

Guide for the Use of Polymers in Concrete

Reported by ACI Committee 548



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Guide for the Use of Polymers in Concrete

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Guide for the Use of Polymers in Concrete

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This guide presents information on how to use polymers in concrete to improve some characteristics of the hardened concrete. Recommendations are included for polymer-impregnated concrete, polymer concrete, polymer-cement concrete, and safety considerations for the use of polymers in concrete. Information is provided on types of materials and their storage, handling, and use, as well as concrete formulations, equipment to be used, construction procedures, and applications. Glossaries of terms and abbreviations are also included.

Keywords: bridge deck; durability; latex; monomer; polymer; polymer concrete; polymerization; repair.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The mission of ACI Committee 548 is to report on the use of polymers in concrete. Since its organization in 1971, the committee has sponsored numerous symposia and technical sessions at ACI conventions, and has produced several documents on a variety of topics concerning the use of polymers in concrete (ACI 548.2R, 548.3R, 548.4, 548.5R, 548.6R).

Benefits derived from the use of polymers in concrete have worldwide appeal, as demonstrated by the extensive international attendance at the many symposia and congresses that have addressed this subject (ACI Committee 548 1973, 1978, 1981, 1985, 1987, 1989, 1993, 1996, 1997, 2003; Bartholomew et al. 1978; Fontana et al. 1978; Fowler et al. 1978; Fukuchi and Ohama 1978; Imamura et al. 1978; Kaeding 1978a,b; Koblischek 1978; Kukacka 1978; Locke and Hsu 1978; McClain 1978; Patty 1978; “Polymers in Concrete” 1976, 1978, 1981, 1984). The contributions made at these meetings, along with the practical experience gained within the growing industry that applies polymer technology to concrete, form the base of applied concrete technology that is limited only by the ingenuity of the concrete user.

1.2—Scope

This guide provides a fundamental background needed to apply the technology of polymers in concrete to a variety of engineering problems and applications.

The guide contains four basic sections that address polymer-impregnated concrete (PIC), polymer concrete (PC), polymer portland-cement concrete (now called polymer-cement concrete [PPCC]), and safety. Each of the three categories of concrete-containing polymers is usually applied to particular types of concrete elements or specific concrete property improvements, although there are significant overlapping areas. Safety, however, is a prerequisite for all polymer usage, and is discussed collectively. The guide does not contain extensive tabulated data from specific studies, as this type of information is available in other documents and does not contribute significantly to an understanding of how the polymers should actually be used in or applied to concrete.

CHAPTER 2—DEFINITIONS, ABBREVIATIONS, AND ACRONYMS

ACI provides a comprehensive list of acceptable notation and definitions through an online resource. These were taken from the Cement and Concrete Terminology page of the

ACI Web site (http://www.concrete.org/Technical/CCT/FlashHelp/ACI_Terminology.htm).

2.1—Definitions

accelerator—a material that increases the rate of a chemical reaction.

additive—a substance added to another in relatively small amounts to impart or improve desirable properties or suppress undesirable properties.

auto-ignition temperature—the temperature at which the vapor-air mixture above a liquid monomer spontaneously ignites at a normal atmosphere with no external ignition source.

bulk polymerization—the production of stable polymer or hardened epoxy by adding a polymerization catalyst and an initiator or heat to a monomer in open-top containers and allowing the monomer to polymerize. Hardeners are added to epoxies to accomplish this.

catalyst—a substance that accelerates a chemical reaction but is not permanently changed by the reaction.

cross-linking agent—a substance that increases the molecular weight of a polymer by chemically linking and bridging the polymer chains.

dry pack placement—method of producing polymer concrete by placing and tamping graded aggregate, completely wetting the aggregate with liquid monomer, and then polymerizing the composite.

emulsifier—a substance that modifies the surface tension of colloidal droplets, keeping them from coalescing and keeping them suspended.

emulsion—a two-phase liquid system in which small droplets of one liquid (the internal phase) are immiscible in, and dispersed uniformly throughout, a second continuous liquid phase (the external phase).

encapsulation—the production of fully impregnated concrete with minimal monomer evaporation and drainage losses during the polymerization process.

endothermic—pertaining to a reaction that occurs with the absorption of heat.

epoxy resins—a class of organic chemical bonding systems used in the preparation of special coatings or adhesives for concrete or as binders in epoxy-resin mortars, concretes, and fiber composites.

exothermic—pertaining to a reaction that occurs with the evolution of heat.

explosive limit—the upper or lower vapor concentration that supports combustion in air at room temperature and normal atmospheric pressure.

flash point—the lowest temperature at which the vapor of a combustible liquid can be made to ignite.

glass-transition temperature (T_g)—the midpoint of the temperature range over which an amorphous material (such as glass or a high polymer) changes from (or to) a brittle, vitreous state to (or from) a plastic state.

hardener—a chemical (including certain fluoro-silicates or sodium silicate) applied to concrete floors to reduce wear and dusting; or in a two-component adhesive, the chemical component that causes the resin component to cure.

impregnation—the act of saturating the voids in hardened concrete with a monomer or resin.

inhibitor—a substance that retards or stops a chemical reaction.

initiator—agent that initiates growth of polymer chains by decomposing into free radicals that actually start the chain's growth. Often incorrectly called a catalyst. Often used in conjunction with a catalyst.

