History of ACI Committee 548: 
The Past Thirty Years

by J. T. Dikeou

Synopsis: The paper reviews the historical development of polymers in concrete, and the history of ACI Committee 548, and its sister organization, the International Congresses on Polymers in Concrete. Polymer concretes and polymer modified concretes have been studied and used since the 1940’s and 1950’s; polymer impregnated concretes have been studied starting in the mid 1960s.

Three categories of concrete that contain polymers are: (1) polymer concrete (PC), (2) polymer modified concrete (PMC), and (3) polymer-impregnated concrete (PIC). Committee 548 was started in 1971, and from the start has been one of the most active and productive committees in ACI. The committee has produced seven documents, most of which have required committee action to reaffirm or revise over the years. The committee has also organized and conducted nine technical sessions at ACI Conventions, which have produced Special Publications (SP), and has organized two National ACI Seminars.

Keywords: ACI Committee 548; historical development; international congresses; properties of polymers in concrete
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INTRODUCTION

Before reviewing the history of ACI Committee 548, I’d like to first discuss a little about the historical use of polymers in concrete.

HISTORICAL DEVELOPMENT

Improvement of the properties of hardened concrete by the addition of polymers is now into its sixth decade. In the 1940's and 1950's, both polymer concrete and polymer-modified concrete were studied and used. Polymer concrete was being used in the mid 1950's in the production of prefabricated wall panels and floor tile (figure 1). Polymers used included both methyl methacrylate and polyester styrene based systems. The products were successful and continue to be used up to the present time.

Polymer concrete using polyester resins was also being considered in the 1950's for use in road and bridge overlays, pothole repairs, and airfield runway repairs. However, early formulations of polymer concrete for highway work, although relatively easy to mix and place, were found to be porous and not resistant to chloride deicing salt penetration, which permits corrosion of reinforcing steel to occur. The early products therefore did not have wide acceptance in the highway industry.

Polymer modified concrete that was developed in the 1950's was actually a mortar rather than a concrete. It was found that by introducing the polymer in the form of a latex, it could be made compatible with portland cement in the fresh mortar. Polymer modified mortars were initially used as overlays for industrial floors and later were used in the construction of prefabricated wall panels and as an admixture for shotcrete. Their use also expanded into the highway field in the production of bridge overlays. However, refining of the materials remained necessary, both in terms of the polymeric component and in terms of modification of the mixture from a mortar to a concrete.
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In 1966, U.S. Government sponsored research was initiated to develop methods for impregnating hardened portland cement concrete with liquid monomers, which are subsequently polymerized in place to form the polymer impregnated concrete composite. Initial tests showed that the structural and durability properties of this new composite could be quite remarkable, prompting the U.S. Government to spend several millions of dollars over the next few years to identify suitable monomers for impregnation, develop impregnation processes, evaluate structural and durability properties of polymer impregnated concrete, and study and develop applications for polymer impregnated concrete.

However, because of the complexity and cost of the treatment process commercial applications for fully impregnated polymer impregnated concrete have not emerged. Nevertheless, the high level of worldwide interest in polymer impregnated concrete stimulated accelerated interest in polymer concrete and polymer modified concrete development, and it was from this point in time that worldwide studies and applications of these composite materials started to rapidly evolve.

ACI COMMITTEE 548, POLYMERS IN CONCRETE

Following approval by the ACI Technical Activities Committee, ACI Committee 548, Polymers in Concrete, held its organizational meeting at the spring 1971 ACI Meeting in Denver, Colorado. The first Chairman of Committee 548 was George B. Wallace, then Head of the Polymer Concrete Group at the Bureau of Reclamation’s Engineering and Research Center in Denver (figure 2). George was a wonderful visionary and organizer who set the Committee on the course which it still follows 30 years later. One of the more interesting procedures that George initiated was that, following the Committee’s business session, George went “around the table” and invited all attendees to present a brief discussion of the particular work with polymers in concrete that they were involved in. This procedure has been and is still followed today. Another procedure George initiated and is still followed today is that document preparation is accomplished in Task Groups and Subcommittees, and presented to the Committee for letter ballot or at Conventions for final action. So, time is not wasted at Committee meetings with boring time consuming activities such as crossing T’s and dotting I’s on Committee documents, as is done at so many other committee meetings.

The first undertaking of the Committee was to prepare a State-of-the-Art Report on Polymers in Concrete. The Committee membership was assigned to one of five task groups, and work was begun. Through George’s initial push, the report was approved and published in some sort of record time for an ACI document.

At the same time that work was started on the State-of-the-Art Report, work was
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started on organizing Technical Sessions on Polymers in Concrete for the Fall ACI Convention in 1972 in Hollywood, Florida, and for the Spring 1973 Session in Atlantic City, New Jersey. Both sessions were quite successful.

Because of a change in employment and professional interests, George Wallace gave up the Chairmanship of Committee 548 at the end of his first 2-year appointment, and I became Chairman at the spring 1973 ACI Meeting, continuing as Chairman until Spring 1979. I was followed by David Fowler, who was Chairman from spring 1979 through spring 1985. The next Chairman was Jack Fontana who served from spring 1985 until Spring 1991, and Jack was succeeded by D. Gerry Walters who was Chairman from Spring 1991 until Fall 1996. And this brings us to our current Chairman Albert O. Kaeding who started his term at the fall 1996 ACI Convention (figure 3).

In my mind, Committee 548 has continued it’s initial impetus of busy activities started in 1971. Over all the years, it has consistently had one of the largest memberships of all ACI Committees, including voting, associate and consulting members from around the world. I can just about guarantee you that no other ACI Committee has been more productive. Let me back this up with the following data regarding published documents, sponsorship of Technical Sessions at ACI Conventions, and organization of ACI Seminars.

**PUBLICATIONS**

Published Committee Reports
ACI 548 Polymers in Concrete, State-of-the-Art Report
ACI 548.1R Guide for the Use of Polymers in Concrete
ACI 548.2R Guide for Mixing and Placing Sulfur Concrete in Construction
ACI 548.3R State-of-the-Art Report on Polymer Modified Concrete
ACI 548.4 Standard Specification for Latex Modified Concrete (LMC) Overlays
ACI 548.5R Guide for Polymer Concrete Overlays
ACI 548.6R Polymer Concrete Structural Applications - State-of-the-Art Report

Along with other Committee work, numerous updates and revisions have been made, approved, and incorporated in the above documents.

**SPONSORSHIP OF TECHNICAL SESSIONS AND PUBLICATION OF ACI SP’S**

Committee 548 has regularly sponsored Technical Sessions at ACI Conventions,
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and has published proceedings of such sessions as ACI SP’s. Following is a listing of the proceedings:

| ACI SP-40 | Polymers in Concrete | 1973 |
| ACI SP-58 | Polymers in Concrete | 1978 |
| ACI SP-69 | Applications of Polymer Concrete | 1981 |
| ACI SP-89 | Polymer Concrete - Uses, Materials, and Properties | 1985 |
| ACI SP-99 | Polymer Modified Concrete | 1987 |
| ACI SP-116 | Polymers in Concrete: Advances and Applications | 1989 |
| ACI SP-137 | Polymer Concrete | 1993 |
| ACI SP-166 | Properties and Uses of Polymers in Concrete | 1996 |
| ACI SP-169 | In-Place Performance of Polymer Concrete Overlays | 1997 |

ACI SEMINARS

At the request of ACI Local Chapters and the ACI Education Department, Committee 548 organized and conducted two ACI Seminars on Polymers in Concrete. The first was held in Denver, Colorado in 1973, in cooperation with the ACI Rocky Mountain Chapter, and the second was held in Albany, New York in 1978, in cooperation with the ACI New York Chapter. Both involved speakers from the Committee 548 membership, and were received with much enthusiasm.

ICPIC ACTIVITIES

I’d like also to say a few words about an offspring of Committee 548, which is the International Congresses on Polymers in Concrete (ICPIC). The first international meeting on polymers in concrete was held in 1975 in London. About 300 persons from over 30 countries attended the First Congress. This Congress proved to be extremely useful. For the first time representatives from around the world gathered to present and exchange information on incorporation of these relatively new synthetic polymer materials into concrete. Much new information was presented on research and development of materials, processes, and properties of a variety of polymer-concrete composites. In addition, the latest information on the technological and economic feasibility of numerous applications was presented and explored. It became apparent that these materials could be used advantageously for many applications.

Following the success of the First Congress, it was decided that such meetings should be held at regular intervals, and I, as current Chairman of Committee 548 was asked if I could find a home for ICPIC-II in the United States. Following the
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Second ICPIC Congress, Committee 548 gave its endorsement of this activity, and the ICPIC Organization became a reality.

The meetings, with dates and locations for ICPIC Congresses, are as follows. Ten Congresses have now been held, as shown below (figures 4, 5, and 6):

<table>
<thead>
<tr>
<th></th>
<th>DATE</th>
<th>LOCATION</th>
<th>ORGANIZED BY</th>
</tr>
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<td>ICPIC-I</td>
<td>May 1975</td>
<td>London, England</td>
<td>The Concrete Society</td>
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<tr>
<td>ICPIC-II</td>
<td>Oct 1978</td>
<td>Austin, USA</td>
<td>University of Texas</td>
</tr>
<tr>
<td>ICPIC-III</td>
<td>May 1981</td>
<td>Koriyama, Japan</td>
<td>Nihon University</td>
</tr>
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<td>ICPIC-IV</td>
<td>Sept 1984</td>
<td>Darmstadt, Germany</td>
<td>Technische Hochschule D</td>
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<tr>
<td>ICPIC-V</td>
<td>Sept 1987</td>
<td>Brighton, England</td>
<td>Brighton Polytechnic</td>
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<tr>
<td>ICPIC-VI</td>
<td>Sept 1990</td>
<td>Shanghai, China</td>
<td>Tongji University</td>
</tr>
<tr>
<td>N.A. Workshop</td>
<td>Sept 1991</td>
<td>San Franzisco, USA</td>
<td>American Concrete Institute</td>
</tr>
<tr>
<td>ICPIC-VII</td>
<td>Sept 1992</td>
<td>Moscow, Russia</td>
<td>Research Institute of Concr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reinforced Concrete</td>
</tr>
<tr>
<td>IBRACON</td>
<td>Oct 1993</td>
<td>Salvador City, Brazil</td>
<td>Instituto Brasileiro do Concr</td>
</tr>
<tr>
<td>Workshop</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ICPIC-VIII</td>
<td>July 1995</td>
<td>Oostende, Belgium</td>
<td>Katholieke Universiteit LeGe</td>
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<td>Central European</td>
<td>Sept 1996</td>
<td>Bled, Slovenia</td>
<td>Institute for Research-Mat</td>
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<td>Applications</td>
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<tr>
<td>ICPIC-IX</td>
<td>Sept 1998</td>
<td>Bologna, Italy</td>
<td>Universita di Bologna</td>
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<td>ICPIC-X</td>
<td>May 2001</td>
<td>Honolulu, USA</td>
<td>ICPIC</td>
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CONCLUSIONS

From the time that Committee 548 was formed in 1971 (30 years ago) to the present, many advances have been made in the commercial and practical applications of polymers in concrete. Many refinements have emerged, as a result of efforts of both researchers and commercial producers, which have converted laboratory processes into commercially and economically feasible products. From a review of what has happened to date, it is evident that much future progress will be made with these “new construction materials.” Time will tell where the economics will balance with the increased costs. But, it is very exciting to view the progress in improvement in properties that are possible.
1. ACI Committee 548, "Polymers in Concrete - State-of-the-Art Report" (ACI 548R-77(81)), American Concrete Institute, Detroit, Michigan, U.S.A., 1981.
2. ACI Committee 548, "Guide for the Use of Polymers in Concrete" (ACI 548.1R-97) American Concrete Institute, Farmington Hills, Michigan, U.S.A., 1997.
6. ACI Committee 548, “Guide for Polymer Concrete Overlays” (ACI 548.5R-94(98)), American Concrete Institute, Farmington Hills, Michigan, U.S.A., 1998.
7. ACI Committee 548, “Polymer Concrete Structural Applications - State-of-the-Art Report” (ACI 548.6R-96), American Concrete Institute, Detroit, Michigan, U.S.A., 1996.
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15. Polymers in Concrete, Proceedings of the Sixth International Congress on Polymers in Concrete, Shanghai, China, September 1990.
16. Polymer Conference, American Concrete Institute SBM –1, 1991.
17. Polymers in Concrete, Proceedings of the Seventh International Congress on Polymers in Concrete; Moscow, Russia, September 1992.
18. Polymers in Concrete, Proceedings of the IBRACON Workshop, Salvador City, Brazil, October 1993.

Figure 1: Precast Wall Panels (courtesy of Prusinski).
Figure 2: George B. Wallace.

Dikeou  Walters  Fontana

Fowler  Kaeding

Figure 3: Committee Chairmen.
Figure 4: The Third International Congress.

Figure 5: The Sixth International Congress.
Figure 6: ICPIC Workshop in Salvador City, Brazil.
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Fifty Years’ History of Polymers in Concrete in Review

by W. S. Wahby

Synopsis: Polymer concrete materials stand today as a very promising group of new building materials. This paper presents a brief overview of the use of polymers in concrete in various industrial applications over the past fifty years. Classification, production, and main advantages and disadvantages of polymer concrete materials are presented. Their physical, mechanical, and chemical properties are reviewed and compared to those of the conventional portland cement concrete. Hazards involved in handling, transporting, storing and mixing the chemicals used to produce polymer concrete materials are discussed, and safety consideration are presented.

Keywords: polymer concrete; polymer-impregnated concrete; polymer-modified concrete; polymers
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RESEARCH SIGNIFICANCE

Polymer concrete materials stand today as a very promising group of new building materials. They possess a remarkable potential through quite a wide variety of interesting features, properties and applications. Although still considered expensive as compared with conventional materials on the basis of the monetary cost per unit weight, yet they compare extremely favorable when judged on parameters like cost-effectiveness, durability, and low maintenance requirements. The need is still there to shed the light on this family of building materials in order to gain new markets that would lead to lowering its cost.

INTRODUCTION

Historical Background

The improvement of properties of hardened concrete by the addition of synthetic polymers is well into its fifth decade (ACI 548.1R-97). Different concrete-polymer materials have proved themselves as reliable construction materials, (DePuy, 1998), especially over the last decade.

The concept of using organic polymers in construction materials is not new. There are indications that people in the early history of mankind have had the experience of combining natural polymers with inorganic materials in order to produce a high-strength and durable construction materials (Okada, 1967). It is believed that as early as the second century BC, the glutinous rice paste-lime mortar was used to build the Great Wall of China (You-Yun, 1981).

Bricks impregnated with vegetable oil, and binding materials mixed with natural polymers were widely used in the ancient construction of palaces, temples, and graves, which are still preserved to the present day (Bares, R., 1967). It is also interesting that one of the recent theories suggests that ancient Egyptians might have known some sort of technology for producing the huge stones used in building the Pyramids using polymeric binders with medium, fine, and very fine
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fillers (Davidovits, J. 1987). However, it was not until the 1950’s when synthetic polymers were applied to concrete.

Polymer concrete was first used commercially in the United States in the 1950's (Kaeding, 1998). “Ar-Lite Panelcraft” polymer concrete building panels were manufactured then by Architectural Research Corporation and were marketed worldwide by the 1970’s. (Prusinsky, 1999). Much research work on polymer impregnated concrete and polymer concrete was performed under the auspices of the U.S. Department of Energy at Brookhaven National Laboratory during the 1960’s to 1980’s (Fontana, J., Kakacka, L.E., Steinberg, M., DiCicou, J.)

Concrete

The general definition of concrete is “an aggregate bound with a binder”. Ordinary “concrete”, or conventional portland cement concrete (CPCC) is a man-made rock, manufactured by binding together fine and coarse aggregates (sand and gravel or crushed stones), by means of a gel that is formed by portland cement and water. In certain situations, special additives or admixtures may be incorporated as need be.

CPCC is one of the most important and versatile building materials in the world, with quite a good range of mechanical properties, and with no equally economic alternative. On the other hand, however, and in spite of the many improvements over the years, CPCC still has some deficiencies such as relatively high permeability, vulnerability to attacks by seawater and organic and inorganic acids, especially at elevated temperatures.

In addition, CPCC also has many undesirable engineering characteristics, such as: low tensile strength, brittleness, low impact resistance, low modulus of elasticity, insufficient insulating properties, heavy weight, and difficulty of shaping into some special tiny or complicated shaped forms.

Researchers in various countries engaged themselves in investigations to improve concrete’s shortcomings. In the process, concrete polymer materials emerged as a possible solution to most of the problems associated with traditional CPCC, and were developed to reduce its deficiencies.

Polymers

Polymers, commonly called “plastics”, are nonmetallic materials, which have undergone tremendous technical developments during the last few decades. A “poly”-“mer” (“many”-“parts”) is formed from a “mono”-“mer” (“one”-
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“part”), or simply a “mer” through a chemical process called polymerization. An example is the monomer vinyl chloride, which is formed into the commonly known polymer, polyvinyl chloride (PVC).

The first modified natural polymers, namely: cellulose nitrate and casein-formaldehyde, were commercially produced about 150 years ago, while the first fully synthetic polymer, phenol-formaldehyde, was made 50 years later, in 1910. Following the tremendous progress of the petrochemical industry, it was only forty years ago, in the late 1950’s, that a booming production and development of synthetic rubber latexes, resin emulsions, and monomers were started.

Today, industries associated with polymeric materials in this country employ more than half of all chemists and chemical engineers, while the annual production of polymeric materials has grown from a few million pounds to several billion pounds.

POLYMER CONCRETE MATERIALS CLASSIFICATION

There are three main types of polymer concrete materials: Polymer-Modified Concrete (PMC), Polymer Impregnated Concrete (PIC), and Polymer Concrete (PC).

PMC has at times been called polymer-portland cement concrete (PPCC) and latex-modified concrete (LMC). It is defined in ACI 548.3R as portland cement and aggregate combined at the time of mixing with organic polymers that are dispersed or redispersed in water. As the cement hydrates, coalescence of the polymer occurs, resulting in a “co-matrix” of hydrated cement and polymer film throughout the concrete.

PIC is a hydrated portland cement concrete that has been dried to remove moisture and free water from its pores, and then impregnated by either atmospheric or pressure soaking with a monomer that is subsequently polymerized in situ. There are two levels of impregnation: partial impregnation (sometimes called surface impregnation) and full impregnation, depending on the degree to which the available space in the concrete is filled with monomer.

PC is a composite material in which the aggregate is bound together in a matrix with a polymer binder. The composites do not contain a hydrated cement phase, although portland cement can be used as an aggregate or filler but not as a binder.
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Polymer-Modified Concrete (PMC)

Selecting the proper polymer depends a great deal on the exposure and service life requirements. Amongst the wide variety of polymers investigated for use in PMC, the latex polymers, epoxies, and acrylics are the three most successful types that have been investigated, accepted and widely used for different applications.

The specific mix proportions selected for any particular application depend on the specific need of the application and the type of polymer used in PMC. For optimum performance, in general, polymer levels of 10 to 20% (based on the weight of polymer solids in the latex solution to the weight of portland cement) will be required.

Polymer Impregnated Concrete (PIC)

In general, all types of aggregates, cements, and admixtures that are used in old and modern concrete technology can be used for PIC. Moreover, almost any shape, size, configuration, orientation and quality of nearly all existing types of hardened CPCC can be impregnated with monomer, to some degree, provided the monomer has access to the void space within the concrete. The main factor in producing high quality PIC is in achieving a high degree of impregnation, and complete polymerization.

Polymer Concrete (PC)

Polymer concrete (PC) is a composite material in which the aggregate is bound together solely with a polymer binder of 8-15% by weight. This is different than using 1 to 5% by weight of cement as admixtures or additives to a fresh CPCC mix.

Generally, PC has many of the advantages of PIC, though its processing techniques are much easier and simpler than those of PIC. Meanwhile, the term PC should never suggest only one product, but rather a family of products. In contrast to PMC and PIC, PC can be made with a wide range of monomers, and the material is suitable for both precast and in-situ applications. Processing techniques depend on the finished product desired, and the required performance.
PROPERTIES

A range of properties for PMC, PIC, and PC is presented in Table (1) (Kakacka, 1975).

INDUSTRIAL APPLICATIONS

Polymer Modified Concrete (PMC)

PMC applications have included, but are not limited to relatively large prefabricated panels of masonry curtain walls, overlays of bridge decks, parking garages and floors, precast operations, and patching any concrete surface.

Polymer Impregnated Concrete (PIC)

The potential applications of PIC include treatment of existing concrete structures and precast concrete elements, protection of concrete bridge decks and spillways from damage, improvement of the structural stability of roof and wall structures in mines, restoration of deteriorated structures and monuments, and repairs of badly fractured concrete, and developing chemically resistant PIC.

Unfortunately, it seems that the excellent structural performance and the enhanced durability of PIC in general could not in themselves, economically, justify its commercial use on a large scale. The complicated techniques and the industrial hazards involved in producing PIC halted the anticipated progress for such materials and led to the obvious dramatic decrease in the rate of its development and production in the last decade.

Polymer Concrete

The use of polymer concrete is equally distributed between load-carrying elements, aggressive media-protecting elements, and decorative or aesthetic elements. Many PC products can be plant-precast more efficiently and economically than site-cast.
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PC is used in the manufacture of overlays and floorings, structural and decorative housing elements, sewer pipes, bricks and building panels, grouting, swimming pool and patio decking, machine parts and tools, PC thermal and insulator panels, electric insulators, shotcreting, and street furniture. PC can also provide a fast-curing, high-strength patching material for repair of CPCC deteriorated highway structures.

MAIN ADVANTAGES OF USING POLYMERS IN CONCRETE

As shown in Table (1), most concrete mechanical properties are improved with polymer inclusion. PC and PMC generally have lower moduli of elasticity than CPCC. The most significant improvements are those related to durability. In certain tests of freeze-thaw resistance, PIC is reported to have a weight loss of almost zero after 3650 cycles, while the corresponding CPCC specimens lost 26% of their weight after only 690 similar cycles. Improvement in erosion and abrasion resistance is remarkable. Chemical resistance for concrete-polymer materials is much better than that of CPCC. High cost of polymer concrete materials can be justified when considering factors like cost-to-strength ratios, mass-to-strength ratios, chemical resistance, time saving or durability.

MAIN DISADVANTAGES OF USING POLYMERS IN CONCRETE

The main disadvantages of polymer concrete materials include high cost, creep behavior and stress relaxation, poor performance under dynamic loads, polymer degradation and the effect of oxidizing agents, handling hazards, some difficulty in mixing and placing, and the lack of perfectly suitable polymers for use with concrete.

SAFETY

Safety is a wide-ranging subject that includes aspects of normal construction practices, special construction practices arising from the use of concrete polymer materials, the intrinsic properties of the chemicals, and the codes and regulations of governmental regulatory agencies, and various groups and associations. (ACI 548.1R-97).
CONCLUSION

Polymer concrete materials stand today as a very promising group of new building materials. They possess a remarkable potential through quite a wide variety of interesting features, properties and applications. Although still considered expensive as compared with conventional materials on the basis of the monetary cost per unit weight, they compare extremely favorably when judged on parameters like cost-effectiveness, durability, and low maintenance requirements.

REFERENCES

<table>
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<th>Properties</th>
<th>Conventional Portland Cement Concrete</th>
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<td></td>
<td>CPCC</td>
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<td>571-929 (40-65)</td>
<td>1214-1643 (85-115)</td>
<td>1000-2000 (70-140)</td>
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<td>1714-2000 (120-140)</td>
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<tr>
<td>Abrasion Resistance, Factor Of Improvement Over Control</td>
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Development and Applications of Various Polymer Concrete Engineering Materials

by J. J. Fontana

Synopsis: A wide variety of advanced construction materials have been developed to meet certain needs and solve specific problems. These materials have all come under the umbrella title of “Polymer Concrete” (PC). Using different types of resins and fillers, composites can be formulated having totally different physical properties.

This paper will review several different PC formulations that were developed at Brookhaven National Laboratory (BNL) and installed at operating facilities by construction contractors. The three materials selected for this review are: A) Insulating Polymer Concrete (IPC) for dike insulation at Liquified Natural Gas (LNG) facilities; B) Electrically Conductive Polymer Concrete Overlays used in conjunction with a cathodic protection system on a deteriorated bridge deck and C) Precast PC vaults for natural gas regulator stations.

Keywords: electrically conductive polymer concrete; insulating polymer concrete; precast polymer concrete
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Jack J. Fontana graduated from Adelphi University in 1963 and has conducted research and development work on polymer concrete materials for the past 38 years. Has developed PC materials for the Federal Highway Administration, for the geothermal energy industry and for the liquified natural gas industry. Most of the materials developed has been implemented for commercial applications. Currently a consultant to the polymer concrete industry.

INTRODUCTION

During the past three decades, a wide variety of advanced construction materials have been developed for different industries to solve specific problems. These materials have generally come under the umbrella title of “Polymer Concrete”. The stigma of trying to compete with low cost Portland cement concrete (PCC) products has restricted the use of many of these engineered composites. It is the opinion of the author that the industry would have been best served if these materials would have been promoted as “Polymer Composites”. Polymer Composites are sophisticated materials that can be formulated for a wide variety of applications with no apparent limits to their use.

Polymer Composites generally consist of three ingredients: resin, aggregate/filler, and additives. Varying one, two, or all three, of these ingredients, can change specific chemical or physical properties in the composite. In general, the type of resin used will mostly influence the chemical properties of the composite, such as, corrosion resistance. Changing the aggregate and fillers will generally change the physical properties of the composite, such as, conductivity (thermal or electrical) or insulating (thermal or electrical). The addition of additives, such as, silanes, will improve the bond between the aggregate and the resin, thereby increasing the strength properties and reducing degradation due to moisture.

Three Polymer Composites will be reviewed to show how different formulations will fulfill different composite requirements. The first composite, to be discussed, was used to insulate the dike areas surrounding LNG storage tanks. The second composite, an electrically conductive material, used as a bridge deck overlay, uniformly distributes the anode current from a cathodic protection system. The third composite was a high strength, highly ductile material used to cast vaults for underground natural gas regulator stations.

INSULATING POLYMER CONCRETE

The natural gas industry has always been concerned with accidental spills of LNG from storage tanks into surrounding impounding dike. The LNG stored in
these tanks is at a temperature of approximately –260 °F. The dikes are generally constructed of tamped soil or of Portland cement concrete slabs over the soil. The LNG, which is leaked to the dike area, boils off very rapidly and the vapors mix with the atmosphere forming a hazardous explosive mixture in the surrounding region. (1,2,3) Analysis of the problem has indicated that the rate and quantity of LNG evaporation are primarily dependent on the rate of heat transfer from the dike surfaces to the spilled LNG in the dike. If the rate of heat transfer is reduced, the total quantity of LNG vapor, per unit time, will also be reduced. Studies by the natural gas industry indicate that insulating the dike areas surrounding these tanks could markedly reduce the hazards associated with accidental spills of LNG from storage tanks. The insulating material is used to construct a thermal barrier between the walls and floor of the dike and the spilled LNG. This will significantly reduce the rate of evaporation in a given time period after an accidental spill.

The insulating composite, designed to meet the criteria, required a very low thermal conductivity to reduce the rate and quantity of LNG evaporated. In addition to the thermal properties, strength and durability were also important. Strength, because the insulated surfaces would have to carry light transient loads, such as, workmen and maintenance vehicles. Durability, because the insulating material will have to withstand atmospheric weathering for several decades. The insulating composite must have a good bond to a concrete surface and must not support combustion. Last but not least, the composite must lend itself to field applications and should be easy to handle by experienced construction personnel.

