

POLYMER CONCRETE FOR REPAIRING DETERIORATED BRIDGE DECKS

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One of the most severe problems facing the highway industry is the rapid deterioration of highway structures. As part of a concerted effort to solve this problem, research is being performed to determine if polymer-concrete materials can be used for the repair of deteriorated and delaminated bridge decks. Polymer concrete consists of an aggregate mixed with a monomer, which is subsequently polymerized in place. It is mixed and placed by using techniques similar to those used for portland cement concrete and, after curing, produces a high-strength, durable material. Process variables studied include monomer type, aggregate size distribution, and polymerization method. Field testing of polymer concrete has been in progress for almost 3 years, and to date deterioration has not been observed. One test on a major arterial highway in New York City has been in progress for 7 months. Based on the success obtained in this experiment and in concurrent laboratory evaluations, further work on the same highway was scheduled for September 1974. These data are summarized.

•FOUR distinct types of material for repairing deteriorated bridge decks are being investigated as a joint effort between Brookhaven National Laboratory (BNL) and the U.S. Bureau of Reclamation (USBR). They are

1. Polymer concrete (PC), which consists of an aggregate mixed with a monomer and which is subsequently polymerized in place;
2. Polymer portland cement concrete (PPCC), a premixed material in which monomer is added during the mixing of water, portland cement, and aggregate and which is subsequently polymerized in place;
3. Polymer-impregnated concrete (PIC), which consists of cured portland cement concrete (PCC) impregnated by a monomer system and which is subsequently polymerized in situ; and
4. Surface-impregnated, cured portland cement concrete.

For each of these main types of material, process variations can be exercised, and variations in properties and characteristics will result.

The main, and most successful, effort in improving the structural and durability properties of PCC has been with PIC. Several reports describing the preparation and testing of these materials have been published (1, 2, 3, 4, 5, 6, 7); these have generated worldwide interest, and research is currently in progress at many laboratories (8). The work has advanced from the determination of basic material characteristics and methods for producing the composite to the design and testing of prototypes and full-sized sections for specific applications.

During the past 3 years, considerable success has been achieved at BNL and USBR in the development of PC. Methods to produce specimens with polymer contents and properties that approach those of PIC have been developed (5). As a result of the premixed nature of the material, the ability to rapidly cure it over a wide range of temperature, and its excellent properties, PC appears to have many potential applications. In Japan, PC pilings, 3 ft wide \times 45 ft long (1 \times 15 m), and precast manholes are

marketed commercially (9). One Japanese firm is reported to produce 4,000 pilings/month. It has also been reported that PC pipe is being produced in Australia (10, 16).

Current work at BNL is to evaluate PC as a patching material for use in the rapid repair of holes in bridge decks and pavements. It may also be possible to use the high-strength PC to enhance the structural characteristics of the decks. The methods for producing these materials, their properties, and the results of field tests are described in this paper.

PRODUCING POLYMER CONCRETE

Monomer Selection

The important considerations in the selection of a monomer system for use in PC include cost, durability under anticipated exposure conditions, adhesion to aggregate, and the ability to be polymerized predictably at ambient temperature by promoter-catalyst techniques. Low vapor pressure is also an important characteristic since it results in reduced evaporation losses and minimizes safety problems.

Two monomer systems that have been studied extensively at BNL are methyl methacrylate (MMA) and polyester-styrene. It is expensive to polymerize MMA alone in a predictable manner by using promoter-catalyst techniques, but, with this exception, both materials meet the selection criteria given above. The polymerization problem can be overcome by the addition of a polyfunctional monomer such as trimethylpropane trimethacrylate (TMPTMA) to the MMA. This results in a greatly enhanced polymerization rate and produces a cross-linked polymer with increased temperature and solvent resistance. Based on this finding, two monomer systems, 95 percent (wt) MMA-5 percent (wt) TMPTMA and 54 percent (wt) polyester-46 percent (wt) styrene are currently being used in laboratory and field tests. Polymerization conditions for these systems and several other monomer mixtures are given in Table 1.