latex—a dispersion of organic polymer particles in water.

microcracks—small, numerous cracks that develop in hardened concrete.

monomer—an organic molecule of relatively low molecular weight that creates a solid polymer by reacting with itself or other compounds of low molecular weight or both.

plasticizer—a material that increases the plasticity of a fresh cementitious mixture; or a substance added to a material to improve the material's flexibility.

polymer—the product of polymerization; commonly a rubber or resin consisting of large molecules formed by polymerization.

polymer concrete (PC)—concrete in which an organic polymer serves as the binder; also known as resin concrete; sometimes erroneously employed to designate hydraulic cement mortars or concretes in which part or all of the mixing water is replaced by an aqueous dispersion of a thermoplastic copolymer.

polymer-cement concrete (PPCC)—a mixture comprising hydraulic cement and aggregate combined at the time of mixing with organic monomers or polymers that are dispersed in water.

polymer-impregnated concrete (PIC)—a hydrated portland-cement concrete that has been impregnated with a monomer that is subsequently polymerized.

polymerization—the reaction in which molecules of one or more monomers combine to form a compound containing the same elements and in the same proportions but of higher molecular weight.

porosity—the ratio, usually expressed as a percentage, of the volume of voids in a material to the total volume of the material, including the voids.

promoted-catalytic method—a polymerization method that uses initiators or accelerators to cause the decomposition of organic peroxide catalysts, and subsequent release of free radicals that allow polymerization to take place at ambient temperature without the need for an external source of energy.

resin—a natural or synthetic, solid or semisolid, organic material of indefinite and often high molecular weight having a tendency to flow under stress, usually has a softening or melting range, and usually fractures conchoidally.

shelf life—the length of time packaged materials can be stored under specified conditions and remain usable.

silane coupling agent—silicon compounds that enhance the chemical bond of organic polymers to inorganic materials such as sand, rock, glass, and metals.

solvent—a liquid in which another substance may be dissolved.

thermal-catalytic method—a polymerization method where catalysts are dissolved in the monomer before introduction

into the concrete. The subsequent application of external heat causes the polymerization to occur at a very rapid rate.

thermoplastic—class of resin capable of being repeatedly softened by an increase of temperature and hardened by a decrease in temperature.

thermosetting—class of resin that, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material.

vapor pressure—the pressure exerted when a vapor is in equilibrium with its liquid or solid form at a given temperature.

viscosity—a measure of the resistance of a fluid to deform under shear stress.

2.2—Acronyms and abbreviations

AIBN—2,2'-azobis (isobutyronitrile)

AMVN—2,2'-azobis-(2,4-dimethylvaleronitrile)

BA—butyl acrylate

BPO—dibenzoyl peroxide

CFR—Code of Federal Regulations

EIFS—exterior insulation finish systems

HQ—hydroquinone

LEL—lower explosive limit

LMC—latex-modified concrete

LP—lauroyl peroxide

MEHQ—methyl ether of hydroquinone

MEKP—methylethylketone peroxide

MFFT—minimum film-forming temperature

MMA—methyl methacrylate

MSDS—Material Safety Data Sheet

OSHA—Occupational Safety and Health Administration

PAE—polyacrylic ester

PC—polymer concrete

PCC—portland-cement concrete

PIC—polymer-impregnated concrete

PMC—polymer-modified concrete

PPCC—polymer-cement concrete (formerly called polymer portland-cement concrete)

PS—polystyrene

PVAC—polyvinyl acetate homopolymers

SADT—self-accelerating decomposition temperature

S-A—styrene

S-B—styrene-butadiene copolymer

SSD—saturated surface-dry

TMPTMA—trimethylolpropane trimethacrylate

U.S. DOT—U.S. Department of Transportation

U.S. EPA—United States Environmental Protection Agency

VAC—vinyl acetate copolymer

VEOVA—vinyl ester of versatic acid

CHAPTER 3—POLYMER-IMPREGNATED CONCRETE

3.1—Introduction

Polymer-impregnated concrete (PIC) is a hydrated portland-cement concrete that has been impregnated with a monomer that is subsequently polymerized in place. Generally, almost any shape, size, configuration, orientation, and quantity of hardened portland-cement concrete can be impregnated to

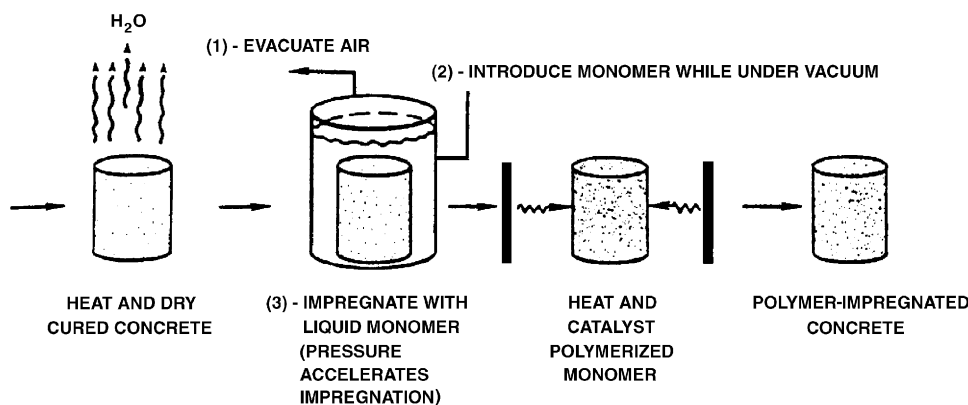


Fig. 3.1—Schematic for the method of producing PIC.

some degree with monomer, provided the monomer has access to the void space within the concrete. A substantial portion of this space is usually obtained by removing free water from the pores in the concrete by drying the concrete.