Insulating Polymer Concrete (IPC) (4,5,6) is a composite that meets all of the requirements specified for dike insulation. A typical composite consists of lightweight multicellular glass nodules bound together in a dense matrix with a polymer binder. Low thermal conductivity is characteristic of organic polymers and lightweight hollow structure aggregates. The composite, formed by these materials, is a closed-cell structure, with low thermal conductivity, low density, low water absorption, good durability, and relatively high strengths. These composites can be cured in-situ at ambient temperatures, with workability properties similar to Portland cement concrete. The IPC formulation used at the Long Island Lighting Company (LILCO) LNG is given in Table 1.

The physical and thermal properties of IPC formulations were measured using ASTM standards wherever possible. The measured properties, of several different IPC formulations, are given in Table 2.

A thermal shock test was simulated on a small field installation of an IPC overlay. Liquid nitrogen (N₂), at a temperature of –320 °F was poured over the IPC overlay which was at a temperature of 60 °F. Wooden sides, glued to the overlaid slab, prevented the liquid N₂ from pouring over the sides. Within a few minutes, a liquid level remained on the surface and slowly evaporated without the boil-off normally associated with cryogenic liquids. There was little, if any,
indication that the IPC overlay had cracked or disbonded. The test was repeated two additional times, on the same slab, with the same results.

In addition to the flammability test, reported in Table 2, another, more severe, burn test was conducted with IPC panels. The panel surface was covered with approximately 0.25 inches of gasoline and then ignited. Since the gasoline did not absorb into the low porosity IPC, the fire self-extinguished as soon as the fuel was consumed. The IPC surface was charred but did not crack or lose its structural integrity.

Specialty construction contractors made several full-scale installations of IPC overlays. In 1984, the first IPC overlay was placed on a dike owned by the Brooklyn Union Gas Company (BUG). The contractor was Polymer Construction Specialties (PCS).

There were two impounding dikes, side by side, located in Brooklyn, NY, near the East River and less than 2-3 miles from downtown New York City. Each dike had approximately 80,000 square feet of surface area that had to be overlaid. The ratio of floor to walls was approximately 3:1. The walls of these dikes were approximately 25-30 feet high and severely sloped. The overlay was placed in vertical sections approximately 6-8 feet wide. Ladders were constructed on both sides of the area to be overlaid, as shown in Figure 1. The materials were mixed in a Respecta continuous mixer. Each batch was transported, in wheelbarrows, to the appropriate area. The composite mixture was applied to a tack-coated surface and leveled with a vibrating screed to a thickness of 0.5 to 0.75 inches. The floors of the dike were much easier to overlay and much larger sections could be done at one time (Figure 2). The second dike, at BUG, was overlaid in 1986. The Taisei Corporation, from Tokyo, Japan, placed this overlay. They had introduced a “Shot Rem System”, at the ICPIC conference in Darmstadt, Germany, in September 1984. (7) The author visited the company in May 1985 and had them try several IPC mix designs with their shotcrete machine. Samples were returned to BNL and their physical and thermal properties were evaluated. The physical and thermal properties of the samples provided by Taisei Corp. were within the standards set by BNL. Upon the author’s recommendation, BUG contracted with Taisei to place the IPC overlay on the second dike, in 1986, using their shotcrete machine (Figure 3,4) with BNL’s composite mix design. The physical and thermal properties of the IPC were monitored several times a week by BNL. These properties were found to be within the limits set throughout the construction phase.

In the summer of 1987, the Long Island Lighting Company (LILCO) proceeded to insulate their dike with a new formulation designed by BNL. New, lightweight spheres, from the 3M Company, made it possible to refine the IPC formulation without interfering with the one used at BUG. The PCS construction company was awarded the contract and, with its previous experience, completed the installation without any problems.
Polymers in Concrete: The First Thirty Years

For several years, after the IPC installations, BNL monitored all three applications. Both visual and physical tests were made to monitor the bond strength of the overlay and its durability. Some repairs were required on the overlays, but these were considered minor since they were less than 1% of the total area placed. There have been some minor spills of LNG, both in the BUG and LILCO facilities. Both companies have been impressed at the slow boil-off of LNG from the IPC surface.

ELECTRICALLY CONDUCTIVE POLYMER CONCRETE OVERLAY

The use of impressed current, cathodic protection (CP), to prevent the corrosion of embedded reinforcing steel, in chloride contaminated bridge decks, received much attention from 1970-1990 (8,9,10). Electrically conductive composites have played a significant role in advancing the use of CP systems installed in highway bridge decks and other concrete structures. In 1984, the Federal Highway Administration (FHWA) contracted BNL to develop an electrically conductive bridge deck overlay and a sprayable conductive coating (11). The non-sagging, sprayable, conductive coating developed has a very low electrical resistivity, 1.6-3.5 ohm-cm, with excellent bonding characteristics to concrete. The mix design, of the coating, combined 60-wt % of calcined coke breeze (an electrically conductive aggregate) with 40-wt % vinyl ester resin containing 3.5-wt % of a thixotropic agent based on modified bentonite clay. Some physical and electrical properties, of the coating, are given in Table 3.

A field demonstration was performed on a bridge substructure near Norfolk, Virginia. The conductive coating was sprayed on the concrete surfaces using a conventional pneumatic spray machine and a fan-jet gun (Figure 5). The permeability of the coating is about one-half that of concrete. This allows any formation of chlorine, hydrogen or oxygen gas, formed by the impressed cathodic protection (CP) current, to permeate through the coating and escape into the surrounding atmosphere. If the coating were not permeable, the gasses would be trapped in the concrete substrate-coating interface. Moisture in the concrete could combine with the chlorine gas and form an acid thus deteriorating the concrete surface and adversely affect the bonding of the conductive coating.

The coatings were monitored for several years by an independent corrosion-engineering firm. They reported that the conductive coating had less than one-percent deterioration.

The second system developed was an electrically conductive composite overlay (12) to uniformly distribute the CP current across the bridge deck surface while providing a skid and wear-resistant surface for the bridge deck. The overlay,
approximately ½-inch thick, will not increase the dead load significantly. Ramps on the slabs will provide a smooth transition to the bridge deck.

A low electrical resistivity composite was obtained with an aggregate mixture of 50-wt % calcined coke breeze and 50-wt % crushed basalt or silica sand with a binder content of 15-20-wt % unsaturated polyester resin. The electrical resistivity of this composite was 2-5 ohm-cm. An overlay of this composite was cast on a concrete slab and tested on BNL’s wear test machine. Tests representing 0.84 to 2.1 x 10⁶-tire passes, on the overlay, indicated there was no measurable wear on the surface. A British Pendulum Tester (ASTM E 303) was used to determine surface texture changes from the wear resistant tests. There was some decay in the BP number however; it was not deemed significant.

A field installation, of a conductive overlay, was made on a two-lane bridge, on Route 99, over Peak Creek, near the town of Pulaski, Virginia. The three span bridge deck had a surface area of 4,400 square feet. The chloride content, of the Portland cement concrete bridge deck, ranged from 1.4 to 5.56 lb.-Cl/yard³. Chloride contents of 1.3 lb.-Cl/yard³ are considered high enough to corrode the reinforcing steel.

About 2,000 square feet (>45 % of total surface) of the bridge deck, was so highly deteriorated that it had to be removed and replaced before the CP system, with the conductive overlay, could be installed. Repairs were made, as per the specifications, of the Virginia Department of Transportation, for Type B repairs.

The deck repairs were cured for a minimum of 30 days before the conductive overlay was placed. The bridge deck surface was prepared for overlay placement by shotblasting. Oil-free compressed air was used to remove residual cement dust. An engineering firm familiar with CP and conductive overlays designed a simple system incorporating both elements. BNL technicians installed the CP system as designed. On the top of the cleaned bridge deck, a platinum-niobium covered copper wire was installed as the primary anode. The conductive overlay functions as the secondary anode to uniformly distribute the CP current across the bridge deck surface.

A Virginia construction company, who had experience in placing both polyester and epoxy resin overlays, was contracted to place the conductive overlay. Screed rails were set for the placement of a ½-inch thick overlay on the westbound lane. An air operated vibratory screed was set on the screed rails and adjusted to provide a uniform overlay thickness across the entire width of the lane.

The conductive composite was mixed in mortar mixers (Figure 6) for 3-5 minutes, transported in wheelbarrows and spread in front of the screed. The screed was pulled along the screed rails by hand (Figure 7). The overlay surface was tyned to provide a skid-resistant surface. There were some inconsistencies in
the mix, due to the batch mixing; however, for a first time installation, it was deemed satisfactory.

A Bidwell paver was used to place the overlay on the eastbound lane (Figure 8). The screed height was adjusted for a ½-inch thick overlay across the bridge deck surface. The paver was self-propelled so it was easier to control for continuous placement. During this placement, a small Bobcat loader was used to transport the mixed composite to load the paving machine hopper. Once the overlay was compacted and screeded to the proper elevation, the surface was tyned across the lane to provide a skid-resistant surface.

The CP system was first activated in December 1987 at 1 mA True Root Mean Square (TRMS) per square foot of anode. The total current was calculated at 4.42 amps TRMS. Test results over the next few years indicated that the rectifier remained very stable and delivered a constant preset current to the CP system. The average anode current density for the first few years of operation was only 1.05 mA-TRMS/r² of anode. During this period, the temperature of the overlay varied from 24-89 °F. The relatively low average voltage, 3.04 TRMS, providing an average current of 4.24 amp TRMS, indicates the high efficiency of the system. The entire system was periodically examined for approximately 10 years and appeared to be operationally sound.

STEEL-FIBER REINFORCED POLYMER CONCRETE

Precast, underground vaults, for natural gas regulator stations used by the Brooklyn Union Gas Company (BUG), Brooklyn, NY and the Consolidated Edison Company of New York (ConEd), New York, NY, have traditionally been fabricated with steel-reinforced PCC. Exterior surfaces, of the vaults, were epoxy coated to prevent the ingress of moisture into the vault. When these vaults are used to replace existing vaults in service, it was often necessary to offset the buried gas lines to align with the precast penetrations or field-cut new penetrations. Cutting through the reinforcing-steel subsequently weakens the structure and/or allows water ingress. The additional time involved, in moving the gas pipelines or altering the vault is costly.

A steel-fiber reinforced PC was developed to precast vaults for natural gas regulating stations (13). A benefit that was gained included longer maintenance-free service life due to increased physical and durability properties as compared to PCC. The higher strengths also allow designers to reduce wall thickness, thereby, decreasing vault weights that allowed for easier transportation and installation. Penetrations can be cut to match existing street lines, at time of installation, thus eliminating the need to have right and left handed vaults. Since the reinforcing steel-fibers are randomly dispersed throughout the PC, there will not be any loss of strength.
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It is well known that silane-coupling agents increase the bond between the aggregate and resin. These will also increase the compressive, flexural and tension strength of the composite by 15-25%. Durability also increases because the increased bond, between aggregate and resin, is less susceptible to moisture intrusion.

A structural design study, of vaults, used by BUG and ConEd was made using the physical properties of PC. The study indicated that the higher strength properties of PC could allow for 50% thinner wall sections. Thus, the overall weight, of the cast PC vaults, will be about half the weight of a PCC vault. The two principal properties that were of concern to the structural design engineers, were flexure strength and the ductility of the PC. The flexure strength measured for the PC formulation, given in Table 4, was 4700 psi with a standard deviation of 500. A typical load-deflection curve is shown in Figure 9. The area under the load-deflection curve, beyond the yield point, is at least ten times the area under the yield point. This indicates that the material is ductile and will not be subject to a catastrophic failure. The ductility, of the PC, was entirely related to the use of ribbed fibers having a 20 to 1 aspect ratio (length to width). In the polyester PC, the load is transferred to the steel fibers and at the yield point they begin to carry most of the load. The steel-fibers slowly pull out of the polymer matrix, as they are being loaded, until the ultimate load is reached. At this point, the structure can no longer carry any load. An epoxy resin PC has a higher yield point, but its bond, to the steel fibers, is so good that the fibers themselves fail in tension, and thus allow a catastrophic failure (Figure 9).

Quarter-scale models, of PC vaults, were cast. The center-to-center dimensions were 2-feet by 1.5-feet by 1.5-feet with a wall thickness of 1-inch. A model vault was evacuated, thereby subjecting it to a uniform pressure. A peak pressure of 1650 psf was obtained. The box was subjected to several complete loading-unloading cycles without suffering any damage. The test actually subjected the model vault to pressures 60% higher than the design load of 1000psf. Tests were also run on model boxes with pipe penetrations installed through the walls and cemented in place with an epoxy mortar (Figure 10). Test results on these boxes were similar to the initial tests.

Full-scale drawings, using the PC design criteria that was developed by BNL, were made for vaults required by both ConEd and BUG. The BUG vault was approximately 7-feet by 7-feet by 6-feet and the ConEd vault was approximately 6-feet by 4-feet by 3-feet. Hardinge Bros., Elmira, NY, was contracted to build the forms and cast two PC vaults, of each type, using the formulation developed by BNL. These were put in service by both utilities and monitored for several years. Within the first year, the ConEd maintenance group was so impressed with the ease of installation and the performance of these vaults that they decided to place them on their standard parts list.
This document has reviewed three different polymer composites that were developed for specific applications. Each one is unique unto itself. By carefully selecting the aggregate and resin formulations, entirely different properties were obtained. Knowledgeable contractors have shown that they can safely work with these materials in field or factory precast applications. These composites may not be inexpensive, but they do have sophisticated uses; therefore, cost may not be an insurmountable objection.

Consumers must understand that each and every PC formulation available was developed for a specific product end use. Thus, every different product developed may require its own unique formulation. Careful developmental studies must first be undertaken to ascertain that physical, chemical, thermal, and/or electrical properties, of the composite, can be obtained. Then, full-scale field or in-house applications must be performed. When these studies have been completed, and the results are satisfactory, a full-scale production operation may commence. Polymer composites are not the panacea for every application, but they certainly can satisfactorily solve many problems.

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<table>
<thead>
<tr>
<th>Materials</th>
<th>Manufacturer</th>
<th>Pounds/cubic foot of IPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrolite 3.5-7</td>
<td>3M Company</td>
<td>5.0</td>
</tr>
<tr>
<td>Macrolite 7-14</td>
<td>3M Company</td>
<td>6.0</td>
</tr>
<tr>
<td>Macrolite 14-30</td>
<td>3M Company</td>
<td>12.5</td>
</tr>
<tr>
<td>Macrolite 30-50</td>
<td>3M Company</td>
<td>2.5</td>
</tr>
<tr>
<td>P-2000</td>
<td>Fillite, USA</td>
<td>2.5</td>
</tr>
<tr>
<td>DE-83R</td>
<td>Great Lakes Company</td>
<td>5.0</td>
</tr>
<tr>
<td>Flexoglass resin</td>
<td>Dural International</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Notes:
1. Macrolite: multicellular glass beads with ceramic shell
2. P-2000: alumina silicate microsphere
3. DE-83R: decabromodiphenyl oxide flame retardant agent
4. Flexoglass: moisture insensitive epoxy resin
## Polymers in Concrete: The First Thirty Years

### TABLE 2
Physical and Thermal Properties of IPC

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Values</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0.1-0.15 BTU/hr-ft²°F @ 80°F</td>
<td>Dynatech comparator</td>
</tr>
<tr>
<td></td>
<td>0.03-0.05 BTU/hr-ft²°F @ -240°F</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>40-55 lb/ft³</td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>1300-2500 psi</td>
<td>ASTM C 495</td>
</tr>
<tr>
<td>Flexure strength</td>
<td>500-900 psi</td>
<td>ASTM C 78</td>
</tr>
<tr>
<td>Tensile bond strength</td>
<td>200-350 psi</td>
<td>ACI-503R Appendix A</td>
</tr>
<tr>
<td>Water absorption</td>
<td>0.1-0.5 wt %</td>
<td></td>
</tr>
<tr>
<td>Flammability</td>
<td>Self-extinguishing in 5-10 seconds</td>
<td>ASTM D 635</td>
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<tr>
<td>Linear curing shrinkage</td>
<td>0.06-0.15 %</td>
<td>BNL test method</td>
</tr>
<tr>
<td>Freezing and thawing</td>
<td>Up to 300 cycles with a 10-20 % loss of strength</td>
<td>ASTM C 666</td>
</tr>
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</table>

### TABLE 3
Properties of Sprayable Electrically Conductive Coatings

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Values</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistivity:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 10-15 mils thick</td>
<td>3.5 ohm-cm</td>
<td>4 pin method with Nilsson Model 400 AC impedance meter</td>
</tr>
<tr>
<td>@ 20-40 mils thick</td>
<td>1.6 ohm-cm</td>
<td></td>
</tr>
<tr>
<td>Tensile bond strength:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of freeze-thaw cycles</td>
<td>450 psi</td>
<td>Elcometer Adhesion Tester</td>
</tr>
<tr>
<td>0</td>
<td>440 psi</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>430 psi</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 10-20 mils thick</td>
<td>5,990 coulombs</td>
<td></td>
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</tbody>
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### TABLE 4
Steel-Fiber Reinforced PC Mix Design

<table>
<thead>
<tr>
<th>Materials</th>
<th>Quantity, wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course stone</td>
<td></td>
</tr>
<tr>
<td>¾ inch max. traprock</td>
<td>13.5</td>
</tr>
<tr>
<td>½ inch max. traprock</td>
<td>13.5</td>
</tr>
<tr>
<td>Graded silica sand (US Sieve 16-100)</td>
<td>40.5</td>
</tr>
<tr>
<td>Silica flour (US Sieve 250-350)</td>
<td>13.5</td>
</tr>
<tr>
<td>Steel fibers, ribbed, 1.5 inch long, aspect ratio=20</td>
<td>9.0</td>
</tr>
<tr>
<td>Resin, orthophthalic polyester</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Notes:
1. Polyester resin must contain 1-wt % silane coupling agent.
2. Polyester resin may be cured at room temperature using cobalt naphthenate and methyl ethyl ketone peroxide.
3. All aggregates and sand must contain less than 0.5-wt % moisture.
Figure 1. Installing IPC overlay on sloped walls of containment dike.

Figure 2. Vibrating screed used to finish IPC overlay.

Figure 3. Taisei Shot-Rem machine.
Figure 4. Spray application of IPC overlay on dike walls.

Figure 5. Spray application of electrically conductive coating.
Figure 6. Mixing the electrically conductive PC overlay composite.

Figure 7. Screeding the electrically conductive PC overlay.

Figure 8. Modified Bidwell paver placing the electrically conductive PC overlay.
Figure 9. Load-deflection curves of steel-fiber reinforced PC.

Figure 10. Quarter-scale model vault after being tested to failure.
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How Polyester Polymer Concrete Highway and Bridge Deck Overlays Became “State of the Art”

by J. Maass

Synopsis: This paper reviews the history of polyester polymer concrete highway and bridge deck overlay with a focus on the work done in California and adjacent states. The paper discusses the early work done at Brookhaven Labs, the watershed I-80 job done at Donner Pass (including updates relating to the job), and then reviews the large number of successes over the last thirty years.

Keywords: bridge and deck overlay; CalTrans; Donner Pass; highway overlay; I-80; polyester resin; polymer concrete; premix method; unsaturated polyester
INTRODUCTION

My goal with this paper is to share with you the history of polyester polymer concrete highway and bridge deck overlay with a focus on the work done primarily in California. I will review the early work done at Brookhaven Labs, the watershed I-80 job done at Donner Pass (including updates relating to the job), and then review the large number of successes over the last thirty years.

According to the best information I have been able to gather, it was definitely over breakfast, and most probably near Barstow, California in 1991. It was at that meeting that Cal-Trans Resident Engineer on the I-15 Project, Fran Flesner, mentioned to the on-site consultant, Steve Frank, that the term “experimental” was being dropped from the polyester polymer process. Steve asked Fran what that meant. Fran answered, “Lots more future work.” He was right.

The first scientific research on the use of polymers on highway and bridge deck overlays began at the Bureau of Reclamation and Brookhaven National Laboratory under sponsorship of the Federal Highway Administration in the late 1960’s. That experimental work first began using unsaturated polyester resins, as well as epoxy and methyl methacrylate and other polymers as potential binders from aggregate to be used for Highway and Bridge Deck Overlays. The Bureau of Reclamation and Brookhaven National Laboratory jointly developed the drop-in or broom and seed method in which first resin and then aggregate are broadcast over the deck until the desired thickness is achieved.

In the early 1980’s, Cal-Trans was using the premix or Oregon method. This method, by contrast, calls for batched concrete mixers to combine the polyester-styrene aggregate mixture and to distribute the resultant mix with screeds and control wires so as to control thickness and finish with regular concrete finishing methods. The resin-to-aggregate ratio is similar in the two methods and so are the costs.
Polymers in Concrete: The First Thirty Years

Cal-Trans elected in 1985 to go forward with its first major application of polyester polymer concrete highway overlay. The site chosen was the Donner Pass section of I-80, just west of the Nevada border. The Pass had gotten its name from weather. The Pass is named for the tragic Donner Party that froze in 1846 enroute to gold country and the warm climate of California. Extreme weather changes are characteristic of the Pass. The Pass is now the route of Interstate 80 as it crosses the Sierra Nevadas between Reno, Nevada and Lake Tahoe, California.

A report on a 1982 field test done under federally funded research entitled, “Experimental Overlays Utilizing Magnesium Phosphate, Methyl Methacrylate and Polyester-Styrene Concrete” describes the I-80 site as follows: “The site was located on eastbound Interstate 80 at approximately 6,500 feet in elevation on a +5% grade with varying super-elevation up to 8%. The existing pavement surface, which was constructed in 1962, consisted of non-reinforced PCC with skewed joints at 15-foot spacing. The pavement was extremely deteriorated due to rain and chain abrasion. The pavement is subjected to large daily temperature fluctuations and severe freeze-thaw conditions.”

The average 1983 daily traffic (ADT) for this four-lane freeway was 9,750 with a truck ADT of 950. The average rainfall is 61 inches, including an average snowfall of 410 inches. (2)

Reichhold’s 32300 flexible isophthalic polyester resin was utilized on this research project. This resin is currently marketed with silane coupling agents premixed into the resin under the specification. The Reichhold product code is 32043.

The 1985 Donner Pass job was, in fact, the culmination of seven years of both lab tests. The California Department of Transportation (Cal-Trans) conducted Field tests and a literature search. Cal-Trans experiments included: (1) high density, low slump PCC, (2) Butadiene styrene latex modified PCC, (3) epoxy bonded PCC, (4) epoxy concrete, (5) methyl methacrylate (MMA) polymer concrete and (6) polyester – styrene polymer concrete.

Of all these systems, Cal-Trans selected the polyester-styrene based system.

Suppliers of the polyester-styrene based systems suggest that the systems have the following benefits:

- Permits rapid application and allows for fast return to use with little or no disruption of traffic
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- Protects steel reinforcements from infiltration of water and chloride ions from de-icing salts, which accelerate corrosion
- Adds minimal additional dead load to the structure
- Creates a long-lasting, skid resistant surface
- Provides high resistance to wear
- Reduces costs by minimizing traffic disruption and control.

Early testing had also concluded that sandblasting of the pavement surface was not adequate to ensure good bonding. A more complete cleaning of all contaminants from the old pavement surface is a must. Humble Equipment provided a shotblaster developed specifically for pavement overlay work. *(Figure 1)*

The shotblaster “throws” 3000 pounds of small steel shot per minute against the roadway. Most of the 0.046-inch diameter shot is caught in a vacuum hood filtered and reused many times.

**THE JOB**

The job was awarded to Brutoco Engineering on May 21, 1985. The project included nearly ten (10) lane miles of polyester-styrene concrete overlay on a three-lane-wide pavement that included a five-percent grade. The PCC pavement was severely abraded due to truck tire chain abrasion. Daily temperature variation of 50 F and more occurred on the site. The contract included repair of several PCC slabs full depth due to severe cracking. Many less severely cracked slabs were overlaid with polyester-styrene concrete.

Following surface preparation with a shotblaster, the contract specified a high molecular weight with methyl methacrylate primer coat or an unsaturated diaromatic oxide glycol fumarate. It was suggested the project be used to evaluate two alternative polyester resins identified as Type II and Type IV respectively. Type II was a wax-free unsaturated isophthalic polyester cut in 40-45% styrene to a viscosity of 75 to 200 cps. This is the unique polyester type, supplied earlier by Reichhold, with which Cal-Trans had had so much success. Its unusual feature is the resin’s high flexibility with tensile strength of 2500 psi and a minimum elongation of 35%. Type II was actually supplied by the Koppers Company (later acquired by Reichhold).

The other system tested was designated as Type IV. It was also an unsaturated isophthalic polyester but more rigid. The resin was supplied by Chagrin Valley Industries (later known as FTI). The following table lists typical polyester-styrene resin’s physical properties: (see Appendix 1).
**Polymers in Concrete: The First Thirty Years**

The aggregate specified was ½-in maximum with less than 25% crushed particles, maximum oil absorption of one percent and a moisture content of less than ½ percent at the time of mixing. Dry Mix Products of Roseville, California delivered aggregate in reusable nylon bags, which held 3,500 pounds of dry aggregate.

A mobile, screw-auger type continuous mixer with self-contained separate aggregate, resin and peroxide initiator compartments was used. The peroxide, methyl ethyl ketone peroxide (Reichhold’s 46-709) was introduced into the resin prior to mixing with the aggregate. Flow sensing valves and alarms were also required.

Each mixer was loaded with five bags of rock and four bags of sand, or about 31,000 pounds in all, which was blended at 55-45 percent ratio. This was then mixed with an additional 12 to 14 percent polymer resin (about 50 to 60 gallons resin and one gallon catalyst per cubic yard). *(Figure 2)* Each mixer carried about 400 gallons of resin and 15 gallons of catalyst in its divided resin tanks. Each mixer was reloaded every 45 minutes. As it was loaded, one crewmember cleaned the screw by running dry aggregate through it, followed by hand scraping if needed. Each evening the system was washed down with acetone. *(Figure 3)*

The finishing machine was Gomaco C-450. Dry screenings were specified to be broadcast over the overlay after finishing to ensure initial skid resistance. The 3.6 miles was applied to a minimum thickness of ¼-in over six weeks in the fall and an additional four weeks in the spring. *(Figure 4)* The schedule allowed for downtime so as to avoid rain and snow so common to the Donner Pass.

**THE UPDATE**

In his 1988 paper, Paul Kraus, then Senior Materials and Research Engineer at Cal-Trans concluded, “Due to the nature and cost of repairing bridge decks, polyester-styrene concrete overlays on bridge decks have proven to be a viable and satisfactory rehabilitation technique. Over twenty-five bridge decks have been overlaid with polyester-styrene concrete overlays and all the overlays are performing well. There have been no delaminations on any polyester concrete overlay placed by contract and only one experimental overlay has shown minor delaminations. None of the bridge deck overlays placed since 1983 have shown signs of wear or cracking. Advantages include: rapid return of the structure to traffic, protection of the reinforcing steel from water and deicing salts, minimal additional dead load, no modifications to the barrier rails required, grade or slope corrections can be made, and installation involves using familiar construction techniques.”
Maass

In 1996, I contacted Henry Jerzak, Cal-Trans Material and Research Associate, now retired, who supplied the wear data shown as Appendix 2.

According to Jerzak, wear data for Type II, the flexible or elastomeric polyester-styrene, was very similar to the Type IV. Based on the ready availability of Type II and its flexibility, a required prerequisite for movement on bridge decks, Cal-Trans continues to specify the Type II flexible polyester (with the addition of 1% silane to improve bonding to the aggregate.) Jerzak says that this is finally the ideal system that sticks to concrete. “If properly primed, it sticks tenaciously” indicated Jerzak. “The few problems encountered were always found to be applications related, i.e. poor surface preparation, severe weather conditions (applied below 40 F) or inadequate catalyst. It is a simple system, but must be done right the first time,” he concludes.