Mix Design

The design of a mix to optimize the properties of PC is largely accomplished by aggregate gradation to give a void volume that will require minimal amounts of monomer to fill the voids and to give good workability to the mix. This work has been described by many authors (4, 5, 11, 12, 13, 14, 15). Generally, the aggregate should be dried before it is used. Some epoxy resins are less affected by moisture, and, therefore, the drying conditions are less stringent. The major mix variables are maximum particle size, gradation, and composition. Crushed stone and natural sand and gravel are generally used. Finely divided materials such as portland cement, powdered chalk, clay, fly ash, and silica have also been used. Test results indicate that aggregate type and composition do not significantly influence the strength properties of the mix (15) but do affect the durability (16). Aggregate gradation and maximum particle size influence the amount of resin required to coat the filler particles and to fill the voids. Tests have indicated that for a well-graded filler larger maximum particle sizes require less resin. Gap grading also tends to reduce the amount of resin required. Conversely, smaller maximum particle sizes produce higher strength mixes. At USBR (5), an aggregate size distribution has been developed that when mixed with 7 to 8 percent (wt) MMA produces specimens with compressive strengths of ~19,000 psi (131 000 kPa). BNL work has indicated that dense-graded aggregate mixes of the type used in asphalt concrete (Table 2) will produce composites with a strength of 13,000 psi (89 630 kPa) when mixed with 9 percent (wt) of an MMA-TMPTMA monomer system (7).

The monomer content of the mix, a dependent variable, is the minimum necessary to coat the aggregate and to fill the voids. Excess monomer will bleed to the surface because of the low density relative to the density of the aggregate. Monomer concentrations ranging from 5 to 30 percent (wt) have been reported. The former was obtained

in a pipe when a compaction method that involved pressure, vibration, and centrifugal force was used on a graded aggregate and filler (16).

Fabrication

The batching, mixing, and placing techniques for producing PC are, to a great extent, based on the adaptation of existing equipment and methods for producing PCC. However, volatile and potentially explosive monomers, such as MMA, require nonsparking and explosion-proof equipment. Mixing should be done in a closed system or outdoors in a well-ventilated area. Some of the chemicals may be irritants or toxic and should be handled safely.

The PC mix is cast into forms or molds in a manner similar to that used for conventional concrete. Wood, steel, glass, and paper molds have all been used successfully. A great variety of mold-releasing agents such as silicone gels, vegetable oils, automobile wax, and paraffins, have also been used.

After the mix is placed, it should be consolidated by external vibration, rodding, mechanical pressure, or application of vacuum to remove entrapped air.

Polymerization

Curing of PC may be performed by radiation, thermal-catalytic, or catalyst-promoter methods (7). Curing times may be varied between a few minutes and several hours, and full strength is attained when polymerization is completed.

If the PC is to be cured at ambient temperature by promoter-catalyst techniques, these materials in concentrations generally ranging between 0.5 and 2 percent (wt) of the monomer are added to the monomer prior to mixing with the aggregate. Materials used are given in Table 1.

Laboratory Testing

When compared to the extensive testing program (at BNL and USBR) that was performed to determine the properties of PIC, the PC evaluation effort has been small. To date, only a few of the mechanical and durability properties have been measured.

One detailed evaluation was performed at USBR (5). Initially, a graded, sand-aggregate mix closely approximating that of PC (1) was integrally mixed by hand with catalyzed MMA and was polymerized at 158 F (70 C). The heat generated during polymerization of these specimens was quite high, and as a result the samples developed relatively low compressive strengths from 8,000 to 12,000 psi (55 160 to 82 740 kPa). Subsequent work on the method and incremental temperature control during polymerization resulted in more consistent specimens with compressive strengths of 11,000 to 12,000 psi (75 840 to 82 740 kPa). The addition of cross-linking and coupling agents, glass-fiber reinforcement, and a change to α tert-butylazoisobutyronitrile catalyst improved the strength to 14,800 psi (102 000 kPa).

