

HIGHWAY APPLICATIONS OF CONCRETE POLYMER MATERIALS

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The deterioration of concrete bridge decks and pavements presents many highway organizations with major problems of providing safe and satisfactory riding surfaces. Concrete polymer materials, with their excellent durability and strength properties, have potential application to highway construction and maintenance and offer potential benefits of an increase in service life and a reduction in the costs, safety hazards, and inconveniences in performing maintenance and repair work. Polymer-impregnated concrete is highly resistant to freeze-thaw damage and water penetration and provides protection from deicing salt penetration and corrosion of reinforcing steel. A precast, prestressed polymer-impregnated concrete bridge deck system is being developed that incorporates the advantages of a precast, prestressed system for rapid construction and strength, and a surface-impregnation technique is being developed for field treatment of newly constructed concrete bridge decks to provide protection of reinforcing steel from deicing salts. Polymer concrete is a versatile, new material with properties comparable to polymer-impregnated concrete and appears to be suitable for both precast and field applications, such as for curbstones, pavement overlays, shotcrete, and rapid-curing patching and repair materials.

•DETERIORATION and premature failure of concrete bridge decks are caused by deicing salts, corrosion of reinforcing steel, freeze-thaw deterioration, spalling, and heavy traffic loads. Maintenance work is costly and difficult to perform under hazardous traffic conditions and presents delays and safety hazards to the traveling public because of lane closures, detours, traffic jams, and the increased risk of accidents. One approach to the problem is the use of concrete polymer materials in new highway construction and for maintenance and repair work. The materials of prime interest are polymer-impregnated concrete (PIC) and polymer concrete (PC), both of which have excellent durability and strength properties.

The Federal Highway Administration (FHWA) has sponsored research at the U.S. Bureau of Reclamation (USBR) to develop both a bridge deck system of precast, prestressed PIC and a field process of surface impregnation for protecting newly constructed concrete bridge decks from deicing salts. The prestressed PIC bridge deck panel program is cosponsored by the Prestressed Concrete Institute, which performed a parallel design of the system with USBR. Other organizations in the United States are engaged in development of field treatments for protection and repair of existing concrete bridges. The University of Texas at Austin, under the sponsorship of the Texas State Department of Highways and Public Transportation and FHWA, is investigating surface impregnation of new, old, and badly deteriorated bridge decks; Pennsylvania State and Lehigh Universities, under National Cooperative Highway Research Program sponsorship, are jointly developing techniques for deep impregnation of chloride-contaminated bridge decks; and Brookhaven National Laboratory is developing techniques for repair of deteriorated bridge decks under the sponsorship of FHWA. Much of this basic work has common application, and there has been a large exchange of information.

POLYMER-IMPREGNATED CONCRETE

PIC is prepared by impregnating hardened conventional portland cement concrete with

a liquid monomer (starting material for making plastics) that is subsequently polymerized. The polymerization reaction converts the liquid monomer into a solid plastic or polymer. The polymer fills voids and microfractures in the concrete, greatly increases strength and durability, and significantly reduces permeability.

Typical mechanical and physical properties of PIC are given in Table 1; the durability properties of PIC are given in Table 2. The concrete specimens were impregnated with methyl methacrylate thermal-catalytic polymerization. The strength of PIC is four to five times greater than that of unimpregnated concrete; water absorption and permeability are greatly reduced, and resistance to freeze-thaw and acid attack is greatly improved.

Fully impregnated PIC requires prior oven-drying of the concrete to remove moisture and an appropriate vessel for impregnation and polymerization. The impregnated concrete is thermal-catalytically polymerized in the impregnation vessel. Methyl methacrylate is the most widely used monomer because of its low viscosity, low cost, and excellent properties in PIC. Various other monomers and combinations of monomers and resins such as styrene, polyesters, acrylonitrile, and trimethylpropane trimethacrylate have been used to make a satisfactory PIC or to improve certain properties. Azonitrile catalysts are used because these compounds are chemically stable and, under appropriate safety conditions, permit storage and reuse of catalyzed monomer.