The monomer is introduced into the concrete by soaking at atmospheric pressure or above. The degree to which the available space in the concrete is filled with monomer during soaking determines whether the concrete is partially impregnated or fully impregnated. Full impregnation implies that approximately 85% of the available void space after drying is filled, whereas partial impregnation implies some degree less than full. Partial impregnation usually consists of a process in which the concrete is impregnated to only a limited depth beneath the surface. The different production methods used for full and partial impregnation produce concrete of differing physical characteristics. Therefore, full and partial impregnation are treated separately in this chapter.

After impregnation, the concrete containing the desired amount of monomer undergoes a treatment to convert the monomer into a polymer. This polymerization reaction causes the molecules of the monomer to chemically link into a long, repeated chain-like structure with higher molecular weight, known as a polymer. The two most common methods used for polymerization are called thermal-catalytic and promoted-catalytic. A third method, involving ionizing radiation, is less commonly used.

After polymerization has occurred, the resulting composite material consists of two interpenetrating networks: 1) the original network of hydrated portland-cement concrete; and 2) an essentially continuous network of polymer that fills most of the voids in the concrete (DePuy 2003).

A simplified process description for PIC using pressure or vacuum soaking and thermal catalytic polymerization is shown in Fig. 3.1.

3.2—Concrete requirements for impregnation

Almost all existing types of concrete, whether they were made with impregnation in mind or not, can become PIC using the steps described in this guide. No special procedures are necessary for the preparation of concrete to be impregnated. All types of aggregates, cements, and admixtures used in preparation of modern concrete can be used for PIC. Similarly, curing procedures and curing duration plus age requirements

needed for strength development before impregnation are not critical. Of course, the final properties of the PIC may vary somewhat, depending on the nature of the materials or curing conditions used. The highest strengths have been obtained with high-pressure steam-cured concrete (Fukuchi and Ohama 1978). The use of a high-quality dense concrete requires less polymer for full impregnation than a more porous, lower-quality concrete. Some badly fractured concrete has also been repaired using impregnation techniques (ACI 224.1R).

3.3—Monomer systems

The selection of a suitable monomer for PIC is usually based on the impregnation and polymerization characteristics, availability and cost, and resultant properties of the polymer and the PIC. In principle, any monomer capable of undergoing polymerization in the void system of a hardened concrete can be used. At ambient temperature and pressure, the monomers can be either gases or liquids, although liquid-type monomers are more easily adaptable to impregnating hardened concrete. In practice, impregnation is usually done using vinyl monomers that contain a polymerization initiator that can be activated by heat. These include acrylonitrile, methyl methacrylate (MMA), and other acrylic monomers; styrene; and vinyl acetate. Generally, the best results in terms of process and performance are achieved with MMA, often in combination with an acrylic cross-linking agent such as trimethylolpropane trimethacrylate (TMPTMA). In general, systems based on MMA are the most widely used. They offer superior rates of both impregnation and polymerization and lead to an optimum combination of pore-sealing and mechanical properties, including durability. While combinations of styrene with acrylonitrile may produce properties comparable to those obtained with the acrylic systems, most users prefer to avoid the problem of toxicity associated with acrylonitrile.

3.3.1 Viscosity—The rate and degree of monomer penetration into hardened concrete depends on the density and pore structure of the concrete, the viscosity of the monomer (Steinberg et al. 1968; Dikeou et al. 1969), and the type of impregnation process used. Table 3.1 lists some common liquid monomers of low viscosity at ambient temperature that are suitable for impregnation.

With greater effort, precast concrete can be impregnated with higher viscosity monomers (greater than 20 centipoise or 20 millipascal seconds) (Kukacka and Romano 1973), although it is usually more economical to reduce viscosity by suitable blends with low-viscosity comonomers (for example, methacrylate monomers) (Kukacka et al. 1975).

3.3.2 Vapor pressure—When selecting a monomer for impregnating precast concrete, considerations should be given to its vapor pressure (Table 3.1) for safety and processability.

The high vapor pressure of vinyl chloride, for example, requires special precautions in handling. Considerations should also be given to the effect of curing temperature on vapor pressures, because monomer depletion on the surface of the specimen may occur due to evaporation (Steinberg et al. 1968, 1969; ACI Committee 548 1973). Refer to Section 3.8 for encapsulation techniques to prevent monomer depletion. Low-viscosity monomers tend to have low boiling points, whereas high-boiling monomers are more viscous (Dikeou et al. 1971).

3.3.3 Chemical stability—See Sections 6.2 and 6.3.2 for descriptions of the chemical stability of monomers and how they should be stored and handled.

3.3.4 Toxicological considerations—Most monomers have distinct odors and varying degrees of toxicity. Precautions recommended for handling monomers include adequate ventilation to keep concentrations in air below the maximum limits recommended by the manufacturers. Emergency washes and drains should be available, and environmentally acceptable provisions should be established for handling an accidentally spilled monomer. Refer to Sections 6.3 and 6.4 for detailed descriptions of potential problems.