Development of the method continued until in its present form oven-dried, Clear Creek aggregate was machine-mixed with the monomer system, placed in molds, and polymerized at room temperature by the promoter-catalyst technique. The specimens are prepared with 7 to 8 percent monomer by total weight of the wet mix. Based on the maximum size of the aggregate and the amount of cross-linking agent in the monomer system, the specimens develop average compressive strengths varying from 18,400 to 20,000 psi (126 860 to 137 900 kPa). These mixes have produced consistent specimens with individual strengths that vary <2 percent from the mix average.

USBR specimens prepared by using conventional concrete-mixing procedures and room-temperature polymerization have been tested for compressive stress-strain, tensile splitting, unit weight, specific gravity, and water absorption (Table 3). Other specimens were exposed to a 5 percent H₂SO₄ solution for two months without any

Table 1. Promoter and catalyst systems for monomer mixtures.

Monomer Mixture (percent)	Viscosity at 77 F	Catalyst	Catalyst Concentration, Percent (wt)	Promoter	Promoter Concentration, Percent (wt)	Ambient Temperature (F)	Gel Time (min)	Cure Time (min)
MMA	0.5	Bzp + AIBN	0.5/0.5	DMA + DMT	0.5/0.5	77	20	60
95 MMA-5 TMPTMA	~1.0	Bzp + AIBN	1.0/1.0	DMA + DMT	1.0/1.0	77	15	36
95 MMA-5 TMPTMA	~1.0	Bzp	2.0	DMA	2.0	82	20	38
70 MMA-30 TMPTMA	1.9	Bzp	1.0	DMT	1.0	77	8	14
90 styrene-10 TMPTMA	~1.0	Bzp	1.0	DMA	1.0	106	—	—
90 styrene-10 TMPTMA	~1.0	Bzp	2.0	DMA	2.0	106	50	1,050
85 styrene-15 TMPTMA	~1.2	Bzp	2.0	DMA	1.0	106	30	220
60 styrene-40 TMPTMA	1.7	Bzp	1.0	DMA + DMT	0.5/0.5	77	15	45
75 styrene-25 polyester	2.4	MEKP	1.0	CoN	0.4	60	53	<120
54 polyester-46 styrene	~100	MEKP	1.0	CoN	0.75	70	20	35

Note: 1 F = 1.8 (C) + 32. Bzp = benzoyl peroxide, AIBN = azobisisobutyronitrile, CoN = cobalt naphthenate, DMA = dimethyl aniline, DMT = dimethyl toluidine, and MEKP = methyl ethyl ketone peroxide.

Table 2. Sieve analysis for aggregate used in Brookhaven National Laboratory polymer concrete.

Sieve Size	Percent Passing Sieve Size	Sieve Size	Percent Passing Sieve Size
3/4 in.	94.8	No. 16	37.1
1/2 in.	83.1	No. 30	30.5
3/8 in.	78.1	No. 50	11.0
1/4 in.	61.6	No. 100	2.6
No. 4	51.8	No. 200	1.2
No. 8	40.9		

Table 3. Property tests on 6- x 12-in. (15- by 30-cm) polymer concrete cylinders.

Test	Temperature (F)	Result
Tensile splitting strength ^a , psi	-15	1,510
	70	1,430
	190	1,370
Compressive strength ^a , psi	-15	24,800
	70	19,600
	120	15,800 ^b
Modulus of elasticity ^a , psi	190	14,100
	-15	6.11 × 10 ⁶
	70	5.28 × 10 ⁶
Poisson's ratio ^a	190	4.44 × 10 ⁶
	-15	0.24
	70	0.23
Elastic limit stress ^a , psi	190	0.22
	-15	14,000
	70	7,500
Ultimate compressive strain, μin./in.	190	4,800
	-15	5,360
	70	7,080 ^c
Unit weight ^a , pcf	190	>8,000
	—	149.1
	—	2.40
Specific gravity ^a	—	0.6
Water absorption ^c , percent	—	

Note: 1 F = 1.8 (C) + 32, 1 psi = 6.895 kPa, 1 μin./in. = 1 μm/m, 1 pcf = 1.602 kg/m³.