The steps for producing fully impregnated PIC are as follows:

1. Dry concrete at 300 F (148.9 C) for 24 hours to remove free moisture (or at a lower temperature for a longer time).
2. Allow concrete to cool to room temperature.
3. Place concrete in the impregnation vessel and apply a vacuum for $\frac{1}{2}$ hour.
4. Introduce catalyzed monomer under a vacuum to completely submerge the specimen, then soak under a compressed air pressure at 25 to 50 psi (170 to 340 kPa) for 2 hours.
5. Drain excess monomer and immediately backfill the vessel with warm water. Submersion in water minimizes monomer evaporation losses.
6. Apply heat (steam is commonly used) and polymerize to completion. Polymerization temperature and length of time depend on the monomer system, the catalyst, and the size of specimens. Polymerization is generally conducted at about 160 F (71.1 C) for about 4 hours.

Partially impregnated or surface-impregnated concrete may be produced by a simpler and less costly process that does not require vacuum and pressure soaking and that consequently eliminates the need for a pressure vessel as required for fully impregnated concrete. The process consists of drying the concrete to remove moisture, soaking it with a monomer at atmospheric pressure, and polymerizing the soaked concrete. Thermal-catalytic polymerization is accomplished by immersing the concrete in warm water or by other appropriate applications of heat. Partially impregnated and surface-impregnated concrete is reported to have good structural properties and excellent resistance to freeze-thaw deteriorations, water penetration, abrasion, and wear and to have a skid resistance at least equal to that of unimpregnated concrete (2, 3).

POLYMER CONCRETE

PC uses a polymer as the cementing material and is made by mixing a monomer or resin system with aggregate and casting and polymerizing the mixture. PC contains no portland cement binder and is sometimes referred to as resin-bound concrete. The material has excellent durability characteristics and good structural properties and is basically suitable for precast and cast-in-place applications. The material has been widely investigated throughout the world, and several PC products and potential applications have been introduced to the market: pipe, piles, curbs, tunnel liners, railroad sleepers, panels, overlays for highway bridge decks and approaches, various surface coatings and linings, patching and repair materials, and specialty products such as window sills, tiles, and sanitary fixtures. When fillers and reinforcement are added,

the material grades into the family of composite materials such as is represented by reinforced plastic mortar pipe. In this paper, PC refers to a concrete material with a polymer content of ≤ 10 percent (wt).

Developmental work on PC has been with epoxy, polyester, and furan resins and more recently with methyl methacrylate and styrene monomers. Epoxy resins are commercially available for use in PC applications that so far appear to be mostly for mortars and patching compounds. The chief obstacle to wider use of epoxies is their relatively high cost. Polyester PC has been widely investigated. The polyesters are usually blended with a styrene monomer, which serves as a solvent and cross-linking agent. A notable demonstration of polyester PC was a highway overlay system applied with a commercial asphalt paving machine.

A feasible method for fabricating PC has been developed at USBR (1, pp. 20-21). Using modified conventional concrete mixing equipment and conventionally graded, oven-dried concrete aggregate plus suitable nonporous fines, which serve as a filler and to improve the workability of the mix. The aggregate is mixed with a methyl methacrylate monomer system, cast, and polymerized at room temperature. The monomer system is composed of methyl methacrylate monomer, trimethylolpropane trimethacrylate, cross-linking monomer, benzoyl peroxide catalyst, dimethyl aniline promoter, and a silane coupling agent. This system polymerizes in about 2 to 4 hours after mixing. In the present procedure, the casting step requires vibrating to fully consolidate the mix and sealing to reduce evaporation of the monomer.

In tests performed on the mechanical and physical properties of PC (Tables 3 and 4), the specimens produced by the method described above are comparable in properties with PIC specimens. The PC specimens contain from 6 to 8 percent (wt) polymer as compared to 5 to 7 percent (wt) polymer for PIC. Compressive strengths of the PC specimens range from 12,000 to 24,000 psi (83 000 to 165 000 kPa). Current creep tests show creep deformation is comparable to that of conventional concrete. After 63 days under a compressive load of 3,938 psi (27 150 kPa), creep deformation for PC was 0.232 $\mu\text{in./in. per psi}$ (0.0059 $\mu\text{m/m/6.9 kPa}$) as compared with about 0.240 $\mu\text{in./in. per psi}$ (0.006 $\mu\text{m/m/6.9 kPa}$) for conventional concrete under a compressive load of 2,313 psi (15 948 kPa).

