

Overview of Current Research on Polymer Concrete: Materials and Future Needs

By John A. Manson

Synopsis: As we have become more and more concerned with the conservation of energy and materials, interest has grown in improving the strength, toughness, ductility, and durability of portland cement concrete or in finding replacements that exhibit a superior cost-property balance. Thus one approach has been to improve the properties of concrete itself; another—the subject of this paper—is to combine the two technologies of concrete and high polymers, using not only familiar kinds of concrete but also less familiar ones. It should be noted that combinations of siliceous materials with polymers require in many cases lower energy inputs per unit of performance than either component alone.

The purpose of this paper is to provide an overview of current research and unsolved problems with the various classes of polymer-concrete materials. While a comprehensive review of the literature is not within the scope of the paper, the general state-of-the-art is described, principal areas of research are illustrated with typical examples, and areas needing further research are suggested.

Indeed, significant progress has been made recently in both fundamental and applied research on all kinds of polymer/concrete systems. It is suggested that further progress to achieve sophisticated understanding, design, and materials selection will still require much work in combining the science, technology, and economics involved.

Keywords: concrete durability; concrete technology; impregnating; plastics, polymers and resins; polymer concrete; polymer-portland cement-concrete; polymerization; research; reviews; strength.

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Classes of Polymer-Concrete Materials

As shown in Fig. 1, three principal classes of polymer-concrete materials exist: (1) polymer-portland-cement concrete (PPCC); polymer-impregnated concrete (PIC); and polymer concrete (PC). The distinctions between these classes are important to the selection of materials and to design. With PPCC, a monomer, pre-polymer, or dispersed polymer is incorporated into a portland cement mix, and a polymer network formed in situ during curing of the concrete. With PIC, previously formed concrete is impregnated with a monomer which is subsequently polymerized in situ; here the polymer adds properties to those characteristic of the original concrete. With PC (or resin concrete), a polymer is used to bind an aggregate together. For typical properties of these systems, see Table 1. Polymeric materials used in small proportions for such purposes as water reduction are not usually considered within these classes, but rather are treated as simple additives.

Historical Development of Polymer-Concrete Materials

While several kinds of what are now called PCs and PPCCs (the latter being latex-modified mortars) were in use during the 1950s, major interest in such materials, and in PIC, developed in the middle 1960s (1-3). A major thrust was the desire to obtain improved materials for rigorous applications such as desalination process equipment, water and waste-water pipes, and bridge decks. Both research and development activities accelerated as the 1970s approached.

In 1971, the American Concrete Society formed Committee 548, "Polymers in Concrete", and by the late 1970s the Society had sponsored two symposia on the general topic (4,5) and a state-of-the-art report (1); a manual of recommended practice is also in preparation. Interest has by no means been confined to the U.S.A. Thus, for example, the Concrete Society (London) formed a working group on this topic, and numerous other symposia, workshops, and seminars have been sponsored and articles written throughout the world (6-7). In particular, it is noteworthy that two major international congresses have been held - the first in London in 1975 (13), and the second in Austin, Texas, in 1978 (14). The papers presented by delegates from over 20 countries covered an extraordinarily wide range of research and applications.

Some polymer-concrete materials have already been in use for many years, some are undergoing their first applications, and some are awaiting acceptance by a justifiably conservative technological world. After about 15 years of research and development, enthusiasm for fascinating new combinations of properties has been tempered with a healthy skepticism about whether or not polymer-concrete materials really have a place in engineering applications. Fortunately, even under the cold and impartial eye of cost-effectiveness, there are indeed applications which appear suitable for the unique properties of such materials.

Thus the field appears to have reached a first level of maturity. Older applications are being consolidated into practice and newer ones are being sought. Indeed a major development has been that several major classes of applications have been, or are being, commercialized generally throughout Europe and the Americas. In fact, a reading of Chemical Abstracts reveals that about 150-200 publications on polymer-concrete materials are currently being abstracted each year. Most of them come from a dozen-odd countries, and an increasing number (about one third) are based on patents, thus reflecting a high incidence of tailor-making products for particular applications.

DISCUSSION

Polymer-Impregnated Concrete (PIC)

General State-of-the-Art--The general principles required for impregnation and polymerization of monomers in situ are now reasonably well established (18-21). Provided that most of the water ($\sim 90\%$) is removed by drying, impregnation to levels of, e.g., $\sim 15\%$ by volume of a wide variety of liquids (monomers, solutions, and even liquid sulfur) has been shown to be feasible. While there is still some disagreement about whether impregnation proceeds by a capillary-rise mechanism or a simple diffusion process (18), the impregnation follows a square-root-of-time rate law over most of its course. Consistent with a capillary-rise phenomenon, the rate of impregnation varies with the square-root of the ratio of surface tension to viscosity times the average pore radius, and with the applied pressure. The kinetics of polymerization may differ somewhat from that in bulk, but it is not difficult to achieve an adequate polymerization of many monomers by use of irradiation or thermocatalytic methods. In this way, one obtains an interpenetrating network system comprising cement gel and a polymer that can confer useful properties.

Much emphasis has been given to acrylic monomer systems such as methyl methacrylate (MMA) or acrylonitrile mixtures because the use of these monomers has generally led to superior properties in the composite. Since such liquids have high surface tensions, low viscosities, good wetting properties, relatively low costs, and high reactivities, the empirical discovery of their virtues has a sound physico-chemical basis (18). Epoxies and other viscous monomers have also been used to produce

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rate of impregnation is necessarily reduced.

With impregnation by an appropriate monomer, the principal effect of technological interest is the sealing of the continuous capillary pore system, resulting in exceptional decreases (to $\sim 99\%$) in the permeability to water and to salts such as sulfates and chlorides. Other effects include increases in the coefficient of thermal expansion (to 30%) and thermal diffusivity (to 13%) and a decrease in specific heat (to 17%). The pore-sealing also minimizes changes in properties, e.g., dielectric constant and loss, that are sensitive to moisture content.

Dramatic improvements in abrasion resistance, Young's modulus and in compressive, tensile, and impact strengths (by factors up to about 5) have been noted by many investigators for impregnation with PMMA and other glassy polymers (Table 2), and related to the polymer loading. In general, impregnation with a glassy polymer yields a solid whose strength-strain behavior is linearly elastic almost to the point of failure. However, the stress-strain behavior can be modified from elastic and brittle to ductile by introducing plasticizing comonomers (15). Indeed, the state of the polymer in the pore is important; relaxation studies have shown that reinforcement requires that the polymer be in its glassy state (15).

A fracture-mechanics approach to strength has been used in a few cases to explain the improvement in strength. Using Griffith's equation it has been suggested that reinforcement improves strength by increasing both E and fracture energy, γ , but especially the latter (22).

In any case, the beneficial effects of impregnation may be due to the ability of the polymer: (i) to act as a continuous, randomly-oriented reinforcing network; (ii) to increase the bond between the aggregate and cement paste; (iii) to absorb energy during deformation; (iv) to penetrate and reinforce the micropores; and (v) to bond with the hydrated or unhydrated cement (23).

As a result of the improvements in properties described above, PIC has long been considered as a potential material where properties such as high strength and stiffness, or resistance to corrosion of concrete or reinforcing steel are important. Thus, from the beginning, end-uses such as in bridge decks, pipes, and structural elements have been examined, and a few large-scale applications have been made, especially with bridge decks (1, 4, 5,13,14). The principal limitation is that of cost, for the process is complex, and monomer costs high if more than a surface impregnation is effected.

Recent Research and Development--While the results of impregnations using various vinyl monomers and epoxies continue to appear, some attention has been given to other impregnants such as oligomeric isocyanates (24), ester acrylates (25), silicates



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(26) and sulfur (26a). In general, it seems likely that impregnation yields products having levels of properties not exceeding those of earlier MMA-based PICs. On the other hand, over the past few years, impressive improvement in mechanical properties have been attained by combining the use of autoclaved high-strength concrete with impregnation (27-29) (see Table 1). The use of impregnated aggregates has also been studied recently (30). Earlier, work on the impregnation of other porous inorganic substrates such as gypsum (19) had been reported. More recently, good results have been reported with pozzolan, lime, and slag-based concretes (31). The impregnation of fiber-reinforced concrete has also continued to receive some attention (32,33).

An interesting spin-off from PIC research has been the adaptation of impregnation techniques to the case of non-polymeric sealants such as linseed oil (34) and silane-type materials (35). By eliminating the polymerization step, this approach can offer economies in process costs, and is currently being evaluated further for bridge-deck sealing (36).

Little research seems to be directed towards either the fundamental aspects of impregnation or process improvement, though the possibility of simplifying the impregnation process is being considered at least on paper (36). The occurrence of shrinkage during impregnation has been studied, and shown to be only slightly greater than that noted during the curing of concrete (37). An interesting approach to characterizing the polymerization process in situ has been reported, based on dielectric measurements (38). This technique should be useful in process control.