^aAverage values for three specimens.

^bValue for single specimen.

^cAverage value for two specimens.

apparent effect on their properties.

Creep tests have also been performed on PC specimens containing MMA. The tests were conducted on 6- × 12-in. (15- × 30-cm) cylinders that were subjected to compressive stresses of 800, 1,301, and 3,938 psi (5515, 8970, 27 150 kPa) for 63 days. The stresses were ~5, 8, and 24 percent respectively of the ultimate compressive strength. After 63 days, the specimens exhibited less creep than normal weight concrete. The unit creep deformation [$\mu\text{in.}/\text{in.}/\text{psi}$ ($\mu\text{m}/\text{m}/\text{Pa}$)] of PC specimens under the 3,938-psi (269 160-kPa) compressive load was close to that of unimpregnated PC under a compressive load of 2,313 psi (15 948 kPa).

PC development work at BNL has focused primarily on highway applications: for repairing holes or as an impervious overlay on bridge decks. Criteria considered essential for these applications are the ability of PC to be mixed and placed conventionally, its rapid predictable polymerization rates over a wide range of temperatures, high strength, and good bonding.

Several studies were performed to select aggregate size distributions that would produce high-strength, low-porosity materials. To date, the best results have been obtained by using a dried, dense-graded aggregate mix such as that used on Long Island in asphalt concrete. A sieve analysis for this material is given in Table 2.

Experiments were performed by using the MMA-TMPTMA and polyester-styrene monomer mixtures. The results indicate that high-strength materials [compressive strengths >10,000 psi (68 900 kPa)] with low water absorptions (<0.5 percent) can be produced with polymer concentrations of 9.1 percent (wt). The water absorptions are similar to those of PIC.

Shear tests have been performed to determine the bonding characteristics of PC when applied to steel or sound concrete surfaces. Two monomer systems, 60 percent (wt) styrene-40 percent (wt) TMPTMA and 53 percent (wt) polyester-28 percent (wt) styrene-19 percent (wt) TMPTMA, were used to produce PC that was applied as $\frac{3}{4}$ -in.-thick (1.9-cm) liners on 6- and 8-in.-wide (15- and 20-cm) steel pipe. A shear strength of 1,100 psi (7584 kPa) was measured for PC applied to sandblasted steel surfaces, and 400 psi (2758 kPa) was obtained for samples that had not been sandblasted.

Cores taken from concrete specimens that contained 6-in.-thick (15.2-cm) PC overlays were subjected to shear strength measurements. Bond strengths at the PC-concrete interface of >1,000 psi (6895 kPa) are normally obtained.

Preliminary tests to determine the coefficient of thermal expansion for PC have been performed. PC specimens containing a 15 percent concentration of 75 percent (wt) styrene-25 percent (wt) polyester exhibited an average value of 8.2 $\mu\text{in.}/\text{in.}/\text{F}$ (8.2 $\mu\text{m}/\text{m}/-17.2\text{ C}$). It is expected that the coefficient will decrease as polymer concentration decreases. Measurements made at USBR (1) on unimpregnated normal weight concrete and PIC containing 5 percent (wt) styrene indicated values of 4 and 5 $\mu\text{in.}/\text{in.}/\text{F}$ (4 $\mu\text{m}/\text{m}$ and 5 $\mu\text{m}/\text{m}/-17.2\text{ C}$) respectively.