In other tests, specimens have been exposed to 5 percent sulfuric acid for 9 months, and no signs of deterioration or loss in weight have been visible. Specimens tested after the 9 months' exposure had an average compressive strength of 18,200 psi (124 000 kPa).

The use of methyl methacrylate requires certain safety precautions because it is flammable and explosive within certain vapor concentration limits. The mixer used must be equipped with an explosion-proof electric motor and nonsparking mixing blades. Mixing should be conducted in a well-ventilated area. Mixing and casting can be accomplished conveniently and safely by following recognized safety procedures for the handling of methyl methacrylate.

PC is versatile and may be conveniently adapted to patching, crack repair, and various applications through modifications of the mix. These would include dissolving polymers in the monomer to control viscosity or to impart certain qualities to the mix, using internal plasticizers such as butyl acrylate to increase ductility or flexibility, and using more rapid promoters such as dimethyl-p-toluidine to accelerate polymerization.

PC was also investigated by several federal agencies for use as shotcrete, a material mixed in and shot from a gun with a nozzle (4). The nozzle of a conventional field type of shotcrete gun was modified for polymer shotcrete application of a three-part shotcrete mix: the aggregate and a two-part monomer system. The monomer system was composed of 72 percent methyl methacrylate, 13 percent trimethylolpropane trimethacrylate, and 15 percent polymethyl methacrylate molding powder and was divided into two parts in which the additions of the catalysts were based on total weight of the monomer system: (a) benzoyl peroxide catalyst in a concentration of 2 percent (wt), and (b) n, n dimethyl-p-toluidine promoter in a concentration of 2 percent (wt). When the two parts of the monomer system are mixed, the mixture has about a 2-min polymerization pot life in 100-g (3.5-oz) bulk samples at room temperature. The application of polymer shotcrete is potentially hazardous and should be used only in well-ventilated areas or outside. Safety precautions to be followed include using protective

Table 1. Mechanical and physical properties of polymer-impregnated concrete.

Property	Unimpregnated Concrete	Polymer-Impregnated Concrete
Compressive strength, psi	5,300	18,200
Modulus of elasticity, 10^6 psi	3.5	6.2
Tensile strength, psi	420	1,500
Modulus of rupture, psi	740	2,300
Abrasion loss, in.	0.050	0.015
Cavitation, in.	0.320	0.020
Water absorption, percent	6.40	0.34
Water permeability, 10^{-4} ft/year	5.3	1.4
Thermal conductivity, Btu/ft-hr-deg F	1.332	1.265
Thermal diffusivity, ft ² /hour (73 F)	0.0387	0.0385
Coefficient of expansion, $\mu\text{in.}/\text{in.}/\text{deg F}$	4.02	5.25
Specific heat, Btu/lb/deg F (73 F)	0.241	0.220
Specific gravity	2.317	2.386

Note: 1 psi = 6.895 kPa. 1 in. = 2.54 cm. 1 ft = 0.305 m. 1 Btu · in./h · ft² · deg F = 0.144 W/m · K. 1 ft² = 0.09 m². 1 Btu/lb · deg F = 4187 J/kg · K. 1 $\mu\text{in.}/\text{in.}$ = 0.025 $\mu\text{m}/\text{m}$. 1 F = 1.8 (C) + 32.

Table 2. Durability properties of polymer-impregnated concrete.

Test	Unimpregnated Concrete	Polymer-Impregnated Concrete
Freeze-thaw		
Number of cycles	740 ^a	10,340
Loss, percent (wt)	25	12.5
Sulfate attack		
Test cycle, days	480 ^a	1,814
Expansion, percent	0.467	0.042
15 percent hydrochloric acid		
Exposure, days	105 ^a	1,395
Loss, percent (wt)	27	10
15 percent sulfuric acid		
Exposure, days	49 ^a	119 ^a
Loss, percent (wt)	35	26
5 percent sulfuric acid		
Exposure, days	210 ^a	423 ^a
Loss, percent (wt)	33	26

^aTest completed; failure criteria are 25 percent weight loss for acid immersion and freeze-thaw test and 0.5 percent expansion for sulfate attack test.

