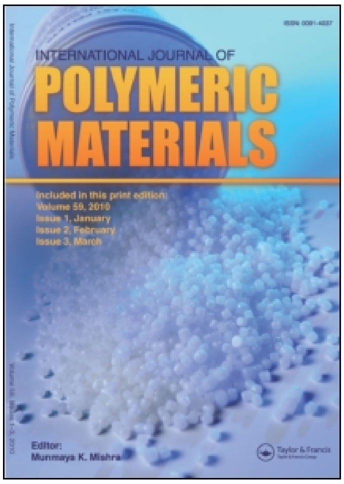

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Polymer-Concrete Composites

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Polymer-Concrete Composites†

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The need for cost-effective, high-strength, corrosion-resistant materials of construction has led to the development of a new class of materials, polymer–concrete composites. Production of such composites may be effected in four ways. This report focuses on "polymer-impregnated concrete" and "polymer–concrete" composites and looks at the technical, processing, and economic merits of these materials. A case for increased research is made.

1 INTRODUCTION

The diversity of materials available for engineering applications is explained by our ability to combine basic materials into composites, alloys, copolymers, etc. This symposium specifically recognizes that fact. The intention of this paper is to bring attention to the technical and economic potential of a class of materials which, though relatively new, are composed of two classic classes of materials, namely polymers and concrete.

Because of the breadth of the subject, and because of my institute's current interest in highway applications, much of this discussion will reflect the latter orientation. To place the significance of highway applications of polymer and concrete composites in perspective, reference to recent National Research Council statements help. They estimated that more than 110,000 bridges in the U.S. are inadequate for heavy loads or in need of major repairs and that another 51,000 have narrow widths, poor clearances, and dangerous approaches. In addition, reports indicate that about 150 bridge failures occur in the United States each year. The use of polymer and concrete composition can significantly improve this position.

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2 COMPOSITE TYPES

A need for materials of construction possessing increased strength and corrosion resistance has led to the development of concrete–polymer composites and related systems. Basically, four distinct types of materials are being actively investigated:

a) Polymer-impregnated concrete (PIC), consisting of a pre-cast portland cement concrete impregnated by a monomer system which is polymerized *in situ*.

b) Pre-cast concrete which is partially impregnated to produce an in-depth polymer coating (penetrating, e.g., 1 inch and more) on-site. (Variation of "a".)

c) Polymer–concrete (PC), an aggregate mixed with monomer and subsequently polymerized in place.

d) Polymer–cement concrete (PCC), consisting of a monomer added to a water-portland cement-aggregate mix which is polymerized as the concrete hardens.

Of these four categories, significant advances have been achieved with PIC and PC, as well as with the process and results of partial impregnation to produce an in-depth polymer coating. Interest in polymer cement concrete (PCC) has subsided as only marginal improvements in mechanical properties have been realized.

2.1 Polymer-impregnated concrete

In the United States, remarkable progress has been achieved in the development of PIC. PIC is generally prepared by impregnating dry pre-cast concrete with a liquid monomer (e.g., methyl methacrylate) and by polymerizing the resin *in situ* by radiation, thermal initiation, with and without catalysts and/or promoters. Addition-type polymers and copolymers are favored, in contrast to the thermosetting, condensation polymers, such as epoxies which were initially favored. The polymer acts to fill the porous voids of the concrete which results in significant improvement in the mechanical properties and durability of the material.

2.1.1 Material properties of PIC The interest of U.S. investigators in polymer-impregnated concrete is understandable. Remarkable increases in the mechanical properties and corrosion resistance of concrete have been achieved by polymer impregnation. Primary emphasis, in highway structural applications, has most recently focused on the polymerization of methyl methacrylate, cross-linked by a trifunctional comonomer, e.g. trimethylolpropane trimethacrylate

(TMPTMA). Except as cited, the polymer and concrete composites, to which we refer are understood to be methacrylate systems.