3.4—Additives and modifiers

Various comonomers and other additives to the monomer system are frequently used to modify or produce desired changes in the properties of the resulting polymer and, hence, in the properties and characteristics of PIC. Safety aspects of these additions are discussed in Chapter 6.

3.4.1 Plasticizers and extenders—Plasticizers, such as dibutyl phthalate, may be added to monomers to improve the flexibility of inherently brittle polymers such as poly(methyl methacrylate) and polystyrene (PS). Specific examples are the addition of internal plasticizers such as vinyl stearate or butyl acrylate (BA) that copolymerize with monomer.

3.4.2 Cross-linking agents—Cross linking by means of the addition of an appropriate bifunctional or polyfunctional monomer increases the rigidity of the polymer, its resistance to the action of solvents, and its softening-point temperature. The amount of change depends on the cross-linking density of the polymer. The cross-linking agent most commonly used in PIC is TMPTMA (Steinberg et al. 1968), that is, a trifunctional acrylic monomer that can copolymerize with other vinyl monomers such as MMA or styrene.

3.4.3 Catalysts—These are not catalysts in the pure chemical sense because they are consumed during the polymerization reaction. Only small amounts of catalysts are generally used. The following commercially available compounds have been used in forming PIC (Steinberg et al. 1968, 1969;

Table 3.1—Physical properties of common monomers used in PIC and PC

	Viscosity, cp (Pa·s) [*]	Density, gm/cm ³ [†]	Vapor pressure, mmHg [‡]	Boiling point, °C	Solubility in 25 °C water, %
Methyl methacrylate	0.34 (0.00034) [§]	0.81	85.0	77	7.4000
Styrene	0.76 (0.00076)	0.91	2.9	135	0.0700
Tert-butylstyrene	1.46 (0.00146) [#]	0.88	1.0 [#]	218	0.0005

^{*}cp = MPa·s = centistroke × density.

[†]gm/cm³ = 1000 kg/m³.

[‡]mmHg at 0 °C = 133 Pa.

[§]25 °C.

^{||}20 °C.

[#]46 °C.

Note: Trimethylolpropane-trimethacrylate is used as a crosslinking agent for MMA, S-A, or tert-butylstyrene.

Dikeou et al. 1969, 1971, 1972): dibenzoyl peroxide (BPO), 2,2'-azobis (isobutyronitrile) (AIBN), a-tert-butyl-azoisobutyronitrile, tert-butylperbenzoate, and methylethylketone peroxide (MEKP). These compounds decompose at different rates over a range of temperatures to generate free radicals. The selection of type and concentration of catalyst and the optimum polymerization temperature are important in the production of a uniformly high-quality PIC. BPO is well suited for most vinyl monomers, such as methyl methacrylate and styrene, because it decomposes well below their boiling points.

BPO is susceptible, however, to induced chemical decomposition, which increases the risk of an accidental bulk polymerization. These problems have not been encountered with such azonitrile compounds as AIBN, which has proven to be useful and convenient for PIC (DePuy 2003). A higher-temperature catalyst, such as tert-butyl-perbenzoate, is more effective with higher boiling point monomers such as diallyl phthalate. Refer to Section 6.2.2 for safety considerations necessary for some catalysts.

3.4.4 Initiators—Initiators, often called accelerators, are reducing-agent compounds added to the monomer system to cause the decomposition of the peroxide catalysts in the system. This decomposition produces the necessary free radicals needed for polymerization at ambient temperatures. Several initiators that have been successfully used are N,N-dimethyl-p-toluidine, N,N-dimethyl aniline, cobalt naphthenate, and mercaptans.

3.4.5 Silane coupling agents—Silane coupling agents are silicon compounds used to chemically bond organic polymers to inorganic materials such as sand, rock, glass, and metals (Marsden 1970; Plueddemann 1970; Sterman and Maisden 1963). They have the general formula (HO)₃SiR, where R is an organic group compatible with thermoplastic or thermosetting resins. Coupling agents are used frequently in PIC for improvements in strength (Dikeou et al. 1972) and to improve aggregate bond in long-term exposure to moisture.

3.5—Polymerization techniques

Two general methods for the polymerization of monomers are commonly used in PIC. These are the free-radical and promoted-catalytic. Both methods result in free-radical

initiated polymerization of properly formulated monomer systems (DePuy 2003).

The selection of a particular polymerization process depends on its particular advantages for a specific application and evaluation of the effects of drainage and evaporation losses from the concrete during the polymerization, safety problems associated with the storage and reuse of large quantities of monomer and catalyst, and the economics of the entire process.

As a third method of polymerization, radiation techniques have been used in the past; they are discussed in Section 3.5.3. This method is not commonly used.

3.5.1 Thermal-catalytic method—This polymerization method involves the use of chemical catalysts and heat, commonly referred to as the thermal-catalytic process, and has been used extensively for preparing PIC. The process can be performed in air or under water. Several catalysts used in this method are described in Section 3.4.3.