In 1991, Al Klail completed the Benicia-Martinez bridge deck over San Francisco Bay for General Contractor, Kiewit Pacific Co. This single bridge consumed approximately 850 cubic meters of polyester polymer concrete. (Figures 5-8) Shortly thereafter, Al was also the key man on site of the approach to the Golden Gate Bridge, the project known as Doyle Drive. Videos of this project installed at night in the fog with bridge traffic moving in adjoining lanes have been shown at TRB.

For the past several years, Cal-Trans has specified approximately two-dozen projects per year. Other states have shown interest in the excellent results obtained by Cal-Trans. The state of Nevada virtually copied the specifications written by Cal-Trans, and has been overlaying bridge decks with the same resin system for 14 years. In 1999, the state of Utah did its first polyester polymer concrete project overlaying two bridge decks on Bengerter Highway, south of Salt Lake City. In 2000, the state of New York led a project in upstate New York, about one hour north of Albany. The project consisted of overlaying Martin Marietta composite bridge panels with polyester polymer concrete. Again in 2000, Cal-Trans also led a project for the polyester polymer concrete overlay of a Martin Marietta composite bridge deck near the town of Mecca, California.

There were several other large projects in 2000: Interstate 405 in Costa Mesa, California; Interstate 5 in Gorman, California; and Highway 395 near Reno, Nevada.

CONCLUSION

Dozens of jobs have now been completed using Polyester Polymer Concrete Highway and Bridge Deck overlays without a single failure. In each case, Reichhold 32043 was the resin of choice. The storage quality is excellent.
Polymers in Concrete: The First Thirty Years

That's the story of how polyester polymer concrete highway and bridge deck overlay has gone from "experimental" to "state of the art."

REFERENCES


Munn, Walter D., P.E. "Polymer Concrete Pavements are Coming," *Highway and Heavy Construction*, October 1986.


The author also utilized information supplied by the following:

a. Frank Fekete, President, FTI, Monroeville, PA,
b. Steve Frank, Product Manager, Atlas Construction Supply, Inc., San Diego, CA,
c. Henry Jerzak, retired. California Department of Transportation, Sacramento, CA.
### APPENDIX 1

<table>
<thead>
<tr>
<th></th>
<th>Type II</th>
<th>Type IV</th>
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<tr>
<td></td>
<td>Polyester Concrete</td>
<td>Polyester Concrete</td>
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<td>Resin Viscosity</td>
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<td>400-500 cps</td>
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<td>(77 °F) (CA 434)</td>
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<td>(CA 434) minimum</td>
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<td>Resin Elongation</td>
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<td>(CA 434) minimum</td>
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<tr>
<td>Flexural Strength</td>
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<td>(24 hours)</td>
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<td>Compressive Strength</td>
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<td></td>
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<td>Bond to Dry PCC</td>
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<td>720 psi</td>
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<td>(24 hours)</td>
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<td>(24 hours)</td>
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<td>Thermal Coef of Expansion</td>
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<td>-</td>
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(2)
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<th>53.33</th>
<th>52.48</th>
<th>52.68</th>
<th>Avg</th>
<th>Mile Post (Approximately)</th>
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<td></td>
<td></td>
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<td>0.62 yr.</td>
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<td>225D</td>
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<td>14</td>
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<td>11</td>
<td>13</td>
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<td>36</td>
<td>24</td>
<td>42</td>
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<td>60</td>
<td>66</td>
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<td>32</td>
<td>54</td>
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<td>09/18/1991</td>
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<td>69</td>
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<tr>
<td>09/23/1993</td>
<td>364D</td>
<td>54</td>
<td>57</td>
<td>32</td>
<td>19</td>
<td>41</td>
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<tr>
<td>09/22/1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.92 yr.</td>
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<td>Total Wear</td>
<td>253</td>
<td>296</td>
<td>197</td>
<td>141</td>
<td>222</td>
<td></td>
</tr>
</tbody>
</table>

Readings are thousandths of an inch. Average wear .028" per year
Donner Pass Job I-80
October 1985

Figure 1: Seven foot shotblaster.

Figure 2: Back of Haws mixer.

Figure 3: Spreading of the premixed polymer concrete.

Figure 4: Placing of the 3/4 inch overlay.
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Benicia-Martinez Bridge Deck
(San Francisco Bay)
Fall 1991

Figure 5: View of the Benicia-Martinez Bridge (San Francisco Bay).

Figure 6: Application of the primer.

Figure 7: Automated deposition of the premixed polymer concrete.

Figure 8: Inspection of placed 3/4 inch overlay.
Twenty-Five-Year Experience with Polymer Concrete Bridge Deck Overlays

by M. Sprinkel

Synopsis: The construction, performance and use of polymer concrete bridge overlays over the past 25 years is summarized. Polymer concrete overlays that have an established history of use and acceptance include multiple-layer epoxy, multiple-layer epoxy urethane, methacrylate slurry and premixed polyester styrene. Evaluations indicate that polymer concrete overlays can provide skid resistance and protection against intrusion by chloride ions for 25 years and are an economical technique for extending the life of concrete decks, particularly when overlays must be constructed during off-peak traffic periods to minimize inconvenience to motorists.

Keywords: bond; bridge; concrete; corrosion; deck; epoxy; epoxy urethane; methacrylate; overlays; permeability; polyester styrene; polymer; skid resistance
Introduction

Polymer concrete overlays similar to those currently in use have been installed on Portland cement concrete bridge decks in many states during the past 25 years. The overlays are usually placed on decks to reduce the infiltration of water and chloride ions into the concrete and improve skid resistance, ride quality, and surface appearance.

Bridges that are good candidates for polymer overlays are those that have peak-hour traffic volumes that are so high that it is not practical to close a lane to apply the surface except during off-peak traffic periods. Polymer overlays are one of the few surfaces that can be installed with short periods of lane closure. Bridges that are also good candidates are those in which increases in dead load, reductions in overhead clearance, and modifications to joints and drains must be held to a minimum. Decks that require a lot of concrete removal are better suited for hydraulic cement concrete overlays.

Three types of overlays are typically used:

- Multiple layer: two or more layers of unfilled polymer binder and broadcasted gap-graded, clean, dry, angular-grained aggregate;
- Slurry: a polymer aggregate slurry struck off with gauge rakes and covered with broadcasted aggregate; and
- Premixed: a polymer concrete mixture consolidated and struck off with a vibratory screed.

Polymer Concretes and Mortars

The most frequently used binders for polymer concretes and mortars are epoxy, epoxy urethane, polyester styrene, and methacrylate. The binders are usually two-component systems: one component contains the resin and the second contains the curing agent or initiator. The aggregates are usually silica and basalt. Typically, uniformly graded aggregates are used with slurry and
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premixed overlays, and gap-graded aggregates are used with multiple-layer overlays and are broadcast on the top of slurry and some premixed overlays (Table 1) (1).

Binders for polymer concretes and mortars are usually classified on the basis of the properties of the uncured and cured binder and the cured polymer concrete or mortar (Table 2) (1). Epoxy urethane binders have properties that are similar to those shown for epoxy with the exception that the viscosity is typically higher (35-70 poises).

Polymer concretes are typically made by combining polymeric binders and aggregates with gradations as indicated in Table 1. However, epoxy slurry overlays have been constructed with gap-graded aggregates similar to those shown for use in multiple-layer overlays. Aggregates are usually specified to be dry (less than 0.2 percent moisture), angular-grained silica sand or basalt and free from dirt, clay, asphalt, and other organic materials. Typical mixture proportions as reflected by application rate for three typical types of overlays are given in Table 3. Table 2 shows typical mechanical properties of polymer concretes used in overlays that have exhibited a long service life and that have been constructed in accordance with AASHTO Task Force 34 specifications.

The curing time is a function of the type and amount of curing agent or initiator, binder content, and curing temperature. Typically, mixtures successfully used for bridge deck overlays have been cured for the minimum time shown in Table 2 before being opened to traffic.

OVERLAY CONSTRUCTION

The successful application of a polymer concrete overlay includes use of acceptable materials, adequate surface preparation, proper batching and placement of materials, and adequate curing before the overlay is subjected to traffic.

Surface Preparation

Surfaces must be sound, clean, and dry in order to obtain a high bond strength. Concrete that does not have a tensile rupture strength of at least 1.0 MPa (150 psi) must be removed and replaced so that the overlay can bond to a sound substrate. Also, concrete with a chloride ion content greater than 0.77 kg/m³ (1.3 lb/yd³) at the reinforcing steel should be removed and replaced prior to placing the overlay. Large cracks should be filled ahead of time with a gravity fill polymer that is compatible with the overlay.
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Once the deck has been patched and large cracks (greater than 1mm in width) have been repaired, the surface should be cleaned by shotblasting and other approved cleaning practices to remove asphaltic material, oils, dirt, rubber, curing compounds, paint, carbonation, laitance, weak surface mortar, and other detrimental materials that may interfere with the bonding or curing of the overlay. Grit blasting must be used to clean along the edges of the deck and other areas that cannot be cleaned by shotblasting. The test method prescribed in ACI 503R (VTM-92) should be used to determine the cleaning practice (size of shot, flow of shot, forward speed of shotblast machine, and number of passes) necessary to provide a tensile bond strength greater than or equal to 1.7 MPa (250 psi) (ACI 503 R) or a failure area at a depth of 64 mm (0.25 in.) or more into the base concrete greater than 50 percent of the test area. A test result should be the average of three tests on a test patch of the overlay of at least 0.3 X 0.9 m (1 X 3 ft). One test result should be obtained for each span or 418 m² (500 yd²) of deck surface, whichever is the smaller area.

Methods of Application

The overlay should be placed the same day the surface is shotblasted. Areas that are not overlaid should be shotblasted again just before the overlay is placed.

Multiple-layer overlays are typically constructed by applying the binder to the surface and broadcasting a gap-graded aggregate to excess over the binder. Once the binder has cured, the unbonded aggregate is removed and a second layer is applied. Approximately 5.4 kg/m² (10 lb/yd²) of aggregate is broadcast onto 1.1 kg/m² (2 lb/yd²) or resin for Layer 1, and approximately 7.6 kg/m² (14 lb/yd²) of aggregate is broadcast onto 2.2 kg/m² (4 lb/yd²) of resin for Layer 2. The resin content of the overlay is about 25 percent by weight (Table 3) (1).

Slurry overlays are typically constructed by application of a prime coat at 0.41 kg/m² (0.75 lb/yd²), followed by a slurry mixture consisting of about 2.7 kg/m² (5 lb/yd²) of binder, 3.8 kg/m² (7 lb/yd²) of silica sand, and 2.7 kg/m² (5 lb/yd²) of silica flour (Table 2). This is followed by a broadcast to excess of a gap-graded aggregate as used in multiple-layer overlays (Table 2) and the application of a seal coat at 0.68 kg/m² (1.25 lb/yd²). The binder content of the overlay (including the prime coat and the seal coat) is about 24 percent (Table 3) (1).

Premixed overlays are constructed by mixing the aggregates shown in Table 2 with about 12 percent binder by weight (Table 3) (1). A primer is usually applied at the rate of about 0.41 kg/m² (0.75 lb/yd²) to enhance the bond strength. A vibratory screed is used to strike off and consolidate the concrete. Continuous batching and paving equipment has been used to place some overlays. Acceptable skid resistance can be obtained by placing grooves in the
freshly placed concrete or by broadcasting aggregate onto the surface. The thickness of the overlays is typically about 6.4 mm (0.25 in.) for the multiple layer, 7.9 mm (0.31 in.) for the slurry and a minimum of 13 mm (0.5 in.) for the premixed.

PERFORMANCE OF OVERLAYS

Decks Evaluated

Decks evaluated to provide an indication of performance are located in California, Michigan, Ohio, Virginia and Washington (3). Three overlays each constructed with multiple-layer epoxy (MLE), multiple-layer epoxy urethane (MLEU), premixed polyester (PP), and methacrylate slurry (MS), and two overlays constructed with multiple layer polyester (MLP) were evaluated. Evaluations were done at the time the overlays were constructed, in 1991 and in 1995 (3,4). The oldest overlay, M44 over the Grand River in Michigan, was evaluated again in 2000 at an age of 24 years. The overlays ranged in age from 6 to 19 years and the average age for the overlay types evaluated ranged from 7 to 12 years when evaluated in 1995 (3).

Tensile Bond Strength

A plot of tensile bond strength (VTM-92) vs age is shown in Figure 1. MLE, MLEU, and PP have not shown much change in bond strength over the life of the overlays. MLP overlays lose strength with time and should fail in approximately 10 years. There is insufficient data to evaluate the performance of MS overlays.

Permeability to Chloride Ion

The relation between permeability to chloride ion (AASHTO T 277) of the top 51 mm (2 in) of the overlay and deck and the age of the overlay is shown in Figure 2 (5). The results indicate that MS overlays provide the best protection and MLE, MLEU, and PP overlays provide negligible to very low permeability throughout their life. The protection provided at 25 years of age is as good or better than that provided by hydraulic cement concrete overlays. MLP overlays show the most increase in permeability with age but provide good protection for 10 years.
The relation between skid number and the age of the overlay is shown in Figure 3. New polymer concrete overlays typically have a bald tire (ASTM E 524) skid number of 50 to 60 (6). The skid number of polymer concrete is usually in the 30's or 40's after 15 to 20 years in service. With the exception of the MS, acceptable numbers are typically being maintained throughout the life of the overlays.

**Service Life**

Polymer concretes used in polymer overlays are very resistant to water, deicing chemicals, acids, and petroleum products (1). Also, overlays have shown good resistance to wear under traffic (1). Projections based on Figures 1, 2 and 3 suggest that, with the exceptions of the MS, and MLP overlays, polymer overlays constructed in accordance with AASHTO specifications should have a service life of 25 years.

**COSTS**

The cost of an overlay is a function of the cost of materials, surface preparation, labor, equipment, overhead, and traffic control. Costs can be expected to vary on the basis of the local labor rates and competitive bidding. MLE overlays are typical constructed in Virginia at a cost of $30 to $42/m² ($25 to $35/ft²). The PP overlay that is frequently used in California costs slightly more. The MS has been used less than polyester and epoxy because of its higher cost. The successful use of polymer overlays in California, Ohio, New York, Virginia, Washington, and other states demonstrates that polymer concrete bridge overlays are an economical alternative for extending the life of bridge decks.

A review of Fiscal Year 1994 and 1995 bid tabulations in Virginia for 27 projects specifying MLE overlays and 52 projects specifying latex or silica fume modified concrete overlays provided the results shown in Table 4 (3). The epoxy overlays cost 25% of the hydraulic cement concrete overlays based on total initial cost and 36% based on life cycle cost assuming a 15 year life for epoxy and a 30 year life for hydraulic cement concrete (HCC). The life cycle cost is even lower if one uses a life of 25 years, which can be justified based on figures 1, 2 and 3.

The differences in cost between MLE and HCC overlays is attributed to the differences in the costs of the overlay materials, miscellaneous construction activities, and traffic control. The initial treatment cost of the epoxy overlay was
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39% of that of HCC. Miscellaneous costs for HCC included building up the approach slabs and back walls and replacing joints. Traffic control costs were higher for the HCC overlays because of the requirements for concrete barricades, removing and installing permanent and temporary pavement markings and longer construction time. Epoxy overlays are installed in a short time using cones for delineation and without the need to replace pavement markings or joints and without raising approach slabs or backwalls.

SUMMARY OF USE

Table 5 shows the number of polymer concrete bridge deck overlays constructed in the United States each year beginning in 1990 and the total constructed prior to 1990 based on data obtained from the seven major suppliers of materials. Use has increased during the 90's and as of 1999 a total of 555 bridges had been overlayed. Polymer concrete overlays constructed in accordance with AASHTO specifications have become an accepted deck overlay system and use is expected to continue.

CONCLUSION

Multiple-layer epoxy, multiple-layer epoxy-urethane, and premixed polyester polymer concrete overlays constructed in accordance with AASHTO specifications can provide a skid resistant wearing and protective surface on bridge decks for 25 years and are an economical alternative to hydraulic cement concrete overlays.

RECOMMENDATION

Departments of transportation should use polymer overlays as described herein to provide bridge decks with skid resistance and protection against intrusion by chloride ions.

REFERENCES


58 Sprinkel


4. M. M. Sprinkel, Nineteen Year Performance of Polymer Concrete Bridge Overlays, American Concrete Institute, SP-169, Farmington Hills, MI, 1997.


Table 1. Typical Aggregate Gradations (Percentage Passing Sieve)

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Multiple-Layer Overlays</th>
<th>Slurry Overlays</th>
<th>Premixed Overlays</th>
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<tr>
<td>0.13 mm</td>
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<td>-----</td>
<td>100</td>
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<tr>
<td>0.10 mm</td>
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<td>83-100</td>
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<td>No. 20</td>
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<td>90-100</td>
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<td>0-1</td>
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<td>93-99</td>
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## Table 2. Properties of Binders and Polymer Concrete

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<th>Epoxy</th>
<th>Polyester</th>
<th>Methacrylate</th>
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<td>1-5</td>
<td>11-13</td>
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<td>Gel time, min</td>
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<td>10-25</td>
<td>15-45</td>
<td>AASHTO T 237</td>
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<td>Tensile strength, at 7 days, MPa</td>
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<td>13.8-34.4</td>
<td>3.4-8.3</td>
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<td>Tensile elongation, at 7 days, %</td>
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<td>30-80</td>
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<td>Compressive strength at 3 hrs. MPa</td>
<td>Minimum of 6.9</td>
<td>Minimum of 6.9</td>
<td>Minimum of 6.9</td>
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<td>Compressive strength, at 24 hrs., MPa</td>
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<td>Minimum of 34.4</td>
<td>Minimum of 34.4</td>
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<td>Adhesive Strength at 24 hrs., MPa</td>
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<td>Cure Time @ 16° C, h</td>
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<td>5-6</td>
<td>4</td>
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1MPa = 145 psi  Degrees Centigrade=0.55 (Degrees Fahrenheit-32)

*Time is based on time to obtain a compressive strength of 6.9 Mpa (1000psi)

## Table 3. Typical Polymer Concrete Application Rates

<table>
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<tr>
<th>Overlay</th>
<th>Multiple Layer Epoxy (kg/m²)</th>
<th>Methacrylate Slurry (kg/m²)</th>
<th>Premixed Polyester (kg/m²)</th>
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<tr>
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<td>7.6</td>
<td>19.1</td>
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<tr>
<td>Prime Coat</td>
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<td>0.41±0.14</td>
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<tr>
<td>Layer 1 resin</td>
<td>1.1±0.14</td>
<td>2.7±0.27</td>
<td>5.29±0.41</td>
</tr>
<tr>
<td>Layer 1 aggregate</td>
<td>5.4±0.54</td>
<td>6.5±0.54</td>
<td>38.6±0.54</td>
</tr>
<tr>
<td>Layer 2 resin</td>
<td>2.2±0.14</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Layer 2 aggregate</td>
<td>7.6±0.54</td>
<td>7.6±2.7</td>
<td>----</td>
</tr>
<tr>
<td>Seal Coat resin</td>
<td>----</td>
<td>0.68±0.14</td>
<td>----</td>
</tr>
<tr>
<td>Approx. resin content, %</td>
<td>25</td>
<td>24</td>
<td>13</td>
</tr>
</tbody>
</table>

1 mm=0.039 in  
1 kg/m²=1.7 lb/yd²
60 Sprinkel

Table 4. Cost of Bridge Deck Protective Treatments, $/m²($/yd²)

<table>
<thead>
<tr>
<th>Overlay</th>
<th>Multiple-Layer Epoxy</th>
<th>Hydraulic Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>28 (24)</td>
<td>73 (61)</td>
</tr>
<tr>
<td>Misc.</td>
<td>0 (0)</td>
<td>27 (23)</td>
</tr>
<tr>
<td>Traffic</td>
<td>10 (8)</td>
<td>56 (46)</td>
</tr>
<tr>
<td>Total</td>
<td>38 (32)</td>
<td>155 (130)</td>
</tr>
<tr>
<td>Life Cycle</td>
<td>56 (47)</td>
<td>155 (130)</td>
</tr>
<tr>
<td>Life (years)</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5. Summary of Use of Polymer Concrete Overlays

<table>
<thead>
<tr>
<th>Year</th>
<th>MLE1</th>
<th>MLE2</th>
<th>MLEU</th>
<th>MLE/ES</th>
<th>ES/MS</th>
<th>PP</th>
<th>MS</th>
<th>Total</th>
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<tbody>
<tr>
<td>90</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>16</td>
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<tr>
<td>91</td>
<td>19</td>
<td>15</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>8</td>
<td>58</td>
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<tr>
<td>92</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>35</td>
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<tr>
<td>93</td>
<td>9</td>
<td>17</td>
<td>7</td>
<td>0</td>
<td>9</td>
<td>3</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>22</td>
<td>7</td>
<td>60</td>
</tr>
<tr>
<td>95</td>
<td>12</td>
<td>12</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>4</td>
<td>44</td>
</tr>
<tr>
<td>96</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>17</td>
<td>1</td>
<td>32</td>
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<tr>
<td>97</td>
<td>13</td>
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<td>14</td>
<td>2</td>
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<td>54</td>
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<tr>
<td>98</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>5</td>
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<td>32</td>
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<tr>
<td>99</td>
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<td>-</td>
<td>9</td>
<td>-</td>
<td>6</td>
<td>24</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Before 90</td>
<td>2</td>
<td>8</td>
<td>56</td>
<td>22</td>
<td>12</td>
<td>23</td>
<td>16</td>
<td>139</td>
</tr>
<tr>
<td>Since 90</td>
<td>78</td>
<td>67</td>
<td>69</td>
<td>25</td>
<td>28</td>
<td>121</td>
<td>28</td>
<td>416</td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>75</td>
<td>125</td>
<td>47</td>
<td>40</td>
<td>144</td>
<td>44</td>
<td>555</td>
</tr>
</tbody>
</table>

Figure 1. Tensile rupture strength (VTM 92) vs age for polymer concrete overlays.
Figure 2. Permeability to chloride ion (AASHTO T 277) vs age for polymer concrete overlays.

Figure 3. Bald tire skid number (ASTM E 524) vs age for polymer concrete overlays.
Development of Polymer Impregnated Concrete

by G. W. DePuy

Synopsis: The historical development of polymer-impregnated concrete (PIC) is reviewed. Starting in 1965, PIC was developed over a period of several years as part of a joint research program conducted by the Bureau of Reclamation (USBR) and Brookhaven National Laboratory (BNL) under sponsorship of the USBR, Atomic Energy Commission (ARC), and the Office of Saline Water (OSW). At various times other organizations funded portions of the program aimed at developing applications directed at their particular interests. Following reports of the research results, research was also conducted by many other organizations in the US and worldwide. The paper reviews the various processes and equipment used to produce both partial and fully impregnated concrete. Included are discussions on drying the concrete, placing it under vacuum, pressure soaking, encapsulation, and polymerization techniques. Monomer and catalyst systems are also discussed. Costs and safety procedures are also mentioned. Comparisons of improvements in properties of PIC over conventional concrete are given.

Keywords: full impregnation; historical development; monomers; partial impregnation; polymer-impregnated concrete; process technology; properties; research
DePuy

Bill DePuy, PE, FACI, was a consulting engineer. Previously, Bill worked for the Bureau of Reclamation for 41 years where, as Head of the Concrete Materials Section, he supervised research on polymer concretes, and investigations of concrete materials, durability, and repair. DePuy was Managing Director of ICPIC. He was Past Chairman of ACI-123, Past Secretary of ACI-548, served on several other ACI Committees, and was active on RILEM, TRB, and ASTM Committees. DePuy authored over 50 papers on concrete. Honors included membership to Sigma Xi, Russian Academy of Engineering, and ICPIC’s Owen Nutt Award.

INTRODUCTION

Limited interest in the development of polymer concrete (PC) and polymer modified concrete (PMC) began in the 1950s and 1960s, but it wasn’t until the late 1960s that widespread interest in concrete polymer materials began to emerge when polymer impregnated concrete (PIC) with its rather remarkable properties was developed. Although PIC has not achieved the level of commercial success enjoyed by other concrete polymer materials, such as PC and PMC, PIC has played an extremely important role in attracting the interest of the US Government, industry, and academia to support and fund research and development activities.

PIC was developed in a joint Bureau of Reclamation (USBR)/ Brookhaven National Laboratory (BNL) research program on concrete polymer materials which included PIC, PC, and PMC. Tests on PIC showed outstanding physical properties and excellent durability, and contributed greatly to the understanding of the behavior of polymers in concrete.

RESEARCH AND TECHNICAL SOCIETIES

The first PIC was produced at BNL in response to a request by USBR in 1965 (Fowler 1974). The request was an initiative by Ted Mermel of the USBR. In 1966, USBR and BNL entered into a formal cooperative R&D program for concrete polymer materials. This was a several million-dollar program sponsored by the US Government (Dikeou 2001). The program initially focused on PIC as the early results demonstrated the technical feasibility of processes for producing PIC and great improvements in mechanical properties and durability as compared with conventional portland cement concrete.

The major sponsors of the USBR/BNL joint program were the USBR, Atomic Energy Commission (AEC), and the Office of Saline Water (OSW). At various times, a number of other organizations also funded portions of the program.
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These included the Federal Highway Administration (FHWA), the Bureau of Mines (USBM), the Corps of Engineers Construction Engineering Research Laboratory (CERL), the Office of High speed Ground Transportation, the American Concrete Pipe Association (ACPA), and the Prestressed Concrete Institute. The results of the joint USBR/BNL program are given in detail in a series of topical reports (Concrete Polymer Materials Topical Reports). A number of applications were investigated. These included peaceful use of atomic energy (radiation polymerization), saline water distillation plants, concrete pipe, precast segmented tunnel liners, concrete structural elements, highway and bridge deck applications, and applications for hydraulic structures.

Research was also conducted by many other organizations in the US and worldwide, notably in Japan (Ohama 1975) and the former Soviet Union (Volgushev and Maksimov 1981), Scanlon 1978), and in many other countries - for example Norway (Solber 1975), Korea (Bynu 1992), Italy (Donate 1978), Denmark (Hastrup 1975), Canada (Manning and Hope 1975), Germany (Schorn 1975), China (Chen 1981), and Italy (Rio and Biagini 1981).

The interest in concrete polymer materials in North America led to the formation of ACI Committee 548 (Dikeou 2001). George Wallace of the USBR was the driving force behind the formation of ACI Committee 548, and we are to this day much indebted to his leadership and hard work in establishing ACI 548. On the international scene, the widespread interest in concrete polymer materials led to the formation of the International Congress on Polymers in Concrete, a nonprofit scientific and educational organization dedicated to promote research and development, the exchange of technical information, and establishing a forum to discuss concrete polymer materials.

In 1973, a formal scientific exchange program was established between the US and the USSR. The program was to run for 6 years. The program involved exchange visits of leading scientists and engineers from US and USSR laboratories (Scanlon 1978). A review of Soviet activities was prepared as an internal USBR document (DePuy 1980).

PIC PROCESS TECHNOLOGY

Large impregnation vessels were constructed at USBR and BNL. The large USBR impregnator was a horizontal cylindrical vessel made of stainless steel, 1.8 m id x 5.8 m long with a horizontal tank for immersion of the specimens. The horizontal tank was large enough to hold 4.9 x 1.2 meter concrete slabs. The impregnator was equipped with fittings for vacuum, introduction of monomer, pressurized air, drainage of excess monomer, water, and steam (DePuy 1975b).
The key findings of the research program were:

1. Drying. The free water in concrete must be removed in order to achieve a significant depth of impregnation. The degree of impregnation (polymer loading) is inversely related to the free water content of the concrete. Water in concrete pores and microfractures blocks and greatly inhibits the penetration of the monomer. This makes it necessary to dry the concrete before impregnation. Heat should be applied gradually to avoid thermal shock and large thermal gradients, which can crack the concrete. The concrete should be unrestrained and free to expand and contract in all directions.