The modeling of PIC as a composite material has recently been studied (39,40) using a lower bound model proposed by others several years previously. Though the model has been questioned (41), it does seem to give reasonable predictions, after allowance is made for uncertainties in the values for modulus of the polymer actually in the pores. At the London Congress (13), several investigators had discussed the question of the properties of the polymer (e.g., molecular weight, physical state, and polymer-matrix interaction). Recent results (42) suggest that acid-base interactions proposed earlier (43) — interactions between, e.g., Ca^{++} ions and ester groups — may well explain the anomalously high softening point of PMMA in the pores of concrete.

The routine characterization of the depth of partial impregnation, has often posed problems. Promising results using petrographic observations (44) and resistivity measurements (45) have been described. New techniques for predicting corrosion rates in reinforcing steel (35) will also be useful in comparing PIC with other protective systems.

As mentioned above, the attainment of exceptionally high strengths by the impregnation of autoclaved high-strength concrete has now been demonstrated in several laboratories

U. S., Italy and most recently, in Japan (29). In fact the compressive-strength-to-density ratio of this material is nearly three times that of steel. Although Young's modulus is not much greater than with ordinary PIC, the maximum strain at break is significantly increased.

Sulfur-impregnated concrete continues to be of interest, and earlier findings about this were confirmed by several groups (see, for example, ref. 26). However, the deleterious effect of water (45a) is troublesome; attempts to inhibit the interaction between sulfur and Ca(OH)_2 have shown promise (45b).

Surprisingly little has been done on design criteria with PIC. Two exceptions are the development of design criteria for post-tensioned PIC beams (46) and analytical studies of ultimate strength and plastic ductility in PIC beams and columns compared with conventionally reinforced concrete beams and columns (47).

While carefully made PIC offers an unusual combination of excellent mechanical behavior and relative impermeability to deleterious salts, most applications involve "hard cases", in which the gain in service life is believed to offset the high cost, or in which no other material or process appears to be more suitable. Thus, in spite of predictions of many different end-uses (see references cited in ref. 1), relatively few applications appear to have reached commercial practice.

Perhaps the most extensive programs continue to be concentrated on highway bridge decks, and an increasing number of impregnations are being conducted by contractors, in collaboration with the Federal Highway Administration (48). Although most of these have involved the shallow impregnation of new decks to hinder the penetration of deicing salts, one project, sponsored by the National Cooperation Highway Research Program (49), demonstrated the feasibility of deep impregnation of salt-contaminated decks in order to delay the onset of corrosion. This project has continued (36), though it is no longer restricted to the polymer-impregnation approach.

Another major area of current interest is in hydraulic structures in which PIC's strength and abrasion resistance makes it an ideal candidate as a material for such applications as spillways and stilling basins (50). PIC is also being used, at least from time to time, in the restoration of structural elements and floors in deteriorated buildings (51). A program of research into PIC for such applications as pipes and storage tanks is being supported in India through the United Nations Development Program. Another example of application is in the use of PIC to contain radiation wastes (52). PIC also shows considerable promise for marine applications (35); in a recent study, PIC pilings showed much less corrosion after prolonged exposure to sealants than controls (53).

Polymer Concrete (PC)

General State-of-the-Art--With PC, a thermoplastic, or more commonly a crosslinked polymer, is used to replace Portland cement as binder in a concrete mix. Since the polymer constitutes the continuous phase, behavior of the composite will clearly be determined by the polymer, whose properties are, of course, very dependent on time and temperature.

A wide variety of monomers, prepolymers and aggregates has been used. While epoxy resins are commonly used in PC, much attention has been focussed on the use of cheaper vinyl monomers such as polyester-styrene, MMA, furane derivative and styrene, usually in conjunction with a crosslinking agent (55,56). Setting times and times for development of a high proportion of maximum strength can be readily varied from a few minutes to hours. Bond strengths to substrates are also usually high. In spite of high cost, PC is particularly useful for maintenance and repairs, especially when delay and inconvenience are important factors (56). Thus the cost/benefit ratio is favorable (Table 1).

By carefully grading the aggregate it is possible to wet the aggregate and fill the interstices by the use of as little as 7-8 wt. % ($\sim 14 - 16$ vol. %) polymer (55). With high packing densities, high compressive strengths can be obtained (Table 1). Flexural strengths, though much higher than for concrete, are limited by the aggregate-matrix bond strength and by asperities in the aggregate, which can introduce stress concentrations. The use of silane coupling agents has been shown to improve compressive strength, presumably by improving bond strength. In general, as with glass-reinforced composites, strengths tend to be reduced by exposure to water, presumably because of deterioration of the aggregate-matrix bond. With proper selection of materials, the dielectric properties characteristic of good insulation can be achieved.

The deformation response of PC is highly variable with elastic moduli ranging up to about 35 GPa for a rigid matrix with a tensile failure strain of $<1\%$; of course, moduli are much lower, and failure strains much higher, for rubbery matrices. It should be noted that shrinkage strains vary from polymer to polymer (high for polyesters, lower for epoxies), and must be considered in any application; such strains may, if not relieved by creep, result in premature failure in a rigid PC. Since a polymer constitutes the continuous phase, it is not surprising that creep is generally higher than for concrete, and enhanced at high temperatures.

The versatility in formulation and in processing has led to many applications in the past, including flooring, cast articles of various kinds, patching, and overlays for highway bridge decks (3,4,13).

Recent Research and Development--Of the 3 classes of poly-



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mer-concrete systems, PC is currently attracting the most attention, at least in the U.S. A major reason for this is the realization that economies of scale can be achieved by continuous rather than batch processing (57). This fact has long been known in Europe, but is only now being fully appreciated in the U.S. Thus while continuous processing of cultured-marble units has been practiced for some time, most other applications have involved batch operations, typically on-site. A second major development in the U. S. has been the rapid development of tailor-made PCs for various uses; indeed an increasing number of companies now offer a range of formulations, many in prepackaged form (57). As these trends continue, and as the need for sophisticated product design and development increases, we may expect to see more intensive basic research as well.

While new formulations continue to appear (for reviews, see ref. 58a), and mix design has been studied systematically (58b), both scientific and engineering research on PCs has been limited in scope. A notable exception has been research associated with the development of PCs for geothermal applications, where the extreme service conditions place exceptionally severe demands on the maintenance of properties at high temperature in an aggressive medium (58-61). Dental and bone cement materials constitute another example of an application posing severe materials problems (62,63). Still another example is the need for patching systems that can cure rapidly and bond to a wet substrate (64).

Thus, much of the recent published research on new monomer systems and on properties and behavior has been stimulated by the applications mentioned. (Presumably much proprietary research has gone on as well.) In the BNL research on geothermal materials, many copolymer systems, both thermoplastic and thermosetting, have been, or are being, studied. Monomer systems include various combinations of divinylbenzene, triallyl cyanurate, siloxanes, various methacrylates, and acrylamides (58-61a). While aggregates such as quartz, silica, fly-ash and portland cement give composites serviceable up to $\sim 220^{\circ}\text{C}$, a combination of silica sand with portland cement is required for use at higher temperatures. The benefits obtained by including portland cement have been noted in other research as well (63). The basic chemistry of the interfacial interactions is under study; the formation of ionic bonds between Ca^{++} ions and carboxylate groups appears to be involved (65-68). Such ionic bonds also provide the basis for the so-called ionomer cements recently developed in the UK as dental cements (61b), and have been suggested to occur in PIC as well (69). With respect to dental cements, at a recent symposium on dental materials sponsored by The American Chemical Society, current research on a wide variety of acrylic and other monomers many containing specialized functional groups was reviewed (62). Research on monomers that can bond effectively to wet substrates is under way at BNL and the University of Texas as part of a program for the development of methods for the rapid repair of aircraft runways.

In all these cases, fundamental knowledge of the chemistry

of the binder and aggregate and the surface chemistry involved in binder-aggregate interaction is required. While such knowledge is not necessary for PCs used in many structural applications it is clearly important in more demanding cases. In addition to the examples mentioned, the use of PCs in load-bearing applications subject to a combination of high stress (static, cyclic or impact) and an aggressive environment (water, high temperature, chemicals) will require a sound base of research. Surface chemistry is also important to demolding. Research into both the physical and chemical factors that can cause failure in PCs has been very helpful in the case of polyester composites (69a).

In spite of the knowledge that creep can be high in PCs, there have been few recent studies. However, at least for an epoxy-based PC (63) it has been recently shown that the viscoelastic behavior was linear at low loads [up to 3ksi] (21MPa). The effects of higher loads are under study. Another important point to note is that in contrast to portland cement concrete, creep in PC is not reduced when the specimen size is increased. This reflects the difference in creep mechanism, that of the polymer involving molecular (segmental) motions. Interestingly, the creep of the PC at given load was only slightly higher (~30%) than that of a typical PCC.

Some research on static and fatigue fracture in bone cement has been reported (70-72). A beneficial effect of carbon fibers has been observed (70), and some environmental studies have been made (72).

Research is also in progress on the ability of PC overlays to minimize the corrosion of reinforcing steel (35), and on bonding to the substrate. The new technique developed by the FHWA (35) for prediction of corrosion rates will be helpful in comparing PCs with each other as well as with other protective systems. Dielectric behavior continues to be of interest, as PC is a candidate for the replacement of porcelain in high-voltage insulators (73-74). The combination of facile processing, good insulating qualities, and high fracture toughness is indeed attractive.