Typically, a conventional concrete (28 days water cured) with a compressive stregnth of 5,000 pounds per square inch (psi) can be impregnated with a polymer and show an increase to 20,000 psi in compression. Water absorption is reduced by 99 % and freeze-thaw resistance has been improved dramatically, e.g., a PIC composite containing 6 % (w/w) of polymethylmethacrylate lost only 0.5 % of its mass after 3,650 cycles while a control of conventional concrete lost 26.5 % mass after only 690 cycles.[1] With high silica cement, strong basaltic aggregate, and high temperature steam curing, strength has been increased from 12,000 psi to 38,000 psi.

Like conventional concrete, PIC composites possess about one-tenth the compressive strength in tension but, in contrast to conventional concrete, PIC exhibits essentially "zero creep properties", i.e. less than one-tenth the creep of conventional concretes. The modulus of elasticity generally increases at least two-fold. As a consequence, the PIC shows mainly elastic behavior, unlike the base concrete which fails plastically (Figure 1). A comparison of typical results of a conventional concrete and polymer-impregnated concrete is given in Table I.[2]

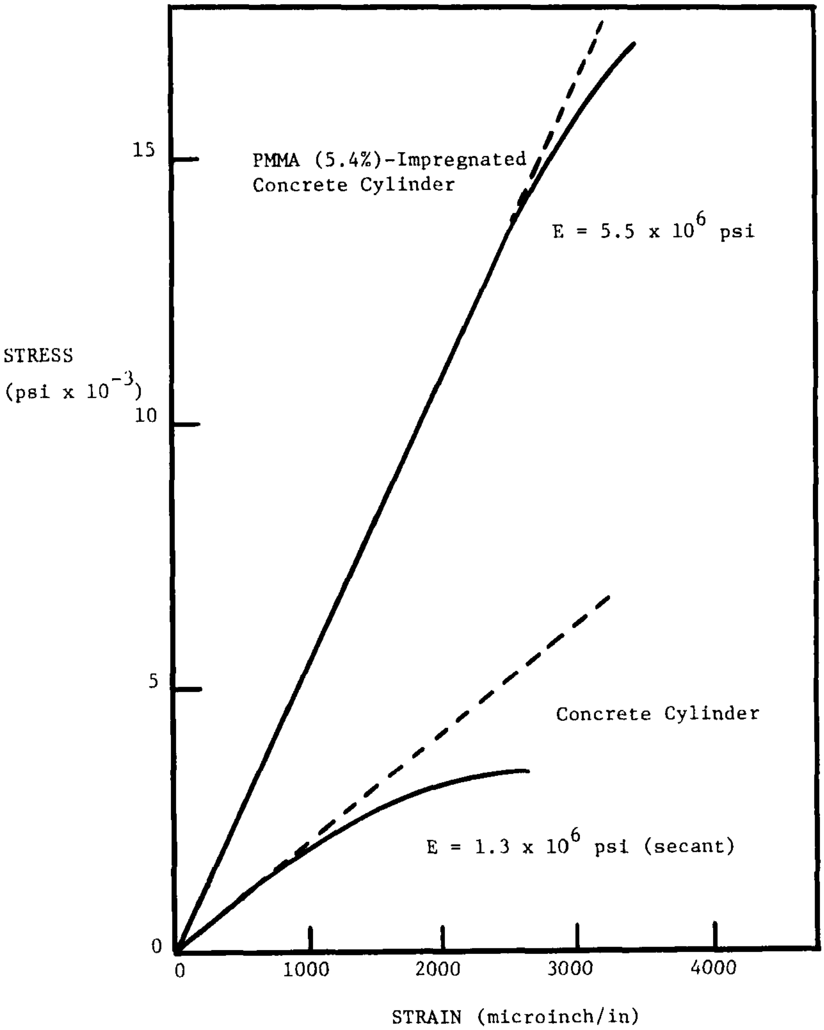
TABLE I
Comparison of mechanical properties of PIC and concrete

Property	Concrete	PIC
Density (D)	156 lb/ft^3	165 lb/ft^3
Compressive strength (C)	5,000 psi	20,000 psi
C/D	32	121
Tensile strength (T)	400 psi	1,600 psi
T/D	2.6	4.7
Elastic modulus (E)	3.5×10^6 psi	6.3×10^6 psi
E/D ($\times 10^{-4}$)	1.9	3.8

2.2 Polymer–concrete composites

Polymer–concrete (PC) composites correspond to concrete in which the cement has been replaced by a polymeric binder.