2. Full impregnation process. Optimum results are obtained using the full impregnation process. This involves drying the concrete, placing the concrete under vacuum, immersion in monomer, and pressure soaking. The excess monomer is then drained; the impregnated concrete specimen is encapsulated, and polymerized.

3. Vacuum and pressure soaking. Placing the concrete under a vacuum before impregnation, and pressure soaking during impregnation improve the polymer loading and shorten process times. These are not absolutely necessary steps, but are recommended to obtain maximum improvements in properties.

4. Encapsulation. The concrete should be encapsulated after impregnation in order to reduce monomer loss from the treated element due to drainage and evaporation. This can include wrapping or immersion in water. As a practical matter, immersion in water is preferred.

5. Improvements in properties related to the degree of impregnation. For a given concrete, strength and quality are a function of the degree of impregnation. Modification of any of the key steps in the process, such as shortening or eliminating drying, vacuum, pressure soaking, soaking time will reduce in the improvements in properties.

6. Monomer and catalyst systems. Methyl methacrylate (MMA) is widely used because of its low viscosity, low cost, and excellent properties in PIC. Azo nitrile catalysts, such as azo bisisobutyronitrile (AIBN), are used as these compounds are chemically stable, and under appropriate safety conditions, it is possible to store and reuse catalyzed monomer (DePuy 1975a).

7. Polymerization technique. Several polymerization techniques are possible. These include radiation, promoter-catalyst (redox) systems, and thermal catalytic polymerization. Radiation polymerization requires access to a high-energy radiation source that greatly limits the application of this method. Promoter-catalyst polymerization has the drawback of not having precise control over the initiation time for polymerization, and prevents the reuse of excess monomer. Thermal catalytic polymerization is recommended as polymerization time can be controlled, and it is possible, with good technical control, to reuse the excess monomer.
8. Surface Impregnation. Fully impregnated PIC requires an impregnation vessel and is therefore limited to handling precast concrete elements that can be fitted into the impregnation vessel. A surface impregnation process was developed for the treatment of large concrete surfaces in concrete structures in the field such as spillways and bridge decks. The process eliminates the vacuum and pressure soaking steps. The process is capable of impregnating concrete surfaces to a depth of 1 to 2 inches (2 to 5 cm), which provides less than optimum protection, but is still sufficient to greatly retard the intrusion of moisture and salt into the concrete. The process involves drying the bridge deck with heaters, spreading sand on the deck to act as a reservoir, saturating the sand with monomer and allowing it to soak in, and then applying heat to polymerize the monomer (Smoak 1978). Some 20 or so bridge decks in the US were treated with this process in the 1970s and 1980s, and so far as is known, none of the treated decks have failed. However, highway departments are currently not using the technique and its status as a recommended maintenance method is in doubt. A number of the treated bridge decks have been observed to contain very fine cracks. It is believed that the cracks do not present a problem, but there is no assurance the cracks are sealed by the process (DePuy 1984).

9. Monomer disposal. Monomer catalyzed with a catalyst such as AIBN can be stored for a limited period of time as long as the inhibitor content is maintained. Disposal of large amounts of used monomer can become a problem. The best way to dispose of used monomer is to convert it into a solid polymer and then store it in a landfill. The monomer can be converted to a solid polymer using a controlled bulk polymerization in an open area and in an open container.

10. Costs. The construction of a sufficiently large impregnator vessel, such as would be required for full impregnation of precast bridge deck panels is prohibitively expensive. To reduce costs, the impregnation process would have to be modified to a limited impregnation, eliminating the vacuum and probably the pressure soak steps.

11. Safety. A safety program should be developed to cover procedures to be followed in the event of emergencies such as spills, fires, and exposure to chemicals. A preconstruction meeting should be held to inform all personnel involved of the safety procedures. This includes emergency phone numbers and location of fire departments, hospitals, and local authorities. As is the case with all chemicals, monomers and catalysts present potential safety hazards if not properly handled. Information on handling and storage is available from manufacturers and suppliers, trade and insurance organizations, and published literature. MMA has a very distinct odor, is classified as a flammable liquid with moderate hazards from fire and explosion, and is regarded as only slightly toxic (Sax 1968). Recommended handling precautions include personal protective gear for those exposed to the monomer, elimination of ignition sources, electrical grounding, ventilation and fume control, emergency washes and drains,
and environmentally acceptable provisions for handling spills (DePuy 1975).

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**Table 1 Typical Properties of PIC**

<table>
<thead>
<tr>
<th>Property Improvement</th>
<th>Unimpregnated Concrete</th>
<th>MMA-impregnated Concrete</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength, psi</td>
<td>5300</td>
<td>18,200</td>
<td>240</td>
</tr>
<tr>
<td>Modulus of Elasticity, $10^6$ psi</td>
<td>3.5</td>
<td>6.2</td>
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</tr>
<tr>
<td>Direct Tensile Strength, psi</td>
<td>420</td>
<td>1500</td>
<td>260</td>
</tr>
<tr>
<td>Modulus of Rupture, psi</td>
<td>740</td>
<td>2300</td>
<td>210</td>
</tr>
<tr>
<td>Flexural Modulus of Elasticity, $10^6$ psi</td>
<td>4.3</td>
<td>7.1</td>
<td>65</td>
</tr>
<tr>
<td>Hardness, L Hammer Abrasion</td>
<td>32</td>
<td>52</td>
<td>60</td>
</tr>
<tr>
<td>Resistance, in. Cavitation</td>
<td>0.050</td>
<td>0.016</td>
<td>210</td>
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<tr>
<td>Loss, in. Water absorption, Wt. %</td>
<td>0.320</td>
<td>0.020</td>
<td>150</td>
</tr>
<tr>
<td>Water permeability, $10^4$ ft/yr</td>
<td>6.4</td>
<td>0.34</td>
<td>90</td>
</tr>
<tr>
<td>Thermal conductivity Btu/ft-hr-°F</td>
<td>1.332</td>
<td>1.265</td>
<td>5</td>
</tr>
<tr>
<td>Coef. of expansion, $10^6$ in/in-°F</td>
<td>4.02</td>
<td>5.25</td>
<td>-31</td>
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</tbody>
</table>
Table 2 Durability of PIC

<table>
<thead>
<tr>
<th>Property</th>
<th>Unimpregnated Concrete</th>
<th>MMA-Impregnated Concrete</th>
<th>% Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze-Thaw, No. of Cycles</td>
<td>740</td>
<td>*3650</td>
<td>400+</td>
</tr>
<tr>
<td>Sulfate Attack days</td>
<td>480</td>
<td>1436</td>
<td></td>
</tr>
<tr>
<td>% Expansion</td>
<td>0.467</td>
<td>0.017</td>
<td>200+</td>
</tr>
<tr>
<td>Acid 15% HCl, days</td>
<td>105</td>
<td>1395</td>
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</tr>
<tr>
<td>% wt loss</td>
<td>27</td>
<td>10</td>
<td>1200+</td>
</tr>
<tr>
<td>Acid, 5% H$_2$SO$_4$ Days**</td>
<td>210</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>% Wt Loss</td>
<td>33</td>
<td>14</td>
<td>-</td>
</tr>
</tbody>
</table>

* Test discontinued, no deterioration observed.
** Radiation-cured specimen
Polymer Impregnation Repairs of Cavitation/Erosion Damage at Dworshak Dam

by E. K. Schrader and S. B. Tatro

Synopsis: This paper discusses polymer impregnation in the repairs of concrete damaged by cavitation/erosion at Dworshak dam. Impregnation was performed on conventional concrete, fibrous concrete, and dry-pack patches. The repairs included vertical and horizontal surfaces. Testing which demonstrated the improved resistance of polymer impregnated concrete to cavitation and erosion damage are summarized. With approximately 25 years of experience, the repairs have performed extremely well, although it should be noted that modifications were made about 8 years after the polymer repairs to minimize cavitation in the outlets by aeration. To date, this is the most complex known polymer impregnation project performed under a construction contract.

Keywords: cavitation; concrete; dams; dry pack; fiber reinforced concrete; outlets; polymer; polymer impregnation; repairs; stilling basin
74 Schrader and Tatro

Dr. Ernest K. Schrader is a consultant specializing in concrete, with emphasis on dams. He was one of the early members of ACI Committee 548, Polymers, and has been active on numerous other ACI Committees.

Stephen B. Tatro is a consulting engineer and concrete materials specialist with the US Army Corps of Engineers. He is active in ACI and currently chairs ACI Committee 207, Mass Concrete.

INTRODUCTION

Spillways, outlets, stilling basins, and similar concrete structures subjected to high-velocity water flows are often faced with the serious problems of cavitation and erosion forces. The stilling basin and an outlet of Dworshak Dam experienced such damage after initial usage. They were repaired using concepts that were new at the time of the work in 1975. This included the first major field application of polymer-impregnated concrete (PIC), the first competitively bid major project for PIC, the first field application of PIC to vertical surfaces, the first field application of PIC to fibrous concrete, and the first impregnation of dry-pack patches.

PROJECT AREA AND DESCRIPTION OF DAMAGE

Dworshak Dam is the third highest dam in the United States, containing 6.5 million cubic yards (5 million cubic meters) of concrete (Figure 1). It is located in a fairly isolated area on the North Fork of the Clearwater River near Orofino, Idaho.

The dam contains three similar regulating outlets that are 12 feet (3.7 meters) wide by 17 feet (5.2 meters) high in section and have their inlet invert elevations 250 feet (76.2 meters) below maximum reservoir elevation. Flows for an individual regulating outlet can be 14,000 ft³/sec (396 m³/sec) under maximum head. The outlets were first used in 1971 and had been used intermittently for four years for reservoir control. In 1974 severe cavitation damage was found about 50 to 75 feet (15 to 23 meters) downstream of the gate in outlet No. 1. For this paper, severe damage is described as massive removal of concrete and removal of reinforcing steel. Downstream of the severely damaged areas medium damage (depth less than one inch (25 mm)) totaling over 60 square yards (50 square meters) of surface area was found throughout the remaining 200 feet (61 meters) of outlet. Surrounding this medium damage were large areas of light erosion or surface scaling.
Polymers in Concrete: The First Thirty Years

The stilling basin received severe damage which removed approximately 1,600 cubic yards (1,223 cubic meters) of high-strength, low water-cement ratio concrete from its 29,261 square-foot (2,718 square meters) floor surface (Figure 2). The damage was initially attributed to debris that fell into the stilling basin during the latter stages of construction. It was later found that an area of epoxy resin surfaced placed as a part of this major repair contract failed in an area that was clear of debris at the upstream end of the basin. Also, debris was later pulled into the basin from downstream of the end sill. The debris impacted the basin floor and walls with velocities on the order of 90 ft/sec (30 m/sec), causing severe impact and erosion. The design discharge of the stilling basin is 150,000 ft³/sec (4,248 m³/sec).

REPAIR DESIGN

Damaged areas in the stilling basin and outlets were built back to their original design lines using techniques that differed depending upon the location and severity of damage. These procedures included massive fill concrete, steel-fibrous concrete, dry-pack patching, post-tensioning, reinforcing steel, grouted anchor bars, and epoxy mortar. Fibrous concrete was used in the repair because, by 1975, it had developed a recent history of excellent resistance to cavitation/erosion. Because its long-term life was unproven, some means of providing additional durability was desired. Epoxy coatings and steel plate linings were not used because of the expense and also the fact that they have a history of failure when subjected to severe cavitation/erosion forces. Laboratory tests had shown tremendous increases in the strength and durability of concrete impregnated with monomer and polymerized in place. It was decided to use this procedure for a surface treatment. This allowed the large areas of medium damage in the outlet to be repaired economically with dry-pack patching, followed by polymer impregnation. Without impregnation, the dry pack would have fallen off the walls soon after the outlets were used again. With impregnation the dry-pack patch was physically “attached” to the base concrete. This “attachment” is more than a surface bond, such as would be expected with epoxy, because the monomer penetrates through the patch and into the base concrete.

PRELIMINARY TESTS

Before preparing the repair specifications Dr. David Fowler at the University of Texas was engaged to determine if impregnation of vertical surfaces was practical and if impregnation of dry-pack patching would, in fact, produce a strong material rigidly attached to the base concrete (2). The tests utilized small
panels that simulated project concrete and surface conditions. Environmental conditions were also duplicated as nearly as possible.

Prior to drying, the concrete was completely saturated with water to simulate the assumed condition of concrete in the dam. During drying the back of the panels were kept in water to provide a continual source of moisture. Drying was accomplished using infrared heaters for two to ten hours at surface temperatures of 260°F to 280°F (127 to 138°C). Tests indicated the importance of allowing the surface to cool to less than 125°F (52°C) to achieve an adequate depth of impregnation. For higher temperatures, monomer polymerized at the surface and prevented additional soaking.

The monomer formulation used for most of the testing consisted of 94.5% (wt) methyl methacrylate, 5.0% (wt) trimethylpropyl trimethacrylate, and 0.5 percent (wt) 2,2'-azobis (isobutyronitrile). In order to soak monomer into vertical surfaces on the test panels a sealed chamber was clamped to the panels and then filled with monomer. It was pressurized to duplicate conditions that would occur with large-scale panels used at the project on the outlet walls. During monomer soak a continual moisture source was kept at the back of the panels. The monomer chamber was sealed by means of a sponge-rubber gasket and silicon adhesive. Pressures anticipated from the monomer were accommodated with this system. The monomer was applied for times ranging from two to six hours, and then the excess was drained off prior to polymerization.

Polymerization of the monomer was accomplished in the laboratory by both hot water and steam injection methods using a chamber attached to the surface of the concrete. With either method the surface temperature was maintained at 176°F to 185°F (80°C to 85°C) for about one hour. Application of steam inside the jacket, by means of a baffle to prevent direct impingement on the concrete, proved to be a suitable method. Polymerization could also be achieved by applying steam to the back of a water-filled jacket attached to the concrete.

Results from the tests with the different variables indicated that drying times of six to ten hours and monomer applications from four to six hours were adequate to produce polymer depths of ½ inch (13 mm) or more. Porosity in the concrete was reduced by 60 to 70 percent by this impregnation. It was also found that voids up to one inch (25 mm) deep in the concrete could be filled with dry-pack patch and be successfully impregnated with polymer. The polymer extended 0.25 inch (6 mm) beyond the patch and into the parent concrete so that it was securely attached to the base material. Concrete in the vertical panels that was purposely fractured prior to the tests to duplicate some of the cracking that was present in the outlet walls. The tests showed that these cracks were not effectively sealed by polymer unless the cracks were less than about 0.020 inch (0.5 mm). This was apparently due to the immediate drainage of the low viscosity monomer from wider cracks before it could be polymerized.
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FULL SCALE CAVITATION/erosion TESTS

As a result of the repairs at Dworshak dam, and repairs at a similar project, Libby Dam in Montana, full-scale cavitation/erosion tests were conducted of various polymer materials. This included large panels of conventional concrete, steel fiber concrete, polymer impregnated steel fiber concrete, and polymer concrete patches. Tests were conducted at the US Army Corps of Engineers erosion test facility at Detroit Dam in Oregon. The facility uses an 8 ft (2.4 m) diameter conduit to supply water from the reservoir to a test flume that has a series of 21 inch wide x 10 ft long (0.5 x 3 m) test panels as its invert. Through a series of gates and transitions the flow can be adjusted to have various heads, volumes, and velocities. This series of tests was conducted at a head of 240 ft (76 m) with a velocity of 120 ft/sec (37 m/sec), and a total flow of 60 ft\(^3\)/sec (1.7 m\(^3\)/sec). Two bolts with washers were installed at the start of the test panels to disrupt the flow and cause cavitation at the surface of the test panels.

The conventional concrete test panels had a 90-day strength of 6000 psi (42 MPa), while the steel fiber concrete had a 90-day strength of 7800 psi (55 MPa). Both mixes had a slump of 2\% inch (64 mm). The w/c ratio for the conventional concrete was 0.40, while the w/c ratio for the steel fiber concrete was 0.43.

Two slabs were left untreated, while two slabs were impregnated using 97% MMA inhibited with 10 ppm MEHQ. The cross linking agent was 2.5% trimethyl/propyl trimethacrylate, and the initiator was 0.5% 2,2’ azobis isobutyl nitrile.

Impregnation was done when test cylinders indicated a strength of 4000 psi (28 MPa). The surface was dried for 24 hours with a typical surface temperature of 220 F (04 C). After drying the concrete was allowed to cool to a surface temperature of 125 F (52 C). The surface of the slabs was then sprinkled with air dry sand and flooded with monomer for 5 hours. This was followed by application of steam to bring the surface to a temperature of 150 C for 2 hours to cause polymerization.

During the soak cycle, monomer evaporated from the surface of the steel fiber test panel, so it was not fully impregnated at the surface. This is an important observation, because this sample would erode quickly during the cavitation test to a depth of about 1 inch (the depth that did not have full saturation of monomer), but once erosion reached the successfully impregnated concrete, no more erosion was measured through the rest of the test duration. Rates of erosion are summarized in Table 1.

Polymer concrete patches were made by filling the eroded conventional concrete with sand, and following the impregnation procedure described above for the
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impregnated panels. The repaired test panel was then subjected to the same testing that cause the original damage. It then developed almost no measurable damage.

SPECIFICATIONS FOR THE REPAIR CONTRACT

One of the most important aspects of this project was preparing a contract specification that would assure successful impregnation, result in a safe job, be competitively bid, and allow some latitude for contractor ingenuity and on-site engineering. The specifications accomplished this by briefly describing the impregnation process, giving one monomer system with suggested suppliers, stating specific safety restrictions, and using wording similar to the following:

The contractor shall dry concrete by heating at a temperature of between 260° and 300°F (127° and 149°C). The duration of drying shall be between eight and ten hours. After successful drying of the concrete it shall be allowed to cool to a temperature of 50° and 100°F (10° and 38°C). After cooling, the concrete shall be soaked with monomer for a period of four to six hours. After successful soaking, excess monomer shall be drained and the impregnated surface shall be polymerized by heating to a temperature of between 150° and 210°F (60° and 99°C) for a period that ranges from twenty minutes to two hours. The exact procedure and technical details of making the system work are the responsibility of the contractor. Based on his procedure, subject to approval, exact restrictions for temperature and durations will be determined by the contracting officer. For example, if a higher drying temperature is used, less time of drying will be required. The contractor shall use some type of vapor proof enclosure to contain the monomer against the wall area being impregnated in the outlet and shall maintain vapor concentrations in the outlets below specified safe levels. Suggested procedures for soaking the horizontal stilling basin floor include using a thin sand coating or saturated burlap sacks at the surface. However, the actual procedure used will be the contractor’s responsibility.

CONSTRUCTION PROCEDURES

Outlets

Vertical surfaces 10 feet high were impregnated in the outlet. No work was done to horizontal surfaces. The walls consisted of (1) existing concrete that had just begun to erode and show a sand-blasted texture, (2) large areas of dry-pack patching that were about 3/8 to 1-inch (1 to 25 mm) deep, and (3) new concrete that contained a low water/cement ratio, high cement factor, and steel fibers.
Concrete was dried using infrared heaters mounted inside 12 by 14-foot (3.7 by 4.3 m) insulated plywood boxes. The boxes were braced against themselves during the drying operation (Figure 3). Insulation kept temperatures at wooden surfaces below the kindling point of the wood and below levels at which plywood glue looses its bond or releases toxic fumes. A reflective surface on the insulation was used to help the efficiency of the heaters. The infrared heaters were spaced on 12-inch (300 mm) centers, were 9 inches (230 mm) from the concrete wall, and used a total of 45 kilowatts to operate (Figure 4). The mounting device for the lamps was arranged so that these dimensions could be easily adjusted. Theoretical dimensions based on reflective angles of the lamps and energy requirements necessary to establish drying temperatures were calculated and used for the initial trial. Thermal couples were bonded to the wall in the general areas of the top and the bottom of the enclosure. They were also placed on the walls directly in front of the heat lamp elements and midway between the elements. This instrumentation was monitored throughout the drying process and was used to keep uniform temperatures over the entire surface.

After the first trial, the initial lamp settings were adjusted to eliminate hot spots directly in front of the lamps and cool spots between them. Additional lamps were added to provide the total energy required to keep the overall surface temperatures above specified minimums. The actual amount of energy loss through insulation and the top of the heat lamp enclosure could only be established in the field during the first polymerization attempt. This first setup was actually a field trial procedure and should have been viewed as such to make necessary adjustments.

The boxes had adjustable openings at the top so that moisture could escape during the drying process. Experience showed that several openings on the order of 2 by 6 inches (50 x 150 mm) were all that was necessary. Without these openings, the air within the enclosure would become saturated with moisture and the degree of drying would be limited.

As was learned in the preliminary tests, the first field trails showed that caution must be used not to over dry at higher temperatures. The following phenomenon can occur: when the surface dries to a depth of, say, 1.5 inches (38 mm) the temperature at that depth may be on the order of 150° to 200°F (66° to 93°C), even though the surface temperature is substantially higher. At a depth of 3 inches (76 mm) the concrete probably would be relatively cool at about 120°F (49°C). If drying is continued, the temperature at the 1.5-inch (38 mm) depth will rise slightly, but the temperature at 3 inches (76 mm) or deeper will rise considerably. During the cool-down period (after drying but before monomer soaking) the surface temperature will drop to the necessary 100° ± F (39° C) without much trouble; but due to the store of excess energy now in the deeper concrete, this area will tend to stay hot and keep the temperature just below the concrete surface fairly warm. If monomer is soaked into the concrete too soon, it
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will only soak to some shallow depth where the temperature is high enough to cause polymerization. The polymerized concrete at the surface then acts as a seal or moisture barrier, which prevents soaking to the desired depths below that surface. In the damp area of the dam a long cool-down period to allow this heat to escape is a poor solution to this problem because it would allow moisture to re-enter the dried concrete and it would result in excessive construction time.

The cooling process was controlled to prevent thermal shock and moisture re-entry at the surface. After drying was completed the heat lamps were turned off but the insulated boxes were left in place until surface temperatures were 230°F (110°C). The boxes were then pulled 6 inches (150 mm) away from the walls until surface temperature dropped to 90°F (32°C). At this time, the boxes were removed and the soaking chamber was positioned against the wall. The procedure resulted in a fairly uniform temperature drop over a period of about two days, which worked well with the construction schedule.

The existing concrete exhibited many cracks and typical crazing patterns on the surface of the concrete. It is possible that the drying and cooling process of the repair could have aggravated this cracking, however no apparent or major damage was observed. Most of the cracks were very tight just below the surface.

Dry-pack patching (total of approximately 60 square yards (50 square meters) to 1-inch (25 mm) deep) was applied to the concrete walls in areas of medium damage. Some of the patches were on the order of 4 inches (100 mm) wide and a few 6 to 8 feet (2 to 2.5 m) high and 30 feet (9 m) long. As expected, these patches became badly crazed and lost their bond to parent concrete during the drying process. Two areas of about 2 square feet (0.2 square meters) each actually fell off the wall due to their own weight after drying. Any dry pack that would have been bumped after drying would have fallen loose. Polymer impregnation was relied on to fill all tight crazing cracks in the dry pack, bond it to the parent concrete, and strengthen the base material.

Soaking was accomplished with two 10-foot by 10-foot (3 meter by 3 meter) panels, which were pressed against the outlet walls to form shallow tanks that contained the monomer (Figure 4). The panels were mounted on a cart, which was pulled up the outlet by cables (Figure 5). A self-adhering sponge rubber gasket was taped to the perimeter of the panel before it was pressed to the wall. The compressed gasket provided about a 1/8-inch (3 mm) gap between the wall and the panel. To assure that this gap was maintained throughout the soak area, washers were tack-welded to the panel surface at about 2-foot (0.6 meter) spacings to act as spacers. A bead of caulking was then placed around the outside panel edge next to the gasket. This system did not work when the panel was filled more than half way. A waterproof tape was put over the caulking so that the tape was half on the concrete surface and half on the outside of the stainless steel panel. By squeezing the caulk material under the tape so that it was forced into the tiny voids of the concrete, an excellent seal resulted.
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However, this did not help the more serious leakage problem at construction joints and open structural cracks. After several trial procedures the following successful system was adopted: a 2-inch (50 mm) wide coat of gel epoxy was applied to the concrete wall surface where the perimeter gasket made contact. This gel was easily applied with a putty knife and had a long pot life. Its physical behavior throughout the short period of time for the PIC process was that of elastic putty having good bond and shear strength. When open construction joints and wide cracks were encountered, they were injection grouted with epoxy at the perimeter of the soak panel.

A small drain trough was provided under the soak chamber to collect any leakage that occurred in case of a gasket failure. The troughs were actually open collection chambers that drained into a separate tank. This precaution was taken so that any spillage would be controlled and not spread monomer over a large area. The chamber was filled through a manifold at the bottom of the stainless steel plate. The manifold was connected by hoses to the monomer tank. By pressurizing the tank with air, the catalyzed monomer solution was forced through the hose and into the soak chamber. Both chambers were filled by the same tank so that internal hydraulic pressures were equal at each wall. About 5 to 7 psi (0.03 to 0.05 MPa) was required to fill the chambers to the top, resulting in a total force between 70,000 and 110,000 pounds (31,752 and 49,896 Kg) against the jack pipes holding the stainless steel plates in place. In addition to the hydraulic load, the pipes carried the force needed to tightly seal the perimeter gasket. A sight glass was installed at the top of each chamber. The air pressure used to force monomer into the chamber was gradually increased until the monomer could be seen at the sight glass. By maintaining that pressure, monomer was continually added from the reservoir at the same rate that it soaked into the concrete, and the chamber was automatically maintained at a full level. During the first monomer filling the standard 55-gallon (0.21 m³) drum used as a pressure tank failed at about 5 psi (0.03 MPa). A second drum failed at about 3 psi (0.02 MPa) pressure rating that the manufacturer had given for them. A special and larger capacity pressure vessel was obtained, tested, and used for the rest of the project.

After soaking for the specified time periods, excess monomer was drained from this chamber, back into a storage tank. At the temperatures in the outlet and with the monomer system used, it was safe to store and reuse monomer for a week. The unused monomer drained from one setup was replenished with new monomer and reused in the next setup. At the end of the week, all catalyzed material was wasted. Although it probably could have been stored in the outlet much longer, MMA is relatively inexpensive, and wasting the material eliminated the risk of bulk polymerization.

After completion of the soak cycle and draining back excess monomer, the tank was refilled with hot water to cause polymerization. Open flames and most other direct heat sources are not acceptable because of potential explosions and the
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possibility of evaporating the monomer before it polymerizes. The hot water heater was kept away from the outlet area to prevent any possibility of explosion due to electrical sparking if high vapor levels had occurred. By the time that the hot water was piped to the soak chamber it had cooled to below the specified 150°F (66°C) minimum temperature needed for polymerization. Electrical resistance heaters totaling 17,500 watts were installed on the back of the stainless steel soak chamber in order to elevate the water temperature. The back of the panel was insulated to reduce heat loss and protect workmen from the hot steel plate. As a safety precaution, the heaters were not activated until after the chamber was filled with water and no explosive vapors were present.

During the construction project a vapor monitor with a remote sensor was continually operated. The remote sensor indicated the atmospheric concentration of monomer vapors in parts per million. A continuous strip chart recording of these readings was maintained to give an accurate history of vapor concentration in the outlet at all times. The vapor monitor was set to activate a visual and audio alarm if the vapor concentration reached 100 parts per million. If this occurred, personnel were to wear protective clothing and facemasks, work would stop, and steps would be taken to decrease the concentration. In actuality, the vapors stayed at very low levels. (range of 3 to 15 parts per million) during construction. The only exception to this was during the first soak when a leak occurred at a construction joint before the procedure for grouting those joints had started.