Table 3. Mechanical properties of polymer concrete.

Property	Test Temperature (F)	Result
Unit weight, pcf	70	149.1
Specific gravity	70	2.40
Water absorption, percent	70	0.6
Coefficient of expansion, $\mu\text{in.}/\text{in.}$	-4 to 70	5.30
	70 to 140	7.53

Note: 1 pcf = 1,602 kg/m³. 1 $\mu\text{in.}/\text{in.}$ = 0.025 $\mu\text{m}/\text{m}$. 1 F = 1.8 (C) + 32.

Table 4. Physical properties of polymer concrete.

Property (psi)	Test Temperature (F)	Result
Compressive strength	-15	24,800
	70	19,600
	120	15,800
	190	14,100
Tensile strength	70	1,610
Modulus of rupture	-10	2,960
	70	3,050
	140	2,940
Shear strength	70	4,100

Note: 1 psi = 6.895 kPa. 1 F = 1.8 (C) + 32.

clothing and respirators, if necessary, eliminating sparks and sources of ignition, and electrically grounding the equipment.

The polymer shotcrete that was applied to a near-vertical surface (Figure 1) cured and achieved full strength in 10 to 15 min after application. Aggregate rebound was estimated at 15 to 30 percent. Cube-shaped specimens taken from the applied shotcrete had a compressive strength of 10,000 psi (69 000 kPa).

PRESTRESSED POLYMER-IMPREGNATED CONCRETE BRIDGE DECKS

The prestressed PIC bridge deck system makes use of prestressed panels for rapid construction, and the polymer protects the steel from deicing salts (3). The concept envisions use of precast panels as long as a deck width, rapid erection and placement of panels at the site, and connection of panels by posttensioning. In the program for development of this system, prestressed panels 16 ft long, 4 ft wide, and 6 in. thick ($4.88 \times 1.22 \times 0.15$ m) were cast, impregnated and polymerized, and tested.

The concrete mix was designed for a compressive strength of 5,500 psi (38 000 kPa) and 4,000 psi (28 000 kPa) at 24 hours for prestress release. Concrete control test specimens [6×12 -in. (0.15×0.30 -m) cylinders] averaged about 5,500 psi (38 000 kPa) at 24 hours and 6,800 psi (47 000 kPa) at 28 days.

The panels were treated at the USBR impregnation and polymerization facility (Figure 2). They were first dried at a temperature of 200 F (93 C). Higher drying temperatures were not used to prevent excessive prestress strand relaxation. The panels were then placed in the specimen carrier (Figure 3), which was rolled into the vessel. Specimens were impregnated and polymerized within the vessel by the pressure-soaking, warm-water bath method. Four panels, about 5,000 lb (2270 kg) each, were treated simultaneously.

The test program for the panels included static- and cyclic-fatigue load tests on single panels and on sets of three connected panels to determine deflections, strain distributions, load at first crack, ultimate load, and load transfer across panel joints. The equipment and specimen arrangement for a three-panel test are shown in Figure 4. The panels are supported by concrete girders on 8-ft (2.44-m) centers. The load is applied to a 5×20 -in. (12.7×50.8 -cm) steel plate to simulate an HS20-44 truck wheel load. The panels withstood loads in excess of the 42,000-lb (19 000-kg) ultimate design load and showed good transfer of the load to adjacent panels. Failure occurred at 95,000 lb (43 100 kg) in the single-panel test and at 160,000 lb (73 000 kg) in the three-panel test.

SURFACE IMPREGNATION OF BRIDGE DECKS

The surface-impregnation technique is being developed at USBR as a method to protect newly constructed concrete bridge decks from damage resulting from the use of deicing salts. The objective of the program is to develop a practical method and equipment capable of impregnating the concrete bridge deck with polymer to a depth of at least 1 in. (2.54 cm).

