and the urethane producer should be consulted. For spray-applied polyether polyurethanes, an epoxy coating applied to the surface closes the pores before the polyurethane is applied (Recker 1994). Satisfactory cure rates of polyurethanes will be attained at relative humidities of 30% to 90% and temperatures between 10 °C and 38 °C (50 °F and 100 °F). Lower temperatures will retard the rate of cure. Polyureas can be applied in extreme conditions of humidity and temperature and will cure at temperatures as low as -20 °C (-4 °F) (Kenworthy 2003).

Aliphatic urethanes have very good abrasion resistance, color and gloss stability, and resistance to ultraviolet light (National Association of Corrosion Engineers 1991). The principal disadvantages of urethane coatings are the very careful surface preparation needed to ensure adhesion and the difficulty in recoating unless the coating is sanded. Multiple coats should be used and an inert filler added if air voids are present on the concrete surface (the coatings are unable to span air voids). Dilute solutions of urethane have been used as floor hardeners (Mailvaganam 1991).

12. Epoxy

These coatings are generally a two-package system consisting of epoxy resin—which may be formulated with flexibilizers, extenders, diluents, and fillers—and a curing agent. The coating properties are dependent on the type and amount of curing agent used. The common curing agents suitable for curing are amines, polyamines, amine adducts, polyamides, polysulfides, and tertiary amines. The polyamide-cured epoxies have less chemical resistance but better physical properties (National Association of Corrosion Engineers 1991).

The single-package coatings are epoxy esters that are generally inferior to the two-package epoxies in chemical resistance. They require an alkali-resistant primer and are not recommended for immersion service. Some epoxy formulations are 100% solids and others are solution coatings. Some water-based epoxies are designed for use as primers over damp or dry concrete prior to application of polyurethane or epoxy topcoats. Solvent-based epoxies are often used as a first coat to penetrate and seal porous concrete. Multiple coats can achieve a dry film thickness of 0.5 mm (20 mils) (National Association of Corrosion Engineers 1991). Two coat, and to a lesser extent one coat, 100% solids epoxy systems are frequently recommended as coatings systems for concrete in aggressive environments (JPCL 2006). The formulator's recommendations should be followed in selecting the right system for the protection needed.

It is also desirable to follow the formulator's recommendations for the best application procedures, temperatures, and allowable working

life. Epoxies are usually trowel or roller applied (National Association of Corrosion Engineers 1991). Generally, two coats must be applied to eliminate pinholes, especially on rough or porous surfaces. Epoxy toppings can be low- or high-build; with aggregate added, they can be up to 6 mm (1/4 in.) thick (National Association of Corrosion Engineers 1991).

Epoxy liners may be formed with reinforcement such as woven fabrics, mats, or chopped-glass fiber. The epoxy coating is applied with a roller to a film thickness of 0.25 mm (10 mils). Then fiberglass cloth is spread over the wet epoxy coating and pressed into it. A second epoxy coating is applied immediately to embed the fiberglass.

One class of coatings, based on flexible epoxy copolymers, is available for use over oil contaminated substrates. These oil-tolerant coatings appear to perform well where other materials cannot. In general, the surface should be sound and have as much contamination as possible removed prior to coating (National Association of Corrosion Engineers 1991).

There are epoxy systems that cure at temperatures of 4 °C (40 °F) single coat, but they require a relatively long cure time or less, bond to damp surfaces, and will cure even if flooded with water immediately after application. Water-based epoxy topcoats are durable, give off little odor, are safety oriented, and easy to clean up. Epoxies will experience some chalking on exposure to ultraviolet light (National Association of Corrosion Engineers 1991). Dilute solutions of epoxies have been used as floor hardeners (Mailvaganam 1991).

Contact with epoxy resins or hardeners can cause skin irritation or allergic reactions, and proper protection, as recommended by the manufacturer, is necessary. If skin contact occurs, a dry towel should be used to wipe the epoxy from the skin before washing with soap and water. Epoxy-and-filler surfacings should conform to ASTM C722. Bond can be checked using ASTM C882, *Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear*. (See ACI 503R and National Association of Corrosion Engineers 1991 for more information.)

13. Neoprene

These coatings may be one- or two-part systems. The one-part system is used as a thinner film than the two-part and generally has a lower chemical resistance. It cures slowly at room temperature, and some curing agents may limit its shelf life. The two-part system may require a holding period between mixing and application.

To allow evaporation of water from the concrete, application of either system should not begin for at least 10 days after removal of the forms. Some coatings require primers while others are self priming. Adhesion is often improved by application of a diluted first coat to increase penetration of the surface. Each coat should be sufficiently solvent-dry before the next application; however, if it becomes too fully cured, it may swell and lose adhesion. Three coats, 0.05 mm to 0.08 mm (2 mils to 3 mils) each, are normally recommended to eliminate the possibility of pinholes. For immersion service, minimum dry thickness should be 0.5 mm (20 mils).

14. Polysulfide

These coatings may be one- or two-part systems. They do not harden with age and they remain rubbery over a broad temperature range. Thick coats of 0.5 to 0.6 mm (20 to 25 mils) can be applied at one time. For the one-part system, atmospheric moisture serves as the curing agent; when humidities are low, curing can be hastened by fogging with a fine water mist. The two-part system usually has a pot life of 30 to 45 minutes and becomes tack-free overnight.

15. Coal Tar—Epoxy

These coatings are classified in three main types according to epoxy resin content: high-resin coatings for dry thicknesses of 0.4 mm (15 mils); medium-resin coatings for integral linings of concrete pipe; and low-resin coatings for building nonsagging barriers up to 1 mm (40 mils) thick. The first type requires a special primer, and its thickness is achieved in two coats. The other types do not require primers and may be applied in a Coal tar—epoxy coatings are a two-package system. A combination of coal tar, filler, solvent, and epoxy resin may be in one package and the curing agent (commonly amine, polyamine, amine adduct, polyamide, or tertiary amine) in the other. These two packages are usually mixed in a ratio of 20:1 or 10:1, but the ratio may be lower. The coal tar, filler, solvent, and curing agent may also be blended together to make up one package and the epoxy resin kept separate for the other. These two packages are generally mixed in a ratio of 3:1. The packages must be proportioned correctly to secure proper cure and chemical resistance. Storage life of the blends can vary from six months to two years, depending on formulation.