The largest laboratory tests performed at BNL consisted of pouring a series of 4- × 4- × 1-ft (1.2- × 1.2- × 0.3-m) slabs. This work was performed to support the field experiments described later. PC containing 13 percent (wt) of a 95 percent (wt) MMA-5 percent (wt) TMPTMA monomer mix and 10 percent (wt) of 54 percent (wt) polyester-46 percent (wt) styrene was used. The materials were mixed and placed conventionally. Both systems cured in <60 min, and essentially no shrinkage was observed. Cores taken from the MMA-TMPTMA PC indicated compressive and shear strengths of 9,600 psi (66 190 kPa) and 2,175 psi (14 996 kPa) respectively. A similar compressive strength, 9,730 psi (67 085 kPa), was obtained for the polyester-styrene PC. Water absorption measurements on both materials indicated values <1 percent. After 150 cycles of freeze-thaw testing, no deterioration was apparent.

FIELD EVALUATION OF POLYMER CONCRETE

Preliminary field testing of BNL-prepared PC has been in progress for almost 3 years. Initially several potholes in a road leading to a receiving depot at BNL were filled with polyester-styrene PC. Since that time, several patches have been made on bridges

located at Sag Harbor and Greenport, New York (7).

Based on the results obtained in the preliminary field experiments, PC was used in New York City to repair a badly deteriorated section of a bridge. The work, which was conducted as a joint venture of the New York State Department of Transportation, the New York City Arterial Highway Maintenance Department, and BNL, involved filling a 3- × 10- × 1.25-ft (1- × 3- × 0.4-m) hole through the bridge on the Major Deegan Expressway at Third and Lincoln Avenues in the lower Bronx (Figure 1). The high traffic densities in this area (~85,000 vehicles/day) prevent closing of a lane for more than 5 hours. Because conventional repair methods could not be used, the hole had been covered with a steel plate.

On December 4, 1973, one lane was closed while the form work was prepared. The hole was filled on December 6 with a PC consisting of 13 percent monomer [95 percent (wt) MMA-5 percent (wt) TMP/MA] and 87 percent of the dense-graded aggregate (Table 2). Because of an ambient temperature of ~50 F (10 C), 2 percent (wt) benzoyl peroxide was used as the catalyst and a mixture of 2 percent (wt) dimethyl aniline and 1 to 2 percent (wt) dimethyl toluidine as the promoter. A silane coupling agent was added at a concentration of 1.5 percent to enhance bonding to the adjacent concrete. Mixing and pouring were completed in 1 hour by using conventional equipment. Polymerization was complete within 1 hour, at which time the side forms were removed. The completed patch is shown in Figure 2. After 1 hour, estimates of the compressive strength made by using a Windsor probe indicated values between 5,400 and 8,000 psi (37 230 and 55 160 kPa). The measured compressive strength of a cylinder cast from the same mix was 12,200 psi (84 116 kPa), and the water absorption was 0.4 percent. At 3:00 p.m., 5 hours after work was started and 2 hours after the pour was completed, the lane was reopened to traffic. The top and underside of the section have been inspected on a routine basis. After 7 months in service, essentially no changes have been noted. Based on the results from this test, work to repair five larger holes in the bridge was scheduled for September 1974.

COST ESTIMATES FOR POLYMER CONCRETE

As a result of the limited number of small-scale field tests that have been performed to date, only the material costs associated with the use of PC have been determined. Attempts to determine placement and traffic control costs will be made in conjunction with repair work scheduled on the Major Deegan Expressway in September 1974.

Since the required formwork and the placement techniques for PC are essentially the same as those used for PCC, installation costs should be similar. Traffic control costs will be significantly lower because of the shorter cure time. Future maintenance costs should also be reduced.

The cost for the materials used in the first test on the Major Deegan Expressway was \$302/yd³ (\$392.60/m³). Of this total, \$77 was directly attributable to the low ambient temperature [50 F (10 C)] during placement, which necessitated the use of 1.25 percent (wt) dimethyl toluidine [\$9.50/lb (\$20.90/kg)] in conjunction with 2 percent (wt) dimethyl aniline [\$1.50/lb (\$3.30/kg)] as the promoter and 2 percent (wt) benzoyl peroxide [(\$1.26/lb (\$2.77/kg))] as the catalyst. For temperatures >70 F (21 C), 1 percent (wt) benzoyl peroxide and 1 percent (wt) dimethyl aniline would be sufficient to produce complete polymerization in <60 min.