As with PIC, highway applications have received much attention (75). Thus the FHWA Implementation Division has encouraged a large number of trials with PC overlays on bridge decks (35,48), and published a user's guide. Indeed, so far the overlays have performed well. The NCHRP has also included PC within the scope of a current program (36). Patching has been of interest for quite a few years (76); as mentioned above, one of the most recent applications is in the rapid repair of aircraft runways (64). PC has been successfully applied to the renovation of structures, both buildings and dams (50,51), and is being evaluated in pilings (35). PC is also to be used in rehabilitating roadbeds of railway lines in the Northeastern corridor. Much successful experience in highway applications in Germany has been reviewed (77).

Miscellaneous applications include: various kinds of panels and tiles, cultured marble, pipes and liners, flooring, pilings and sanitary ware (54, 57). Current potential applications in electric utilities include: tunnel segments, conduits, support structures, and as mentioned above, high-voltage insulators (78). Examples of other extremely demanding applications such as materials for dental and bone cements and geothermal applications have already been given.

Polymer-Portland Cement Concrete (PPCC)

General State-of-the-Art--From the standpoint of process technology, this most obvious approach is attractive.

Unfortunately typical vinyl monomers such as MMA or styrene either interfere with the hydration of the cement or one degraded by the high alkalinity present (21). Prepolymers such as polyester-styrene and epoxies can be effective, though fairly high proportions are usually required if mechanical properties are to be improved. However, most attention has been given to the incorporation of a polymeric latex. In this case, the physical process of film formation is required rather than the chemical process of polymerization. Also, since the emulsion lubricates the mix, less water is usually needed for workability, so that the optimum water content from the standpoint of final properties can be approached. In fact, polymer latexes—usually of acrylics, styrene-butadiene copolymers, poly(vinylidene chloride), epoxies, and poly(vinyl esters)—have been used in mortars and concrete for about 45 years.

In general, latex-type PPCs exhibit excellent bonding to steel reinforcement and to old concrete, good ductility, resistance to penetration by water and salt, and excellent durability to freezing and thawing. Not surprisingly, the precise balance of properties depends on the nature of the polymer and its concentration. While flexural strength and toughness are usually increased, the modulus may or may not be increased; the more rubbery the polymer, the lower the modulus.

Several factors are apparently involved in improving properties the reduction in water-cement ratio and, hence, in the volume of capillary porosity; the entrainment of air as a fine dispersion; specific interactions with the cement gel; and specific properties of the polymer, for example, toughness. More specifically, the following requirements for the polymer are believed to exist:

(1) The latex must be able to form a film under ambient conditions, to coat cement grains and aggregate particles, and to form a strong bond between the cement matrix and the aggregate.

(2) The polymer network must possess the capacity to intercept a growing microcrack and, by dissipating energy through microfibril formation (across a crack without separation from the

crack walls), hinder crack propagation.

Actual bonding between Ca^{++} ions and polymer appears to exist. It has also been shown that the latex particles coat the cement gel and aggregate surfaces with a monolayer, which eventually coalesces as the various particles come into contact. Thus, evidently some kind of composite action is involved, not just the reduction made possible in capillary porosity.

The most common applications have been in mortars, patching compounds, flooring, and overlays for bridge decks.

Recent Research and Development--The most common latex systems have been based on copolymers of styrene-butadiene, vinylidene chloride, and acrylics. The use of self-emulsifying epoxies is also of current interest. Poly(vinyl acetate) is used to some extent, though the products are sensitive to moisture. Other systems described recently have been based on vinyl chloride copolymers (79), natural rubber (52), nitrile rubber (80), and aldehyde-type resins (81). High strengths have been reported for systems based on PMMA emulsions (82); these systems required heating to effect film formation. Ordinarily the selection of latex and the maximum properties obtainable are limited by the requirement that the polymer be film-forming. By effecting film formation at an elevated temperature, a wider range of properties and products should be attainable.

Earlier findings that the use of monomers per se tends to yield low quality PPCCs have been confirmed with a number of monomers (83). However, some fundamental research on latex-based PPCCs has led to some important conclusions. In a study of mortars and concretes incorporating a vinylidene-chloride-based emulsion system (84) the effects on the aggregate-mortar interface were examined, as well as the effects of PMMA polymerized in situ and of a de-adhesion agent. Equations were developed to predict the strength and modulus of the concrete in terms of the mortar properties, adhesion and the friction angle. While strength was affected by the adhesion, the property of the mortar itself was dominant. In another study of latex systems (85), it was found that the presence of the polymer results in a significant increase in the cracking stress and strain of the concrete, and an increase in creep. It was also noted that dry curing was especially favorable. Creep and shrinkage of a styrene-butadiene latex system has been recently measured (86); the values of 120% and 240% higher than for controls.

Latex-based PPCC continues to be evaluated as a bridge-deck overlay (87); in general, experience has been quite favorable. Trials of these materials as pilings are under study by the FHWA (35).

Problem Areas

While some progress in research has been made since the

author's critical review in 1977 (21), much of the research has been developmental in nature as commercialization has begun to take a firmer hold in the U.S. There is still a need for good basic and engineering research in several areas. Several examples follow.

(1) If we are to develop adequate predictive models (of a kind commonplace in the composites industry), we need to know more about the chemistry of our system. In particular, such topics as the interfacial chemistry, curing phenomena, fire resistance, and degradation/stabilization mechanism are especially important.

(2) Much more needs to be known about mechanical behavior, e.g., fracture toughness, fatigue resistance, and creep. For sophisticated application, the design engineer needs to know such fundamental parameters. All these phenomena need to be correlated with the chemistry. Of particular importance are the effects of severe environments coupled with mechanical stress.

(3) Cost-effectiveness needs to be carefully documented or, if this is not possible, estimated in an objective manner. Models that could be adapted to deal with polymer-concrete systems exist, and should be tried. Effects to standardize performance tests should be continued.

Thus, the chemist and the engineer (chemical, civil, materials, design), still must collaborate in bringing together the science, technology, and economics. If this can be effected properly, the prospects for society's gain by combining polymers with concrete in imaginative and useful ways will be dramatically enhanced.

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TABLE 1. TYPICAL PROPERTIES OF
POLYMER/CONCRETE COMPOSITES (2-4,14)

	PCC	PIC	PIC(A) ^a	PC	PPCC
Compressive Strength, psi ^b	5,000	20,000	39,000	19,000	5,500
Tensile strength psi ^b	350	1,500	2,100	1,400	800
Young's modulus psi ^b x10 ⁻⁶	3.5	6	7	5	2
Shear strength, psi ^b	125	---	---	≥650	≥650
% water adsorption	5.5	0.6	≤0.6	0.6	---
Freeze-thaw resistance	700/25	3,500/2	---	1,600/0	---
Acid resistance ^d	---	10X	≥10X	>20X	4X
Benefit/cost	1	2	3	4	---

^aBased on autoclaved concrete.

^bConversion: 1 psi = 7kPa.

^cNo. of cycles/% wt. loss.

^dImprovement factor.

^eAn approximate, estimated figure of merit.

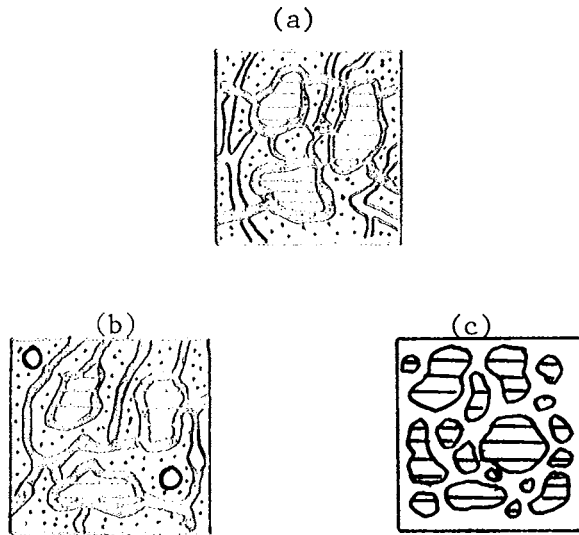


Fig. 1--Schemata for (a) polymer-portland cement-concrete, (b) polymer-impregnated concrete, and (c) polymer concrete (not to scale). Crosshatched areas represent aggregate particles; open and polymer-filled capillary pores are shown in (a) and (b); dots represent gel pores, some of which are polymer-filled in polymer-impregnated concrete

Use of Concrete Polymer Materials in the Transportation Industry

*By Jack J. Fontana
and John Bartholomew*

Synopsis: Every segment of the transportation industry is experiencing maintenance problems with rapidly deteriorating portland cement concrete structures. The Federal Highway Administration, aware of such problems, has sponsored research and development work to find a rapid-setting durable composite that can be used to repair deteriorated concrete and/or to effectively reduce chloride and moisture penetration into concrete.