It is important that the two packages be thoroughly mixed, and power agitation is strongly recommended. Mixing small quantities is not advisable. Insufficient mixing will be revealed only after the coating has cured. For some coatings, a one-half hour waiting period between mixing and application is desired. Pot life is generally 3 to 4 hours at 21 °C (70 °F), but it may vary from several minutes to 8 hours, depending on solvent content and formulation.

Some coal tar-epoxy coatings should not be applied at temperatures below 10 °C (50 °F) or when there is danger of their becoming wet within 24 hours of application. However, there is a coal-tar epoxy that can be applied at temperatures lower than 4 °C (40 °F) that will not be harmed by becoming wet immediately after application and can be recoated even after several weeks. Spray applications generally result in better coverage. However, the sides of a short, stiff bristle brush or a long-nap roller may be used. The second coat should be applied within 48 hours to prevent adhesion problems between coats. If the first coat dries at air temperatures above 24 °C (75 °F), the producer's maximum recommended time between coats must be observed. These coatings should not be put into service until a minimum of 5 days' curing time has elapsed.

Coal tar-epoxies are less commonly used today due largely to health concerns over long term exposure and direct contact (by coating applicators) to the tar. Cleanup and disposal require special precautions to protect the environment

16. Chemical-Resistant Masonry Units, Mortars, Grouts, and Concretes

Chemical-resistant brick and tile are usually solid, kiln-fired masonry units made from clay, shale, or mixtures thereof for masonry construction. Units can also be made from carbon (see ASTM C1106), graphite, or other materials where additional chemical resistance is required. Chemical-resistant brick and tile should conform to ASTM C279, *Specification for Chemical-Resistant Masonry Units*. The three types of masonry units are Type I (formerly Type H) for locations where low absorption and high acid resistance are not required; Type II for locations where low absorption and high acid resistance are required; and Type III (formerly Type L) for locations where minimum absorption and maximum acid resistance are required.

Chemical-resistant industrial floor brick should conform to ASTM C410, *Specification for Industrial Floor Brick*. ASTM C410 Type H brick is used where chemical resistance is a service consideration but low absorption is not required. ASTM C410 Type L brick is used where minimal absorption and high chemical resistance are required. Although highly abrasion resistant, Type L brick usually has limited thermal and impact resistance.

Chemical-resistant mortar or grout must be used to fill the joints between chemical-resistant brick or tile. Mortars are troweled on the sides and bottom (or faces to be bonded) of the brick to about 3 mm ($\frac{1}{8}$ in.) thickness before the brick is placed. Grouts are usually applied to joints, about 6 mm ($\frac{1}{4}$ in.) wide, after the masonry units are set in place on the floor. The chemical resistance of mortars or grouts may be evaluated by ASTM C267, *Test Method for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacing and Polymer Concretes*. The most commonly used mortars or grouts are:

a. Asphaltic and bituminous membranes—for use over a limited range of low temperatures. Some are sand filled, others are not. They may be applied either as mastics that depend upon evaporation of solvent or as hot-melt compounds.

b. Epoxy-resin mortars or grouts—two- or three-part systems with either amine or polyamide curing agents. They should conform to *Specification for Chemical-Resistant Resin Mortars* (ASTM C395) or *Specification for Chemical-Resistant Resin Grouts for Brick or Tile* (ASTM C658). For instructions on their use, see *Practice for Use of Chemical-Resistant Resin Mortars* (ASTM C399) or *Practice for Chemical-Resistant Resin Grouts for Brick or Tile* (ASTM C723). ASTM C881, *Specification for Epoxy-Resin-Base Bonding Systems for Concrete*, may also contain helpful information.

c. Furan-resin mortars or grouts—should conform to ASTM C395 or C658. Normally, a membrane of 1.5 mm to 6 mm ($\frac{1}{16}$ in. to $\frac{1}{4}$ in.) in thickness is applied to concrete, and then a furan mortar is used as a bond coat or bed joint. Furan-resin mortars have the broadest range of resistance of all resin mortars to both acid and alkali (pH 0 to 14) and temperatures up to about 220 °C (425 °F) (Mailvaganam 1991). For their use, see ASTM C399 or C723.

d. Hydraulic-cement mortars or grouts—For instructions on their use, see *Practice for Use of Hydraulic Cement Mortars in Chemical-Resistant Masonry* (ASTM C398). These include the use of portland, blended, and calcium aluminate cements.

e. Phenolic-resin mortars—should conform to ASTM C395. For instructions on their use, see ASTM C399.

f. Polyester-resin mortars—should conform to ASTM C395. General purpose isophthalic resin systems have limited resistance to strong chemicals, but will withstand mildly oxidizing solutions such as bleaches. Other polyesters are available that are highly chemical resistant, even to strong acids. For instructions on their use, see ASTM C399.

g. Silicate mortars—should conform to *Standard Specification for Chemically Setting Silicate and Silica Chemical-Resistant Mortars* (ASTM C466). For instructions on their use, see *Practice for Use of Chemically Setting Chemical-Resistant Silicate and Silica Mortars* (ASTM C397).

h. Sulfur mortars—should conform to *Specification for Chemical-Resistant Sulfur Mortar* (ASTM C287). For instructions on their use, see *Practice for Use of Chemical-Resistant Sulfur Mortar* (ASTM C386).

i. Vinylester-resin mortars—should conform to ASTM C395. For instructions on their use, see ASTM C399.

A bed of mortar and an impervious membrane lining are usually placed between the masonry lining and the concrete. Rubber and vinyl sheets or properly primed and hot-applied 10-mm, ($\frac{3}{8}$ -in.) thick asphaltic materials, both plain and glass-cloth reinforced, are preferred for the membrane lining, depending on the corrosive substance. The primer should conform to *Specifications for Asphalt Primer Used in Roofing, Dampproofing, and Waterproofing* (ASTM D41), except that the asphalt content should not be less than 35% by weight. Floor slabs that are to receive a masonry lining should have a smooth wood-float finish. A slab having a steel-trowel finish may be too smooth for adhesion of the asphaltic membrane.