The primary advantage of the thermal-catalytic polymerization method is that the polymerization rates are very rapid and, therefore, processing times are short. Relatively simple electric ovens, water, or raw steam can be used as a heat source (Sopler et al. 1973; Fowler et al. 1973; Kukacka et al. 1972, 1973; DePuy and Dikeou 1973). A disadvantage is that the chemical catalyst has to be dissolved in the monomer before introducing the mixture into the concrete. In a commercial operation of almost any size, this involves storing and handling large batches of monomer that contain a chemical catalyst. Although potentially dangerous, using relatively stable azo-type catalysts in conjunction with established safety practices can reduce the hazards to manageable levels (Dikeou et al. 1972; Kukacka et al. 1973; DePuy 2003).

3.5.2 Promoted-catalytic method—Decomposition of organic peroxide catalysts can be accomplished by the use of initiators or accelerators (Section 3.4.4) instead of temperature or heat, as in the case of the thermal-catalytic method. The decomposition produces the free radicals, which then allows the polymerization to take place at ambient temperature without the need for an external source of energy. Promoted-catalyst systems can induce polymerization at an ambient temperature of 40 °F (5 °C) or lower. Disadvantages of this method are the difficulties in obtaining predictable polymerization times and in being able to match the monomer saturation time with that of the onset of polymerization. As the induction period for polymerization begins immediately on adding the initiator to the monomer-catalyst system, its use in PIC is limited.

3.5.3 Radiation method—Radiation-induced polymerization of monomers in concrete has been successfully performed in both air and water (Steinberg et al. 1968, 1969; Dikeou et al. 1971; Kukacka et al. 1973; Levitt et al. 1972).

The production of free radicals during initiated polymerization can also be achieved by using such ionizing radiation as gamma rays emitted by cobalt-60. Absorption of the radiation energy by the monomer results in secondary processes, including the production of free radicals. The rate of polymerization varies with the different monomers under constant radiation and temperature conditions. The polymeriza-

tion rate is dependent on the square root of the intensity, but at high radiation intensities, it reaches a limiting value.

An important advantage of radiation is that chain reactions can be initiated at room temperature or lower. Lower-temperature polymerization increases the chain length of the polymer and tends to reduce the amount of monomer lost by evaporation before complete polymerization takes place, particularly when monomers of high vapor pressures are used.

Because catalysts and initiators are not required for this process, the inhibited monomer can be used directly as it comes from the manufacturer, has essentially unlimited storage, and can readily be reused once opened. Relatively thick sections of impregnated concrete can be polymerized uniformly using radiation.

Disadvantages of radiation include the high cost of radiation sources, the necessity of massive biological shielding, and the low polymerization rates. The latter, when combined with the radiation attenuation due to the thick sections and high density, results in large radiation requirements and long processing times. Some monomers also require high radiation doses and polymerize slowly.

3.6—Partially impregnated concrete

Partially impregnated concrete (sometimes called surface-impregnated concrete) is usually accomplished by impregnating conventional portland-cement concrete to a less-than-full depth using a simple soaking technique, in contrast to fully impregnated concrete (Section 3.7), which has been impregnated to the full depth of the section using the vacuum-pressure technique (Fig. 3.1). The partial impregnation is intended to provide the concrete with a relatively impermeable, in-depth protective zone to increase its durability. While there would be some increase in strength in the impregnated zone, the primary purpose of partial impregnation is to increase durability by reducing the permeability of the concrete to moisture and aggressive solutions. The concrete pores in the impregnated zone contain less polymer than could be achieved with the full impregnation techniques.

3.6.1 Applications of partial impregnation—The potential applications include treatment of precast concrete elements and existing concrete structures to improve durability, reduce maintenance requirements, and restore deteriorated structures (Kaeding 1978a). Most of the work on partially impregnated concrete has been in developing a technique to protect concrete bridge decks and spillways from damage caused by deicing salts and freezing-and-thawing deterioration (Fowler et al. 1973; Smoak 1975; Schrader et al. 1978; Bartholomew et al. 1978; Schrader 1978). The process has also been applied to concrete stilling basins, curbstones, concrete pipes and mortar linings, and deteriorated buildings (Kaeding 1978a).

In some cases, the use of partial impregnation may be advantageously combined with the use of other systems such as PC or PPCC. In a rehabilitation project, PC or polymer-modified concrete (PMC) may be used to repair cracks and holes, with impregnation used to treat the entire surface.

3.6.2 Characteristics of partially impregnated concrete—The impregnation of concrete surfaces with a suitable

Table 3.2—Mechanical properties of PIC using methacrylate (MA) esters*

Polymer	Viscosity of monomer, centistokes (mm ² ·s ⁻¹) [†]	Loading weight, %	Compressive strength, psi (MPa) [‡]	Modulus of elasticity, 10 ⁶ psi (GPa)
Control	—	0.00	6600 (45)	3.5 to 4.5 (24 to 31)
MMA	0.60	5.27	16,350 (113) [§]	6.12 (42)
Isobutyl-MA	0.98	4.99	16,290 (112) [§]	5.42 (37)
Stearyl-MA	10.50	2.52	6920 (48)	3.48 (24)
Isobornyl-MA	6.00	2.80	9060 (62)	4.70 (32)
Isodecyl-MA	3.30	3.51	7000 (48)	3.38 (23)
+ 20% MMA	—	3.63	8510 (59)	3.78 (26)
+ 40% MMA	—	4.97	14,060 (97)	4.85 (33)
+ 80% MMA	—	5.19	16,593 (114) [§]	5.90 (41)

*Brookhaven National Laboratory (1968, 1969, 1971, 1973).