Keywords: bridge decks; concrete construction; corrosion; deterioration; durability; field tests; impregnating; maintenance; patching; polymer concrete; portland cements; repairs; resurfacing; strength; transportation.

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John Bartholomew, for the past four years, has headed the Federal Highway Administrations polymer program within the Office of Development and is responsible for materials development and field testing of concrete polymer materials for highways and bridges. He is currently a member of ACI Committee 548, Polymers in Concrete.

INTRODUCTION

Deterioration of concrete bridge decks is generally caused by chloride induced corrosion of reinforcing steel which results in cracking and spalling of the concrete because of the volumetric increase of the corroded steel. Environmental exposures, such as freeze-thaw cycling, and high wheel loadings are also prime factors in the deterioration of concrete bridge decks, pavements, and runways. The high maintenance costs, the public inconvenience, and the safety hazards associated with concrete repairs have resulted in a concerted effort by the Federal Highway Administration (FHWA) to develop a durable, rapid-curing patching material and an impermeable skid-resistant overlay material.

Under contract to the FHWA, Brookhaven National Laboratory has developed a polymer concrete patching material that combines the premix characteristics of PCC with strength and durability properties that are higher than PCC. PC overlays have been shown to be highly impermeable to water and chlorides. Laydown techniques have been developed to allow bridge maintenance crews to place the overlays with little or no problems.

Today several manufacturers are marketing PC materials, and their acceptance is becoming widespread.

DISCUSSION

The deterioration of portland cement concrete bridge decks and pavements has in recent years become a major maintenance problem. Concrete deterioration is influenced to some degree by the quality of the concrete, loading conditions, and environmental exposure. The primary causes of deterioration, however, are freeze-thaw cycling and spalling of concrete due to the accelerated corrosion of reinforcing steel caused by the extensive use of deicing salts.

Concrete with its open-pore structure is permeable to water and other chemically reactive fluids. Therefore, when deicing salts are used on bridge decks, the chloride ions penetrate to the reinforcing steel and accelerate the corrosion of the steel. The corrosion products result in an increase in volume of the steel reinforcement which causes cracking and spalling of the concrete. In the same manner water, which has permeated the concrete, expands upon freezing and causes stresses within the concrete which lead to cracking and spalling.

In recent years the use of air-entrained concrete has relieved some of the problems associated with freeze-thaw deterioration, and epoxy-coated reinforcing steel has relieved most of the corrosion problems. Older concrete structures, however, continue to decay and highway maintenance costs are soaring. A recent study indicated that one of every six bridges in this country is in need of repair, (1) and replacement costs for these structures could be as high as 25 billion dollars.

The high maintenance costs, the public inconvenience, and the safety hazards associated with the repair of deteriorated concrete have resulted in a concerted effort by the Federal Highway Administration (FHWA) to develop a long-lasting, rapid-curing patching material and a skid-resistant impermeable overlay material.

Other segments of the transportation industry such as commercial and military airport runways as well as the railroad industry can also utilize the materials developed for the highway industry. Commercial airport runways are showing signs of wear and decay, due in large extent to the bigger and heavier airplanes used today. Repairs must be effected rapidly to avoid closing down available runways. Military runways are under constant threat of bomb damage during wartime. Therefore, both commercial and military airports would benefit from quicker-setting and longer-lasting patching materials than have been available to them in the past. The Federal Railroad Administration (FRA) is investigating the possible use of rapid-setting patching materials to repair or replace track beds in areas where service delays cannot be tolerated, such as the Northeast corridor.

Considerable success has been achieved at Brookhaven National Laboratory (BNL) under contract to FHWA in the development of a polymer concrete (PC) patching material.(2, 3) PC consists of an aggregate system mixed with a monomer mixture that is subsequently cured in situ. PC composites combine the premix characteristics of portland cement concrete with a unique set of properties. These include (a) rapid curing at ambient temperatures, (b) high strengths, (c) good adhesion to concrete surfaces, (d) long-term durability to freeze-thaw cycling, and (e) low permeability to water and deicing salts. As a result of these characteristics, PC appears suitable for use in the repair of concrete structures where traffic (auto, air, or rail) conditions restrict closing of the repair site to only a few hours.

In recent years several commercial manufacturers have introduced PC prepackaged patching materials that are gaining acceptance as a concrete maintenance material throughout the United States. These materials exhibit the same unique set of properties previously described. Although the initial material costs are high, significant savings in downtime of bridges, roadways, runways and railroads show that PC is cost effective.

In addition to PC patching materials, PC overlay materials (4, 6) have been used on bridges in several states and these have also performed well. There are three types of overlay placements presently being evaluated.

A thin PC overlay which is placed by building up alternating layers of monomer and aggregate has been shown to be highly impermeable to the penetration of water and deicing salts. In addition, this overlay provides a good skid-resistant surface and thus can be used to restore the skid resistance of polished pavement. This type of overlay has been placed manually and with semi-automated equipment, generally with equally good results. Vinyl esters, polyester, and epoxies have been used as the monomer for this type of overlay.

Premixed PC overlays incorporating vinyl ester or polyester resins have been placed using concrete paving machines. The overlays are impermeable and bond well to cleaned concrete surfaces. Some shrinkage cracking has been noted to date but, modifications of the resins should eliminate this problem in the future.

Other premixed PC overlays featuring methyl methacrylate or epoxy and placed by hand, are presently being evaluated. These overlays are generally placed 0.64 to 1.27 cm thick and are screed finished. Laboratory evaluation indicates that the bond strength to concrete and the resistance to wear is very good. When placed properly the permeability is acceptable. However, skid-resistance measurements have not yet been made in the field.

Concrete surface impregnation, using mixtures of acrylic monomers, was shown to be an effective way of sealing concrete to water and chloride penetration in the laboratory. The Bureau of Reclamation and the University of Texas independently developed process techniques to impregnate bridge deck surfaces.(7) To date, 14 bridge decks in 9 states have been impregnated and are presently being evaluated. Chloride ponding tests of cores taken in the field have indicated that the concrete immediately below the impregnated zone (1.25 to 2.54 cm) has a high chloride content ($\sim 1.5 \text{ kg/m}^2$). At this time it is believed that drying the concrete prior to monomer impregnation causes minute cracking of the concrete or enhances shrinkage curing cracks that are already in the concrete, thus allowing chloride penetration past the impregnated zone.

FIELD APPLICATIONS

Field placement testing of polymer concretes (PC) containing polyester-styrene (PES) and mixtures of methyl methacrylate (MMA) and trimethylolpropane trimethacrylate (TMPTMA) have been in progress for over seven years, and to date detrimental effects have not been noted. One of the first major applications (8) of PC patching was on the Major Deegan Expressway, Third and Lincoln Avenue Viaduct in the lower Bronx, New York City. The structure is an 8-span steel stringer bridge with a non-composite reinforced concrete deck and two 39-ft-wide (11.9 m) roadways separated by a 4-ft (1.2 m) median.

Damage to the bridge resulted from pavement shove which crushed the deck at the center of the bridge and created a hole ($\sim 0.6 \times 6.1 \text{ m}$) in the southbound roadway and one ($\sim 0.6 \times 9.2 \text{ m}$) in the northbound roadway. Each hole extended through the 38.1-cm-thick deck. As a temporary repair the holes had been covered for 3 years with 2.54-cm-thick steel plates and asphalt.

Wooden bulkheads were constructed to divide the holes into smaller sections and plywood forms treated with a release agent were placed between the stringers under the holes from beneath the deck (Figures 1,2). The forms were sealed with caulking compound to make them watertight to eliminate monomer drainage. A dried well-graded crushed limestone and silica sand aggregate was used in the PC mixed for the structural repairs.

Two monomer systems, 95 wt% MMA - 5 wt% TMPTMA and 54 wt% polyester - 46 wt% styrene, were used in those repairs. The former was used in the three PC placements on the northbound lanes. The polyester-styrene mixture was used in the southbound lanes.

The PC was mixed in a conventional-type skip-loader concrete mixer (Figure 3). After the aggregate and monomer had been mixed for about 2 to 3 minutes, the composite mixture was

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placed in the area to be repaired and was hand tamped or vibrated with a stinger for compaction (Figure 4). Finishing was accomplished using a hand-screed and/or steel trowel. The PC cured in ~1 hr and traffic was allowed to resume over the patched areas in about 2 hr.

Compression strength and water absorption tests were performed on cylinders cast during the placement of the methyl methacrylate and polyester PC. The former had an average compressive strength of 102 MPa and the water absorption was 1.5%. The polyester PC measured had an average strength of 53 MPa and a 1.0% water absorption.

Cores taken from the acrylic PC after 10 months in service had an average compression strength of 60 MPa and a water absorption of 1.1%, and good bonding to the adjacent concrete was evident. Cores taken from the polyester PC after 64 months' service had an average compressive strength of 56.5 MPa and water absorption of 0.94%.

In August 1976 the Minnesota Highway Department, with assistance from BNL, placed approximately 46.5 m² of shallow (~5.1 to 7.6 cm) PC patches on the 94th Street overpass (Minneapolis) of Interstate Highway 35 W. Spalling of the concrete deck due to corrosion of the reinforcing steel made the repairs necessary.