Monolithic surfacings (often called coatings, toppings, or thin overlays) can also be made with the base materials (cement or resin) in a through i above. Many surfacings were discussed in earlier categories (epoxy, polyester, and so forth). They are used without masonry units to cover a concrete surface. Epoxy, polyester, and other resin-and-filler monolithic surfacings should meet the requirements of ASTM C722, *Specification for Chemical-Resistant Resin Monolithic Surfacing*. Also see ASTM C811, *Practice for Surface Preparation of Concrete for Application of Chemical-Resistant Resin Monolithic Surfacing*.

j. Sulfur concretes—should conform to ACI 548.2R (1993) *Guide for Mixing and Placing Sulfur Concrete in Construction*. A typical mix design by weight is: 38% coarse aggregate, 38% fine aggregate, 8% mineral filler, and 16% sulfur cement (McGovern 1992).

k. Polymer concretes—should conform to *Standard Specification for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar* (ASTM 1438) and to ACI 548.3R (2003), *Polymer-Modified Concrete*.

l. Silicate-based concretes—used in precast concrete elements. Class F fly ash, silicate solution, and an alkaline activator are the most commonly used cementitious materials (Oswald 1998).

17. Sheet Rubber

Soft natural and synthetic rubber sheets 3 mm to 13 mm ($\frac{1}{8}$ in. to $\frac{1}{2}$ in.) thick may be cemented to concrete with special adhesives. Sometimes two layers of soft rubber are used as a base, with a single layer of hard rubber over them.

Chemical-resistant synthetics available as sheeting are neoprene, polyvinylidene chloride-acrylonitrile, plasticized polyvinyl chloride, polyisobutylene, butyl, nitrile, polysulfide, and chlorosulfonated polyethylene rubbers.

18. Resin Sheets

Synthetic resins, particularly polyester, epoxy, and polyvinyl chloride, are available as sheet materials. These sheets are not referred to in the guide for selecting protective treatments, but may be used wherever comparable resin coatings are recommended. They are often glass fiber reinforced and may be cemented to concrete with special adhesives. Types of resin sheets include acrylic; polyethylene and polypropylene; polystyrene; polyvinyl chloride. ABS sheet, fiberglass-reinforced plastic sheet, and polycarbonate sheet.

19. Lead Sheet

In the United States, lead sheet used for chemical resistance is called chemical lead. The sheets should be as large as possible (to minimize the number of joints) but not too heavy to handle—the thinnest sheet may be as large as 2.5 m x 6.0 m (8 ft. x 20 ft). Thicknesses range from 0.4 mm to 13 mm ($\frac{1}{64}$ in. to $\frac{1}{2}$ in.). Lead may be cemented to concrete with an asphaltic paint. Each sheet should be overlapped and the seam welded by conventional lead-burning techniques. If the lead is to be subjected to high temperatures, it may be covered with chemical-resistant masonry to reduce thermal stresses.

20. Glass

Two types have been used for corrosion resistance: high-silica glass and borosilicate glass. Borosilicate glass, the more alkali-resistant material, is recommended because alkalis in concrete may cause glass etching. Glass may be cemented to the concrete. Thermal shock is often a cause of failure in glass-lined structures.

21. Acrylics, Methyl Methacrylate, and High Molecular Weight Methacrylate (HMWM)

Methyl methacrylates, acrylic polymers, and their modified forms are often applied with squeegees and rollers to concrete to reduce water, chloride-ion, and chemical ingress. They are often used on bridge and parking-garage surfaces and on architectural concrete. Pure methyl

methacrylate systems can be made impermeable or breathable depending on their formulation. Some formulations are also considered to be both penetrating and crack repairing. Methacrylates are often used in conjunction with non-skid aggregate.

Acrylic copolymers may also be added to portland cement mortars and concretes in breathable overlay systems. Some acrylic formulations are solvent free, so they experience no shrinkage upon curing. Varying the formulations allows for either flexible or hard materials. Some acrylics can be used at temperatures as low as $-10\text{ }^{\circ}\text{C}$ ($14\text{ }^{\circ}\text{F}$) and cure very quickly at low temperatures (Mailvaganam 1991). In one study, acrylic rubber coatings showed excellent resistance to weathering. The three-coat system of primer, base coat, and a top coat of acrylic urethane had an overall thickness of 1 mm (40 mils). The base coat maintained its elasticity over a wide temperature range, from $-50\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$ ($-58\text{ }^{\circ}\text{F}$ to $+158\text{ }^{\circ}\text{F}$). After 2½ years in severe exposure, crack widths of up to 14 mm (0.55 in.) were bridged. Crack bridging ability improved with time: the surface coating was in excellent condition after 8 years of exposure. The adhesion strength was as much as 1 MPa (145 psi), and the coating prevented salt intrusion (Swamy 1993).

22. Silane and Siloxane (Organosilicon Compounds)

The most commonly used organosilicon compounds are silane, siloxane, and mixtures of the two. They are available in both solvent-borne or water-borne formulations. Silane- and siloxane-based materials are single-component penetrating materials commonly used to reduce chloride-ion ingress into concrete bridges and parking garages, thereby reducing corrosion of reinforcing steel. They are also used to reduce water permeance on concrete and concrete masonry. They may offer some protection to concrete in sulfate exposures (Stark 1997 and 2002).

Currently commercially available water repellents contain a carrier such as alcohol and can be classified according to their active ingredient content by weight, up to 100%. Performance usually increases with an increase in solids content; however, higher percentages of active ingredients might darken the concrete. Most siloxane-based water repellents currently on the market have much less than 10% active ingredient; available silanes may have 40% active ingredient (Fliedner 1996). Siloxanes are less volatile than silanes, and therefore there is less loss of active ingredient during application. For this reason, siloxanes are usually used with a lower percentage active ingredient than silanes. Silanes and siloxanes are applied with low pressure, 100 kPa to 200 kPa (15 psi to 30 psi), at a rate of 2.5 to 3.7 sq m per liter (100 to 150 sq ft per gallon) (Fig. 9). They can be applied with brush, roller, or pump-up or airless sprayer. Silanes and siloxanes are breathable materials that allow water vapor to pass through the concrete. The advantages of these materials are that they do not discolor the concrete, and they have no effect on the coefficient of friction.

Silanes, which have a smaller molecular size, penetrate better than siloxanes when the substrate is dry, but the two have comparable levels of penetration on moist or damp surfaces (McGill 1990). In one



Fig. 9. 100% silane sealer is being applied to a parking garage. (IMG25538)

study (Fliedner 1996), an almost linear relationship between penetration depth and silane concentration (% active ingredient) was found. The more concentrated the silane solution, the greater the penetration depth: 100% concentrations penetrated about 8 mm (0.3 in.) into concrete (w/c of 0.6). Silanes require more care during application; they can evaporate under hot or windy conditions, reducing the amount that remains on the surface and decreasing the effectiveness of the treatment. Siloxanes are heavier, and even warm ambient temperatures or high winds little affect the amount that remains on the surface.