Even with the resistance heaters, local cool areas were present at isolated locations in the chamber. Cores taken from areas where the surface temperature of the soak chamber was less than 150°F (66°C) had incomplete or no polymerization. It was necessary to add a water circulation system to the chamber to more uniformly heat the monomer. This consisted of pumping water from the top and the bottom of the chamber (collected in manifolds) back into the center of the chamber. The velocity of flow was kept minimal. Before uniform water temperatures high enough to cause complete polymerization were achieved, a minor amount of monomer would enter the circulating water. Occasionally, it would polymerize (solidify) in the pumps, which then had to be dismantled and cleaned by hand.

Stilling Basin

All concrete that was impregnated in the stilling basin was on a horizontal surface and contained steel fibers. At least three days’ cure was specified prior to drying the concrete for the PIC process but, in actuality, most of it was about several weeks old at the time it was dried. The reasoning for allowing drying so early was as follows: only the top surface of the concrete would be dried and heated; concrete below the dried area would not be affected. Any concrete in the dried area would be soaked with MMA and polymerized. Studies show that the
tremendous increase in physical strength properties for polymerized concrete is quite independent of the original concrete quality. If the drying did damage concrete near the surface, it would be repaired beyond its quality with the polymerization process.

Concrete in the stilling basin was treated in sections covering 700 square feet (65 square meters) (58 feet (17.8 m) long by 12 feet (3.7 m) wide) at a time. A 2-foot (0.6 m) high enclosure with insulated plywood sides and a removable top was placed over each area treated (Figure 6). Before drying, free water was swept away or vacuumed up and a bead of caulk was placed around the base of the enclosure to keep water from re-entering. About a 3/8-inch (10 mm) thick layer of sand was then spread over the surface to act as a wick during soaking and to cause better distribution of the monomer. Infrared heat lamps spaced at 24-inch (610 mm) centers and 18 inches (460 mm) above the floor were installed in the enclosure, and a lightweight insulated roof was placed over it (Figure 7). The lamps used totaled 93 kilowatts or 134 watts per square foot and normally accomplished the drying in 10 to 15 hours. At a thermostatic setting of 450°F (232°C) for the air inside the enclosure, a surface temperature of 220°F (104°C) could be attained in about 2 hours. By leaving the thermostatic at that setting, the surface would stay between 220°F (104°C) and 320°F (160°C) for the remainder of the drying cycle. Moisture was allowed to escape through holes (about 4 x 4 inches (100 x 100 mm)), spaced about every 5 feet (1.5 m) in the enclosure walls. Distribution of temperatures within the concrete was measured during the drying process of the first setup using embedded thermocouples that had been cast into the fibrous concrete slab. Results of these measurements as for a complete and uninterrupted PIC cycle are shown in Figure 8.

After drying, the concrete went through a controlled cooling process. The heat lamps were turned off, but the roof sections for the enclosure were kept in place. After a brief period the roof panels were cracked open about an inch. After a total cooling period of about 6 hours, the surface temperature was about 120°F (49°C). The roof sections were then removed and the monomer was applied.

Application of the monomer was accomplished with a 12-foot (3.7 m) long sprinkler pipe, which was carried back and forth above the surface to be impregnated until a predetermined amount of monomer had been applied. The monomer flowed by gravity from an elevated mixing drum, through a hose, and into the sprinkler pipe. A polyethylene sheet was draped over the surface to reduce the evaporation losses, the roof sections were reinstalled, and another polyethylene sheet was laid over the entire enclosure to minimize the odor from any escaping fumes (Figure 7). The first application was a trial in which a total of 55 gallons (0.21 m³) of MMA were applied. The amount was gradually increased to about 80 gallons (0.31 m³) per setup (.115 gallons per square foot (4.7 l/m²)) where the surface sand would just begin to stick to the floor, indicating that the concrete could not absorb any more monomer. Since application of the monomer began when the surface temperature was near the
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point at which polymerization could start, the percentage of a cross-linking agent was decreased from 5% to 2-1/2%. This adjustment made the mixed monomer a little bit more difficult to polymerize due to a slower rate of reaction in the temperature range of about 1000 to 1400 F (430 to 600C). However, since very hot steam was used to polymerize the stilling basin floor, obtaining complete polymerization was no problem. After a usual soak of 6 hours, the concrete was polymerized using wet steam at 700 to 850F (370 to 455C). The portable steam generator used for this was fed by a ½-inch (19 mm) air hose at 115 psi (0.8 MPa) pressure. The steam was distributed through a manifold in the center of the enclosure. Within a minute the entire area being polymerized was uniformly filled with steam. After 1-1/2 hours the steam was turned off and the process was completed. Total time for both the impregnation and the polymerization cycle in the stilling basin was normally 24 hours, excluding initial set-up and final cleanup.

EVALUATION

Costs

It is difficult to use this project as a guide for the cost of performing PIC work because of the unprecedented nature of the work, the confined work areas, the tight schedule, the many unknowns, and the isolated project location. However, for the readers’ benefit, the composite 1975 value of bid items from the low bidder for the original outlet work and estimated quantities (excluding initial mobilization) are: 300 gallons (1.13 m³) of monomer material @ $6.50 per gallon, 13 square yards (10.3 m²) of dry-pack patching @ $50 per square yard, and 410 square yards (343 square meters) of wall impregnation @ $118.71 per square yard. Polymerization for the stilling basin floor, including materials, cost about $6.50 per square foot. This compares very favorably to an unpolymered section of the floor surface, which was repaired with epoxy mortar at a cost of about $15.50 per square foot.

Analysis of Impregnation Depths

Six-inch (150-mm) and three-inch (76-mm) diameter cores were taken from the treated material to evaluate the depth of impregnation. Because of the dark gray color of Dworshak Dam concrete, visual inspection of the cores very seldom gave a positive indication of the penetration depth. Many field techniques, including dyes, soaking, heating, scratch tests, and acid wash were tried in an attempt to rapidly determine polymer depths. The most reliable field procedure used was to place the core horizontally on a flat surface and strike it near the top
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with a hammer. The top of the core would break off near the maximum depth of penetration. If monomer had soaked into the concrete but had not been polymerized, its odor could be easily detected. At least one core was taken from each setup in the outlet and field-tested using the hammer technique. The cores typically showed impregnations ranging from 0.75 to 2.75 inch (19 to 32 mm) deep. None of the cores taken through dry-pack patches failed in the dry pack at the interface between it and the parent concrete. Cores from the stilling basin indicated typical impregnation depths of ½ inch (13 mm) when broken.

Controlled laboratory tests were made in an effort to accurately evaluate the results of different polymerization setups. These tests included direct tensile, indirect tension, compressive, absorption, and unit weight. Because only a very small test sample could be taken from the core due to shallow impregnation depths, none of these procedures was very effective. With the ¾-inch (19-mm) and 3-inch (76-mm) maximum size aggregate concrete that was used on the project, accurate physical tests for small samples were impossible. The only positive way to determine polymer presence in the concrete required a more elaborate test involving infrared pyrolysis. The concrete cores were individually tested at different depths using the following procedure: a sample of the concrete or dry-pack material was taken from each core at different depths, starting with the surface and then at ¼-inch intervals (6 mm) (i.e., 0, ¼, ½, ¾-in, etc.). Each sample was then placed in a closed evacuated cell, heated to about 1,000°F (538°C), and a spectrum recorded of the vapor phase to detect any pyrolyzed products of polymer. If polymer was present, it was positively identifiable. Results from infrared pyrolysis compared favorably with field-testing.

During impregnation of the stilling basin floor, moisture kept migrating up through vertical construction joints and cracks. Most of this moisture evaporated soon after it came to the surface, but areas within about 6 inches (150 mm) of the cracks or joints could not be adequately dried. Consequently, cores taken at cracks and joints showed no polymer impregnation, while cores taken away from the damp areas had successful impregnation.

During the polymerization work, a number of random cracks were noticed in the fibrous concrete floor. When the surrounding areas were dry, the cracks showed a dark trail of moisture and became very apparent. These cracks were NOT caused by the drying process. Such cracks were also present in surfaces that were not cleaned and dried. The original cracks were mapped or marked prior to drying for several setups. After the polymerization cycle was completed, there were no new cracks and there was no apparent growth of the old cracks. The width of the cracks was not measured, but the authors believe the cracks did increase as a result of drying. If moisture could have been kept out of the cracks, they would have been filled and structurally sealed with monomer.

The outlet walls soaked in about 0.13 gallons of monomer per square foot (5.3 l/m²), regardless of whether it was in an area of dry-pack patching, new fibrous
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concrete, or the original concrete. The impregnation depths were also similar in each of the three materials. At first the fibrous concrete was expected to soak up the least monomer because of its excellent consolidation and relatively low entrained air content. Apparently, the mortar portion of the fibrous material was tighter than mortar in the original concrete, but the mix used smaller aggregate and correspondingly had more mortar. The additional mortar took extra monomer and, in the long run, both concretes soaked about the same total volume.

The stilling basin floor soaked up all the monomer when applied at a rate of .086 gallons per square foot (3.5 l/m²). When applied at a rate of 0.115 gallons per square foot (4.7 l/m²), a small amount of monomer would remain at the surface and stick some of the sand coating to the floor when polymerized. It is difficult to explain why the outlet walls soaked in more monomer and correspondingly had greater depth of impregnation than the stilling basin floor, but the reason can undoubtedly be attributed to at least one of the following:

1. Moisture was being forced up through the concrete due to uplift pressures (a system of post-tensioning the stilling basin floor to resist uplift was used in lieu of relieving the pressure through drains). This made drying more difficult and refilled the microvoids with water between the depths of ½ to 1 inch (13 to 25 mm) during the cool-down cycle. During the soak phase, monomer could not enter the concrete below ½ inch (13 mm) since it was already saturated with water.

2. The cool-down period was not sufficient to allow concrete deeper that ½-inch to be polymerized. During the soak cycle, monomer would penetrate into the concrete to a depth of 1/2 inch (13 mm). The temperatures of the concrete at ½-inch (13 mm) deep were high enough to cause polymerization of the monomer. The polymerized monomer acted as a barrier, not allowing unpolymerized monomer to soak into concrete beyond that depth. Since the amount of cross-linking agent was purposely reduced to help avoid this situation, its occurrence is unlikely.

3. Insufficient drying duration and/or temperature was initially thought to be a reason. However, records indicate durations of drying above 2200°F (1204°C), but most of that time the temperature was probably between 260 and 3000°F (127 and 1490°C), about the same or slightly less than for the outlets. Durations of drying for the stilling basin were generally on the same order as for the outlets, but with some setups being a little longer and some a little shorter. Records of cores from most of these areas are not complete enough to determine if the variations had any effect on impregnation depth. The first setup for the stilling basin floor was known to have a long drying period at
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temperatures up to 3200°F (1600°C), but it only had ¼ to ½ inch (6 to 13 mm) of impregnation depth; therefore, the lesser durations and temperatures used for subsequent setups (where some tests show polymer depths to ½ inch (13 mm) were probably not detrimental.

PERFORMANCE

Since completion of the outlet repairs in December 1975, the outlets have been used intermittently for 25 years without significant additional damage. During this usage, discharges varied from minimal amounts to about 20,000 ft³/sec (566 m³/sec). These are generally on the same order of normal usage that caused the original untreated concrete to fail. Because of changes in outlet operation, recent years have been the time of greatest flows for the longest durations.

Eight years after the polymerization repairs to the outlet were completed, the gate frames in each of the three outlets were modified by the addition of aeration fins. These small wedges deflect the discharge flow away from the vertical and invert concrete surfaces thus directing the sheet flow away from the surfaces near the gate and allowing the entrainment of more air into the flow. Their long-term effect is difficult to quantify except to note that the progress of erosion damage in non-polymer impregnated outlets has also been significantly reduced.

The condition of the impregnated dry-packed materials has shown little change. Only minor surface erosion of the fibrous concrete and existing concrete has been observed. The greatest change is observed along cracks and at lift joints where moisture control during the polymerization was most difficult. During one of the outlet inspections, an attempt was made to break some of the impregnated dry-pack patching loose from the parent concrete, but this was impossible to do even with a hammer and chisel. There is currently no erosion damage of the scale observed in 1974 just prior to repairs and no progressive damage that would necessitate even minor repairs.

Similarly, the spillway and stilling basin usage has continued for the last 25 years. A detailed inspection of the stilling basin was done in 1976 by an underwater diver in communication with the repair designer. The basin contains loose gravel, rebar, channel irons, long steel pipe, and miscellaneous debris that were apparently pulled into it from tailwater. This material has been pounding around in the stilling basin and has certainly given the polymer-impregnated concrete some tough, initial usage. The floor area repaired with epoxy mortar has already failed (about 25 percent is gone with the underlying concrete exposed). Indications are that the untreated conventional concrete beneath the epoxy has started to fail as it becomes exposed. The floor surface that was treated with monomer is in excellent condition. There is some minor erosion to
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about 1 inch (25 mm) deep at cracks and joints. As described earlier, these areas were not successfully polymerized due to moisture in the cracks. Areas where some of the sand coating from the polymerization process was stuck to the floor surface (polymerized in place) still have the sand in place. It should be noted that so far the untreated fibrous concrete floor topping has also performed well.

In 1980, the stilling basin was modified to prevent downstream material from being drawn into the stilling basin during operation. The stilling basin training wall was extended to provide an underwater barrier that prevents rock, gravels, and construction debris from entering the basin from the tailrace area. Subsequent underwater inspections of the basin since have shown no significant changes in the basin condition.

CONCLUSIONS

Based on the work completed at Dworshak Dam, the following conclusions are made:

1. Polymer impregnation of vertical surfaces is not easy, but can be accomplished even under very difficult field conditions.

2. Polymer impregnation of horizontal surfaces is a relatively simple field procedure IF the correct procedures and proper safety precautions are followed.

3. An approximate depth of polymer impregnation into concrete can be determined by breaking the top off a 3-inch (76-mm) diameter core and measuring the depth to where it broke. An accurate depth of impregnation can be determined using an infrared pyrolysis technique.

4. Polymer impregnation of dry-pack patches will strengthen the patch. If the parent material to which the patch is applied is also penetrated with polymer, the patch will be securely bonded.

5. Long term experience indicates that polymer-impregnated concrete will provide excellent resistance to cavitation, erosion, and impact forces.


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<th>Depth of Erosion</th>
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<th>2 to 3 inch</th>
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<td>Polymer Concrete Patches</td>
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Figure 1—Dworshak Dam with the low-level outlets discharging into the stilling basin.
Figure 2—Typical damage to conventional concrete in the stilling basin.

Figure 3—Outlet wall drying enclosure.
Figure 4—Typical section through the enclosures for drying, soaking, and polymerizing the outlet walls.
Figure 5—Polymerizing panels for the outlet walls mounted on a cart.

Figure 6—Enclosure for drying, soaking, and polymerizing the stilling basin floor.
Figure 7—Typical section through the enclosure for drying, soaking, and polymerizing the outlet walls.

Figure 8—Typical uninterrupted floor polymerizing cycle.
The Cass County Jail—28 Years Later

by A. O. Kaeding

Synopsis: A cast in place reinforced concrete building built in 1913 was repaired in 1975 using polymer impregnation, epoxy crack injection and epoxy grouting. The project is an example of using polymer impregnation to restore severely deteriorated, under-strength concrete. Original plans were to extend the useful life of the building by 15 years. This paper briefly reports that the building has been in service for 28 years since the restoration and is being replaced this year because it is no longer large enough. The building remains serviceable and there has been discussions of historic preservation after the new facility is completed.

Keywords: concrete slabs; epoxy crack injection; historic buildings; polymer impregnation; polymers in concrete
Albert Kaeding is the Vice President of Engineering for CDR Systems Corporation and chairman of ACI Committee 548 Polymers in Concrete. He has written numerous papers, specifications and reports on uses of polymers in concrete published by ACI, the International Congress on Polymers in Concrete and the World of Concrete. Mr. Kaeding directs polymer concrete product precasting operations at CDR Systems Corporation.

BACKGROUND

Structural restoration of the Cass County Jail in Fargo, North Dakota was completed in 1975 using polymer impregnation and epoxy crack injection. It may be the only significant building structure to have been restored using polymer impregnation. The intent of the restoration project was to repair a structurally unsound reinforced concrete building so that it could continue to function as a county jail for an additional 15 years.

BUILDING HISTORY

The Cass County Jail was built in 1913 at a cost of $40,000. It is a cast in place, reinforced concrete structure faced with sandstone. The building is divided into four three-story high cellblocks supported by concrete columns in the basement. The first and second floors extended to the exterior walls and the third floor had a balcony in front of the cells overlooking the second floor. A ceiling slab above the third floor formed the floor of an uninhabited attic and was a key shear element providing lateral support to the mass of the cellblocks.

The building was closed in the fall of 1974 after a thorough review of the structure determined that the building was unsound. This examination was ordered after a prisoner dug a hole in the 5-inch reinforced concrete attic slab large enough to crawl through in one night using a dinner spoon. Concrete in the foundations and columns in the basement was sound. Compressive strengths from cores indicated that the strength decreased as the structure went up. This was attributed to the use of less cement in the mix in the upper floors. Compressive strength of the third floor ceiling/attic floor was so low that cores could not be withdrawn intact. Extensive cracking and delamination was found primarily in walls of the larger rooms where the unit loads were higher. A representative area of one of the floors was load-tested to assure adequate capacity.

The Cass County Board of Commissioners decided to restore the building structurally and architecturally for a project cost of about $1 million. Estimates at the time indicated that building a new, smaller jail would cost over $4 million.
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Kaeding reported the details of the evaluation and restoration project at the ACI spring convention at Mexico City in 1976 (1).

PROJECT SUMMARY

The attic slab was restored using polymer impregnation. The system used was 89.5% methyl methacrylate, 10% trimethylpropane trimethacrylate and 0.5% azobisisobutynitrile as the polymerization initiator. Since the slab was severely deteriorated with extensive cracking and voids, the monomers tended to soak through the slab rapidly and drip off of the bottom. The bottom of the slab was sealed with an epoxy coating to prevent leakage. The top surface was also coated with epoxy and injection ports were installed on a 24 inch by 24 inch grid. Monomers were delivered to the injection ports using a pressure vessel set at 2 psi. Injection was continued until an average monomer loading of 5% by volume was achieved. Electric curing blankets were placed on the slab to provide polymerization. The top of the slab was heated to 170 degrees F and the bottom was heated to 145 degrees F. Temperature was maintained for 18 hours. Compressive tests on subsequent core samples of the slab indicated an average compressive strength of 3000 psi.

Cracks and delamination in the walls of the lower floors were repaired using epoxy crack injection. Over 5,000 linear feet of cracks were injected. Deteriorated surfaces and spalls were repaired using epoxy mortars and grouts.

RESULTS

Figures 1 and 2 show the jail in the spring of 2002, 28 years after the restoration work. The building is now almost 90 years old. It has continued in service as a jail for the county during this time. So, its continued useful life has been nearly double that anticipated from the restoration project.

The Fargo Forum has reported frequently on the Cass County Jail over the past two years since the county ordered a new jail facility to be built in May of 2001. The new facility is being built because the current building is no longer large enough. While the building was originally designed to house 78 prisoners, a second bed was installed in each 6 foot by 10-foot cell prior to 1999 to increase capacity. Up to 140 inmates have been incarcerated there at one time over the past few years (2).

The new building has a capacity for 208 prisoners and is being built at a cost of $18 million (3). It is likely that the Cass County Jail will be demolished this year. While there has been extensive discussions reported of historic
preservation, the costs associated with that have been too high for the county residents. Costs to renovate the structure for other uses have been estimated to be $5.9 million (4).

CONCLUSIONS

This project has demonstrated the successful use of polymer impregnation for use in restoring buildings. Under strength concrete can be improved adequately to make it serviceable.

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Figure 1. The Jail in May 2002, Side

Figure 2. The Jail in May 2002, Front
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Polymer Concrete: A Historic Artifact?

by R. C. Prusinski and C. Bodea

Synopsis: The earliest use of polymers in concrete may date back to ancient Egypt. Modern day use of polymer concrete for architectural precast products began in 1957 with precast polymer concrete curtain wall panels. Applications may be found nearly worldwide.

Keywords: architectural precast panels; curtain walls; polymer concrete
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Richard Prusinski, Director of Polymer Concrete Consultants International, a member of ACI 548 and ACI 227 and the former chairman of Plastics in Construction of the Society of Plastic Engineers. Considered the “father of the industry”, over the last forty years he developed highly innovative and successful polymer concrete products. He now lectures at universities worldwide, is a consultant to the P.C. Industry, and has authored many technical papers.

Constantin Bodea, President, Metro Cast Corporation. For many years he was Technical Chief of Engineering Construction and was responsible for many high-rise buildings in Romania, most of them built with precast concrete panels. Later he held the position of Director with a major precast plant employing over 500 employees. In the United States he was the head of engineering with Architectural Research Corporation, a large polymer concrete facility in Michigan.

artifact, n. 1. Any object made by man, esp. with view to substantial use. 2. Biol. A substance, structure, or the like, not naturally present in tissue but formed by artificial means, as chemicals (L. phrase Ante Factum something made with skill).

The question arose as to whether polymer concrete would fit into such a category. Upon checking with the Random House Unabridged Dictionary, it appeared obvious that, although it is thought of as a relatively recent development, both historically and quantitatively as indicated by current usage, polymer concrete fits well into this definition.

Historically, some scientists claim that the Romans had used a type of natural resin, when combined with various aggregates and other inert fills, produced a type of paste or concrete (concrete, N. Latin Concretus, to grow together) to be used in castings. Some even claim that the Egyptians had somehow used such a techniques in constructing the pyramids.

As it is also believed that the Chinese used a glutinous rice paste-like mortar in building the Great Wall of China. In a contemporary perspective, polymers (resins) were developed in the late 19th century and as a solid usable raw material were originally produced under the name of Bakelite (named after its inventor Dr. D. Baker). Since then, many forms of polymers have been developed, but two main categories define their scope thermoset and thermoplastic. In order to understand each one’s innate characteristics one must comprehend their individual properties.

Thermoplastic polymers (resins) are made soft and pliable (moldable) by heat and pressure without changing their inherent properties. This process can be basically repeated e.g. a plastic bottle; by the application of heat & pressure can
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change its form completely—say into a ping-pong ball.

Thermosetting polymers, once set (hardened) by heat or chemical additives (catalysts) cannot be remolded, e.g., a fiberglass boat or many automotive body parts (they can be destroyed but never remolded).

**KEY:** Thermo—Plastic—can be changed
Thermo—Setting—once "set" it will remain that way.

Prior to 1957, the theory of adding fill materials to a thermosetting resin (sic), polymer, was mainly used to extend the quantity. The approach of using the resin only as a binder similar to cement somehow never occurred to anyone who would incorporate it into a viable end product.

The German chemical giant Bayer was knocking on the door of this theory in the 50's but the binder costs did not justify extensive commercial application. In the late 50's, resin manufacturers had greatly expanded their production facilities to accommodate post war needs. A major recession caused less demand than was anticipated and consequently prices declined dramatically. It was at this point in time that an idea was conceived to take advantage of these less expensive binders, thus the development and marketing of the first true polymer concrete products began. The year was 1957!

Polymer concretes with their high strength to weight ratio combined with stronger compressive characteristics and short cure times lend themselves particularly well to building products. Precast building panels were first developed as simple thin facings (3/4" to 1") reinforced with fiberglass cloth and attached either through the face or from the back by simple "T" nut inserts. Although initially highly successful, architects were more comfortable with a thicker "image". In the creation of this type of panel, the use of urethane foam core helped develop the desired thickness. Figures 1 through 4 show examples of various panels.

It actually now gave industry a relatively thin (compared to cementitious concrete) panel with two finished faces and a high U-value core (a good thermal insulator). From these beginnings, and recognition of polymer concrete's versatility, other types of building related products evolved.

A simple polymer concrete brick-like block used as a substitute for wood block floors in heavy industrial production facilities (figure 5). It completely changed the way major automotive factories structured both old and new floors. Frequently replaced wooden blocks were changed to flooring that never has to be replaced again. Even though initial costs were much higher, usage soared. Millions of polymer concrete floor blocks now cover many U.S. auto plant floors and other heavy industrial floors also.
Prusinski and Bodea

Inasmuch as one of the main qualities of polymer concrete is its resistance to most corrosive and degrading chemicals, channel drains were a creative development of a German firm, which in the early seventies revolutionized the underground drainage and sewage market.

Polymer concrete was also quickly and creatively applied in the electrical industry since it has desirable dielectric properties. Underground junction boxes (figure 6), cable and fiber optic trenches and even insulators, some as large as 136kv, were now being accepted by the very conservative utilities industries. The transportation field was not to be ignored thus roadway appurtenances were developed which could withstand harsh weather assaults along with corrosive deicing chemicals. "New Jersey type" barriers (figure 8), visible curb facing forms (figure 7), bridge and roadway surfacing now grace our nation's highways and tunnels.

But, can all of these products be called artifacts? Is current usage "historic"? The concept that was conceived thousands of years ago was almost lost, and now it is resurrected and deserves a place in the category of HISTORIC ARTIFACTS.

The oldest artifact displayed here was recently removed from a garden where it was used as a stepping-stone for over thirty-five years. Note the lack of any deterioration even though it underwent the harsh winters of Michigan. Because the polymer concrete is impervious to water, the rebar shows no sign of corrosion—but note a similar cementitious concrete specimen next to it! This is probably why the Pyramids and The Great Wall of China have not deteriorated throughout the ages.

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Figure 1. Several Panels in Section View
Figure 2. Building in Boston, MA

Figure 3. Reinforced thin panel detail
Figure 4. Insulated panel detail

Figure 5. Photo of a block floor
Figure 6. PC boxes

Figure 7. Visi-curb photo
Figure 8. Barrier photo
Polymers in Concrete: Where Have We Been and Where Are We Going?

by D. W. Fowler

Synopsis: Concrete-polymer materials that include polymer-impregnated concrete (PIC), polymer concrete (PC) and polymer-modified concrete (PMC), have been developed within the past 50 years. PIC, which started out with great promise, has essentially disappeared from the scene. PC has been widely used for repairs, floor and bridge overlays, and precast components, but has not achieved the volume of use that had been projected. PMC has been widely used for overlays and repairs, including spray-on applications. There are many potential applications for the future related to materials processing and applications, which will ensure these materials will continue to be important in the construction field.

Keywords: applications; concrete; polymer concrete; polymer-impregnated concrete; polymer-modified concrete; polymers
INTRODUCTION

Polymers in concrete have witnessed a steady growth in popularity since they first became known in construction in the 1950s. They became much more widely known after polymer-impregnated concrete received considerable attention in the late '60s and early '70s. Polymer concrete became well known for repairs, overlays, and precast components. Polymer-modified concrete, particularly latex-modified concrete, became widely used for concrete repairs, particularly for overlay, and for spray-on coatings for concrete structures. Monomers and epoxy resins were eventually developed for crack repair. Many applications of past uses will be discussed.

Future uses of polymers in concrete will be discussed. New developments in materials and innovative applications will keep concrete polymer materials in the forefront of construction materials in the 21st century.

WHERE HAVE WE BEEN?

Polymer-Impregnated Concrete

Polymer-impregnated concrete (PIC) was one of the most exciting material developments in years when it was announced in the late '60s. PIC involved drying the concrete, evacuating the air from the pores, forcing a low viscosity monomer into the pores under pressure, and curing by means of heat or radiation. The results were very impressive: compressive strengths of 15,000 to 20,000 psi or more; flexural strengths of 1200 to 2000 psi; excellent durability as measured by resistance to freezing and thawing and abrasion; and negligible creep. Many potential applications were predicted: water and sewer pipe; precast beams; flooring; wall panels; and sanitary ware. Partial-depth impregnation was developed with the goal of producing PIC in the field. Omitting the vacuum and pressure, impregnated depths of 0.75 to 1.5 inches could be obtained. The most obvious applications were bridge decks for corrosion protection; floors for abrasion resistance; and hydraulic structures for wear and abrasion resistance (Polymers in Concrete, 1973).