The deteriorated concrete was removed with chipping hammers. The top layer of reinforcing steel was exposed and sound concrete reached (Figure 5). The exposed surface of concrete and the reinforcing steel were sandblasted and air dried prior to the PC repair operation.

The repairs were made with PC made with local graded aggregates and monomer mixtures of MMA and TMPTMA (95 wt% - 5 wt%). Ambient temperature curing was obtained using benzoyl peroxide 70 (BPO 70) initiator and dimethyl aniline (DMA) promoter.

Two methods of applying of PC patches were used. One method used predried, graded aggregate placed and tamped in the patched area (Figure 6). Volumetric quantities of initiated, promoted monomer were then sprinkled over the aggregate until it was completely saturated (Figure 7). The area was screeded and troweled (Figure 8) and allowed to cure. The remaining patches were made by premixing the aggregate and monomer in a concrete mixer (~0.1 m³ capacity). The mixed PC was placed in the areas to be patched and then finished.

The repaired areas were checked with a DeLam Tech every year for three years and no evidence of disbonding was found. The surfaces of the patched areas were wearing well but did show evidence of some peripheral cracks near the bond line and some cracks through the larger patches. A visual inspection by FHWA

personnel in July 1980 indicated that the patches were still well bonded to the concrete and wear was unnoticeable (Figures 9,10). The cracking had not increased and the patching was deemed acceptable.

During the summer of 1978 and spring of 1979, 103 pavement cracks were repaired with PC on Interstate Route 64 near Huntington, West Virginia. The cracks extended the full width (~7.3 m) of the 23-cm-thick concrete pavement. The cracks, generally referred to as third-point cracking, were spaced approximately 6 m apart. The PC formulation used was the same as that defined in Implementation Package 77-11, Polymer Concrete Patching Materials, Volume 1, Users' Manual. The aggregates used were obtained locally; however, during the course of the repair the gradations were changed five times because of the availability of the aggregate.

Saw cuts were made on both sides of the crack (~7 to 10 cm deep) into good concrete (Figure 11). The deteriorated concrete was then chipped out. Compressed air was used to dry the exposed concrete surface. In some cases a propane-fired weed burner was used to dry any extremely wet concrete.

The PC was mixed in a concrete mixer, transferred to a wheelbarrow, and placed in the repair area. Consolidation was obtained by tamping, and the surface of the repair area was screeded and troweled (Figures 12,13). A total of 23 m³ of PC was used to repair the 103 cracks.

Because of several changes in the aggregate gradation, ~10% of the repairs exhibited surface erosion to a depth of 1.3 to 6.4 cm. In September 1979 eleven patches were repaired with a prepackaged PC material developed at BNL. The surfaces to be repaired were sand blasted to remove loose debris and road film. A tack coat was applied to the exposed PC surface to be repaired and allowed to cure. The PC mortar was mixed by hand in buckets and placed directly into the repair areas. Finishing was by hand with wooden screeds and trowels. The repaired areas have been in service since then without any recurring problems.

In October 1978 the NYS DOT placed a thin polymer concrete overlay on the eastbound Manorville overpass, on NYS Route 495, Manorville, New York. The bridge is a 1003-m² three-span structure consisting of steel I-beams and a reinforced concrete deck.

The overlay consisted of three alternating layers of polyester resin (LB183-13) and silica sand per layer. Silica sand normally passing a sieve opening of 1.41 mm and was retained on a 1.00-mm sieve opening was used in the first layer. The second and third layers used a sand that passed a sieve opening of 2.38 mm and retained on a sieve opening of 1.41 mm.

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Delaminated and unsound concrete was removed and repaired with a PC patching material. The entire bridge deck was then sand blasted to remove oils and tars and expose a clean dry concrete surface.

The resin was applied to the deck using a pressurized distribution system with a spray nozzle (Figure 14). While this system worked with some degree of efficiency, it did not allow for a uniform distribution of resin over the deck. Therefore, it was necessary to spread the resin over the deck using street brooms. The aggregate was broadcast with an automatic spreader mounted on a flat bed trailer. The sand was moved from the hopper to the spreading trough with a screw and was broadcast by a rotating rubber covered roller (Figure 15). The spreader can be rotated 180° on the trailer bed to broadcast sand from either side of the trailer. The aggregate was compacted into the resin using a pneumatic rubber-tired roller (Figure 16).

A total of 6350 kg of resin was used in placing the overlay. The final thickness of the overlay has a nominal thickness of 1.25 cm. Skid trailer measurements were made by NYS DOT and SN of 55 to 65 were obtained at speeds of 56.3 to 88.5 km/hr. Skid measurements taken 1 yr later showed reductions of ~10%. To date the overlay has shown no indications of wear, and the skid resistance and the bond strength to the concrete substrate are still high.

Since then similar overlays have been placed in Georgia, two additional ones in New York, New Mexico, Idaho, and Oregon. One of the overlays in New York was placed and paid for with NYS DOT maintenance personnel and funds. The other overlays mentioned were all placed with state personnel and are part of an FHWA implementation program.

Thin premixed PC overlays using commercially available materials were placed in November 1979 by several manufacturers on Interstate Route 80 eastbound truck lane to Donna Pass in California (Figures 17,18). PC was mixed by hand and spread over a Blast-Trac prepared concrete surface. Screeds, magnesium, or wood were used to finish the PC surface at the desired height of ~1 cm thickness. These overlays were placed in an effort to evaluate the commercial PC materials for studded tire wear resistance. The participating manufacturers were Adhesives Engineering of California, Dupont of Delaware, and Transpo-Materials of New York.

In May 1979 Dural International and Transpo-Materials, both of New York, placed thin PC overlays on the 59th Street bridge between Queens and Manhattan in NYC. This deck was a steel-grid concrete-filled deck. The concrete has begun to wear below the steel-grid surface, and the deck is slippery. Dural placed both a methyl methacrylate and an epoxy PC (Figures 19,20) while Transpo-Materials placed its methyl-methacrylate-based PC. All of the overlays have performed well to date in that the overlays

are well bonded and have not worn noticeably. The sections are too short to perform skid measurements.

The impregnation of concrete bridge deck surfaces with MMA-TMPTMA monomer mixtures has been carried out in 9 states across the country. Most of the impregnations were sponsored by FHWA with technical assistance being provided by the Bureau of Reclamation or the University of Texas at Austin.

The process includes four major steps: (a) drying the concrete surface, (b) allowing the surface to cool to 39°C or less, (c) soaking the concrete with the impregnant and (d) curing the impregnant in situ. At the first bridge site (Cherry Hills Village, Colorado) this cycle took 122 hr. As experience was gained in the field and modifications were made to the equipment used, the process time for a cycle was reduced to less than 40 hrs. Costs have ranged from \$8.33 to 83.33/m². One of the latest surface impregnations was performed in Gallop, New Mexico, at a price of \$21.67/m².

CONCLUSIONS

The properties of PC make it suitable for the repair of concrete structures and for the placement of impermeable, skid resistant overlays. PC patching and premixed overlays can be cast in place and will cure rapidly over a wide range of temperatures (0° to 38°C), develop high strength in a few hours, and bond well to portland cement concrete. The thin sand-filled overlays placed to date have shown excellent skid-resistant properties and good bonding characteristics to concrete. It appears that impermeable PC overlays will help extend the life span of even salt-contaminated bridge decks.

Polymer impregnation of concrete surfaces has not yet proved to effectively seal the entire bridge deck. Hairline cracks through the impregnated zone allow chlorides to pass through the impregnated zone and are concentrated generally near the top layer of reinforcing steel.

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Fig. 1--Full depth hole in bridge deck prior to filling with polymer concrete