Silane penetration depth and waterproofing effectiveness improve as the permeability and water-cement ratio of the concrete decreases. Silanes do not need to be diluted with alcohol, and 100% silanes without carrier penetrate better and are more effective sealers than 40% silane sealers. Surfaces previously treated can be retreated with silane, and the depth of penetration generally improves if the concrete has had sufficient time to dry (Carter 1994). Salt-exposed concrete of good quality should have increased service life when sealed with 100% silane materials. Silanes may not be the best choice for concrete subjected to prolonged submerged conditions in the presence of freezing and deicing chemicals.

23. Metalizing

Corrosion-resistant metals can be applied to concrete surfaces by using flame-spray or arc-spray techniques. The flame-spray process melts the metalizing wire with a combustible gas, and compressed air atomizes the molten metal and projects the metal spray onto the prepared concrete surface. The liquid metal is impinged onto the concrete and cools. After cooling, the metal can be ground, polished, and finished as desired.

Thermal-arc spraying uses an electric arc to melt the metalizing wire. The molten metal is then blown onto the concrete surface by compressed air to form the metal coating.

Aluminum, copper, bronze, stainless steel, chrome, nickel, monel, tin, zinc, and other metals and alloys can be used. Ceramics such as zirconium oxide can also be applied.

Guide to the Effect of Substances on Concrete and Selecting Protective Treatments

This guide refers only to common protective treatments. More exotic treatments, such as lead sheet, glass, or metalizing, are not referred to unless necessary, but they should be considered for extreme or unusual circumstances. Different treatments provide different degrees of protection and

therefore product manufacturers listed on pages 28 to 31 should be consulted as to the applicability of particular treatments.

The guide is adapted with a few modifications from ACI 515.1R. Footnotes appear at the end of each section of the table. Readers are encouraged to submit information on materials and protective treatments not listed.

Acids

Material	Effect on concrete	Protective treatments
Acetic		
<10%	Slow disintegration	1, 2, 9, 10, 12, 14, 16 (b, c, e, f, g, h)
30%	Slow disintegration	9, 10, 14, 16 (c, e, f, g)
100% (glacial)	Slow disintegration	9, 16 (e, g)
Acid waters (pH of 6.5 or less)	Slow disintegration.* Natural slightly acid waters may erode surface mortar but then action usually stops. Disintegration increases as pH decreases. See "Acids" under "Design Considerations."	1, 2, 3, 6, 8, 9, 10, 11, 12, 13, 16 (b, c, e, f, g, h), 17
Arsenious	None	
Boric	Negligible effect	2, 6, 7, 8, 9, 10, 12, 13, 15, 16 (b, c, e, f, g, h), 17, 19
Butyric	Slow disintegration	3, 4, 8, 9, 10, 12, 16 (b, c, e, f)
Carbolic	Slow disintegration	1, 2, 16 (c, e, g), 17
Carbonic (soda water)	0.9 to 3 ppm of carbon dioxide dissolved in natural waters disintegrates concrete slowly	2, 3, 4, 8, 9, 10, 12, 13, 15, 16 (b, c, e, f, h), 17
Chromic		
5%	None*	2, 6, 7, 8, 9, 10, 16 (f, g, h), 19
50%	None*	16 (g), 19
Formic		
10%	Slow disintegration	2, 5, 6, 7, 10, 12, 13, 16 (b, c, e, g), 17
90%	Slow disintegration	2, 7, 10, 13, 16 (c, e, g), 17
Humic	Slow disintegration possible, material depending on humus	1, 2, 3, 9, 10, 12, 15, 16 (b, c, e)
Hydrochloric		
10%	Rapid disintegration, including steel	2, 5, 6, 7, 8, 9, 10, 12, 14, 16 (b, c, e, f, g, h), 17, 19, 20
37%	Rapid disintegration, including steel	5, 6, 8, 9, 10, 16 (c, e, f, g, h)
Hydrofluoric		
10%	Rapid disintegration, including steel	5, 6, 7, 8, 9, 12, 16 (carbon and graphite brick; b, c, e, h), 17
75%	Rapid disintegration, including steel	16 (carbon and graphite brick; e, h), 17
Hypochlorous		
10%	Slow disintegration	5, 8, 9, 10, 16 (f, g)
Lactic		
5%–25%	Slow disintegration	3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, g, h), 17, 21
Nitric		
2%	Rapid disintegration	6, 8, 9, 10, 13, 16 (f, g, h), 20
40%	Rapid disintegration	8, 16 (g)
Oleic, 100%	None	
Oxalic	No disintegration. It protects concrete against acetic acid, carbon dioxide, and salt water. POISONOUS, it must not be used on concrete in contact with food or drinking water.	
Perchloric, 10%	Disintegration	8, 10, 16 (e, f, g, h)

Effects of Substances on Concrete and Guide to Protective Treatments

Phosphoric 10%	Slow disintegration	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 (b, c, e, f, g, h), 17, 19
85%	Slow disintegration	1, 2, 3, 5, 7, 8, 9, 10, 13, 14, 15, 16 (c, e, f, g, h), 17, 19
Stearic	Slow disintegration	5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, g, h), 17
Sulfuric 10%	Rapid disintegration	5, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16 (b, c, e, f, g, h), 17, 19, 20
100% (oleum)	Disintegration	16 (g), 19
Sulfurous	Rapid disintegration	6, 7, 9, 10, 11, 12, 13, 16 (b, c, e, h), 19, 20
Tannic	Slow disintegration	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 16 (b, c, e, g), 17
Tartaric, solution	None. See wine under "Miscellaneous."	

* In porous or cracked concrete, it attacks steel. Steel corrosion may cause concrete to spall.