A typical formulation involves the machine mixing of oven-dried aggregate with the monomer system which is then placed in molds and polymerized at room temperature by a promoter-catalyst technique.[3] The specimens are prepared with 7–8 % monomer by total weight of the wet mix. Depending on the maximum size of the aggregate and the amount of crosslinking agent in the monomer system, the specimens develop average compressive strengths, at room temperature, varying from 18,400 to 20,000 psi, i.e. values approximately



Reference: Kukacka *et al.*, FHWA-RD-75-507 (April 1975).

FIGURE 1 Compressive stress–strain curve for PMMA-impregnated concrete.

equivalent to those of PIC systems. These mixes have produced very consistent specimens with individual strengths that vary $<2\%$ from the mix average.

While the tremendous advances in properties of polymer–concrete systems should inspire investigation and exploitation of new structural applications, it should be recognized that certain inherent limitations must be overcome with these systems. Fundamentally, these involve the temperature, time, and strain dependency on their mechanical properties. Table II illustrates the influence of the former variable while still emphasizing the superior properties of an acrylic–concrete system.

Despite these limitations, it is felt that the selection of monomers and polymers now under investigation has been unduly limited, when one considers the wide range of commercially available polymers, copolymers, and terpolymers. A further fundamental restriction is that, despite some excellent theoretical and fundamental research, the parameters of molecular weight of polymers often has been ignored. This property is directly related to fundamental mechanical properties and to the processibility of the polymers. Considerable attention has been addressed to these considerations in the Russian technical literature.

TABLE II
Properties of polymer concrete
6-inch by 12-inch cylinders

Test	Temperature	Result
Compressive strength[a]	−15°F	24,800 psi
	70°F	19,600 psi
	120°F	15,800 psi[b]
	190°F	14,100 psi
Tensile splitting[a]	−15°F	1,510 psi
	70°F	1,430 psi
	190°F	1,370 psi
Modulus of elasticity[a]	−15°F	6.11×10^6 psi
	70°F	5.28×10^6 psi
	190°F	4.44×10^6 psi
Poisson's ratio[a]	−15°F	0.24
	70°F	0.23
	190°F	0.22
Unit weight[a]	—	149.1 lb/ft^3
Specific gravity[a]	—	2.40
Water absorption[c]	—	0.6 percent

Specimens prepared with 8 percent monomer by total weight. Monomer system consisted of 97.5 percent MMA + 2.5 percent THPTHA.

[a] Average value for three specimens.
[b] Value for single specimen.
[c] Average value for two specimens.

Reference: FHWA-RD-75-507, page 79 (April 1975).

3 APPLICATIONS

A number of applications of polymer–concrete systems are under investigation. The U.S. Office of Saline Water is investigating corrosion-resistant PIC for the construction of desalination vessels for the economical distillation of fresh water from sea water. The U.S. Bureau of Mines is studying the use of PIC for use as inflammable mine supports and for the stabilization of rock formations by polymerization after injection. The U.S. Navy has demonstrated interest in the use of PIC for underwater buoys and habitats. A number of studies have begun in the application of PIC as sewer pipes, tunnel linings, and supports, etc. It is being used for beams and building blocks in durable housing.

Kukacka and others have summarized Federal Highway Administration applications.[4] Federal studies have concentrated on three major areas:

1) Material properties of polymer-impregnated concrete.
2) Repair of deteriorated and delaminated bridge decks.
3) Impregnation (partial) of new bridge deck surfaces.