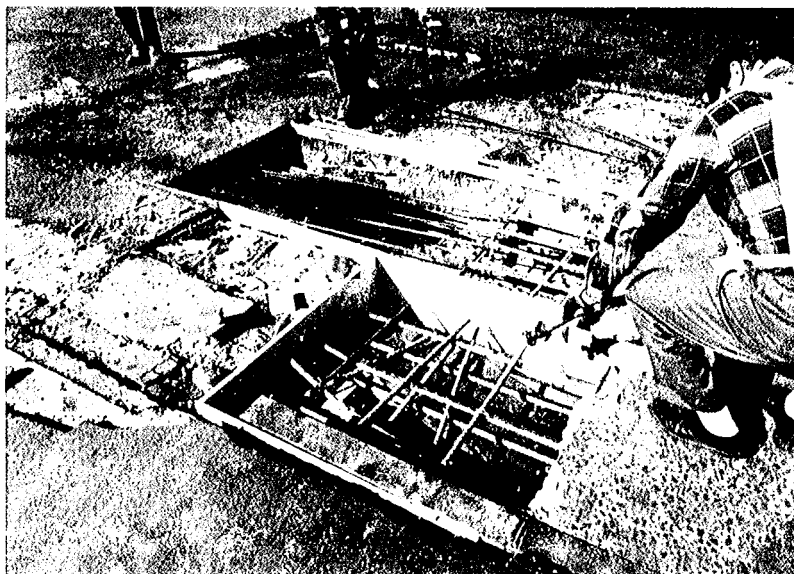


Fig. 2--Full depth hole in bridge deck prior to filling with PC



Fig. 3--Placement of PC for full depth repair



Fig. 4--Compaction of PC using finger vibrator

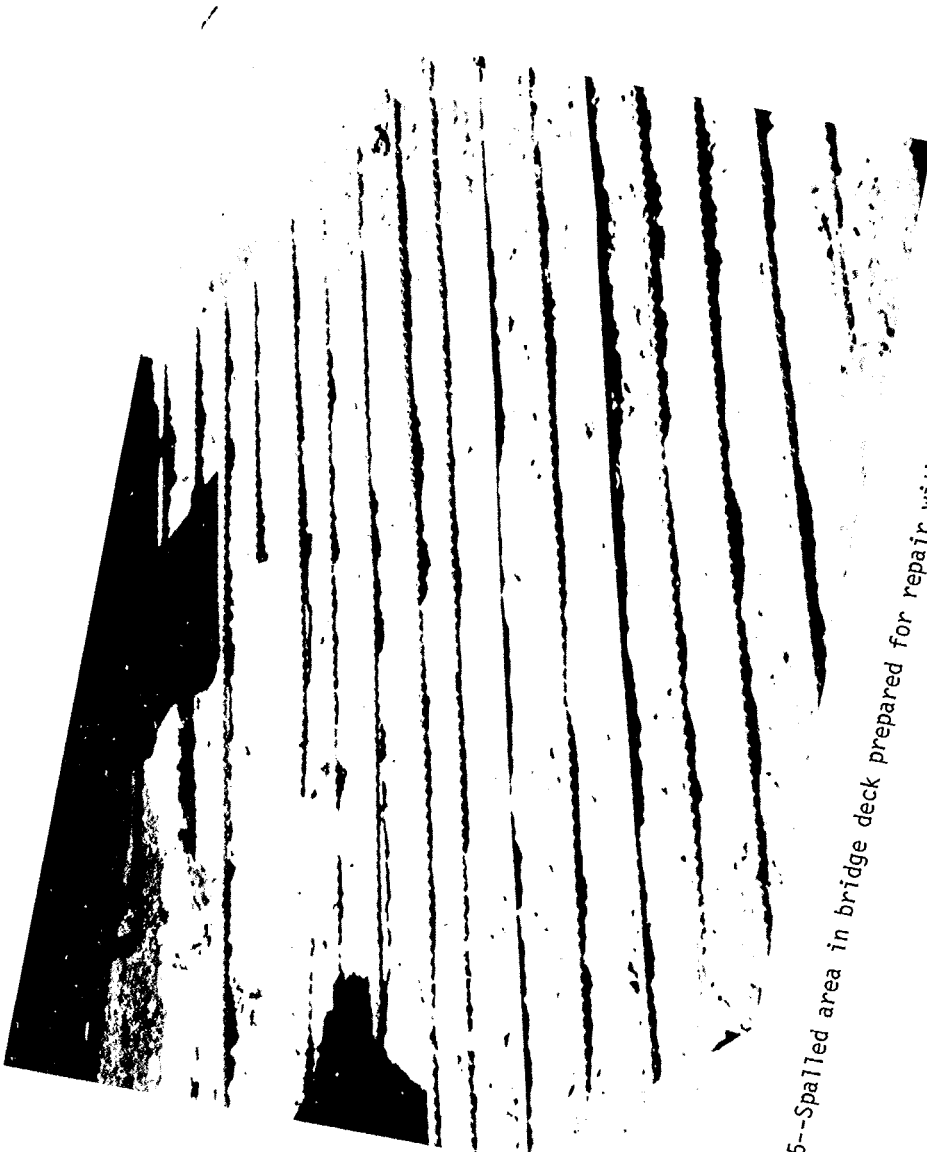


Fig. 5--Spalled area in bridge deck prepared for repair with PC



Fig. 6--Placement of dry aggregate for PC repair by dry pack method



Fig. 7--Monomer saturation of dry aggregate for PC repair by dry pack method



Fig. 8--PC finishing techniques



Fig. 9--PC repairs after four years service



Fig. 10--PC repair after four years service



Fig. 11--Pavement cracking on Interstate Route 64, Huntington, West Virginia, being prepared for PC patching



Fig. 12--Repair of pavement cracks with PC



Fig. 13--Repair of pavement cracks with PC



Fig. 14--Resin application for PC overlay using a pressurized spray nozzle

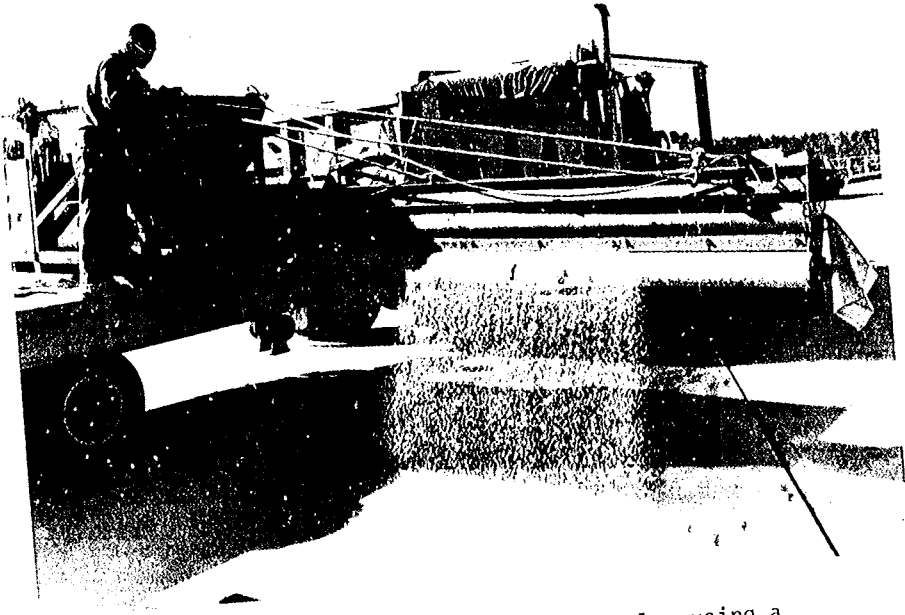


Fig. 15--Sand application for PC overlay using a wing spreader

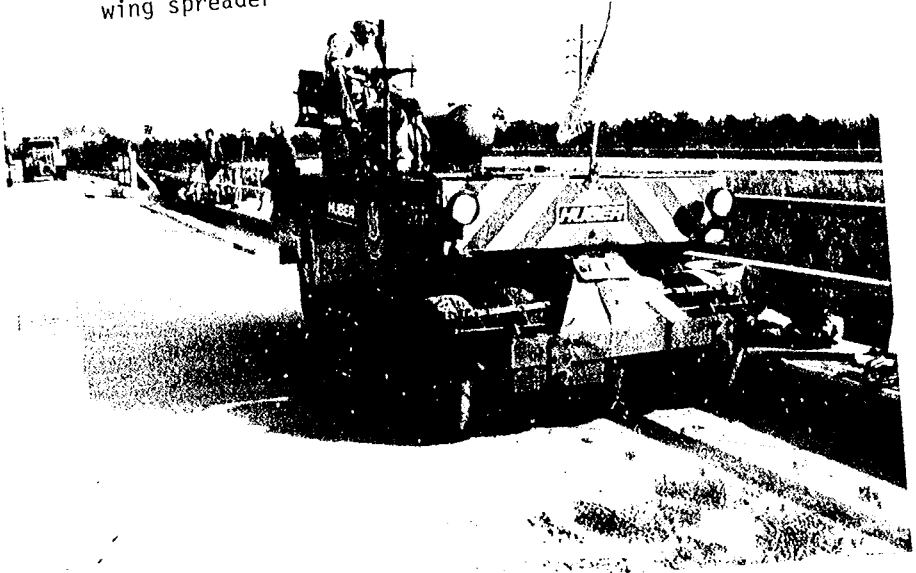


Fig. 16--Compaction of sand into resin for PC overlay using pneumatic rubber-tired roller

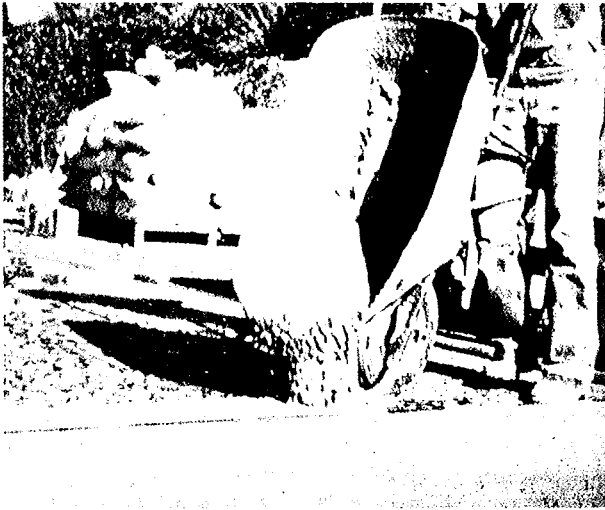


Fig. 17--Application of premixed PC overlay near Donna Pass, California



Fig. 18--Application of premixed PC overlay near Donna Pass, California



Fig. 19--Application of premixed methyl methacrylate PC overlay on concrete-filled steel grid deck, Queensboro Bridge (59th Street Bridge between Queens and Manhattan), New York City



Fig. 20--Application of epoxy mortar on concrete-filled steel grid deck, Queensboro Bridge (59th Street Bridge between Queens and Manhattan), New York City

Applications of Concrete Polymer Materials in Hydrotechnical Construction

By John M. Scanlon, Jr.