[†]Centistoke = 1.0 mm²/s = cp/density.[‡]1 psi = 7 kPa.[§]Exceeded capacity of testing machine.**Table 3.3—Physical properties of PIC (thermal-catalytically cured; dried at 105 °C [221 °F] before impregnation)***

Property	Control		MMA	Styrene	MMA + 10% TMPTMA
	Undried	Dried			
Hardness (impact hammer)	32.000	27.000	52.000	50.000	—
Water absorption, %	6.400	6.200	0.340	0.700	0.21
Water permeability, 10 ⁴ ft/yr (10 ⁴ m/yr) [†]	5.300 (1.6)	29.000 (8.8)	1.400 (0.43)	1.500 (0.46)	1.2 (0.37)
Thermal conductivity, btu/ft·h·°F (W/(m·K)) [‡]	1.332 (0.63)	1.105 (0.52)	1.265 (0.60)	1.305 (0.62)	—
Thermal diffusivity, ft ² /h (mm ² ·s ⁻¹) [§]	0.039 (1.01)	0.039 (1.01)	0.039 (1.01)	0.041 (1.06)	—
Specific heat, btu/lb·°F (kJ/(kg·K))	0.241 (1.01)	—	0.220 (0.92)	0.221 (0.93)	—
Thermal coefficient of expansion, 10 ⁻⁶ in./in.·°F (10 ⁻⁶ mm/mm·°C)	4.020 (7.236)	4.280 (7.704)	5.250 (9.450)	5.000 (9.000)	5.06 (9.108)

*Brookhaven National Laboratory (1968, 1969, 1971, 1973).

[†]1 ft = 0.305 m.[‡]1 btu/ft·h·°F = 1.7 W/m·K.[§]1 ft²/h = 25.8 mm²/s.^{||}1 btu/lb·°F = 4.19 kJ/kg·K.

monomer that is subsequently cured in-place has been shown to improve several important properties, including tensile, flexural, and compressive strengths; Young's modulus; abrasion resistance; resistance to penetration by, and damage from, water, acids, salts, and other deleterious media; and resistance to freezing and thawing.

Resistance to typical freezing and thawing is good when the polymer depth is more than 1 in. (25 mm), and abrasion resistance is increased significantly. In addition, some laboratory evidence indicates that impregnating a chloride-contaminated concrete can effectively immobilize the chloride, at least to the depth of the impregnation, if the cracks induced by drying are effectively sealed by the polymer (Manson et al.

Table 3.4—Ductility of PIC (thermal-catalytically cured; dried at 105 °C [221 °F] before impregnation)*

Property	Control		MMA	Styrene	MMA + 10% TMPTMA
	Undried	Dried			
Freezing-and-thawing: no. of cycles	740	440	3650	5440	4660
Freezing-and-thawing: weight loss, %	25	28	2	21	0
Sulfate attack: no. of days	480	605	720	690	630
Sulfate attack: expansion, %	0.466	0.522	0.006	0.030	0.003
Acid resistance, 15% HCl: no. of days	105	106	805	805	709
Acid resistance, 15% HCl: weight loss, %	27	26	9	12	7
Acid resistance, 15% H ₂ SO ₄ : no. of days	49	77	119	77	—
Acid resistance, 15% H ₂ SO ₄ : weight loss, %	35	30	26	29	—
Abrasion loss, in. (mm)	0.050 (1.27)	0.036 (0.91)	0.015 (0.38)	0.037 (0.94)	0.019 (0.45)
Abrasion loss: % weight loss	14.0	7.0	4.0	6.0	5.0
Cavitation (2-hour exposure), in. (mm)	0.032 (0.81)	0.262 (6.65)	0.020 (0.51)	0.009 (0.23)	—

*Brookhaven National Laboratory (1968, 1969, 1971, 1973).

1978). With respect to salt intrusion, however, such sealing has not been demonstrated under field conditions, and chloride intrusion after impregnation has been observed in most cases. Refer to Tables 3.2 to 3.4 for typical data on mechanical properties on fully impregnated concrete. Resistance to chloride intrusion and resultant corrosion is improved by partially impregnating concrete before it is open to service and before chlorides are present (Texas State Department of Highways and Public Transportation 1977).

Although increases in strength may be observed as a result of the partial impregnation, such increases in strength are usually not as great as the increases produced by full impregnation. The increases in strength are a function of the depth of impregnation and the polymer loading in the impregnated zone, which is generally only a small proportion of the cross section of the member. Partial impregnation does not significantly increase the strength of a member unless the partial impregnation is specifically designed to increase the strength and the increases in strength are verified by tests.

3.6.3 Limitations of partial impregnation—Polymer impregnation reduces the permeability of concrete and thereby increases its durability in exposure to aggressive agents. Note that the impregnation does not render the concrete completely impermeable, and that in exposure to very aggressive agents, such as sulfuric acid, concrete is attacked slowly. In such cases, the impregnated concrete should be given an additional protective coating treatment of a suitably resistant material. The polymer used for the impregnation may be a suitable protective coating system. The protective coating should be applied in two or three layers to ensure that pinholes or defects are sufficiently covered.