Efforts in Georgia follow the same outline. Interest focuses on the repair and/or design of more durable bridge decks. The most frequently encountered structural problem has been that of cracked and deteriorated decks. Additionally, the repair and maintenance of critical pavement areas is being studied.

The major deficiencies associated with the use of conventional concrete materials in these applications include high permeability to environmental attack, low strength, cracking, low wear resistance, and spalling. The mechanisms causing deterioration include frost action, differential expansion and contraction, reinforcement corrosion, chemical attack, traffic loads, etc.

These mechanisms can be retarded effectively by use of concrete–polymer composites which extend service life and durability.

The use of polymer impregnation to prevent chloride penetration into bridge decks has been demonstrated in tests performed at FHWA. After 267 daily salt applications, the maximum chloride concentration found at a depth of 1 inch was negligible. On the basis of these results, the use of polymer-impregnated concrete to prevent the corrosion of reinforcing steel with resultant spalling of the concrete appears to be a solution of the bridge deck deterioration problem. Field treatment of a full-size (30 $\times$ 60 ft) bridge deck in Denver, Colorado was performed in late 1974 by the USBR.[5]

Investigators at the University of Texas[6] have had some success in partial impregnation of concrete slabs by using a layer of saturated sand to reduce monomer losses. This technique has been adapted by FHWA and is being used in Georgia.

The State Highway Commission of Kansas has developed a routine resin injection process for the repair of delaminated and cracked structural and architectural concrete. Modification of the process by BNL led to the replacement of epoxy resins with monomers (including promoters and catalysts) which were six times less than the cost of epoxy resin.

Polymer–concrete materials have been used quite successfully for road and runway repair and rehabilitation. A Syracuse University study[7] described a microwave irradiation technique which allowed polymer–concrete to be cured within one hour. A PC placement was made on the Major Deegan Expressway in New York City which resulted in permanent repair within a few hours, using a conventional promoter-catalyst technique—but at the low ambient temperature of 10°C.[11]

Russian engineers and scientists have produced extremely optimistic results, in terms of mechanical properties, chemical resistance, and projected economies for their polymer–concrete materials.

Ivanov attacked the problem of "creep" by studying a furfural-acetone polymer–concrete and he demonstrated that it may be used as a structural material suitable for use in the load-carrying parts of buildings, which take up compressive forces acting for long periods and are subjected to various corrosive environments.[8] He also concluded that parts made of polymer–concrete, subjected to tension and bending, must be reinforced. While he recommended the use of steel rods, late developments indicate that glass fiber reinforcement is promising.

T. M. Fraint[8] reports on the successful use of polymer concretes for the construction of motorways, ships, bridges, etc. in the U.S.S.R. Among his findings, the resistance to wear of polymer–concrete hardened with polyethylenemine was about thirty times greater than that of a control concrete (test conducted with a 42-ton caterpillar-tracked vehicle).

It appears that polymer–concrete materials are being used successfully (both technically and economically) as water-tight "timbering" in potash mines in the U.S.S.R. and, given the corrosive environment, that widespread use is underway for underground structures.[9]

Adams[10] documented various polymer–concrete structures and mechanical devices for promoting highway safety, including highway signs, barriers, medians, breakaway poles and supports, parapets, guard rails, etc.

As Fontana[2] indicates, the batching, mixing, and placing techniques for producing PC in highway applications are largely based on adaptation of existing equipment and methods for Portland cement concrete—with the limitation that non-sparking and explosion-proof equipment be used with the volatile organic compound.

Patuerov[8] describes in detail the optimization of physicomechanical properties of polymer–concretes by varying binder-to-aggregate weight ratios, aggregate grading distribution, deaeration, the effects of pressure and high vacuum *vis-à-vis* the surface tension and cohesive strengths of polymers during the molding process.

A patent application[12] has been filed by the Department of the Interior which concerns the production of polymer–concrete, in essentially the manner described by Fontana. Polymerization is accomplished in 3–5 hours, using methyl methacrylate.