Synopsis: Concrete polymer materials are a series of composite materials which have strength and durability characteristics far superior to those of portland cement concrete.

In the USA, a number of hydrotechnical rehabilitation projects have used polymer impregnated concrete (PIC) in order to repair cavitated or eroded stilling basins. Examples of these projects are Dworshak Dam and Libby Dam. Although both of these projects used polymer-impregnated fiber-reinforced concrete, indications are that the fibers do not increase the resistance of the concrete to normal erosion. It is reasonable to assume that the fibers may help to resist cavitation forces since fibers increase the tensile strength of the PIC. Epoxy resins have been used for many years and if applied correctly, results have been found to be excellent when used in the repair of hydraulic structures. In 1977, the Water and Power Resources Service (formerly the Bureau of Reclamation) used polymer concrete (PC) containing vinyl ester in test repairs on two concrete drop structures on the Madera Canal, Central Arizona Project, in California, where erosion damage resulting from abrasive sediments carried by flowing water was evident.

In the USSR, much experimental work is being performed on new hydrotechnical structures; precast PC and PIC slabs are being used in high velocity water and sediment passages.

With the help of the construction industry, new inexpensive techniques could be developed; and concrete polymers could become the construction material of the near future.

Keywords: composite materials; concrete construction; concrete durability; costs; epoxy resins; erosion; fiber reinforced concrete; hydraulic structures; impregnating; maintenance; polymer concrete; portland cements; precast concrete; repairs; strength.

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INTRODUCTION

In the USA, due to the requirements of the National Dam Safety Act, all flood control structures are required to have continuing periodic inspections to evaluate their safety. A 1978 survey of existing US Army Corps of Engineers (CE)-completed hydraulic structures revealed the following:

Ages of CE Hydraulic Structures *

<u>Age, Years</u>	<u>Number</u>	<u>Percentages</u>	<u>Cumulative Percentage (Read Up)</u>
0-9	64	12	100
10-19	154	29	88
20-29	104	19	59
30-39	78	14	40
40-49	74	14	26
50-59	21	4	12
60-69	12	2	8
70-79	9	2	6
80+	24	4	4
	<u>540</u>	<u>100</u>	

* Includes flood control and power producing dams and associated structures, and locks and dams on inland waterways.

Due to the increasing age of existing hydraulic structures, the declining funding available for new construction, and the national concern for dam safety, it is necessary to maintain these structures far beyond their design life. Engineering organizations have discovered that repairing an old structure requires completely different techniques than those required to construct a new project. Also recognizing the present funding situation and that the situation may not improve in the near future, most hydraulic engineering concerns are trying to repair these structures to last longer than the originally constructed structure and to upgrade the design to comply with present-day criteria. The knowledge obtained from research on maintenance and preservation of the hydraulic structures is being transferred to the standard practices being used to design and construct new structures.

Soviet Union research institutes are doing much research in the area of rehabilitation of older hydraulic structures; consequently, the US and USSR established, in 1974, a joint US/USSR

polymer concrete team to address the "Utilization of Polymer Concrete in Wear- and Cavitation-Resistant Linings of Hydrotechnical Structures and for the Repair of Concrete Structures." The author and Dr. P. I. Kovalenko, Director, Ukrainian Scientific Research Institute of Hydraulic Engineering and Land Reclamation (UkrNIIGiM) are serving as leaders for the US and USSR Polymer Concrete Teams, respectively. The Soviet Union has taken their research to the field, and not only are they using concrete polymer materials to repair older structures, they are incorporating PC and PIC slabs in new hydrotechnical projects.

APPLICATIONS WITHIN THE UNITED STATES

A number of applications of concrete polymer materials in hydrotechnical construction have occurred within the United States.

Pomona Dam

In 1968, it was discovered that erosion caused by the abrasive action of rocks and other debris had occurred at the downstream end of the transition slab and on the upstream one-third of the basin slab. Part of the repair included a minimum 1/2-in. (13-mm) thick epoxy mortar applied to the transition slab and to the upstream face of three upstream baffles. The surfaces to receive the epoxy mortar were cleaned by sandblasting to expose approximately 50 percent aggregate. The cleaned surfaces were primed with epoxy resin binder just prior to placement of the epoxy mortar. Specifications required the epoxy coating to be kept dry and above 60F (16C) for a period of one week. However, during a period of rainy weather, backwater flooded the epoxy overlay; only two days of curing had occurred. Five years later the stilling basin was again dewatered and inspected; the epoxy mortar overlay had not suffered any visible erosion damage, however, cracks were observed in several areas. In one of these areas the epoxy mortar coating did not appear to be bonded to the concrete. Upon removal of the mortar in this area (approximately 25 sq ft (2.3 sq m)), it was observed that the majority of the failure plane occurred in the concrete at depths up to 3/4 in. (19 mm). Following removal, the area was cleaned and backfilled with a low modulus, moisture-insensitive epoxy mixed with approximately 3-1/4 parts sand to 1 part epoxy. In all other areas the epoxy mortar appeared to be well bonded. This is generally typical of epoxy repairs performed on other CE projects.

Upper St. Anthony Falls Lock¹

The Upper St. Anthony Falls Lock is located on the Mississippi River in Minneapolis, Minnesota. During 1975 the lock's filling and emptying system was dewatered, inspected, and repaired. Considerable abrasion-erosion was discovered and in a few areas, the depth of erosion was 23 in. (584 mm). The repair became an excellent test area because the following types of repair material were used:

1. Epoxy mortar. A low-modulus epoxy mortar, 1/2- to 1-in. (13- to 25-mm) thickness.
2. Conventional concrete. 3/8-in. (10-mm) maximum size aggregate (probably the same as the fiber concrete w/o the fibers).
3. Fiber concrete. 1/2-in. (13-mm) steel fibers, using 900 lb (408 kg) cement, 1500 lb (680 kg) SSD fine aggregate, 958 lb (435 kg) 3/8-in. (10-mm) coarse aggregate, 200 lb (91 kg) steel fibers, and 360 lb (163 kg) of water.
4. Epoxy concrete. 1 gal (0.004 m) of low-mod epoxy, 25 lb (11 kg) grit, and 20 lb (9 kg) silica sand.
5. Steel plate. 1/2-in. (13-mm) thickness.

Approximately two years after the repairs, dewatering of the locks allowed an examination of the repairs with results as follows:

1. Epoxy mortar. Good condition.
2. Conventional concrete. Gone.
3. Fiber concrete. Gone.
4. Epoxy concrete. Good condition.
5. Steel plate. Excellent condition.

Libby and Dworshak Dams

Much has been written and spoken about the repairs of the stilling basins and sluiceways. At Dworshak Dam,⁴ an estimated 2000 cu yd (1530 cu m) of concrete had eroded from the stilling basin, exposing bedrock in some areas. Since so much has been written on these repair projects, I will not go into details, but basically at Dworshak, the eroded areas were backfilled within 15 in. (380 mm) of final floor elevation with structural grade unreinforced concrete. The top 15 in. (380 mm) was filled with fibrous concrete containing 3/4-in. (19-mm) MSA and 120 lb/cu yd (71 kg/cu m) of 1-in. (25.4-mm) steel fibers. Approximately one-half of the new fibrous concrete surface was surface impregnated with methyl methacrylate (MMA) monomer. Each area to be polymerized was enclosed and dewatered with a wet vacuum to reduce drying time for the concrete. Sand was then applied by hand within the enclosed area to a depth of approximately 3/8 in. (10 mm). The sand acted as a wick to assure uniform distribution of the monomer during the saturation phase because the concrete could not be finished absolutely level. Infrared heat lamps were used to dry the concrete. The temperature of the concrete surface was elevated to approximately 300°F (149°C) in 4 hr and maintained for 7 hr. The most effective monomer system used consisted of 97 percent MMA, 2.5 percent cross-linking agent (TMPTMA), and 0.5 percent catalyst.

(VAZO 64). The repairs at Libby were very similar except that polymer impregnations were only performed in 4-ft (1.2-m) sections along the construction joints. Recent inspections at Dworshak indicate there is some general wear at the joints and some grooving in the concrete surface near the center of the basin running in the up- and downstrea, direction. The wear at the joints at Dworshak occurred where impregnation was not successful because hydrostatic pressure forced water up through the joints preventing impregnation; this problem was alleviated at Libby⁷ by installing horizontal waterstops in the joints.