Although partial-depth (surface) impregnation is a relatively feasible process for the treatment of concrete surfaces to

reduce permeability and increase resistance to abrasion, freezing and thawing, and corrosion, the status of surface impregnation for the protection of concrete bridge decks is currently in doubt. The principal reason for using the technique on concrete bridge decks is to prevent deicing salts from penetrating the concrete and corroding the reinforcing steel. It appears that concrete invariably cracks over a period of time. The surface-impregnation technique requires the application of heat to dry the concrete surface, which may induce cracking. If the cracks are not sealed, they could serve as channels for salt solutions and possibly cause local concentrations of salt in the concrete, thereby defeating the purpose of the impregnation treatment. In addition, the impregnation process changes the coefficient of thermal expansion of the concrete; therefore, a successful application of partial impregnation must include a minimum depth, which will vary with the concrete being treated. Shallow depths of impregnation, for example, less than 1/4 in., upon changes in the temperature, will likely exceed the shear capacity at the transition line between concrete that is monomer impregnated and concrete that is not monomer impregnated and subsequently result in spalling of the impregnated concrete. Partial impregnation, however, is more commonly used in Japan on precast concrete items.

3.6.4 Monomers and polymers for partial impregnation—The various monomers that can be used for partial impregnation are described in Section 3.3. As noted, impregnation is normally achieved using vinyl monomers containing a polymerization catalyst that can be activated by raising the temperature. At present, such systems offer the best available combination of cost, convenience, and performance.

While raising the temperature to initiate polymerization does add a process step, it is generally desirable to do so because it is difficult using ambient-temperature polymerization catalysts to coordinate the time of polymerization initiation with the time required to achieve the desired depth of impregnation.

3.6.5 Partial impregnation process—The principal steps in partial impregnation are surface preparation, concrete drying, concrete cooling, monomer soaking, polymerization, and cleanup.

3.6.5.1 Surface preparation—The surface of the concrete to receive the monomer should be cleaned of contaminants such as oil, grease, or dirt. Conventional cleaning methods and materials are adequate to do this. Any undesirable irregularities in the surface (such as popouts, spalls, bugholes, and large cracks) should be repaired at this time.

3.6.5.2 Concrete drying—The concrete surface should be dried for 6 to 8 hours at a surface temperature of 250 to 275 °F (121 to 135 °C). The rate of temperature development to reach the drying temperature should not exceed 100 °F (38 °C) per hour. Before drying, surfaces that can retain a sand layer should be covered with clean sand to a depth of 3/8 to 1/2 in. (9 to 13 mm); this helps to minimize the temperature gradient in the concrete. The sand should be composed of hard, dense, low-absorption particles that pass a No. 16 (1.18 mm) sieve, but with not more than 5% passing a No. 100 (0.15 mm)

sieve. Infrared heaters have been used successfully in many projects for drying concrete.

3.6.5.3 Concrete cooling—After drying, the concrete surface temperature should be allowed to cool to 100 °F (38 °C) or lower before adding any monomer. On cold days, the rate of cooling should be retarded by placing a covering over the heated surface. This helps to minimize temperature-gradient-induced cracking of the surface.

3.6.5.4 Monomer soaking—Monomers can be introduced into the concrete by either atmospheric soaking or pressure soaking. The simplest approach is to immerse the concrete in a low-viscosity monomer and soak under atmospheric pressure. This technique is applicable to precast concrete elements and is based on the ease of penetration to a limited depth by a low-viscosity monomer and the economics of a simple process that does not require an elaborate vacuum, pressure soaking facility, or both. For horizontal surfaces, the monomer should be applied to the sand layer (Section 3.6.5.2) on the concrete surface at a rate of approximately 0.8 lb/ft³ (13 kg/m³) and allowed to soak for 6 hours. The sand helps to retain even distribution of the monomer over the surface. The monomer-saturated sand should be covered with plastic film to reduce evaporation. A commonly used monomer system for this type of soaking consists of 95% (by weight) MMA and 5% (by weight) TMPTMA with 0.5% (by weight) 2,2-azobis-(2,4-dimethylvaleronitrile) (AMVN) or AIBN catalyst.

For soaking surfaces that cannot have monomers ponded on them (for example, walls), a shallow (1/4 to 3/8 in. [6 to 10 mm]), leak-tight enclosure should be constructed and attached to the surface. The enclosure is then completely filled and maintained filled with a monomer. Soaking times from 4 to 6 hours are usually satisfactory, at which time the excess monomer is drained from the enclosure.

Another approach is to use a higher-viscosity monomer and pressure soaking. This approach is based on the assumption that the higher-viscosity monomer gives a dense polymer loading in the impregnated zone, and that the pressure soaking can be controlled to produce a consistent penetration to a predetermined depth. Therefore, it should be possible to realize economies in production by impregnating the concrete to a controlled depth, minimizing the amount of monomer used for impregnation. Lower-viscosity monomers can also be used with pressure soaking. The manner in which the pressure is applied depends, to a degree, on the orientation of the surface being impregnated. Horizontal surfaces can be enclosed to prevent lateral movement of the monomer, while a uniform weight distribution (for example, water) is applied to the top surface of the liquid monomer, with perhaps an interface barrier of polyethylene sheeting to prevent intermingling. Any significantly inclined or vertical surface would probably need a pressure-tight enclosure to hold the monomer to the concrete surface while external pressure (for example, air pressure) was applied to the free surface of the monomer.