Salts and Alkalies (Solutions)*

Material	Effect on Concrete	Protective treatments
Acetate		
Calcium magnesium	Slow disintegration†	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, g, h), 17
Potassium		
Sodium		
Bicarbonate		
Ammonium	None	
Sodium		
Bisulfate		
Ammonium**	Disintegration	5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 (b, c, e, f, h), 17
Sodium		
Bisulfite		
Sodium	Disintegration	5, 6, 7, 8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17
Calcium (sulfite solution)	Rapid disintegration	7, 8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17
Bromide		
Sodium	Slow disintegration	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16 (b, c, e, f, h), 17
Carbonate		
Ammonium	None	
Potassium		
Sodium		
Chlorate sodium	Slow disintegration	1, 4, 6, 7, 8, 9, 10, 16 (f, g, h), 17, 19
Chloride		
Calcium†	None, unless concrete is alternately wet and dry with the solution.** However, concentrated CaCl ₂ solutions disintegrate concrete, whereas weak solutions do not.	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, g, h), 17, 21
Potassium		
Sodium†		
Strontium		
Ammonium	Slow disintegration**	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, g, h), 17
Copper		
Ferric (iron)		
Ferrous		
Magnesium†		
Mercuric		
Mercurous		
Zinc		
Aluminum	Rapid disintegration**	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, h), 17
Chromate, sodium	None	
Cyanide		
Ammonium	Slow disintegration	7, 8, 9, 10, 12, 13, 16 (b, c), 17
Potassium		
Sodium		

Dichromate			
Sodium	Slow disintegration with dilute solutions		1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, h), 17
Potassium	Disintegration		1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, h), 17
Ferrocyanide, sodium	None		
Fluoride			
Ammonium	Slow disintegration		3, 4, 8, 9, 10, 13, 16 (a, c, e, h), 17
Sodium			
Fluosilicate, magnesium	None		
Fromate			
Potassium	} None†† See "Deicers" under "Miscellaneous."		
Sodium			
Hexametaphosphate, sodium	Slow disintegration		5, 6, 7, 8, 9, 10, 12, 13, 15, 16 (b, c, e), 17
Hydroxide			
Ammonium	} None		
Barium			
Calcium			
Potassium, 15%††			
Sodium, 10%††			
Potassium, 25%	} Disintegration. Use of calcareous aggregate lessens attack.		5, 7, 8, 10, 12, 13, 14, 15, 16 (carbon and graphite brick; b, c), 17
Sodium, 20%			
Nitrate			
Calcium	} None		
Ferric			
Zinc			
Lead	} Slow disintegration		2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16 (b, c, e, f, g, h), 17, 20
Magnesium			
Potassium			
Sodium			
Ammonium	Disintegration**		2, 5, 6, 8, 9, 10, 11, 12, 13, 16 (b, c, e, f, g, h), 17, 20
Nitrite, sodium	Slow disintegration		1, 2, 5, 6, 7, 8, 9, 10, 12, 13, 16 (b, c), 17
Orthophosphate, sodium (dibasic and tribasic)	None		
Oxalate, ammonium	None		
Perborate, sodium	Slow disintegration		1, 4, 7, 8, 9, 10, 13, 16 (d, f, g, h), 17
Permanganate, potassium	None unless potassium sulfate is present		
Persulfate, potassium	Disintegration of concrete with inadequate sulfate resistance		1, 2, 5, 7, 8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17
Phosphate, sodium (monobasic)	Slow disintegration		5, 6, 7, 8, 9, 10, 12, 15, 16 (b, c), 17
Pyrophosphate, sodium	None		
Stannate, sodium	None		
Sulfate			
Ammonium	Disintegration**		5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 (b, c, e, f, g, h), 17
Aluminum	} Disintegration of concrete with inadequate sulfate resistance. Concrete products cured in high-pressure steam are highly resistant to sulfates.		1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, g, h), 17
Calcium			
Cobalt			
Copper			
Ferric			
Ferrous (iron vitriol)			
Magnesium (epsom salt)			
Manganese			
Nickel			
Potassium			
Potassium aluminum (alum)			
Sodium			
Zinc			

Sulfide		
Copper	}	None unless sulfates are present
Ferric		
Potassium		
Sodium	}	Slow disintegration Disintegration
Ammonium		
Sulfite		
Sodium	}	None unless sulfates are present Disintegration
Ammonium		
Superphosphate, ammonium		Disintegration**
Tetraborate, sodium (borax)		Slow disintegration
Tetrachloride, carbon		Impervious concrete is required to prevent loss from penetration. Sometimes used in food/processing and requires compatible coating. See tetrachloride, carbon under "Solvents and Alcohols."
Thiosulfate		
Sodium	}	Slow disintegration of concrete with inadequate sulfate resistance.
Ammonium		

* Dry materials generally have no effect.

** In porous or cracked concrete, it attacks steel. Steel corrosion may cause concrete to spall.

† Frequently used as deicer for concrete pavements. Any material used as a deicer on concrete can cause scaling if the concrete contains insufficient entrained air or has not been air dried for at least 30 days after completion of curing. For more information see Deicers under "Miscellaneous" and Cody (1994); National Cooperative Highway Research Program (2007); and Kozikowski et al. (2007).

†† If concrete is made with reactive aggregates, disruptive expansion may occur.

Petroleum Oils

Material	Effect on concrete	Protective treatments
Heavy oil below 35 °Baumé* Paraffin (should not be used on masonry)	}	None
Gasoline Kerosene Light oil above 35 °Baumé Ligroin Lubricating oil* Machine oil* Mineral spirits		
Mineral oil		Slow disintegration if fatty oils are present
Gasoline, high octane		None. Surface treatments are generally used to prevent contamination with alkalis in concrete.

* May contain some vegetable or fatty oils and the concrete should be protected from such oils.

Coal Tar Distillates

Material	Effect on concrete	Protective treatments		
Alizarin Anthracene Carbazole Chrysen Pitch	}	None		
Benzol (benzene) Cumol (cumene) Phenanthrene Toluol (toluene) Xylol (xylene)				
Creosote Cresol Dinitrophenol Phenol, 5%–25%				
			Slow disintegration	1, 2, 16 (c, e, g), 17, 19
				1, 2, 11, 12, 16 (b, c, e, f, g), 19