Like the little girl who was all dressed up with no place to go, PIC remains a material with great potential based on considerable research but with essentially
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no applications. Approximately 20 bridges were treated and performed well (Bartholomew, 1978). A jail with very deteriorated concrete was given new life (Kaeding, 1978). The most significant application was the impregnation of Dworshak Dam in Idaho, the third highest dam in the United States. Cavitation had seriously damaged the walls of one of the outlet tunnels that carried water through the dam. The walls were repaired and, using techniques developed at The University of Texas at Austin, the walls were dried and soaked with monomer that was polymerized in situ. The floor of the stilling basin suffered extreme abrasion and wear, resulting in holes over 10 feet deep. After repairs, including 18 inches of steel fiber-reinforced concrete, the floor was impregnated under very difficult conditions-cold, wet weather, and very high hydraulic pressure that forced water up into the slab as it was being dried (Schrader, 1978). Follow-up inspections have shown that both walls and floor have performed extremely well after 25 years of service.

The process, however, was very time consuming, requiring a long drying period with temperatures at the surface reaching 250°F or higher. After drying, the concrete had to be cooled before applying monomer. The monomer was soaked for several hours in a thin layer of sand applied to the surface. The concrete was heated to about 160°F to cure the monomer. The process generally took 48 hours. Some concern was expressed that microcracks created during drying were not sealed during the polymerization. Another concern was safety—the flammable monomer had to be handled carefully to prevent fires.

Other materials served as formidable competition to PIC. Durable coatings and polymer concrete overlays provided faster, less expensive solutions for protecting concrete walls and bridges. Improved portland cement concrete and precast polymer concrete became the materials of choice for precast components requiring high strength and durability. At the present time, only a few applications of PIC are being reported: PIC stay-in-place concrete forms and troughs in Japan and partial depth impregnation of floors and statuary using plastic sheets which permits a vacuum to be applied and monomer to be soaked into the concrete. But these very limited applications are a far cry from the many innovative applications prophesied in the 70s.

Polymer Concrete

Polymer concrete, PC, is a composite material consisting of aggregate with a polymer binder. Acrylic, epoxy, polyester-styrene, and sulfur are the most common binders. The fast curing, excellent strength and durability, excellent damping properties, and wide range of elastic moduli available have made PC a very versatile material with many applications. Its primary disadvantages are high cost (binder cost ranges from less than $1 per pound to many dollars per pound); sensitivity of properties to temperature; volatility and flammability of monomers and resins; and lack of experience with PC by many users.
Fowler

PC was first used in the building industry in 1958 for fabricating innovative precast wall panels (Prusinski, 1978). It was used in Europe as a prepackaged repair material in Europe as early as 1961 (Peschke, 1978). But the interest in PIC in the late '60s and early '70s led researchers to explore the use of monomer and resins as a binder for aggregate. PC rapidly proved to be an excellent repair material for concrete. Thin overlays were produced which had the advantage of providing light weight, fast curing, durable, skid resistant surfaces for bridges, floors, and sports stadiums. Repair and overlays have proven to be excellent applications for PC.

Precast PC has been widely used for flooring, utility boxes, manholes, drains, wall panels, and machine bases. Precast PC can be produced quickly, as compared to precast concrete or machined cast iron, has a high strength-to-weight ratio, and can be produced with cast inserts. The excellent damping characteristics of PC make it a very attractive material for machine bases which support high frequency equipment. One manufacturer has developed a PC shell, which is placed over deteriorated concrete bases supporting pumps, compressors, or other equipment. The void between concrete and shell is filled with a durable grout. The repairs can be made quickly, eliminating the need for extensive shut down time.

Some very innovative building components have been produced using PC. Wall panels, furniture, domes, statuary, roofing panels, and flooring have been successfully produced.

PC has shown steady, although unspectacular growth over the years. Cost, and to some extent safety concerns, have kept it from becoming even more widely used.

Polymer-Modified Concrete

Polymer-modified concrete (PMC) is portland cement concrete to which a polymer is added during batching. PMC has proven to be a very popular construction material. Styrene-butadiene, acrylic latex, polyvinyl acetate, and ethylene vinyl acetate have been widely used in the United States and other countries. The primary advantages of these materials over PIC and PC have been their more conventional technology (similar to other admixtures for portland cement concrete) and lower cost. The primary advantages are very good bond to concrete, very good flexural strength, and good resistance to intrusion by chlorides. The compressive strength ranges from lower to higher than for conventional portland cement concrete (PCC).

Strength gain is similar to that of PCC; however, since the polymer film forms quickly some of the latexes require wet curing to begin within 15 minutes after
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placement and to continue for 24 to 48 hours. General, mobile batching is required because of the short working time.

PMC has been most widely used for repairs: overlays for repairing parking garages and bridge decks, over-the-counter repair materials, spray-on mortars for vertical surfaces, and general concrete repairs. It is also used as bedding grout for floor tile.

PMC has been perhaps the steadiest performer of the concrete-polymer materials. It is likely to continue to grow in popularity and use.

WHERE DO WE GO FROM HERE?

The growth of concrete-polymer materials has not met some of the ambitious projections made in the '70s and '80s. The industry has matured, similar to that experienced by epoxies in the '70s and '80s. Research has slowed considerably over the last 15 years. In order to regain the momentum, significant advances in one or more areas will be needed. Some projections for the future include:

Materials

- Lower cost resins for PC from recycled plastics. Currently the cost of recycled resins is not significantly less than for virgin resins. With the increased emphasis on sustainable development, the cost is likely to be reduced. Recycled resins have been shown to produce PC with a wide range of properties, and for most construction materials the impurities associated with recycled plastics are not a problem.
- Smart polymer concrete, which has the ability to respond to stimuli—deflection, temperature, and stress, and to compensate for changes caused by these stimuli. This is a very promising area for development.
- Improved high performance polymers. The polymer industry has made tremendous strides in the past 50 years. It is quite likely that new and improved polymers will be developed.
  - Polymers with more stable properties over a wide range of temperatures.
  - A much wider range of polymers that is compatible with fresh concrete to provide improved properties for PMC.
  - Monomer, perhaps in the form of vapors that can be used for producing PIC much more rapidly and simply.
  - Resins that are designed to be recycled.
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Processing

- Improved batching processes that will provide for denser, void-free PC. Several processes are now available.
- Improved proportioning methods that result in more efficient aggregate packing with the objective of requiring less resin but providing adequate workability.
- Improved, more rapid processes for impregnating concrete. There is a tremendous need to significantly improve the performance of existing concrete structures, especially those subject to alkali-silica reaction, sulfate attack, freezing and thawing, abrasion, chloride intrusion, and cavitation. PIC offers great potential for accomplishing this goal.

Applications

- Rapid, user friendly, reduced labor systems for more efficiently using concrete-polymer materials for repairs, particularly on pavements and bridge decks, in order to make them cost competitive and safer to install.
- PIC post-tensioned beams and girders. These members can carry several times more load, are highly resistant to chloride intrusion, have negligible creep, and much higher flexural and compressive stresses.
- Replacements for metal castings. The greater strength-to-weight ratio, much easier just-in-time fabrication, reduced or eliminated machining, much improved damping, and improved insulation offer many advantages for a wide range of new applications.
- Composite PC-PCC components. The use of thin overlays of PC over ordinary PCC will result in lower cost, very good durability (chloride intrusion, abrasion, chemical resistance, and freezing and thawing), fire resistance, very good strength due to the sandwich construction, and a choice of aesthetic finishes.
- Thin PC facing panels attached to lightweight steel or aluminum framing members. The framing members serve both as the erection frame and the in-place, non-load-bearing wall framing. The dead load is much less and the durability much greater than for ordinary PCC panels.
- Thin sheets or tiles made of PC or PMC that can be bonded to floors, bridges and other horizontal and vertical surfaces. This process would eliminate the placing and curing of polymer materials and the associated safety problems. The materials would be much more user friendly.
- Complex PC castings used for structural applications. Railroad ties (sleepers) are an excellent example. The optimum shape is much more complex than the block PCC tie currently used. The use of rapid, automated casting processes utilizing robots along with the rapid turn around due to very rapid curing should make PC ties very competitive when life cycle costs are considered due to the excellent durability and strength.
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- Containment vessels for toxic and/or hazardous wastes. PC and PIC are potentially excellent alternative materials for containment.
- Components using intelligent PC. Examples are containment vessels that could warn of leakage problems and then seal the cracks; beams that could straighten when excessive deflection occurred; and foundation supports that could adjust for differential settlement.

These are a few possible developments that are likely to be coming on stream in the next few years. The future is as bright as innovative as enterprising people dare to dream.

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Precasting with Polymer Concrete—
The Anatomy of a Dome

by C. Bodea

Synopsis: A novel and innovative use of polymer concrete to precast a dome is described. The finished dome meets architectural criteria for the project and is lightweight and durable, making field installation easier and faster. The project demonstrates the versatility of architectural precast polymer concrete.

Keywords: architectural precast products; dome; precast polymer concrete
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Constantin Bodea graduated from the Polytechnical University in Timisoara, Romania. He was Technical Chief of Engineering Construction and was responsible for many high-rise buildings in Romania. Later he held the position of Director with a major precast plant employing over 500 employees. In the United States he was the head of engineering with Architectural Research Corporation, a large polymer concrete facility in Michigan. Mr. Bodea is currently President of Metro Cast Corporation.

INTRODUCTION

Church architects and general contractors know how difficult, time consuming and costly the construction of a dome can be when using conventional framing techniques with copper cladding, or other standard methodologies. A revolutionary technique has now been developed by the Metro Cast Corporation of Westland, Michigan, which permits the creation of large prefabricated dome sections that can be quickly and economically assembled in place at a job site.

PROJECT DESCRIPTION

This innovative casting procedure utilizes a high strength precast polymer concrete combined with custom designed stud framing members to create interlocking sections that insure positive watertight joints. These lightweight polymer concrete domes are cast in one-inch thick sections. The polymer matrix has a compressive strength in excess of 12,000 psi and a tensile strength in excess of 2,000 psi. A support framing system was custom designed to fully meet all wind and dead load requirements. In addition to its cost and time saving advantages, the polymer concrete dome sections are impervious to water penetration and can be cast in a durable polymer copper exterior if desired, or in any specific color selected by the design architect.

As soon as the supporting structural steel is in place, erection work can proceed to completion very quickly. The 22' diameter dome for All Saints Greek Orthodox Church in Canonsburg, Pennsylvania is an example of the unique capabilities of polymer concrete in dome construction. It was completely installed in only three working days. The project architect, Mr. John Krusienski of Domianos Brown Andrews Architects, Inc. of Pittsburgh, PA wrote the manufacturer upon completion of the project, "Your ability to fabricate this entire dome in only four sections with a tight interlocking joint detail facilitated and accelerated completion of the total project. The dome color is exactly the shade we wanted and the uniformity is excellent. From both a cost and performance point of view, we feel your new innovative polymer concrete system offers an effective approach to future dome construction."
In order to appreciate this simplistic yet ingenious structure each step must be analyzed so as to be able to visualize its creation (figure 1).

Initially, a skeletal dome shape is formed in four sections and pre-erected so as to check alignment and fit and to simulate the finished shape (figure 2).

Plywood is then attached from the inside to create the casting mold (figure 3). Each section is then placed casting face up. The mold surface is finished to a desired smooth texture and coated with parting agents (figure 4).

Working from the sides as well as utilizing a platform-like gantry, the polymer concrete matrix is applied by skilled trowlers who at times can be considered artisans for performing this tedious and demanding task. Specially designed inserts are cast into it along with fiberglass reinforcement (figure 5). Performed galvanized structural steel trusses are then permanently welded to the cast-in inserts (figure 6).

After a twenty-four hour ambient temperature cure, the entire unit is lifted from the mold by a hi-low truck and set aside until all the other sections are completed (figure 7). The units are then test assembled (figures 8 and 9).

All surfaces are checked for any imperfections (figure 10). The joining of each of the four spherical pieces is tested for water tightness (figure 11) and accuracy and then dis-assembled, placed on a low-bed trailer (figure 12) and transported to the job site, in this case a distance of 300 miles.

The dome sections were lifted and placed onto the structural base, utilizing a simple lightweight crane. All on-site assembly work was done from the inside.

**CONCLUSION**

Thus, the world’s first prefabricated polymer concrete dome (figure 13) is now gracing this edifice in Pennsylvania, a symbol of the versatility and creativity possible with polymer concrete. Similar polymer concrete techniques can be utilized and applied for use in creating arches and domes of almost any size or contour in segments to fit design criteria.
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Figure 1. Dome Characteristics

- DOME DIVIDED INTO 4 SECTIONS
- DIAMETER = 22'-0"
- RADIUS = 11'-0"
- WT. PER SQFT = 15 lb./sqft.
- TOTAL SQFT = 780 sqft.
- TOTAL WEIGHT = approx. 12,000 lb.

Figure 2. Form Framing

Figure 3. Completed Forms
Figure 4. Form Prepared for Casting

Figure 5. Casting and Trowling PC on to Form

Figure 6. Attaching Backing Structure
Figure 7. Removing Dome Segment from Forms

Figure 8. Finished Segment

Figure 9. Pre-assembly
Figure 10. Checking Fit

Figure 11. Completed Pre-assembly

Figure 12. Transportation to Job Site
Figure 13. Completed Project
Long-Term Durability Studies of Acrylic Polymer Modified Cement

by D. A. Schmidt

Synopsis: Acrylic polymers are widely recognized for their excellent UV durability and water resistance properties. When acrylic polymers are used as modifiers in Portland cement formulations, those polymer properties translate into excellent long-term outdoor durability and wet adhesion durability in the modified concrete. A number of lab prepared series of acrylic polymer modified portland cement formulations have been placed in outdoor exposure and tested periodically for the durability of various properties. Some of these experimental series have been on exposure for as long as 30 years. The results of these studies indicate that acrylic polymers are the ideal cement modifiers with respect to outdoor durability and wet adhesion durability.

Keywords: acrylics; durability; polymer-modified concrete
Donald A. Schmidt received a B.S. and M.S. in Chemistry from the State University of New York at Stony Brook. He has worked at Rohm and Haas Company for 28 years in process scale-up, Operations and Marketing management, and currently as a Technical Services Group Leader in the area of acrylic polymer modification of concrete. He is an active member of ACI Committee 548 (Polymers in Concrete).

Perhaps the acrylic polymer product most familiar to the average person is Plexiglas (TM) acrylic sheet. Its excellent durability under long term exposure to sunlight, which contains invisible ultraviolet (UV) radiation, and outdoor weathering conditions makes it a perfect product for use in applications such as aircraft glazing, automobile sunroofs, architectural skylights, etc. This weathering durability is a direct consequence of the basic properties of acrylic polymers, which include excellent ultraviolet (UV) light transparency and water resistance. In fact, acrylis are the sole class of commercial polymers that are UV transparent and therefore unique in their excellent durability under UV radiation exposure. In the construction industry, aqueous acrylic polymer emulsions have been used commercially to modify Portland cement mortars for more than 30 years, and the UV radiation and weathering durability properties of these acrylic polymer modified mortars are the reason for their success in this industry.

Studies have been made on a number of Portland cement formulations modified with acrylic polymers that have been placed in outdoor exposure, and at times under lab conditions simulating field exposure, and tested periodically for durability. Some of these experimental series have been on outdoor exposure for as long as 30 years. The result of these studies is the subject of this paper.

In the first study, cement asbestos building panels were sprayed with a white Portland cement mortar applied in 3 passes using a compressed air hopper gun at 20 psi air pressure. The mortar had a 1:1 weight ratio of white Georgia marble aggregate to white Portland cement Type I, both of which were chosen to achieve a decorative effect. The mortar on one panel was modified with 0.10 acrylic polymer solids/cement weight ratio, the mortar on a second panel was modified with 0.10 styrene-butadiene (SBR) polymer solids/cement weight ratio, and the mortar on a third panel was prepared using no polymer modifier. The dry components of the three mortars were identical to one another. The three mortars were prepared so that the workability was the same for each, using the water/cement weight ratio to adjust the workability. The resulting water/cement weight ratios used in this study are summarized in the following table.
Polymers in Concrete: The First Thirty Years

<table>
<thead>
<tr>
<th>Polymer modifier type</th>
<th>Water/cement weight ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>0.28</td>
</tr>
<tr>
<td>Styrene-butadiene (SBR)</td>
<td>0.33</td>
</tr>
<tr>
<td>No polymer modifier</td>
<td>0.46</td>
</tr>
</tbody>
</table>

The panels were placed outdoors exposed south at 45° to horizontal in Spring House, PA (suburban Philadelphia area) in November 1972, which is now 30 years ago. The following photos show the appearance of the surface of these panels in June 2002.

The appearance of the panel with acrylic polymer modified mortar has withstood exposure with excellent appearance after 30 years. Microphotographs of these panels, taken in May 2002, are presented in Photos 1 – 3. It can be seen that the panel with the SBR polymer modified mortar has eroded significantly during the exposure period. Although it cannot be observed in these photographs, data in the files for this exposure series states that the SBR polymer modified mortar became severely yellow during the first six months of outdoor exposure, followed by chalking and disappearance of the yellowing. This phenomenon is believed to be due to decomposition of the SBR polymer upon exposure to UV radiation outdoors. The panel with the unmodified mortar has undergone even more severe erosion than the SBR polymer modified mortar during the 30 years of outdoor exposure.

The test specimens in this first exposure series were based on a formulation designed for spray application. Other exposure series have been prepared using mortar formulations designed for trowel application. The test specimens in those series were evaluated using an adhesion test method more appropriate for such trowel-applied formulations.

One major reason that acrylic polymer modifiers are used in concrete is to enhance the adhesion of a mortar to a substrate. The shear-bond adhesion strength of a polymer modified mortar, a non-ASTM test method, can be determined using substrate blocks cast from unmodified concrete and measuring 4 inches x 6 inches x 1 inch thick. Two patches of the polymer modified test mortar measuring 2 inches x 2 inches x ½ inch thick are applied to each substrate block and allowed to cure under conditions appropriate to the study being conducted. At the time of testing, the blocks are placed in a Tinius-Olsen Universal Testing Machine and a metal block is moved against the edge of the polymer modified test patches in shear mode at a crosshead speed of 0.05 inch/minute. In addition to recording the quantitative adhesion strength in psi, the qualitative mode of failure is noted, which adds another dimension to the understanding of the adhesion strength. The qualitative mode of failure is described as either adhesive failure, where failure occurs at the plane of the bond, or cohesive failure, where failure occurs within the substrate block or the
test patching material itself. Cohesive failure indicates that the bond of the test patching material to the substrate block is stronger than the material that fails cohesively (the substrate block or the test patch material).

The second exposure series to be presented consists of test specimens cast for determining shear-bond adhesion strength. The mortar was prepared using a 3:1 weight ratio of 45-mesh sand to gray Portland cement Type I. One set of samples was prepared from a mortar that was modified with an acrylic polymer and a second set of samples was prepared from a mortar with no polymer modifier. The water/cement weight ratio was adjusted to yield the same workability in both sets of samples, and the ratios used in preparing the test specimens are summarized in the following table.

<table>
<thead>
<tr>
<th>Polymer modifier type</th>
<th>Water/cement weight ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>0.43</td>
</tr>
<tr>
<td>No polymer modifier</td>
<td>0.60</td>
</tr>
</tbody>
</table>

The water/cement weight ratio for the acrylic polymer modified mortar was 0.43 and the water/cement weight ratio for the unmodified mortar was 0.60. The test specimens were placed outdoors in suburban Philadelphia in a horizontal position and tested after four years of exposure.

The shear-bond adhesion strength of these two mortars was tested at the initial time that the test specimens were prepared and after 4 years of outdoor exposure. The results are presented in Graph 1.

It was observed that at the initial time and after 4 years of outdoor exposure, the shear-bond adhesion strength of the acrylic polymer modified mortar was greater than the unmodified mortar. In addition, the acrylic polymer modified mortar failed cohesively in shear-bond mode both initially and after 4 years of outdoor exposure. In contrast, the unmodified mortar failed adhesively in shear-bond mode both initially and after 4 years of outdoor exposure.

The third exposure series to be presented also consists of test specimens cast for determining shear-bond adhesion strength. The test specimens were all prepared using a dry mix having a 2.5:1 weight ratio of 60 mesh sand to gray Portland cement Type I. One set of samples was modified with a dry acrylic polymer and a second set of samples was modified with a dry ethylene vinyl acetate (EVA) polymer, both at 0.10 polymer solids/cement weight ratio. The water/cement weight ratio was adjusted to yield the same workability for both mortars and the levels used in preparing the test specimens are summarized in the following table.
<table>
<thead>
<tr>
<th>Polymer modifier type</th>
<th>Water/cement weight ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>0.47</td>
</tr>
<tr>
<td>Ethylene vinyl acetate (EVA)</td>
<td>0.55</td>
</tr>
</tbody>
</table>

A set of test specimens were tested in November 1985 for shear-bond adhesion strength after curing for 28 days, and then the remainder of the test specimens were placed outdoors in a horizontal position in Spring House, PA. A set of test specimens was most recently tested in June 1997 after 11.5 years of outdoor exposure. The results of these shear-bond adhesion strength tests are presented in Graph 2.

It was observed that the shear-bond adhesion strength of the acrylic polymer modified samples was greater than those modified with the EVA polymer, both initially and after 11.5 years of outdoor exposure. Even more importantly, all of the acrylic polymer modified shear-bond adhesion samples failed in a cohesive mode, while all of the EVA polymer modified shear-bond adhesion samples failed in an adhesive mode. This indicates that the adhesion of the acrylic polymer modified mortar is stronger than the substrate or patching material both initially and after 11.5 years of outdoor exposure.

The fourth series is an accelerated durability test run according to a method developed by the Illinois Division of Highways. In this test, concrete blocks were coated with a layer of test concrete and allowed to cure. The blocks were then subjected to freeze/thaw cycles consisting of:

1. Pond about 120 ml of water on the surface of the test mortar and place the block in a 30°F freezer for 16 hours.

2. Place 48 grams of rock salt on the surface of the test mortar while the block is still in the freezer. Allow the block to stand for 4.5 hours in the freezer with the rock salt applied.

3. Remove the block from the freezer, rinse the test mortar surface with water, and allow the block to warm to room temperature for 3.5 hours.

This freeze/thaw exposure regimen was applied to test mortars prepared from dry mix composed of 2.5:1 weight ratio of sand to Type I Portland cement. One set of samples was prepared from mortar modified with an all-acrylic latex polymer and another set of samples was prepared from mortar modified with a styrene-butadiene (SBR) latex polymer, both at 0.10 polymer solids/cement weight ratio. Two sets of samples were also prepared using unmodified mortar. The substrate blocks to which the test mortars were applied measured 3 inches x 7 inches x 12 inches and were cast using a sand and Type I Portland cement dry mix design.
with 1/8 inch pea gravel and no polymer modifier. The test mortars were trowel applied to the substrate blocks at ¼ inch thickness after the substrate blocks were cured by total immersion in water at room temperature for 7 days.

The samples prepared from mortar modified with the all-acrylic polymer, the samples prepared from mortar modified with the SBR polymer, and one set of the unmodified samples were air cured under controlled conditions of 25°C and 50% relative humidity. The other set of unmodified mortar samples were moist cured under controlled conditions of 25°C and 99% relative humidity. The moist cured unmodified mortar samples were included in the study to represent the best practice for curing unmodified mortars. Such moist curing would require a large, probably impractical, amount of effort in the field.

The surface appearance of these test specimens were compared next to one another both before and after 60 cycles of testing to determine the relative durability of these mortars to this freeze/thaw exposure regimen. It was observed that the air cured unmodified mortar had over 50% of its surface scaled. The moist cured unmodified mortar withstood the cycling better, with only about 10% surface scaling. The mortar modified with the SBR polymer and air cured performed better than either of the unmodified mortars, however it was noticeably pitted after the cycled exposure. The mortar which was modified with the acrylic polymer and air cured was observed to have virtually no change in appearance after 60 cycles of this freeze/thaw cycling regimen.

In summary, the results of these experimental series demonstrate the value of modifying Portland cement mortar with an acrylic polymer to achieve long-term outdoor durability. In these experimental series, long-term durability was determined by observation of mortar erosion under outdoor weathering conditions, adhesion of a mortar to a substrate under outdoor weathering conditions, and mortar erosion upon salt water freeze/thaw cycling testing.
Polymers in Concrete: The First Thirty Years

Graph 1

Shearbond Adhesion Strength, psi

<table>
<thead>
<tr>
<th>Polymer Modifier Type</th>
<th>Initial</th>
<th>4 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>518</td>
<td>441</td>
</tr>
<tr>
<td>None</td>
<td>52</td>
<td>133</td>
</tr>
</tbody>
</table>

Pounds per Square Inch

Graph 2

Shearbond Adhesion Strength

<table>
<thead>
<tr>
<th>Polymer Modifier Type</th>
<th>Initial</th>
<th>11.5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>619</td>
<td>495</td>
</tr>
<tr>
<td>EVA</td>
<td>191</td>
<td>202</td>
</tr>
</tbody>
</table>

Shearbond Adhesion Strength, psi
Photo 1: Microphotograph of the acrylic polymer modified mortar after 30 years exposure.

Photo 2: Microphotograph of the SBR polymer modified mortar after 30 years exposure.
Photo 3: Microphotograph of the mortar with no polymer modifier after 30 years exposure.
Polymer Concrete Overlays for the Repair and Protection of Concrete

by G. W. DePuy and F. E. Dimmick, Sr.

**Synopsis:** Polymer concrete (PC) overlays are often an effective way to repair or protect concrete surfaces exposed to hostile service conditions. The various applications of PC overlays include industrial floors exposed to abrasion and chemical spillage, concrete spillways and water conveyance structures exposed to abrasion erosion and freeze-thaw attack, and bridge decks exposed to severe weather conditions, deicing salts, and heavy traffic. Three general types of PC overlays are used: premixed PC, multiple-layers PC, and slurry PC. Polymer binders include methacrylate monomer systems, and epoxy, polyester, and vinyl ester resins systems. Applications of PC overlays and progress in the development of standards are discussed.

**Keywords:** concrete protection; concrete repair; overlays; polymer concrete
Bill DePuy, PE, FACI, was a consulting engineer. Previously, Bill worked for the Bureau of Reclamation for 41 years where, as Head of Concrete Materials Section, he supervised research on polymer concretes, and investigations of concrete materials, durability, and repair. DePuy was Managing Director of ICPIC. He was Past Chairman of ACI-123, Past Secretary of ACI-548, served on several other ACI Committees, and was active on RILEM, TRB, and ASTM Committees. DePuy authored over 50 papers on concrete. Honors included membership to Sigma Xi, Russian Academy of Engineering, and ICPIC’s Owen Nutt Award.

Floyd E. Dimmick, Sr., Crown Polymers LLC. His career has focused in areas of polymer and concrete science for the repair and preservation of concrete. Currently a member of ASTM, TRB and 3 committees with ACI, he is a past chairman of ACI 548-B Polymer Concrete Overlays.

**POLYMER CONCRETE**

Polymer concrete (PC) is a strong, durable, and versatile material consisting of aggregate bound with a polymer binder (ACI 548). The excellent strength and durability properties of PC are due to the polymer binder. The polymer binder forms an impermeable matrix of the concrete and has greater chemical resistance than conventional portland cement. PC is well suited for the protection and repair of concrete surfaces such as bridge decks, ramps, pavements, slabs, industrial floors, secondary chemical containment areas, and canals and spillways.

The properties of PC greatly depend on the formulation, but in comparison to conventional portland cement concrete, PC generally has higher compressive, tensile, and flexural strength; greater impact and abrasion resistance; much lower permeability to water and dissolved salts; and greater resistance to weathering, freeze-thaw, and chemical attack.