Podagel and Kudzis[13] found that infrared irradiation is an effective means of intensifying the hardening process of polymer–cement composites, making it possible to obtain a high-quality concrete of tempered strength.

While polymer–concrete has not been used extensively in the U.S. for highway applications it has been exploited for use and sale as concrete building panels. PC imparts an outstanding strength-to-weight ratio to a building panel, permitting the designer to use less support structure and fewer fasteners. Whereas cement concrete is often reinforced with steel, commercial polymer concrete uses reinforcing glass fiber cloth. This allows PC panels to be thinner in profile since there is no need to embed the steel in a heavy concrete cover to prevent corrosion.

The prime polymer binders are the polyesters, the epoxies, and acrylic compounds. Performance depends on the service conditions, of course, but for this application certain polyesters have proven to be best.

The use of polymer–concrete in construction materials began in the early 1950s when the Bayer Company of Germany first replaced cement with polymers for architectural building panels. In 1957, R. Prusinski *et al.* developed the first practical PC building material and the first commercial application in 1958. The use of PC-panels on a 14-storey steel frame structure will allow the designer to reduce steel tonnage by at least 11 %. Buildings exposed to the elements for over 18 years showed no visible signs of deterioration of the PC panels, while similar results were observed for 50 years (equivalent) of accelerated weathering tests.

4 DESIGN FACTORS

While it is accepted generally in the United States that polymer-impregnated concrete composites possess tremendous potential for use as structural materials such as in highway bridge systems, the cautionary note is quite appropriately made that PIC is susceptible to catastrophic brittle failure unlike conventional concrete which displays plastic-type yield before failure. With polymer–concrete composites the failure modes may be varied widely, i.e. the designer possesses the ability to select stress–strain properties appropriate to the application and service conditions of a component. Basically, polymer–concrete composites offer the designer a choice of materials which corresponds in mechanical behavior, at least at room temperature, to that of conventional concrete. However, as we mentioned earlier both static, dynamic, and time and strain-dependent properties must be assessed if one is to fully describe and provide the design data necessary for structural components. Temperature dependency and plasticizer effects must be evaluated. The nature of bonding at the polymer–aggregate interface must also be determined and controlled. Organosilanol compounds and other organometallics have been used to improve the bonding strength and chemical resistance at the interface.

There is a real need to classify the viscoelastic behavior of polymer–concrete composites particularly if one is to aim at applying these materials to critical structural application such as highway bridges. It is possible that reliable structures may be achieved by incorporation of high tensile strength, high modulus reinforcing fibers into the polymer–concrete systems. The opportunity also exists to vary the matrix or aggregate moduli in such a way as to alter the fracture mechanism of the composites.

Design programs are available to provide initial approximations on the behavior of polymer–concrete systems. However, their reliability is unknown and it is anticipated that considerable modification will be required. Reich and Koplik[14] at Brookhaven concluded that there was not enough test data to yield a clear-cut theory for polymer-impregnated concrete failure. At this stage of development, one may conclude that the same comment holds true for polymer–concrete composites. But it should be recognized that related studies of composite materials provide a wealthy reservoir of property data which may be used for highway application.

5 ECONOMICS

The economics associated with the introduction of a new material are difficult to project until fairly extensive experience with design and production, as well as actual service conditions have been established. The data on economic analyses of the polymer and concrete composites is scarce.

Steinberg *et al.* completed a cost comparison on the basis of both unit cost and on the cost-to-volume strength ratio (Table III).[1] The advantages of PIC composites are obvious.

In our attempt to make as conservative a projection of materials costs as possible for PIC, we undertook to use the least favorable values available to make a materials cost analysis.