Solvents and Alcohols

Material	Effect on concrete	Protective treatments
Carbon tetrachloride	None*, **	1, 2, 10, 12, 16 (b, c, e, g)
Ethyl alcohol	None† (see deicers under "Miscellaneous")	1, 2, 5, 7, 10, 12, 13, 14, 16 (b, c, e, f, g, h), 17, 19
Ethyl ether	None*	11, 12, 16 (c, e), 19
Methyl alcohol	None*	1, 2, 5, 7, 10, 12, 13, 14, 16 (b, c, e, f, g, h), 17, 19
Methyl ethyl ketone	None*	16 (c, e), 17, 19
Methyl isoamyl ketone	None*	16 (c, e), 17
Methyl isobutyl	None*	16 (c, e), 17
Perchloroethylene	None*	12, 16 (b, c, e)
t-Butyl alcohol	None*	1, 2, 5, 7, 10, 12, 13, 14, 16 (b, c, e, f, g, h), 17, 19
Trichloroethylene	None*	1, 2, 12, 16 (b, c, e, g)
Acetone	None.* However, acetone may contain acetic acid as impurity (see under "Acids").	1, 2, 16 (c, e, g), 17, 19
Carbon disulfide	Slow disintegration possible	1, 2, 11, 16 (c, e, g)
Glycerin (glycerol)	Slow disintegration possible	1, 2, 3, 4, 7, 10, 11, 12, 13, 16 (b, c, e, f, g), 17
Ethylene glycol†	Slow disintegration	1, 2, 7, 10, 12, 13, 14, 16 (b, c, e, f, g, h), 17

* Impervious concrete is required to prevent loss from penetration, and surface treatments are generally used.

** Sometimes used in food processing or as food or beverage ingredient. Check with Food and Drug Administration regarding coatings for use with food ingredients.

† Frequently used as deicer for airplanes. Heavy spillage on concrete containing insufficient entrained air may cause surface scaling.

Vegetable Oils

Material	Effect on Concrete	Protective treatments
Rosin and rosin oil	None	
Turpentine	Mild attack and considerable penetration. Impervious concrete is required to prevent loss from penetration, and surface treatments are generally used.	1, 2, 10, 11, 12, 14, 16 (b, c, e)
Almond Linseed* Olive Peanut Poppyseed Soybean* Tung* Walnut	Slow disintegration For expensive cooking oils, use 20	1, 2, 8, 10, 11, 12, 14, 16 (b, c, e, f), 17.
Margarine	Slow disintegration, faster with melted margarine	1, 2, 8, 10, 11, 12, 13, 16 (b, c, e, f)
Castor Cocoa bean Cocoa butter Coconut Cottonseed Mustard Rapeseed	Disintegration, especially if exposed to air	1, 2, 8, 10, 11, 12, 14, 16 (b, c, e, f), 17

* Applied in thin coats, the material quickly oxidizes and has no effect. The effect indicated above is for constant exposure to the material in liquid form.

Fats and Fatty Acids (Animal)

Material	Effect on concrete	Protective treatments
Fish liquor	Disintegration	3, 8, 10, 12, 13, 16 (b, c, e, f), 17
Fish oil	Slow disintegration with most fish oils	1, 2, 3, 8, 10, 12, 13, 16 (b, c, e, f), 17
Whale oil	Slow disintegration	1, 2, 3, 8, 10, 12, 13, 16, (b, c, e, f), 17
Neatsfoot oil Tallow and tallow oil	Slow disintegration	1, 2, 3, 8, 10, 12, 13, 16 (b, c, e, f), 17

Beef fat Horse fat Lamb fat	}	Slow disintegration with solid fat, faster with melted	1, 2, 3, 8, 10, 12, 13, 16 (b, c, e, f), 17		
Lard and lard oil				Slow disintegration, faster with oil	1, 2, 3, 8, 10, 12, 13, 16 (b, c, e, f), 17
Slaughterhouse wastes				Disintegration due to organic acids	8, 10, 12, 13, 16 (b, c, e)

Miscellaneous

Material	Effect on concrete	Protective treatments
Alum	See sulfate, potassium aluminum, under "Salts and Alkalies"	
Ammonia		
Liquid	None, unless it contains harmful ammonium salts (see under "Salts and Alkalies")	
Vapors	Possible slow disintegration of moist concrete and steel attacked in porous or cracked moist concrete	8, 9, 10, 12, 13, 16 (a, b, c, f), 17
Ashes		
Cold	Harmful if wet, when sulfides and sulfates leach out (see sulfate, sodium, under "Salts and Alkalies")	1, 2, 3, 8, 9, 10, 13, 16 (b, c, e)
Hot	Thermal expansion	16 (calcium aluminate cement, fire-clay, and refractory-silicate-clay mortars)
Automobile and diesel exhaust gases	Possible disintegration of moist concrete by action of carbonic, nitric, or sulfurous acid (see under "Acids")	1, 5, 8, 10, 12, 16 (b, c, e)
Baking Soda	None	
Beer	No progressive disintegration, but in beer storage and fermenting tanks a special coating is used to guard against beer contamination. Beer may contain, as fermentation products, acetic, carbonic, lactic, or tannic acids (see under "Acids").	8, 10, 12, 16 (b, c, f), 17
Bleaching solution	See the specific chemical, such as hypochlorous acid, sodium hypochlorite, sulfurous acid, etc.	
Borax (salt)	See tetraborate, sodium, under "Salts and Alkalies"	
Brine	See chloride, sodium, or other salts under "Salts and Alkalies"	
Bromine	Disintegration if bromine is gaseous, or if a liquid containing hydrobromic acid and moisture	10, 13, 16 (f, g)
Buttermilk	Slow disintegration due to lactic acid	2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 16 (b, c, e, f), 17
Butyl stearate	Slow disintegration	8, 9, 10, 16 (b, c, e)
Carbon dioxide	Gas may cause permanent shrinkage or carbonation. * See carbonic acid under "Acids."	1, 2, 3, 6, 8, 9, 10, 11, 12, 13, 15, 16 (b, c, e, f, h), 17
Caustic soda	See hydroxide, sodium, under "Salts and Alkalies"	
Chile saltpeter	See nitrate, sodium, under "Salts and Alkalies"	
Chlorine gas	Slow disintegration of moist concrete	2, 8, 9, 10, 16 (f, g), 17
Chrome plating solutions	Slow disintegration	7, 8, 9, 10, 16 (f, g), 20
Cider	Slow disintegration. See acetic acid under "Acids."	1, 2, 9, 10, 12, 14, 16 (b, c, e, f, g), 17
Cinders cold and hot	See ashes above	
Coal	None, unless coal is high in pyrites (sulfide or iron) and moisture. Sulfides leaching from damp coal may oxidize to sulfurous or sulfuric acid, or ferrous sulfate (see under "Acids" and "Salts and Alkalies"). Rate is greatly retarded by deposit of an insoluble film.	1, 2, 3, 6, 7, 8, 9, 10, 12, 13, 16 (b, c, e, h), 17
Coke	Sulfides leaching from damp coke may oxidize to sulfurous or sulfuric acid (see under "Acids")	1, 2, 3, 6, 7, 8, 9, 10, 12, 13, 16 (b, c, e, h)
Copper plating solutions	None	
Corn syrup (glucose)	Slow disintegration	1, 2, 3, 7, 8, 9, 10, 12, 13, 16 (b, c, e), 17