The monomer or resin system is the most important single factor in determining the properties of the PC. Not all PCs are the same since several different polymer systems may be used. Properties of different polymers vary and produce corresponding variations in the PC. The ideal monomer or resin system is a low volatility, 100% reactive system that can be cured at ambient temperatures to form a strong, low shrinkage polymer. Epoxy, methacrylate, and polyester resins are most commonly used. Other systems also used include epoxy-urethane, sulfur (Vroom 1997) and vinyl ester (Causey 1977, 1978). New developments with monomers and resin systems may be expected to produce further improvements in the future (Ohama 1998, Namshik and Fowler 1998, Taha 2001).
As rheological properties of the various monomer and resin systems, and particle shapes and gradations of aggregates vary greatly, each mixture should be individually proportioned. The aggregate is important as poor quality particles, wet aggregates, and improper gradation can cause poor workability, compaction, curing, adhesion, and degradation problems. Aggregates should be hard and resistant to polishing and fracturing (Mendis 1986).

PC is cured by a chemical polymerization reaction that turns liquid monomer or resin into a solid polymer. Most PCs are cured at temperatures between 10°C (50°F) to 35°C (95°F); special systems are cured from -18°C (0°F) to 50°C (120°F).

Although PC is more durable and stronger than conventional portland cement concrete, the main reasons for using PC are usually ease of use, rapid curing, very fast strength development, and cost savings. PC overlays can be placed in thin lifts and in a short period of time, using less material than conventional concrete overlays with an overall reduction in construction costs (Cremaschi 1986, Dimmick 1997). PC overlays are advantageous when short down time is critical.

**PC OVERLAYS**

PC overlays have an excellent track record, and are a good choice for the enormous highway bridge rehabilitation market (Fairweather 1986). The Strategic Highway Research Program Project C103 review of PC overlays on concrete bridge decks indicated a 20-year service life for multiple-layer epoxy and epoxy-urethane PC overlays, and a service life of about 10 years for multiple-layer polyester overlays (Sprinkel 1997). A survey in New York showed PC overlays had good performance during the first 5 to 7 years, with no differences among the various materials (Doody and Morgan 1993). Earlier problems with PC overlays were attributed to a poor substrate surface.

Thin PC overlays for bridge decks are particularly attractive as these can be rapidly applied at relatively low cost with minimal traffic disruption (Sprinkel 1983 and 1984, Scarpinato 1984). Thin polymer wearing surfaces have been reported to have a service life of up to 20 years in severe cold climates with moderate traffic volumes (Carter 1993). Thick PC overlays are more expensive and may cost up to twice as much as conventional concrete. However, costs are usually offset by short down time, rapid curing and strength gain, ease of application, high strength and durability, longer service life, and low life cycle costs.

Most PC overlays are applied using a bond coat, which in most cases is the same as the monomer used as the binder for the PC. High molecular weight methacrylate monomer has been used as a bond coat for polyester PC.
The beneficial properties of PC do not automatically insure a good application. Cracking and delamination problems may result from moisture, contaminants and inadequate surface preparation in the base concrete; improper selection of improper materials and faulty proportioning; excessive curing shrinkage; and from incompatibility problems arising from differences in modulus of elasticity and coefficient of thermal expansion between the overlay and base concrete.

Incompatibility problems can be alleviated by matching the properties of the overlay with the base concrete, such as by reducing the amount of polymer in the mixture and using a more flexible, low modulus polymer (Sprinkel 1983, Mendis 1986, Daly 1993, Dimmick 1997b). One investigator recommends a modulus of 90,000 to 150,000 psi (400-1000 MPa), tensile elongation of at least 30%, minimum tensile strength of 2500 psi (17 MPa), compressive strength of 5000 to 8000 psi (35-55 MPa), long-term flexibility or resistance to age hardening, and tough aggregates (Scarpinato 1984). Restrained shrinkage can induce high stresses in overlays (Zalantimo and Fowler 1996). A study of thermal stresses showed highest stresses occur at the PC/concrete interface. Thinner and lower elastic modulus PC develops lower interface stresses than thicker, higher modulus PC (Choi et al. 1996). Slower curing systems can reduce polymerization-shrinkage induced stresses.

PC overlays must be applied to a clean, dry, and sound concrete base. Good surface preparation is required. Unsound, contaminated, or delaminated concrete should be removed and depressions filled with a compatible patching material. PC should not be applied over moving cracks, as reflective cracks will appear. Cracks should be stabilized and rebonded with epoxy. Jackhammers, scabblers, and heavy chipping tools should not be used as these may damage the concrete substrate and loosen rebar (Warner et al. 1998).

When applied to concrete with corroded reinforcing steel, chloride contaminated concrete must be removed to a depth below the rebar and the rebar cleaned to a bright appearance. Surfaces should be cleaned by abrasive blasting, shot blasting, or high pressure water blasting (ICRI 1996). The concrete base should have a tensile strength of at least 1 MPa (150 psi) (Sprinkel 1997). ACI 548 has developed a standard to determine cleanliness and surface soundness of the concrete substrate, and the adhesion of the overlay. The standard uses a tensile pull test and calls for a minimum tensile strength of 1.7 MPa (250 psi), with failure occurring in the substrate (ACI 503 R).

The base concrete should be dry before applying the overlay as moisture affects adhesion and may cause delamination and blistering. A simple field test for moisture is to tape a polyethylene sheet to the concrete surface. If moisture appears, the concrete is too moist and should be dried. Progress is being made in developing systems for wet applications, but this is still in the research stage.
US organizations developing guidelines and specifications for PC overlays include ACI (ACI 548), AASHTO-AGC-ARBTA Task Force 34 (AASHTO 1995), Virginia Department of Transportation (VDOT 1991), New York State Department of Transportation (Doody and Morgan 1993), California Department of Transportation (Caltrans), and Bureau of Reclamation (Smoak 1997). ASTM has specifications for epoxy resins that may be applied for overlays (ASTM C 881). Good safety practices are essential, and adherence to established safety practices, good ventilation, organic respirators, and protective clothing are required.

**TYPES OF PC OVERLAYS**

- Premixed overlays. In the customary method, all aggregate and resin are premixed before application. In the "broadcasted" method, up to 30% of the aggregate is withheld during mixing and is later broadcasted onto the wet surface after the mixture is placed. Premixed non-broadcasted overlays are generally applied using a prime coat, and struck off and compacted by a screed.
- Multiple-layer overlays (so-called “broom-and-seed” overlays) are applied by first spreading polymer binder on the deck and then by broadcasting aggregate onto the wetted surface. Two or three layers of resin and aggregate are typically used, producing an overlay about 6 to 9 mm (1/4 to 3/8 in). Multiple-layer PC overlays reflect the surface contour and are best suited for relatively smooth concrete surfaces with good riding qualities.
- Slurry overlays (AASHTO 1995) are prepared by mixing resin and sand in a slurry and pouring the wet mixture on the deck in a layer about 2 to 3 mm (1/16 to 1/8 in) thick. Aggregate is broadcast on the surface, as in multiple-layer overlays, to improve friction. Slurry applications do not require a prime coat and may require a seal coat to lock in the aggregate cover. Slurry and premixed PC overlays are suitable for rougher surfaces since they fill in surface irregularities (Sprinkel 1997).

**EPOXY PC**

Epoxy PC is a very versatile overlay material with excellent performance in bridge decks, parking garages, ramps, slabs, and industrial floors (ACI 548.5R, Fagley 1998, Kesner and Poston 1995). Epoxy PC is easy to clean, can be colored and formulated for aesthetic effects, and has many architectural and decorative uses. Other uses include protection from chemicals, resistance to fungi and bacteria, control static electricity as a electrical conductive overlay, resistance to temperatures up to 260 C (500 F), as reflective coatings, and to

Two component epoxy systems are used for epoxy PC. A wide variety of epoxy resins and curing systems are available, and the resultant properties likewise will vary widely. Most epoxy resins for civil engineering and industrial applications are made from bisphenol A and epichlorohydrin (Mendis 1989, Popovics 1993, Dimmick 1997b). The epoxy resins are hardened by mixing with a curing agent, usually an amine compound, which causes a crosslinking polymerization reaction with the epoxy resin.

Epoxy resins for PC should be 100% solids systems, with low odor and little or no shrinkage. Properties of epoxy systems are modified by selection of the curing agent, and by blending with other resins, monomers, and additives. Modifications are made to improve wetability and adhesion, increase flexibility and extensibility, lower the modulus of elasticity, reduce viscosity, or to produce systems that can be cured at temperatures ranging from -18 C (0 F) to 60 C (140 F) (Dimmick 1997b). Low viscosity epoxy resins containing solvents are not recommended as due to problems with shrinkage and with environmental regulations on volatile organic components.

**METHACRYLATE PC**

Methacrylate PC has been successfully used in the US and Europe for about 30 years and has a good reputation. Much of the current attention on PC overlays is due to the early success and commercial development of MMA PC. MMA PC is used in both thin and thick bonded overlays and patches, renderings, and bearing pads (Dimitz and Ferri 1989, Meinheit and Riesterer 1997). MMA PC is probably used more extensively in rehabilitation of buildings and other structures than on highways. A study of a parking garage repairs in Nashville, TN showed good performance and no signs of wear after 13 years service (Meinheit and Riesterer 1997). Laboratory and 7-year field tests in Japan indicate MMA PC with hard aggregates gives good wear resistance (Omata et al. 1997).

MMA PC is a strong, very durable, and versatile material with excellent weathering properties, and is especially good for resistance to outdoor weathering. It is suitable for resurfacing concrete, thin overlays, grouting between sections, and a variety of construction applications (Pasco et al 1985). MMA monomer has a very low viscosity and mixes easily with aggregates. MMA is also an excellent solvent, and generally does not present the clean up problems encountered with epoxy and polyester PC. The vapor pressure of
MMA is similar to that of water, and may evaporate if not covered or if a evaporation reducing agent is not used.

High molecular weight methacrylate (HMWM) monomers were developed to overcome volatility problems of MMA. These are used as sealers, crack healers, PC binders, and primer for PC overlays. HMWM monomers have a viscosity of 8 to 20 cps, low vapor pressure (less than 1 mm Hg @ 25 C (77 F)), and molecular weight of about 200. The term HMWM monomer refers to a methacrylate molecule having a higher molecular weight than MMA and does not refer to a specific molecular formula. There are several varieties of HMWM monomers, and different products may be expected to show differences in properties.

**POLYESTER PC**

Polyester PC is widely used in California and Nevada (Caltrans, Smith 1991). The system is attractive as the materials are widely available and relatively inexpensive. Tests conducted by California Department of Transportation (Caltrans) showed good results on PC made with a type II wax-free, unsaturated, flexible, isopthalic polyester containing 40-45% styrene, viscosity in the range of 75 to 200 cps, 35% tensile elongation, and tensile strength of 17 MPa (2500 psi). Caltrans is currently using the type II polyester resin. Polyester PC overlays placed since 1983 are performing well with no signs of wear or cracking (Maass 1997).

Most polyester resins contain styrene monomer and are considered flammable. Volatile emissions should be monitored by standard air quality testing methods and should not exceed 60 grams per M2 loss. Applications should be made outdoors or in well-ventilated areas.

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Table 1 Generic Types of PC Overlays Used in State Highway Construction in the US

<table>
<thead>
<tr>
<th>Year</th>
<th>Epoxy</th>
<th>Epoxy-Urethane</th>
<th>Methacrylate</th>
<th>Polyester</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 1990</td>
<td>32</td>
<td>22</td>
<td>12</td>
<td>23</td>
<td>125</td>
</tr>
<tr>
<td>1990</td>
<td>7</td>
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<td>2</td>
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<td>1991</td>
<td>40</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>50</td>
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<td>1992</td>
<td>15</td>
<td>4</td>
<td>4</td>
<td>6</td>
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<td>9</td>
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<td>23</td>
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<td>1996</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>17</td>
<td>31</td>
</tr>
<tr>
<td>1997</td>
<td>19</td>
<td>2</td>
<td>4</td>
<td>17</td>
<td>54</td>
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<td>1998</td>
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<td>1999</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>24</td>
<td>39</td>
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<tr>
<td>Total</td>
<td>202</td>
<td>125</td>
<td>40</td>
<td>144</td>
<td>511</td>
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</table>

Source: Michael Sprinkel
Virginia Transportation Research Council
Curtain Wall Panels

by A. O. Kaeding and R. Prusinski

Synopsis: The use of polymer concrete (PC) curtain wall panels was started in the U.S. and other countries in the late 1950’s. Panel finish was typically an exposed aggregate with stone size and color selected to meet architectural requirements. Uninsulated panels were 5/8 to 1-in. thick and insulated sandwich panels were 2 to 4-in. thick. Unsaturated polyester with styrene monomer was used as the PC binder. The original developer and manufacturer of curtain wall panels performed extensive testing on the products and the PC used in production. Compressive strength, flexural strength, modulus of elasticity, tensile strength, freeze-thaw resistance, thermal transmittance, and resistance to weathering, coefficient of thermal expansion and flammability were all investigated. Full-scale load testing confirmed the strength and wind load resistance of the panels. Attachment and erection details were developed and tested. Panels with these properties have been performing successfully for the past 40 years. Unpublished results of this testing, the associated details and recommended specifications are presented in this paper. Properties determined in the tests reported are pertinent to other structural applications as well and expand the knowledge base for polymer concrete structures.

Keywords: architectural panels; curtain walls; polymer concrete properties; polymer concrete structures
INTRODUCTION

The use of polymer concrete for precast curtain wall panels began in the United States in 1957 (1). Precast polymer concrete (PC) curtain wall panels employ natural aggregates imbedded in a copolymer thermosetting resin to produce a textured surface.

Tests have shown the PC to be impervious to moisture, stains, fumes, and gases. Accelerated tests run under conditions of freezing, thawing, and exposure to ultraviolet radiation produced no change in PC properties. Tests were performed on materials of construction to define various physical and mechanical characteristics. Tests were also performed on full-scale panels to determine wind load response.

Three panel types were produced. Facing panels, 5/8 to 1 in. thick, were used for facing old buildings or covering block and wood studded areas of new structures. They give the effect of a precast wall without the weight burden. In addition, they have moisture-sealing ability and are easy to install. Insulated panels, 2 to 4 in. thick, employed a foamed glass or polyurethane core. They provided insulation and contributed less dead weight to the structure. It is possible to enclose larger spaces with a thinner, lighter structure using the properties of polymer concrete, allowing considerable savings in heating and structure costs. Cast-in panels, 5/8 to 3 in. thick, consisted of a ¼ in. cement asbestos back face placed into a metal curtain wall frame. A variable amount of foamed glass or polyurethane insulation was then inserted and covered with a 5/8 in. thickness of a facing aggregate panel. The entire assembly bonded into one monolithic piece, metal and all. It was light in weight, insulated, and economical to install. Ideal in aluminum or steel multi-rise curtain wall construction, this panel allows the architect to achieve a textured surface (2).
Successful application of the panels depends on wind load resistance, proper anchorage to the building frame and moisture resistance of the field joints. The method used for panel attachment depends on the substrate to which the panel will be mounted and the panel type. Architectural details incorporate features to shed water and protect the joints. Tongue and groove joints, ship lap joints and shadow joints are commonly employed for horizontal joining. Vertical joints may be butt joints, spline joints, butt-batten joints or rabited joints. Typical jointing details are shown in Table 9.

When mounting directly to concrete or unit masonry construction, panels are mounted using expansion anchors, toggle anchors or screw and shield anchors. When furring is required, the furring is attached using traditional methods and the panels are then attached to the furring with screws. Panels can also be mounted directly over plywood sheathing or directly to wood or metal studs. Insulated panels are mounted using welded or bolted clips to the structural frame. These clips can be attached directly by welding or bolting or with adjustable inserts or lap plates. Several jointing details are used, depending on the architectural finish to be achieved. Typically, ¼ to ½-in. of space is planned between adjoining panels to allow for construction tolerances and to permit caulking (3).

Tests (4) to determine the capacity of threaded anchors are summarized in Table 4 and show ultimate values of 7,683 lbs for direct pullout and shear strength of 5,477 lbs. Based on these values, minimum fastener sizes and locations were determined and are tabulated in Table 1 to 3.

**MATERIAL PROPERTIES**

Flammability test (5) results in Table 5 show that the panels were suitable for exterior cladding within the requirements of most standard building code requirements. Environmental and chemical resistance tests (Table 6) showed the panels to be resistant to common environmental conditions and to strong acid and base exposure. Material physical properties determined by testing are listed in Table 7.
Full size panels were tested to determine wind load capacity. Panels were tested in the horizontal position supported on 2-in. bearing plates on roller-pin supports. Since the panel is used in a vertical position but was tested horizontally, the self-weight of the panel was included when strength was calculated. The resulting maximum moment within the span was calculated and an “equivalent” distributed load on a simple span of equal length was found which would cause the same maximum moment. This equivalent distributed load was then added to the applied load when calculating the maximum moment. For finding the deflection resistance, the dead load was not included, but deflection readings were started at zero with the panel in place and with no applied load.

The test load was applied at third points of this span by means of a pressure bag, the load of which was uniformly distributed across the width of the panel. The weight of the test equipment totaled 502 pounds. The pressure applied on the platform area, by means of filling the bag with air, was measured in pounds per square foot with a manometer containing a fluid with a specific gravity of 2.9. Each additional unit (psf) of pressure resulted in 48-lbs additional load on the specimen.

Section properties (cross-sectional area, moment of inertia and section modulus) for each panel tested were determined. A transformed section using a modular ratio of 14.5 (polymer concrete modulus of elasticity = 2,000,000 psi) was used for those panels including steel reinforcing. The resulting properties were used to determine the modulus of elasticity and the flexural stress on the section at failure. Two of the panels tested failed, and the resulting flexural strengths were 1,223 psi and 948 psi. Two of the panels not taken to failure were loaded to stresses of 1,244 psi and 1,920 psi. Load-deflection curves were developed from the test data.

Figure 1 shows the load-deflection measurements on a 2-in.-thick panel tested using spans of 120 in., 144 in. and 168 in. Properties of this panel and test notes are shown as test numbers 1, 2 and 3 in Table 8. Load-deflection results for a 3 in. thick panel are shown in Figure 2. This panel and its tests are described in Table 8 under tests 4, 5 and 6. Tests were performed using spans of 144 in. 168 in. and 192 in. Failure occurred at an applied load of 34.4 psf with a 192 in. span. Figure 3 shows test results on a 3 in. thick panel that incorporated an internal longitudinal rib. Tests were performed at spans of 144 in., 168 in. and 192 in. Panel properties and test data are listed in Table 8 under tests 7, 8, and 9. The panel failed at an applied load of 28.1 psf with a span of 192 in. Each figure includes the calculated deflection under load using the section and material properties for the panel tested. Calculated deflections were conservative in all cases using the assumed modulus of elasticity of 2,000,000 psi.
Polymers in Concrete: The First Thirty Years

Table 8 also shows results of testing on the panels using some other configurations. Test 10 was a 4 in. thick panel tested to failure at a load of 43.6 psf using a 222 in. span. Test 11 was performed on a panel supported on its anchoring inserts and loaded to 40 psf. Tests 12, 13 and 14 were of a special 4 in. thick panel containing a large access opening. Test 15 was performed on a special 2 in. thick panel.

PANEL DESIGN EXAMPLE

Verify the suitability of a 3-in. thick insulated panel, 8-ft wide by 20-ft high for use when subjected to a 25-psf-wind load. Panel weight is 2400 lbs.

Choose anchors from Table 3.

For a 96x240-in. panel, nine anchors are required. Select three rows of three \( \frac{1}{2} \)-in. diameter bolts each.

Check tension per anchor from wind load.

Total wind load on the panel is 20x8x25 = 4,000 lbs.

then, the force per anchor is \( \frac{4,000}{9} = 444 \) lbs.

Anchor failure load, from Table 4, is 7,683 lbs each, so the anchors are adequate.

Check anchor shear loads from panel weight.

Shear per anchor = \( \frac{2400}{9} = 267 \) lbs each

Anchor shear capacity from Table 4 is 5,477 lbs, so anchors are adequate.

Calculate moments and bending stress in the panel.

For a uniformly loaded two-span beam, moments are \( 0.0703wL^2 \) and \( 0.125wL^2 \), or 1,400 ft-lbs and 2,500 ft-lbs, respectively.

From Table 8, the section modulus is 54 in\(^3\) and the maximum bending stress is 1,223 psi.

Calculating the flexural stress,

\[ M/S = 555 \text{ psi}, \]

shows the panel to be adequate.
Kaeding and Prusinski

Review expected deflections. From Figure 2, deflection will be about 0.5 in. with a 25-psf load.

Limiting deflection is $l/180$ or 0.67 in., so deflections are OK.

CONCLUSIONS

Unsaturated polyester PC architectural panels can be designed using rational design methods. Panel and material properties determined by testing provide basic information needed to perform structural analysis. Panels manufactured with the material properties summarized herein have been accepted for use by many building code jurisdictions (6). The success of design is verified by 40 years of satisfactory performance of PC panels in service.

REFERENCES

1. Prusinski, Richard C., and Bodea, Constantin, Polymer Concrete, A Historic Artifact?, ACI 2000 Fall Convention Session, Bridging the Centuries with Innovation and Value”, Toronto, Canada, October 2000.
## Polymers in Concrete: The First Thirty Years

Table 1 Minimum Fasteners for 3/4-in Facing Panels

<table>
<thead>
<tr>
<th>Panel Length, inches</th>
<th>Panel Width, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 36</td>
</tr>
<tr>
<td>Up to 36</td>
<td>4</td>
</tr>
<tr>
<td>36-60</td>
<td>6</td>
</tr>
<tr>
<td>60-72</td>
<td>6</td>
</tr>
<tr>
<td>72-96</td>
<td>8</td>
</tr>
<tr>
<td>96-132</td>
<td>10</td>
</tr>
<tr>
<td>132-168</td>
<td>12</td>
</tr>
</tbody>
</table>

(Maximum spacing 2'-6” o.c.)

Table 2 Minimum Fasteners for 2-in Insulated Panels

<table>
<thead>
<tr>
<th>Panel Length, inches</th>
<th>Panel Width, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 144</td>
</tr>
<tr>
<td>Up to 144</td>
<td>4</td>
</tr>
<tr>
<td>144-180</td>
<td>6</td>
</tr>
</tbody>
</table>

(10'-0” maximum vertical spacing)

Table 3 Minimum Fasteners for 3-in Insulated Panels

<table>
<thead>
<tr>
<th>Panel Length, inches</th>
<th>Panel Width, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 168</td>
</tr>
<tr>
<td>Up to 168</td>
<td>4</td>
</tr>
<tr>
<td>168-240</td>
<td>6</td>
</tr>
</tbody>
</table>

(12'-0” maximum vertical spacing)

Table 4 Anchor Holding Capacity

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor pull-out strength</td>
<td>1/2-13 UNC bolts</td>
<td>7683-lbs tension</td>
<td>Panel split at bolt</td>
</tr>
<tr>
<td>Anchor pull-out strength</td>
<td>3/4-20 UNC bolts</td>
<td>635-lbs tension</td>
<td>PC pulled off around bolt</td>
</tr>
<tr>
<td>Anchor shear strength</td>
<td>1/2-13 UNC bolts</td>
<td>5477-lbs shear</td>
<td>Insert sheared off</td>
</tr>
</tbody>
</table>

Table 5 Fire Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Flame Spread Test</td>
<td>ASTM E-84-59T, NFPA #225, UL 723 &amp; UBE #42-1</td>
<td>Results indicate passification as a Class A building material</td>
<td>With an application of heat ranging up to 500 degrees, no appreciable change was noted on the surface area. At higher temperatures, it was noted that the sample test did not support combustion</td>
</tr>
<tr>
<td>Tunnel Flame Spread Test</td>
<td>ASTM E84-59T</td>
<td>Flame Spread Rate = 3 Fuel Contribution Factor = 0 Smoke Density Factor = 55</td>
<td>Present a minor hazard with respect to flame spread and fuel contribution and a moderate hazard with respect to smoke emissions in relation to smoke emissions obtained from red oak flooring</td>
</tr>
</tbody>
</table>
Table 6 Durability Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (7)</td>
<td>ASTM C236-60</td>
<td>$U = 0.022 \text{ Btu/hour-sq ft-}^\circ\text{F}$</td>
<td>Panel cast into 2' aluminum channel frame made up with 1/4&quot; cement-asbestos board interior, 3/4&quot; polyurethane foam, 7/8&quot; aggregate facing</td>
</tr>
<tr>
<td>Accelerated Weathering (8)</td>
<td>ASTM E 42-57</td>
<td>No visual deterioration or discoloration</td>
<td>1 1/2&quot; in length, 1&quot; in width and 3/4&quot; in thickness, 50 hours exposure.</td>
</tr>
<tr>
<td>Barcol Hardness</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Chemical Resistance</td>
<td>NaOH solution (pH 8)</td>
<td>Slight loss of texture but no deterioration of the matrix.</td>
<td>72 hours at room temperature then boiled 10 hours.</td>
</tr>
<tr>
<td>Chemical Resistance</td>
<td>H$_2$SO$_4$ (pH 2)</td>
<td>There was a slight loss of texture on this sample but no deterioration of the basic matrix</td>
<td>Boiled 8 hours.</td>
</tr>
</tbody>
</table>
| Chemical Resistance             | 5% solution of NaOH | The matrix on this sample was disturbed quite a bit. Immediately after the boil test the bond was good and surface uniform. The material stood up exceptionally well | Boiled 24 hours.                                                          

Table 6 is continued on the next page
<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Resistance</td>
<td>10% HCL</td>
<td>Excellent results</td>
<td>Boiled 24 hours.</td>
</tr>
<tr>
<td></td>
<td>30% Alcohol</td>
<td></td>
<td>No visible effects</td>
</tr>
<tr>
<td></td>
<td>Epson Salts</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10% Acetic Acid</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glycerin</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10% Ammonia</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grease</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beer 3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen Peroxide</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boric Acid</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lipstick</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brine (NaCL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lemon Juice</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10% Caustic Soda</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lime Juice</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calcium Chloride</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Milk</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Citric Acid</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mustard</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crayon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10% Potassium</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydroxide</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soaps</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cod Liver Oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cream of Tartar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Detergents</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solax</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeze &amp; Thaw Test</td>
<td>50/50 cycles</td>
<td>The average loss was 0.544%</td>
<td>There was less than 1% splitting, cracking or other noted resin failures. There was less than 1% splitting or spalling of the stone.</td>
</tr>
</tbody>
</table>