RESULTS OF RECENT RESEARCH

Investigation of maintenance and preservation problems associated with hydrotechnical concrete structures was initiated in February 1977 at the US Army Engineer Waterways Experiment Station (WES). One of the many objectives of this investigation is to develop and evaluate materials and techniques for repair and rehabilitation of these structures. In response to this objective, Dr. Tony C. Liu, Research Structural Engineer in the Concrete Technology Division, developed a new test method² which simulates the erosion-abrasion action to which many of our stilling basins are being exposed. Figure 1 shows a cross sectional view of the device. The apparatus consists of essentially a drill press, an agitation paddle, a cylindrical steel container which houses a disk-shaped concrete specimen, and 70 steel grinding balls of various sizes [ten 1-in. (25.4-mm), thirty-five 3/4-in. (19-mm), and twenty-five 1/2-in. (12.7-mm) diameter balls].

The water in the container is circulated by the immersed agitation paddle, which is powered by the drill press rotation at approximately 1200 rpm. The circulating water, in turn, moves the abrasive charges (steel grinding balls) on the surface of the concrete specimen producing the abrasive effects. The average water velocity on the surface of the specimen as measured by a blunt nose Pitot tube is approximately 6 ft/sec (1.8 m/sec). This test method seems to duplicate the abrasive action of waterborne particles in prototype stilling basins. As can be seen in Figure 2, the surface conditions of the tested specimens are very similar to the eroded concrete surfaces observed in stilling basins. Dr. Liu's program has, as of March 1980, evaluated:

1. three concrete types (conventional, fiber, and polymer),
2. seven aggregate types,
3. three principal w/c ratios (0.72, 0.54, and 0.40), and
4. six types of surface treatment (vacuum, polyurethane, acrylic mortar, epoxy, furan resin, and iron aggregate).

Dr. Liu's complete report is Reference 11. From the report the appropriate information on concrete polymers can be discussed.

The following concrete polymer material systems were evaluated:

1. Polymer-Impregnated Concrete (Surface by heat).
 - methyl methacrylate (MMA) inhibited with 25-ppm HQ (monomer)
 - trimethylpropane trimethacrylate (TMPTMA) (cross-linking agent)
 - VAZO 64 (initiator)
2. Polymer Concrete
 - MMA (monomer)
 - TMPTMA (cross-linking agent)
 - Benzoyl Peroxide-70 (initiator)
 - N,N-dimethyl aniline (DMA) and N,N-dimethyl-p, toluidine (DMT) (promoters)
3. Vinyl Ester Polymer Concrete
 - vinyl ester resin containing 36 percent styrene by mass (monomer)
 - methyl ethyl ketone peroxide (MEKP) (catalyst)
 - cobalt and naphthenate (CON) and N,N-dimethyl aniline (DMA) (promoters)
4. Polymer Portland Cement Concrete (PPCC)
 - two-component water dispersible epoxy mixed at a 0.20 polymer/cement ratio

Actual test results have been included in Figures 3, 4, 5, 6, 7. Figure 3 shows that the abrasion-erosion loss of PIC is approximately 33 percent of conventional concrete after testing for 72 hr. Also in Figure 4, we can see that polymer-impregnated fiber-reinforced concrete is approximately twice as resistant to abrasion-erosion as plain fiber-reinforced concrete. Figure 5 shows the relative abrasion-erosion resistance of conventional concrete and polymer portland cement concrete. Figure 6 depicts the relative abrasion-erosion resistance of PIC, PPCC, and two types of PC. Additional work was done with various coatings such as polyurethane, epoxy resin mortar (high and low mod), furan resin mortar, acrylic mortar, and iron aggregate topping. Figure 7 depicts these relative results.

The Water and Power Resources Service (WPRS) (formerly the Bureau of Reclamation (USBR)) has been very involved in research relating to applications of concrete polymer materials in hydrotechnical construction. Based upon the results from laboratory and field tests performed on sections of concrete partially impregnated with MMA, the WPRS recently issued a specification for work to treat a section of the prototype spillway floor of Shadow Mountain Dam⁵ in Colorado. The specification was based upon similar work performed on bridge decks by the WPRS in conjunction with

the Federal Highway Administration and called for bidding purposes for the treatment of 261 sq yd (218 sq m) of surface. Required steps in the specification included cleaning of the concrete surface by sandblasting, application of a 0.25- to 0.5-in. (0.6- to 1.3-cm) thick layer of washed sand, drying of the surface for 8 hr at minimum and maximum temperatures of 250F (121C) and 275F (135C), respectively, cooling, saturation of the sand by the application of monomer at a rate of ~0.8 lb/sq ft (3.9 kg/sq m), and polymerization. A contract was awarded, and the work performed during the summer of 1978. No problems were encountered. Inspection of the section will be performed on a regular basis.

In 1977 the WPRS used PC containing vinyl ester in test repairs on two concrete drop structures on the Madera Canal,⁶ Central Valley Project, in California, where erosive damage resulting from abrasive sediments carried by flowing water was evident. In some places the concrete floors were eroded to a depth of ~2 in. (5 cm), exposing some of the reinforcing steel. Earlier attempts to repair the areas using conventional shotcrete had proven unsuccessful.

Three areas: 4 by 4 ft (~1.21 by 1.21 m), 2 by 5 ft (~0.61 by 1.83 m), and 0.5 by 5 ft (~0.15 by 1.53 m) were repaired. The first area was on a 1.5 to 1.0 slope; the other two areas were on a slight slope.

Immediately prior to the application of the PC, the section on the slope was cleaned by sandblasting. The other two areas were blown clean with compressed air to remove any loose debris.

A vinyl ester containing a silane coupling agent and polymerized using methyl ethyl ketone peroxide as an initiator and cobalt naphthenate as a promoter was used in the PC. The same materials were used as a bond coat which was applied to the area to be repaired to assure good bonding between the PC and the concrete surface.

The monomer and aggregate were mixed at a ratio of 10 parts aggregate to 1 part monomer in a conventional concrete mixer. The PC was mixed, placed, and finished using a trowel without difficulty. On the sections which had little slope, a smooth surface was obtained by finishing. A rougher surface was attained on the sloped surface primarily because of the difficult working conditions which necessitated the workmen being supported by ropes attached around their waists. The final thickness of the overlays varied from 0 at the edges of the patches to ~1.5 in. (3.3 cm) over the reinforcing bars. Inspections of the overlays were scheduled, but to date these results have not been published.

APPLICATIONS WITHIN THE SOVIET UNION

To date, especially in hydrotechnical construction, the Soviets have not performed surface impregnation of cast-in-place

concrete. Most of the concrete polymer materials used in hydro-technical work have been precast PC slabs, surface impregnation of precast concrete slabs, and surface patch repairs with epoxies⁸ and/or other coating materials. Research on polymer concrete based on the furfural acetone (FA) system was started in about 1960.³ Subsequent modifications to the FA system made by the addition of urea formaldehyde and epoxies have improved the bond strength of the PC to concrete sufficiently to permit the use of field-applied PC overlays. Polymer concrete panels approximately 2.2 m by 1.2 m by 23 mm as protective overlays on spillways have been in test in a prototype structure since 1974. Approximately 1200 sq m of lining is in test. Good resistance is indicated and most new spillways will be protected by this method. Data for cavitation-resistant PC were given as follows:

<u>Material</u>	<u>Time to Some Damage Condition</u>
Concrete	2-3 hr
PC	60 hr
Granite	90 hr

These data were developed from small, approximately 4-by 8-in. (102- by 204-mm) specimens with water velocities at 105 ft/sec (32 m/sec). Also, a great deal of emphasis is placed upon aggregate selection for use in PC. The durability of the aggregate should be greater than the polymer binder and the time of crushing the aggregate is very important. If crushed immediately before mixing with monomer, it was claimed that covalent bonding between the filler and polymer is obtained.

During a 1979 visit to the Soviet Union, discussions with the technical staff, disclosed that damage had recently been discovered at the New Nurnurek Central Asia Power Station, which is an earth dam 985 ft (300 m) high. It has four levels of outlets with 179 sq yd (150 sq m) cross sections and velocities exceeding 131 ft/sec (40 m/sec). After two years' service, the surfaces had to be strengthened with most of the damage occurring approximately 230 ft (70 m) from the exit. Damage was 8 to 10 in. (20 to 25 cm) deep and was repaired with a polymer mastic and coated. They used a FAED system, which is an 80-20 mixture of furfural resin and epoxy.

During this trip, we were also introduced to developments in a new material called "Sprut." This material was used in waterproofing and as a bond coat to attach fresh concrete to old concrete. It is composed of:

Polyester resin (PE)	100 parts
Polyurethane	80 parts
Filler	200-250 parts
Accelerator (initiator)	Depending on conditions

An experiment at a new structure on the Tupalang River^{9,10} near Denaw (close to Tashkent) in the District of Surhandarjinskaga was described. Two bays in a spillway (about 1250 sq m) are to be