Deicers and anti-icers†	Chlorides (calcium, magnesium, and sodium), and non-chlorides (calcium magnesium acetate, potassium and sodium acetates and formates, urea, and ethyl alcohol) cause scaling of non-air-entrained concrete. Air-entrained concrete does not need added protection from deicers.	50% solution of boiled linseed oil in kerosene, soybean oil, modified castor oil, cottonseed oil, sand-filled epoxy, coal-tar epoxy, 21**
Distiller's slop	Slow disintegration due to lactic acid	1, 8, 9, 10, 12, 13, 15, 16 (b, c, e, f, h), 17
Fermenting fruits, grains, vegetables, or extracts	Slow disintegration. Industrial fermentation processes produce lactic acid (see under "Acids").	1, 2, 3, 8, 9, 10, 12, 16 (b, c, e), 17
Flue gases	Hot gases (200 °C–600 °C; 400 °F–1100 °F) cause thermal stresses. Cooled, condensed sulfurous, hydrochloric acids disintegrate concrete slowly.	9 (high melting), 16 (g, fireclay mortar)
Formaldehyde, 37% (formalin)	Slow disintegration due to formic acid formed in solution	2, 5, 6, 8, 10, 11, 12, 13, 14, 16 (b, c, e, f, g, h), 17, 20
Fruit juices	Little if any effect for most fruit juices as tartaric and citric acids do not appreciably affect concrete. Sugar and hydrofluoric and other acids cause disintegration.	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 16 (b, c, e), 17
Gas water	Ammonium salts seldom present in sufficient quantity to disintegrate concrete	9, 10, 12, 16 (b, c)
Glyceryl tristearate	None	
Honey	None	
Hydrogen sulfide	Slow disintegration in moist oxidizing environments where hydrogen sulfide converts to sulfurous acid	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16 (b, c, e, f, g, h), 17, 19
Iodine	Slow disintegration	1, 2, 6, 10, 12, 13, 16 (b, c, e, g), 17
Lead refining solution	Slow disintegration	1, 2, 6, 8, 9, 10, 12, 16 (carbon and graphite brick; b, c, e, h), 17, 20
Leuna saltpeter	Disintegration. See ammonium nitrate and ammonium sulfate	5, 6, 8, 9, 10, 11, 12, 13, 16 (b, c, e, f, g, h), 17
Lignite oils	Slow disintegration if fatty oils present	1, 2, 6, 8, 10, 12, 16 (b, c, e, f)
Lye	See hydroxide, sodium and potassium, under "Salts and Alkalies"	
Manure	Slow disintegration	1, 2, 8, 9, 10, 12, 13, 16 (b, c, e)
Marsh, fermenting	Slow disintegration due to acetic and lactic acids and sugar	1, 8, 9, 10, 12, 13, 16 (b, c)
Milk	None, unless milk is sour. Then lactic acid disintegrates concrete slowly.	3, 4, 8, 9, 10, 11, 12, 13, 16 (b, c, f), 17
Mine water, waste	Sulfides, sulfates, or acids present disintegrate concrete and attack steel in porous or cracked concrete	1, 2, 5, 8, 9, 10, 12, 13, 15, 16 (b, c, e, f, h), 17
Molasses	Slow disintegration at temperatures of 50 °C (120 °F) or more	1, 2, 7, 8, 9, 10, 12, 13, 16 (b, c, e), 17
Nickel plating solutions	Slow disintegration due to nickel ammonium sulfate	2, 5, 6, 7, 8, 9, 10, 13, 16 (c, e, f), 17
Niter	See nitrate, potassium, under "Salts and Alkalies"	
Ores	Sulfides leaching from damp ores may oxidize to sulfuric acid or ferrous sulfate (see under "Acids" and "Salts and Alkalies")	2, 9, 10, 12, 13, 15, 16 (b, c, e, f, g), 17
Pickling brine	Steel attacked in porous or cracked concrete. See salts, boric acid, or sugar.	1, 7, 8, 9, 10, 12, 13, 16 (b, c, e, h), 17
Sal ammoniac	See chloride, ammonium, under "Salts and Alkalies"	
Sal soda	See carbonate, sodium, under "Salts and Alkalies"	
Saltpeter	See nitrate, potassium under "Salts and Alkalies"	
Sauerkraut	Slow disintegration possible due to lactic acid. Flavor impaired by concrete.	1, 2, 8, 9, 10, 12, 13, 16 (b, c, e, f), 17
Seawater	Disintegration of concrete with inadequate sulfate resistance and steel attacked in porous or cracked concrete	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 (b, c, e, f), 17

Sewage and sludge	Usually not harmful. See hydrogen sulfide above.	
Silage	Slow disintegration due to acetic, butyric, and lactic acids, and sometimes fermenting agents of hydrochloric or sulfuric acids	3, 4, 8, 9, 10, 12, 16 (b, c, e, f)
Sodium hypochlorite	Slow disintegration	7, 8, 9, 10, 13, 16 (d, f), 17
Sugar (sucrose)	None with dry sugar on thoroughly cured concrete. Sugar solutions may disintegrate concrete slowly.	1, 2, 3, 7, 8, 9, 10, 12, 13, 15, 16 (b, c, e, f), 17
Sulfite liquor	Disintegration	1, 2, 3, 5, 6, 8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17, 19
Sulfur dioxide	None if dry. With moisture, sulfur dioxide forms sulfurous acid.	2, 5, 6, 8, 9, 10, 12, 13, 16 (b, c, e, f, g, h), 17, 19
Tanning bark	Slow disintegration possible if damp. See tanning liquor below.	1, 2, 3, 6, 8, 9, 10, 11, 12, 13, 16 (b, c, e), 17
Tanning liquor	None with most liquors, including chromium. If liquor is acid, it disintegrates concrete.	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 13, 16 (b, c, e), 17
Tobacco	Slow disintegration if organic acids present	1, 8, 9, 10, 12, 13, 16 (b, c, e, f), 17
Trisodium phosphate	None	
Urea	None (see deicers)	
Urine	None, but steel attacked in porous or cracked concrete	7, 8, 10, 12, 13, 16 (b, c, e)
Vinegar	Slow disintegration due to acetic acid	9, 10, 12, 16 (b, c, e, h), 17
Washing soda	None	
Water, soft (<75 ppm of carbonate hardness)	Leaching of hydrated lime by flowing water in porous or cracked concrete	2, 3, 4, 8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17
Whey	Slow disintegration due to lactic acid	3, 4, 5, 7, 8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17
Wine	None—but taste of first wine batch may be affected unless concrete has been given tartaric acid treatment. Solutions from wine-making process can cause slow disintegration.	For fine wines, 2 or 3 applications of tartaric acid solution, 320 g of tartaric acid in 1 liter of water (1 lb tartaric acid in 3 pints of water), 2, 8, 10, 12, 16 (b), 20
Wood pulp	None	
Zinc refining solutions	Disintegration if hydrochloric or sulfuric acids present	8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17
Zinc slag	Zinc sulfate (see under "Salts and Alkalies") may be formed by oxidation	8, 9, 10, 12, 13, 16 (b, c, e, f, h), 17