The porosity of concrete is usually between 10 and 20% corresponding to a maximum weight gain when polymer is added of c. 5–10% (N.B. only c. 80% of the porosity of water-cured cement becomes filled with polymer). Using the following unit cost data, which was applicable at the height of the plastics

TABLE III

Materials cost analysis[a]

	Unit cost of material in finished product, cents/lb	Strength-to-wt ratio, psi-ft³/lb	Cost-to-volume strength ratio, cents/psi-ft³
Concrete	3	32	0.09
PIC	6	121	0.05
Steel	15	86	0.50

[a]Compressive strength comparison.

materials shortage, and using a costly formulation (reactive at 10°C) employed for bridge deck repairs,[11] the unit cost (cents/lb) for polymer impregnant is 56 cents/lb.

On the basis, therefore, that 10% of PIC is polymer, and using a unit cost of 1 cent/lb for concrete, we arrived at a figure of 6 cents/lb for the PIC.

While this analysis apparently suggests a negative trend, it does indicate that PIC is at least competitive with the base material when both strength and the fact of thinner sections are considered. An equally important factor, particularly so for highway structures, is the effective increase in longevity of the material. Demonstration projects show, after at least five years, that virtually no deterioration has been observed in polymer-treated concrete structures. It has been shown that buildings featuring concrete/polymer panels have been exposed to the elements for over 18 years with no visible signs of deterioration, while panels subjected to the equivalent of 50 years in accelerated weathering tests have indicated no failure.

The economics are not in fact dominated by materials costs but are significantly affected by production costs of polymer-impregnated concrete.

A cost analysis has indicated that a precast, pre-stressed PIC deck may cost as much as 83% more than a conventional membrane and cast-in-place, asphalt-topped concrete deck. The higher cost was expected to be offset by extended life expectancy and reduced maintenance costs. The analysis included costs of capital investment and additional labor as well as material costs.[2]

In another study,[15] a 40–50% increase in cost was adequately offset by increased durability. Methyl methacrylate was to be polymerized by cobalt-60 irradiation.

The case for the economic feasibility of employing polymer-impregnated concrete as a structural material, e.g. in highway bridge structures has been put forward. It is apparent that there are strong indices to suggest that the material is, on a performance-to-cost basis, superior to conventional concrete. Indeed, partial or full recovery of costs may be realized by improved performance at the extra cost by making thinner sections, by increasing service life, by cutting storage time, and by pre-stressing at higher levels, etc.

What of polymer–concrete composites then?

Since polymer loadings are very similar in both PIC and PC composites, one can expect materials costs to be approximately the same.

For the special formulation (required because of low ambient temperatures) used on the Major Deegan Expressway costs began at $302/yd^3$ and dropped to $260/yd^3$.[11] Estimates for polyester-styrene costed at $170/yd^3$. These costs pertain to those polymers alone, of course, and at a peak shortage period, and for a different application.

The major saving, which has to be very considerable, is in production costs. Polymer–concrete can be produced rapidly by conventional casting techniques of polymer technology, and by using a variety of processing variables to optimize production cycles and material properties. There is clearly no need for forming a pre-stressed, pre-cast conventional concrete block which acts as a massive heat sink in PIC production. The savings in weight adds the advantage of lower materials handling costs, and, perhaps, most importantly, when a thermoplastic binder is used, the material may be re-cycled.

In a comparison of resin–concrete components (epoxy and polyester) with pre-cast concrete slabs, McCurrich and Kay[16] in a cost analysis demonstrated that while polymer–concrete had the disadvantage of high cost (N.B. they used epoxies which were three times as expensive as polyesters), PC composites were faster setting (reduced production time), possessed higher ultimate strengths, lower water absorption, were frost-resistant, abrasion-resistant, and required low maintenance while repair was easy and fast (reduced maintenance costs). These authors described successful use of polymer–concrete for providing a hard edge for expansion joints in black top road surfacing at the edge of bridge decks, and to provide support pads for bridge beams and machinery. They noted that despite the higher cost of polymer–concrete compared to conventional cement mortars, the savings in time in allowing full load transfer to the bearing, more than outweighed the increased material cost.

6 CONCLUSION

Polymer-impregnated concrete (PIC) and polymer–concrete (PC) composites represent a new class of structural materials which have strong technical, design, and economic potential for applications in numerous fields, particularly in highway applications.

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