3.6.5.5 Polymerization—Any of the methods described in Section 3.5 can be used. A common method used on horizontal surfaces is the thermal-catalytic method. This method, described in Section 3.5.1, include application of heat to the surface of the impregnated concrete so that a

temperature at the surface of 165 to 195 °F (74 to 90 °C) is maintained for 5 hours. Infrared heat units within shallow enclosures over the areas to be polymerized have been successful in accomplishing this.

Concrete surfaces that used monomer-tight enclosures for soaking can be filled with hot water, and the required temperature can be maintained by strip heaters mounted on the back of the enclosure (Schrader et al. 1978). In all cases, open-flame heat sources that could cause combustion of monomer vapor should not be used.

3.6.5.6 Cleanup—Spillage of monomers should be avoided for safety reasons. An absorbent compound may be used to contain spills until they can be removed for disposal. After the polymerization step is complete, the absorbent compound used to contain the monomer can usually be shoveled or swept from the impregnated surface. Hardened polymer sand composites are often very difficult to remove from concrete.

3.6.6 Depth of impregnation—Depth of impregnation can usually be determined by visual inspection of small cores or samples taken from the polymerized concrete. Other methods that have been successful in determining polymer depths include acid etching, color enhancement by use of phenolphthalein in conjunction with microscopic examination, petrographic examination of polished sections using polarized light, nondestructive sensitivity measurements, thermal analysis, and pyrolysis coupled with infrared spectroscopy (Heller 1977; Locke and Hsu 1978; Patty 1978).

3.7—Fully impregnated concrete

Full impregnation is obtained by first thoroughly removing free moisture from the concrete to provide the maximum amount of previously water-filled pore space for monomer filling. This is followed by complete monomer saturation, usually under pressure, and subsequent polymerization of the monomer system. The principal reason for full impregnation of the concrete is to improve the strength characteristics of the concrete. This improvement is accompanied by improved resistance to water penetration and improved durability. In many instances, the modulus of elasticity is also significantly increased. The improved strength and increased modulus can be used effectively to establish economies in both design and construction.

3.7.1 Applications for fully impregnated concrete—The physical requirements for moisture removal and monomer saturation needed for fully impregnated concrete usually dictate the size and configuration of concrete elements that can undergo this treatment. Therefore, fully impregnated concrete is usually restricted to concrete that can be made and handled in precast plant operations. Examples of fully impregnated concrete elements include precast tunnel lining and support systems, beams, pipes, curbstones, plumbing and electrical fixtures, prestressed piling, fender piling, wall panels, trench covers, and other smaller elements (Dikeou 1976, 1980; Fowler 1983; Schrader and Tatro 2003).

3.7.2 Characteristics of fully impregnated concrete—PIC looks very much like conventional concrete, but may have a surface coating of polymer if it was not cleaned after polymer-

ization. Increases in strength in compression, tension, and flexure can be achieved by as much as four to five times those of unimpregnated concrete strengths. PIC can be made from both high-quality and low-quality concrete; however, the strength of PIC made from high-quality concrete is generally higher than the strength of PIC made from lower-quality concrete. Strength is directly related to the degree of impregnation achieved. Concrete subjected to either high- or low-pressure steam curing before impregnation generally results in higher strengths than comparable concrete that are moist cured at room temperature (Steinberg et al 1968; Dikeou et al. 1972; Auskern 1971). Tables 3.2 and 3.3 give some typical mechanical properties for PIC.

The strength increase attributed to polymer impregnation depends on the temperature of the exposure conditions. The strength of PIC shows a gradual decrease with an increase in the temperature at which it is tested. Exposure to elevated temperatures for short periods of time followed by a return to normal temperatures usually shows no noticeable effect. Prolonged exposure at elevated temperatures may result in a permanent decrease in strength. Exposure to temperatures at or above the glass-transition temperature of the polymer produces a more rapid strength loss.

For fully impregnated concrete, increases in modulus of elasticity (compressive and flexural) accompany the strength increases of PIC over unimpregnated concrete. For partially impregnated concrete, the increases (or decreases) are not significantly different from the control specimens.

Durability of PIC to most forms of environmental attack is significantly improved over that of untreated concrete. This is attributed primarily to filling of the pore system in the concrete with a polymer. Typical durability information for PIC is shown in Table 3.4.

3.7.3 Limitations of full impregnation—Full impregnation is limited almost exclusively to precast plant operations. Capital expenditures to begin production may be large. The monomer storage and transfer system should be designed to be completely enclosed to reduce hazards and offensive odors of monomer vapors escaping to the atmosphere. Disposal of curing water containing polymers requires additional filtration systems. Safety is a primary consideration.

Another limitation of PIC is the loss of stiffness and strength at temperatures greater than the softening point of the polymer. The designer should consider the softening point of the particular polymer used in relation to the expected service temperature. For a typical acrylic-concrete system, however, the improved mechanical properties should be retained because of the excellent insulating properties of concrete. Therefore, for most purposes, this is not a limitation, though the possibility of such a loss should be considered in designing structural elements that may be subjected to these high temperatures and that are not reinforced with steel. Fire resistance has been studied, and evidence suggests that typical PICs are self-extinguishing (Carpenter et al. 1973).

3.7.4 Monomers and polymers for full impregnation—The various monomers that can be used for full impregnation are described in Section 3.3.