Further reductions in cost can be obtained by use of polyester-styrene. As indicated above, PC containing 10 percent (wt) of a 54 percent (wt) polyester-46 percent (wt) styrene mixture produced compressive strengths of 9,730 psi (67 090 kPa) in <60 min. Polymerization conditions for the mixture were given in Table 1. Based on a current price of \$0.37/lb (\$0.81/kg) for the polyester-styrene, the materials for this mix can be obtained for \$170/yd³ (\$221/m³).

Compared to the cost of PCC, PC is expensive, and as a result it will probably not be used as a general substitute for concrete. There are, however, many specific applications for which the properties of concrete are inadequate. One such application would appear to be as a specialized bridge deck or pavement patching material. For

Figure 1. Hole in Major Deegan Expressway before filling with polymer concrete.

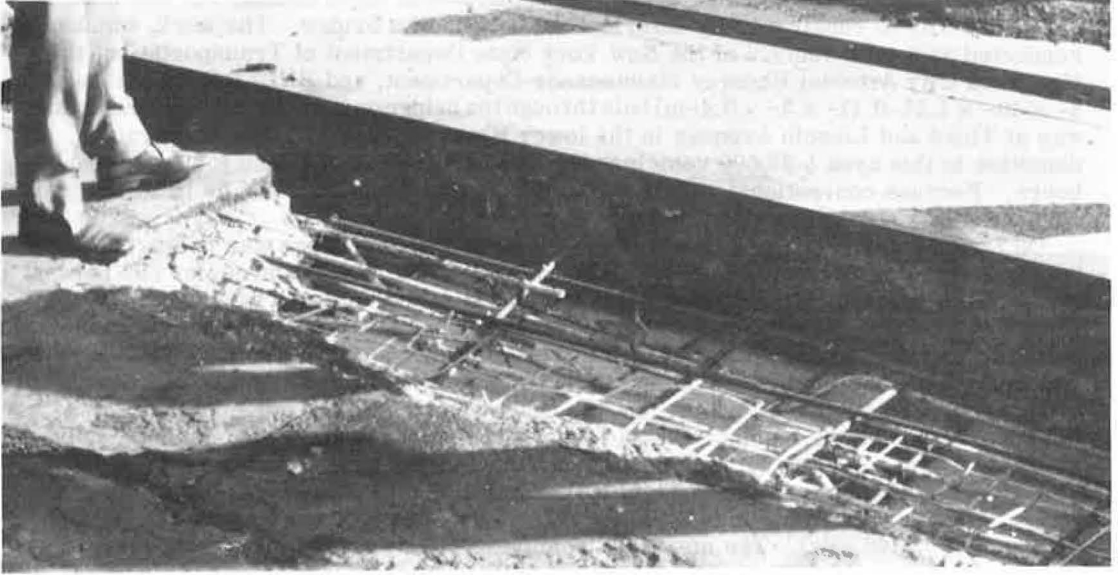
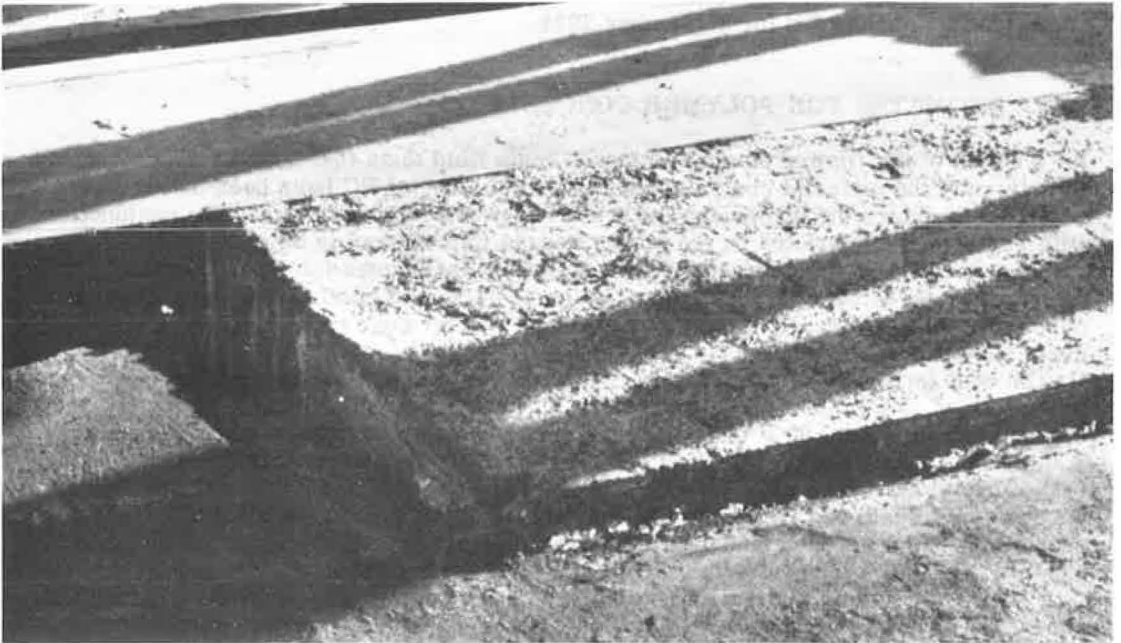