* Carbonation will not harm plain (nonreinforced) concrete; however, steel embedded in carbonated concrete is prone to corrosion. See "Corrosion of Reinforcement" under "Design Considerations."

** Impermeable materials, such as most epoxies, should not be used on exterior slabs on ground or other concrete where moisture can freeze under the coating. The freezing water can cause surface delamination under the impermeable coating.

† Potassium acetate deicers or anti-icers and to a lesser extent potassium formate and sodium acetate or formate may accelerate alkali-silica reaction when reactive aggregates are present (Rangaraju and Olek 2007).

Sources of Products

The Society for Protective Coatings (SSPC) and Paintsquare.com, the webportal to the Journal of Protective Coatings and Linings, and Journal for Architectural Coatings, publish a buyers guide for Coatings and Linings for Industrial and Marine Applications http://www.paintsquare.com/bg/buyers_guide.cfm. Coatings and manufacturers can be searched for by application/environment, system, or generic coating type.

NACE International also publishes an annual a Buyers Guide on its website <http://www.nace.org/nace/index.asp>. Corrosion control products can be searched for by category or company name.

Additional information on chemical suppliers can be obtained from *Hanley-Wood's Industry Sourcebook*, which is available online at <http://www.concreteconstructiononline.com/industry-sourcebook-search.asp> or *R&D Magazine Product Source Guide*, website <http://www.rdmag.com/BuyersGuide.aspx>.

ASTM Standards

American Society for Testing and Materials* documents related to concrete that are relevant to or referred to in the text are listed as follows:

A767/A767M *Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*

A775/A775 M *Specification for Epoxy-Coated Reinforcing Steel Bars*

C39 *Test Method for Compressive Strength of Cylindrical Concrete Specimens*

C150 *Specification for Portland Cement*

C215 *Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens*

C260 *Standard Specification for Air-Entraining Admixtures for Concrete*

C267 *Test Method for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacing*

C279 *Specification for Chemical-Resistant Masonry Units*

C287 *Specification for Chemical-Resistant Sulfur Mortar*

C305 *Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*

C386 *Practice for Use of Chemical-Resistant Sulfur Mortar*

C395 *Specification for Chemical-Resistant Resin Mortars*

C397 *Practice for Use of Chemically Setting Chemical-Resistant Silicate and Silica Mortars*

C398 *Practice for Use of Hydraulic Cement Mortars in Chemical-Resistant Masonry*

C399 *Practice for Use of Chemical-Resistant Resin Mortars*

C410 *Specification for Industrial Floor Brick*

C466 *Specification for Chemically Setting Silicate and Silica Chemical-Resistant Mortars*

C494 *Specification for Chemical Admixtures for Concrete*

C595 *Specification for Blended Hydraulic Cements*

C618 *Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*

C658 *Specification for Chemical-Resistant Resin Grouts for Brick or Tile*

C722 *Specification for Chemical-Resistant Resin Monolithic Surfacing*

C723 *Practice for Chemical-Resistant Resin Grouts for Brick or Tile*

C811 *Practice for Surface Preparation of Concrete for Application of Chemical-Resistant Resin Monolithic Surfacing*

C876 *Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*

C881 *Specification for Epoxy-Resin-Base Bonding Systems for Concrete*

C882 *Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear*

C989 *Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars*

C1005 *Measurement of Dry-Film Thickness of Organic Coatings Using Micrometers*

C1017 *Specification for Chemical Admixtures for Use in Producing Flowing Concrete*

C1106 *Test Method for Chemical Resistance and Physical Properties of Carbon Black*

C1152 *Test Method for Acid-Soluble Chloride in Mortar and Concrete*

C1157 *Performance Specification for Blended Hydraulic Cement*

C1218 *Test Method for Water-Soluble Chloride in Mortar and Concrete*

C1240 *Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar*

C1438 *Specification for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar*

C1524 *Test Method for Water-Extractable Chloride in Aggregate (Soxhlet Method)*

C1580 *Test Method for Water-Soluble Sulfate in Soil*

D41 *Specification for Asphalt Primer Used in Roofing, Dampproofing, and Waterproofing*

D1212 *Measurement of Wet Film Thickness of Organic Coatings*

D1973 *Guide for Design of a Liner System for Containment of Wastes*

D3963/D 3963M *Specification for Epoxy-Coated Reinforcing Steel*

D4138 *Method for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive Means*

D4258 *Practice for Surface Cleaning Concrete for Coating*

D4259 *Practice for Abrading Concrete*

D4260 *Practice for Acid Etching Concrete*

D4261 *Practice for Surface Cleaning Concrete Unit Masonry for Coating*

D4262 *Method for pH of Chemically Cleaned or Etched Concrete Surfaces*

D4263 *Method for Indicating Moisture in Concrete by the Plastic Sheet Method*

D4414 *Practice for Measurement of Wet Film Thickness by Notched Gages*

D4541 *Method for Pull-Off Strength of Coatings Using Portable Adhesion-Testers*

D4787 *Practice for Continuity Verification of Liquid or Sheet Linings Applied to Concrete Substrates*

D6132 *Nondestructive Measurement of Dry Film Thickness of Applied Organic Coatings Using an Ultrasonic Gage*

D6237 *Guide for Painting Inspectors (Concrete and Masonry Substrates)*

D7234 *Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers*

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