This surface-impregnation technique is a modification of the basic full-impregnation technique and uses adaptations of the method being developed at the University of Texas at Austin (3). The present procedure involves drying the bridge deck, applying the catalyzed monomer, and polymerizing the impregnated concrete by application of heat. The procedure uses relatively simple equipment and does not require vacuum or pressure apparatus. Initial test results indicate this method is capable of producing a 2-in.-deep (5-cm) layer of polymer in the concrete.

The surface-impregnation technique was demonstrated on a newly constructed bridge in Denver during October 1974. The entire bridge deck, 28 ft wide \times 61 ft long (8.5×18.6 m), was treated at one time. The concrete bridge deck was dried under a portable enclosure by blowing hot air over the surface. The framework for the enclosure is

Figure 1. Application of polymer shotcrete using a modified commercial shotcrete gun.



Figure 2. Impregnation and polymerization facility.

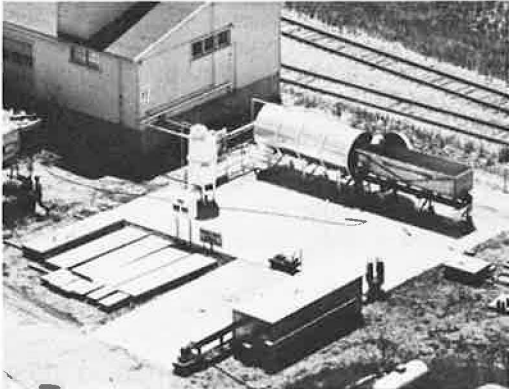


Figure 3. Loading bridge deck panel into carrier for impregnation and polymerization.

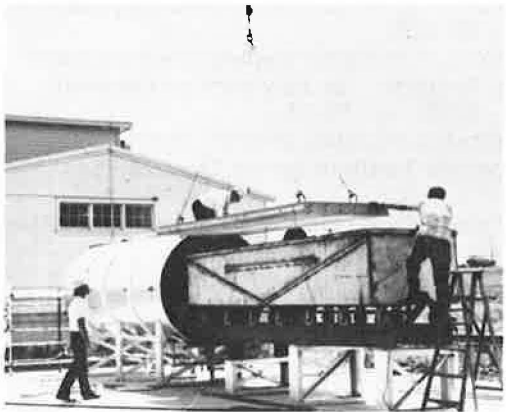


Figure 4. Load test set up for polymer-impregnated concrete bridge deck panel.

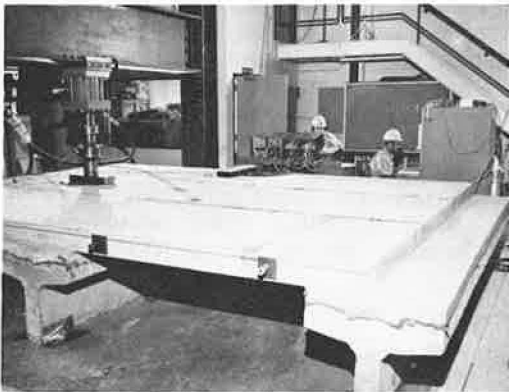


Figure 5. Drying one lane of small concrete bridge before surface impregnation.



Figure 6. Applying monomer to concrete bridge deck.



shown in Figure 5. Air temperature under the enclosure was maintained at 250 F (120 C) for about 3 days or until the concrete was sufficiently dried to a depth of 3 to 4 in. (8 to 9 cm). The enclosure was then removed, and the concrete deck allowed to cool overnight. Sand was spread over the bridge deck to a depth of about $\frac{1}{4}$ in. (6.35 mm) and then thoroughly saturated with monomer that was allowed to penetrate the concrete overnight (Figure 6). The sand serves as a reservoir for the monomer. A polyethylene sheet was placed over the monomer-saturated sand to prevent evaporation of the monomer. Monomer was reapplied several times to maintain a sufficient supply of monomer for penetration. The enclosure was then placed over the monomer-saturated sand and polyethylene evaporation barrier, and hot air was blown into the enclosure at a temperature of about 160 F (70 C) to initiate polymerization. Cores taken from the deck indicated a little more than 1-in. (2.5-cm) polymer penetration.

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