Figure 2. Completed polymer concrete patch on Major Deegan Expressway.



these applications, the high-strength, rapid-curing characteristics and good durability will result in minimum traffic delays and improved safety and in some cases may eliminate the necessity of constructing expensive detours. In these cases, the material cost becomes insignificant.

CONCLUSION

Polymer-concrete has the potential of combining the premix characteristic of PCC with strength and durability properties approaching those of PIC. As a result of the premixed nature of the material, its quick cure time at ambient temperature, and high strength, PC appears suited for use in the repair of highway structures where traffic conditions allow closing of the area for only a few hours.

Field testing of materials containing MMA-TMPTMA and polyester-styrene has been in progress for almost 3 years, and to date no detrimental effects have been noted. The most severe test was performed on the Major Deegan Expressway in New York City where a 3- × 10- × 1.25-ft (1- × 3- × 0.4-m) hole through a bridge deck was filled with a PC containing 13 percent (wt) of a 95 percent (wt) MMA-5 percent (wt) TMPTMA mixture. Polymerization was completed within 1 hour, and traffic was restored 2 hours after completion of the pour. After 7 months in service, no deterioration was apparent. Hopefully, the use of PC has resulted in a permanent repair to the bridge deck. All of the work was confined to the non-rush-hour period and therefore minimized the inconvenience to the traveling public to a few hours rather than for several days. With further PC experience, the repair time could undoubtedly be reduced.

When compared to the material cost for PCC, PC is expensive: \$170 to and \$302/yd³ (\$221 to \$392.60/m³). Installation costs should be essentially the same as for conventional concrete. Since the material cost represents only a small part of the total repair cost on major highways, where traffic conditions impose severe limitations on the type of repairs that can be made or require the construction of expensive detours, the use of a more expensive PC to make a permanent repair may be cost effective.

ACKNOWLEDGMENTS

We wish to acknowledge the help in program planning of R. E. Hay and R. G. Pike of the Federal Highway Administration. R. Mediatore and A. Levine of Region 10, New York State Department of Transportation, arranged for the bridge test sites and provided technical assistance during the experiments. The efforts are also acknowledged of J. Amaro, J. Fedelem, R. Sick, and W. Vogel of Brookhaven National Laboratory and many unidentified New York State Department of Transportation employees for their assistance during the experimental work.

Support for this research was provided by the U.S. Atomic Energy Commission, Office of Saline Water, Federal Highway Administration, and the U.S. Bureau of Reclamation.

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