Table 6 is continued on the next page
<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze in Air and Thaw in Water</td>
<td>ASTM C-291</td>
<td>Defects in each specimen present at 300 cycles of freeze-thaw. All specimens free of defects caused by repeated cycles of freeze-thaw</td>
<td>Due to the insulation material present within the panels, the final weights increased ranging from 388 to 663 grams as a result of an additional absorption of water in the freeze and thaw process.</td>
</tr>
<tr>
<td>Impact Resistance</td>
<td>30 in-lbs</td>
<td>No visible damage</td>
<td>30 in-lbs max. on tester.</td>
</tr>
<tr>
<td>Salt Spray Resistance</td>
<td>PC curtain wall sample slab, 2500 hours</td>
<td>No surface failure or delamination</td>
<td></td>
</tr>
<tr>
<td>Sand Blast Test</td>
<td>Sand blasting with #1 silica sand under 100 pounds pressure.</td>
<td>No appreciable change occurred in basic matrix.</td>
<td></td>
</tr>
<tr>
<td>Tabor Abrasion Resistance</td>
<td>1000 cycles</td>
<td>100 cycles - 0.020 grams, 1000 cycles - 0.212 grams</td>
<td></td>
</tr>
<tr>
<td>Thermal Deflection</td>
<td>4-in thick panel, 19.0 span</td>
<td>0.06 in deflection with a 100 deg temperature differential.</td>
<td></td>
</tr>
<tr>
<td>Washability Test</td>
<td>Gardiner Straight Line Washability Testing Machine</td>
<td>The surface showed no visible signs of change after being subjected to 5,000 cycles of the standard test</td>
<td></td>
</tr>
<tr>
<td>Weatherometer, mid Fadometer Test</td>
<td>Atlas Weatherometer for 2,000 hours.</td>
<td>No visible change was recorded in fading, physical appearance, or adhesive qualities.</td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>Results</td>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>------------------</td>
<td>-----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>2050-psi</td>
<td>Briquettes, 4-days, 2 layers fiberglass reinforcing</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>873-psi</td>
<td>Briquettes, 4-days</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>1690-psi</td>
<td>Briquettes, 6-days, 1 layer fiberglass reinforcing</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>1719-psi, 1.6% elongation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>2616-psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression Test</td>
<td>more than 10,000-psi</td>
<td>testing machine capacity was 300,000-lbs</td>
<td></td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>6,860-psi</td>
<td>4-days, 3-in dia cylinders</td>
<td></td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>6,719-psi</td>
<td>7-days, 3-in dia cylinders</td>
<td></td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>9,406-psi</td>
<td>28-days, 3-in dia cylinders</td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Linear Expansion</td>
<td>0.00001289 inches/degree F</td>
<td>No Reinforcing</td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Linear Expansion</td>
<td>0.00001264 inches/degree F</td>
<td>one layer fiberglass cloth</td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Linear Expansion</td>
<td>0.00001009 inches/degree F</td>
<td>2 #3 Rebars</td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Linear Expansion</td>
<td>0.00001243 inches/degree F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 8 Wind Load Resistance (9)

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen</th>
<th>Method Summary</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5’x14’x2” Panel</td>
<td>Simply supported 10-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 33.5-psf. Deflection of 0.67-in (l/180) was at a load of 23.6-psf. See Figure 1. ($f = 951$ psi)</td>
</tr>
<tr>
<td>2</td>
<td>5’x14’x2” Panel</td>
<td>Simply supported 12-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 79.7-psf. Deflection of 0.80-in (l/180) was at a load of 13.2-psf. See Figure 1. ($f = 1210$ psi)</td>
</tr>
<tr>
<td>3</td>
<td>5’x14’x2” Panel</td>
<td>Simply supported 14-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 34.6-psf. ($f = 1920$ psi) See Figure 1.</td>
</tr>
<tr>
<td>4</td>
<td>5’x18’x3” Panel</td>
<td>Simply supported 12-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 40.0-psf. Deflection of 0.80-in (l/180) was at a load of 31.0-psf. See Figure 2. ($f = 800$ psi)</td>
</tr>
<tr>
<td>5</td>
<td>5’x18’x3” Panel</td>
<td>Simply supported 14-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 45.7-psf. Deflection of 0.93-in (l/180) was at a load of 25.0-psf. See Figure 2. ($f = 1244$ psi)</td>
</tr>
<tr>
<td>6</td>
<td>5’x18’x3” Panel</td>
<td>Simply supported 16-ft span and pneumatically applied uniform load.</td>
<td>Panel failed at a load of 34.4-psf. Maximum moment was 1,100-ft-lbs. ($F_u = 1223$ psi)</td>
</tr>
<tr>
<td>7</td>
<td>5’x18’x3” Panel with rib</td>
<td>Simply supported 12-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 44.5-psf. Deflection of 0.80-in (l/180) was at a load of 33.2-psf. See Figure 3. ($f = 845$ psi)</td>
</tr>
</tbody>
</table>

Table 8 is continued on the next page
<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen</th>
<th>Method Summary</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5’x18’x3” Panel with rib A = 69.4 in², I_{xx} = 76.4 in⁴, S_{xx} = 56.9 in³</td>
<td>Simply supported 14-ft span and pneumatically applied uniform load.</td>
<td>The maximum load applied was 37.5-psf. Deflection of 0.93-in (f/180) was at a load of 22.8-psf. See Figure 3. (f = 969 psi)</td>
</tr>
<tr>
<td>9</td>
<td>5’x18’x3” Panel with rib A = 69.4 in², I_{xx} = 76.4 in⁴, S_{xx} = 56.9 in³</td>
<td>Simply supported 16-ft span and pneumatically applied uniform load.</td>
<td>Panel failed at a load of 28.1-psf. See Figure 3. (F₀ = 948 psi)</td>
</tr>
<tr>
<td>10</td>
<td>4’x19’6”x3” Panel A = 69.4 in², I_{xx} = 76.4 in⁴, S_{xx} = 56.9 in³</td>
<td>Simply supported 18’6” span and pneumatically applied uniform load.</td>
<td>Panel failed at a load of 43.6-psf</td>
</tr>
<tr>
<td>11</td>
<td>8’-2 5/8” x 11’ 0” x 2” Panel A = 101.4 in², I_{xx} = 76.7 in⁴, S_{xx} = 68.2 in³</td>
<td>Supported at 2 lines of 3 inserts each with a clear span of 5’10”</td>
<td>The maximum load applied was 40-psf. Deflection of 0.125-in was at a load of 20-psf. (f = 240 psi)</td>
</tr>
<tr>
<td>12</td>
<td>4’ x 8’ x 7/8” containing a 2’ 8” x 4’-0” access panel</td>
<td>The maximum load applied was 20-psf. Deflection of 0.318-in was at a load of 20-psf.</td>
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<tr>
<td>13</td>
<td>4’-1 3/4” x 8’ x 7/8” containing a 2’8” x 4’ access panel</td>
<td>The maximum load applied was 20-psf. Deflection of 0.159-in was at a load of 20-psf.</td>
<td></td>
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<tr>
<td>14</td>
<td>4’-11 3/8” x 12’-3 ½”x0’-3”</td>
<td>Simply supported 11.44-ft span and pneumatically applied uniform load.</td>
<td>Panel failed at a load of 180-psf Deflection of 0.5-in was at a load of 89-psf.</td>
</tr>
<tr>
<td>15</td>
<td>5’x14’x2” Panel</td>
<td>Simply supported 10-ft span and pneumatically applied uniform load.</td>
<td>Panel failed at a load of 79-psf. Deflection of 0.6-in was at a load of 30-psf.</td>
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<tr>
<td>1</td>
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<td><img src="image1.jpg" alt="Diagram" /></td>
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<tr>
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<td>Tongue and Groove Joint</td>
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<td>Shadow Joint</td>
<td><img src="image3.jpg" alt="Diagram" /></td>
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<td>4</td>
<td>Butt-Batten and Rabbeted Joints</td>
<td><img src="image4.jpg" alt="Diagram" /></td>
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<td>5</td>
<td>Direct Point Insert</td>
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<tr>
<td>6</td>
<td>Butt Joint Caulking</td>
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<td>Attached Directly to Studs</td>
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<td>11</td>
<td>Anchorage to Masonry</td>
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<tr>
<td>14</td>
<td>Applied over Sheathing</td>
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<td>16</td>
<td>Weld Plate Direct</td>
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Figure 1 Wind load test on 2-in. panels

Figure 2 Wind load test on 3-in. panels
Figure 3 Wind load tests on 3-in. panels with internal ribs
Self-Repair Epoxy Modified Mortar for Rehabilitation and Strengthening Applications Using FRP

by M. M. Reda Taha

Synopsis: Strengthening and rehabilitation of reinforced concrete structures using externally bonded Fibre Reinforced Polymers (FRP) strips has become a well-established technique with a large research database. Epoxy-modified mortar (EMM) has been used in the industry for more than three decades for various strengthening and rehabilitation purposes.

Epoxy modified mortar without a hardener has recently been investigated. The new EMM without a hardener includes polymer/cement ratios as low as 20 percent compared to the 40-60 percent that is usually required to provide suitable mechanical properties of conventional EMM. The new EMM utilizes the cement hydrates to polymerize the epoxy resin in the cement matrix in the absence of a hardener through ring-opening polymerization. The use of ring-opening polymerization provides EMM (without a hardener) with an interesting ability to grow through any developed crack and to repair itself, thus showing enhanced fracture toughness with age. The new self-repair epoxy mortar (SREM) has shown better mechanical performance than the conventional EMM with the same polymer/cement ratio.

The objective of this work is to discuss the potential use of SREM to bond FRP laminates to existing concrete substrates in rehabilitation and strengthening applications. A multi-phase research programme examining the different strength, fracture and durability criteria of the SREM-FRP composite is proposed here. Fracture mechanics principles in conjunction with microstructural investigations will explain and maximize the material ability to self-repair.

Keywords: concrete repair; epoxy-modified polymers; epoxy mortar; externally bonded fiber reinforced polymers; fiber reinforced polymer (FRP); rehabilitation; self-repair; self-repair epoxy mortar; strengthening
170 Reda Taha

Mahmoud M. Reda Taha, Ph.D., P. Eng. is a structural engineer at Stantec Consulting Ltd, Calgary, Canada. He is member of ACI Committee 440 (Fibre Reinforced Polymers-FRP) and 548 (Polymers in Concrete). His research interests include reinforced and prestressed concrete structures, applications of artificial intelligence in structural engineering, fracture mechanics and the use of FRP in structures.

INTRODUCTION

Strengthening and rehabilitation of reinforced concrete structures using externally bonded FRP strips have been widely accepted with well-established technical and design guidelines (1, 2, 3 and 4). While FRP used to be cost-effective only when concrete was subjected to aggressive corrosion environments, FRP has recently proven to be cost-effective in many other conditions as well. This is attributed to the decrease in the unit price of FRP material, the significant decrease in labour cost due to the ease of handling (weight), and the fast application of FRP strips compared to steel plates resulting in fewer potential disruptions of traffic or work place activity. With increased knowledge and experience externally bonded FRP has become a competitive strengthening alternative. This is reflected in the growing demand of FRP for strengthening applications. Figure 1 shows a typical concrete slab of an office building strengthened by Carbon Fibre Reinforced Polymers (CFRP) strips to allow increased slab loading and retail changes.

CHARACTERISTICS OF FRP STRENGTHENING SYSTEM

Applying the principles of stress equilibrium and strain compatibility, strains and stresses in the FRP strip can only be determined by assuming that the FRP strip is strongly adhered (bonded) to the concrete substrate (5). Epoxy resins are usually used to bond FRP to the concrete substrate. While the bond is basically achieved through electron interchange and absorption/diffusion mechanisms between the epoxy material and the concrete surface, the mechanical interlock due to rough and irregular concrete surface significantly contributes in developing this bond strength. Recent research work showed that good mechanical interlock between two concrete layers enhances the interface bond strength by 50% with no adhesives or shear reinforcement added (6).

Failure of the Concrete-adhesive-FRP composite can occur through four major different patterns as shown in Figure 2. While, failure in the concrete substrate is the most common failure mode, cohesive failure within the adhesive or bond failure in the epoxy-FRP have seldom been reported (7, 8 and 9). Failure in the
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bond between the epoxy and the concrete substrate has only been reported when poor epoxy resin was used (10).

Practically, crack initiation occurs at the weakest point of the composite and then the crack propagates in a mixed mode combining two or more modes of failure. Therefore, injection of the substrate cracks is essential to eliminate crack initiation points within the substrate. Figure 3 shows transverse shrinkage cracks in a spandrel concrete beam injected with epoxy filler prior to the application of adhesive and the FRP strips for strengthening.

In the mean time, experimental work by Riad (11) for rehabilitation of bridge girders using CFRP strips showed no difference in load carrying capacity of the rehabilitated girders when conventional epoxy mix was used to bond the FRP to the girders. This is because the composite capacity in these experiments was always governed by the strength of the concrete substrate. With the weak substrates, cracking was observed to initiate from a point of high stress in the substrate and then propagate through the substrate parallel to the FRP interface.

Applying a simplified truss model, shown in Figure 4, it was shown that failure of the substrate is enforced due to the missing vertical ties necessary to transfer the load to the FRP strips. However, crack propagation will be dependent on the properties of the adhesive layer in the vicinity of the substrate.

Analyzing a large number of experimental observations Meier (10) pointed out that optimizing the adhesive layer strength and stiffness is necessary to create a ductile strengthening system. This is because if the adhesive layer is overly strong and/or overly stiff, vertical cracks in the substrate will not be able to propagate in the adhesive layer. This will induce a stress concentration in the FRP strip at this location and may result in premature brittle failure of the FRP or brittle failure by FRP peeling off due to crack propagation in the substrate. Figure 5 shows the effect of the adhesive layer strength/stiffness on the performance of the FRP composite. Using an optimized strength and stiffness bond layer “weaker than the conventional FRP adhesive but stronger than the substrate” would allow vertical substrate cracks to propagate in the adhesive layer. These cracks will be stopped by the FRP. If such cracks can be closed with time, the performance of the FRP composite will be rather strong and ductile.

RESEARCH SIGNIFICANCE

This paper describes the potential use of the innovative self-repair epoxy mortar (SREM) as the adhesive layer for FRP materials in strengthening and rehabilitation of existing concrete structures. The development of a self-repair FRP strengthening/rehabilitation system should eliminate problems associated
with inadequate load transfer due to possible substrate cracking and will provide a significant increase in the service life of the FRP strengthening system.

SREM AS AN ALTERNATIVE TO BOND FRP

The required strength and stiffness of the adhesive layer could be achieved by using epoxy-modified mortar (EMM) as the adhesive material. This would allow optimization of the strength and stiffness of the adhesive layer without detracting from its bond strength. However, permanent cracking of the EMM layer would affect the durability performance of the FRP composite. Therefore, it is proposed to use epoxy-modified mortar without a hardener as the adhesive layer due to its self-repair performance (12). The use of self-repair epoxy mortar (SREM) would be an excellent alternative providing the targeted ductility of the FRP composite, while conserving the structural integrity of the strengthening system.

SREM is an epoxy modified mortar (without a hardener) with polymer/cement ratios as low as 20 percent that utilizes the cement hydrates, in the absence of a hardener, to polymerize the epoxy resin through ring-opening polymerization in the cement matrix. If a crack propagates in the SREM adhesive layer, the encapsulated non-hardened epoxy will be exposed to CH crystals in the crack vicinity. The hydroxyl ion will harden the Epoxide by ring-opening polymerization forming a straight-chain polymer that will self-repair the crack. Microstructural investigations by Ohama et al. (13) proved the ability of the cement hydrates to polymerize the epoxy resin in the absence of a hardener. Figure 6 shows a proposed schematic diagram explaining the mechanism of SREM when used to bond FRP composites.

Recent research by Ohama and Demura (12) showed SREM to have acceptable mechanical and durability performance. The adhesion “shear” strength for FRP-Epoxy-Concrete composite is usually governed by the tensile strength of the existing concrete substrates. 2.0 MPa pull-off strength is a widely accepted criterion for adhesion between the adhesive and the concrete substrate provided that failure takes place within the concrete substrate. The reported adhesion strength of SREM with concrete exceeds the 2.0 MPa limit. In addition to the acceptable mechanical performance, SREM is expected to have enhanced fracture toughness and durability compared to conventional adhesive materials. In the mean time, the considerably low epoxy content of SREM will reduce the creep deformation of the FRP composite significantly. Therefore, a multi-phase analytical and experimental programme examining the different strength, fracture and durability criteria of SREM when used to bond FRP is proposed.
The research programme examining the possible utilization of SREM for rehabilitation and strengthening applications using FRP incorporates both analytical and experimental investigations. The analytical investigation using finite element analysis examines the effect of changing the modulus of elasticity of SREM on its bond performance with concrete substrate. This is directly related to the polymer content of SREM. The experimental programme includes the following:

- Examining the mechanical performance of SREM including compressive, tensile, flexural and adhesion strength of SREM with both concrete substrates and FRP strips.

- Examining the creep performance of SREM in comparison to conventional epoxy adhesives under tensile stresses.

- Examining the fracture toughness and the rate of growth of fracture resistance with time for SREM.

- Examining the adhesion-durability of the FRP-SREM-concrete composite.

Further details about fracture toughness and the adhesion-durability testing follow.

**Fracture mechanics testing**

The fracture mechanics of the SREM-FRP composite will be examined in two phases. The first phase will examine the fracture toughness of the SREM materials itself under flexural stresses and the rate of fracture resistance growth of SREM with time. Principles of quasi-brittle fracture mechanics will be applied to SREM to analyze its fracture performance under pure flexural stresses (14 and 15).

The effect of polymer content on SREM fracture criteria will be also investigated. Microstructural investigation using SEM micrographs will show the ability of the new polymerized epoxy to bridge the cracks and repair the FRP composite. In the second phase the fracture performance of the SEM-FRP composite will be examined using the peel test. The ability of the peel test to provide mixed mode loading will allow evaluation of the major fracture energy parameters of the FRP-SREM interface in both mode I and II fracture.
Due to the importance of combining the stress and environmental conditions while testing FRP composites (16), the SREM will be tested after being exposed to freeze-thaw cycles, chloride ion solutions (as a result of using deicing salts in wintertime), moisture and thermal exposure and ultra violet radiation. The new composite should not show degradation of adhesion strength after being exposed to these environmental conditions for a suitable time period. Due to the absence of standard tests for the adhesion durability new tests are proposed.

The durability-adhesion tests will be performed in three phases: the first phase includes testing the effect of environmental exposure on the pull-off strength of SREM-concrete combination. The examined samples will be compared to non-exposed samples to identify the damaging effect of the environmental conditions. The second phase will examine the effect of environmental exposure on the direct shear strength of the samples shown in Figure 7. The samples will be prepared so that the FRP-SREM-Concrete portion will be the only region subjected to the surrounding environment. The rest of the sample will be protected using Styrofoam, sealant compounds, etc. This will ensure that if strength degradation due to environmental exposures takes place, the interface will govern the strength of the composite when tested.

The third phase will examine the effect of environmental exposure on the bending shear “adhesion” strength. Small-scale beams strengthened using the SREM-FRP composite and designed to fail in shear “adhesion” will be tested. The beams will be tested before and after being environmentally exposed. Testing preparations similar to that proposed in the second phase will be considered to ensure the SREM-Concrete will be the only region exposed to the different environmental conditions.

CONCLUSIONS

* An optimized strength and stiffness of the adhesive layer between FRP strips and concrete substrate is necessary for proper performance of the FRP composite. This is because an overly strong and/or overly stiff adhesive layer can result in stress concentration in the FRP strip at substrate crack locations, which may result in premature tensile or peeling failure of the FRP.

* SREM has shown acceptable mechanical and durability performance in addition to its proven self-repair criterion. Therefore, it is proposed to use SREM as an alternative to bond FRP strips to concrete substrates. The new adhesive layer is expected to provide the targeted ductility of the FRP composite, while conserving the structural integrity of the strengthening system.
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A multi-phase research programme to examine the utilization of SREM to bond FRP laminates to concrete substrates is discussed. Further details will be published soon.

ACKNOWLEDGEMENTS

The work described here is a part of a research programme developed in cooperation with Dr. Nigel Shrive at the University of Calgary whose efforts are greatly acknowledged. The author wishes to extend his thanks to Dr. S. Lissel for reviewing this manuscript.

REFERENCES


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Figure 1: Structural slab strengthened by CFRP strips [Courtesy M. Reda Taha 2000]

Figure 2: Failure modes of FRP-Epoxy-concrete [Karbahari et al. 1997]
Figure 3: Beam cracks injected with epoxy fillers before applying FRP
[Courtesy of M. Reda Taha 2000]

Figure 4: Simplified truss model FRP strengthened system [Riad et al. 1998]
Figure 5: Effect of bond layer strength and stiffness on FRP stress distribution [Meier 1995]
[a] Strong and stiff bond layer results in high stress concentration of FRP
[b] Optimized bond layer results relieves potential stress concentration of FRP

Figure 6: Proposed mechanism of SREM when used to bond FRP composites
Figure 7: Examining the effect of different environmental exposure factors on the adhesion strength of FRP-SREM composite
Long-Term Durability of Sulphur Concrete in Harsh Chemical Environments

by G. J. Fallis

Synopsis: In recent years, sulphur concrete has proven to be capable of withstanding attack by some of the most aggressive chemicals used in industry. This fast setting, acid and salt resistant concrete is well suited for use in the mineral processing and fertilizer production industries. This paper briefly describes the properties, production, application and performance of this new construction material, with references to actual commercial installations and reviews the long term durability of these projects in harsh chemical environments.

Keywords: chemical resistance; concrete repair; corrosion-proof; restoration; sulphur concrete
182 Fallis
Garth Fallis, P.Eng. - Vice-President Construction Technologies, Vector Construction Group - Garth has been with Vector Construction Group for over 20 years specializing in concrete restoration and projects throughout Canada, the United States, and other areas in the world.

INTRODUCTION

Sulphur concretes have been the subject of laboratory investigation for more than 100 years. Experimenters were fascinated by the high strength, corrosion resistance, impermeability and fast setting that were characteristic of the laboratory products so readily obtainable by mixing heated aggregates with molten sulphur and allowing the mixture to cool. They were disappointed, however, when these products showed very poor durability when exposed to changing temperatures. It was only in the 1930's that further study showed it was necessary to modify the crystallization of the sulphur to avoid deterioration. Duecker (1) was the first to report, in 1934, that sulphur could be chemically modified to overcome these problems with durability.

In spite of this discovery, there was no immediate development of a commercial sulphur concrete because of the high cost of Duecker's process and the offensive odour it imparted to the product. Dale and Ludwig (2) worked with other sulphur plasticizers or modifiers including dipentene and dicyclopentadiene in the 1960's but these also were not fully satisfactory.

THE DEVELOPMENT OF SULPHUR CONCRETE

In 1972, the senior author, in cooperation with the National Research Council of Canada and McGill University, commenced a research program aimed at developing a method of modifying sulphur to overcome the problems experienced by other researchers. By December 1975, the first sulphur concrete manufacturing plant began production of precast products.

Most other attempts to develop sulphur concretes have been aimed at trying to keep the sulphur in an amorphous (non-crystalline) state. Chemical additives and reactions have been selected accordingly.

The Sulphur concrete process for making sulphur concrete uses a highly stable concentrate of polymeric sulphur known as Sulphur concrete modifier polymer to modify and stabilize additional elemental sulphur. The additional sulphur is not polymerised or held in an amorphous state by the Sulphur concrete modifier polymer. It is allowed to crystallize to the only physical form that is stable below
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90°C, orthorhombic sulphur. The Sulphur concrete modifier polymer does, however, prevent the growth of macro sulphur crystals. When one part of Sulphur concrete modifier polymer is dissolved in ten parts by weight of liquid sulphur and the solution is allowed to cool, the sulphur crystals are generally smaller than 1 micron.

The significance of this is that sulphur has a relatively high thermal expansion coefficient (64.13×10⁻⁶/°C at 40°C) and a low thermal conductivity (0.184g-cal/cm²/sec @ 1°C/cm). When a material containing adjacent macro crystals of sulphur is subjected to changing temperatures, there will be a constant movement between these macro crystals as one expands or contracts against the other. This movement will gradually break bonds with other cross-laid crystals, causing a severe weakening of the structure and an eventual formation of cleavage planes.

Failures have been observed in sulphur concretes in which the sulphur is supposedly being held in an amorphous state. It is suggested that this is due to a growth of macro sulphur crystals as the amorphic sulphur gradually reverts to the more stable orthorhombic form.

An independent scanning electron micrographic study published by ASTM (5) has revealed graphically how Sulphur concrete modifier modifies the physical form of sulphur to impart strength and durability. This study also shows that Sulphur concrete modifier will satisfactorily modify 10 times its weight of sulphur.

Since 1976 approximately 40 companies in Canada, the United States, Europe, and South Africa have used over 35,000 tonnes of sulphur concrete.

PROPERTIES OF SULPHUR CONCRETE

Table 1 compares the properties of Sulphur concrete made with limestone aggregate and portland cement concrete made with the same aggregate. It will be noted that Sulphur concrete possesses higher mechanical strength, somewhat higher modulus of elasticity, and higher abrasion resistance.

The most outstanding physical property of Sulphur concrete is its extreme corrosion resistance. It is completely unaffected by most salts, acids, and mild alkalis. When made with acid resistant aggregates such as granite and other siliceous materials, it is unaffected by continuous exposure to 37% hydrochloric acid and to sulphuric acid up to 93% concentration. It has good resistance to ammonium nitrate, ammonium sulphate, nickel sulphate, potash, sodium sulphate, zinc chloride and may other salts.

Another characteristic of importance for many applications is its impermeability. Sulphur concrete repels water penetration because both sulphur and the Sulphur
concrete modifier polymer additive are hydrophobic, the particles of aggregates are coated with these substances and the normal voids between particles are filled with them. Water absorption after 24 hours of immersion in water at 20°C is generally 0.1 to 0.3 percent by weight.

Sulphur concretes also exhibit extreme fatigue resistance. Lee and Klaiber have shown (6,7) that sulphur concrete exhibits fatigue properties drastically different from those of conventional portland cement concrete. Beams were subjected to one and two million repetitive loadings at 90-95% of their modulus of rupture without failure. There appeared to be an endurance limit at 85-90% modulus of rupture compared to 50-55% for conventional concrete.

While sulphur concrete does not support combustion, sulphur present in the surface will slowly burn when exposed to direct flame but it self-extinguishes when the flame is removed. Flame spread tunnel tests conducted in accordance with Underwriters Laboratories of Canada test S-102.2-1977 show zero flame spread, zero fuel contribution and very low smoke density. This fire resistance is primarily due to the presence of the Sulphur concrete modifier polymer additive that forms a protective surface char when exposed to direct flame. This char, together with the low thermal conductivity of sulphur, results in slow penetration of heat. Prolonged exposure to fire will cause structural damage if the internal temperature rises above the melting point of sulphur, i.e., 119°C (246°F).

The sulphur / Sulphur concrete modifier cement that bonds the aggregates in Sulphur concrete has thermoplastic properties. Sulphur concrete can be crushed, remelted and reformed without loss of strength or other properties. In other words, it can be completely recycled.

The setting or hardening of Sulphur concrete takes place simply on cooling to about 110°C (230°F). No chemical reaction occurs. For these reasons, the hot mix may be poured at either very high or very low ambient temperatures. In cold weather conditions Sulphur concrete can be poured without heating and hoarding.

**RAW MATERIALS FOR SULPHUR CONCRETE**

1. **Sulphur:** The form and purity of the sulphur is quite unimportant, providing that the impurities do not represent more than about 4% clay or other water-expansive material.

2. **Aggregates:** These may be of many types including gravel, crushed rock, natural or manufactured sand, slag, volcanic ash and lava, and most mining wastes. While small amounts of salt, organic matter or other impurities may be tolerated; the aggregates should be essentially free (<1%) of unfired clay or other swelling materials such as shale, lignite and cellulose fibre. If the sulphur concrete is to be
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exposed to mineral acids, granitic or siliceous aggregates should be used.

3. Mineral Fillers: As with asphaltic concrete, fine mineral fillers are generally required in sulphur concrete mixes. For this purpose, one may use fly ash, dust from the crushing of quarry rock, or other finely divided, insoluble, inorganic material that does not contain clay or other water-expansive substance. The preferred particle size is minus 100 microns. If manufactured sand, made by crushing clean quarry rock or gravel, is used, mineral filler may not be required because of the high percentage of fine dust in such sand.

4. Sulphur concrete modifier Polymer: This proprietary additive is currently manufactured and supplied from Alberta, Canada.

MANUFACTURING EQUIPMENT AND METHODS

Sulphur concrete is normally manufactured in a modified asphalt batch plant. Many different makes and sizes of these plants have been used successfully in recent years.

The process involves first drying and heating the aggregates to a temperature higher than the melting point of sulphur. The hot aggregates, sulphur (either liquid or solid), Sulphur concrete modifier polymer and mineral filler are then combined in the pug mill or other heated mixer.

The mix design is of critical importance and is determined by the aggregate and application requirements. A typical mix design using a graded minus 20 mm coarse aggregate would be:

<table>
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<tr>
<th>Ingredient</th>
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<td>Coarse aggregate</td>
<td>44</td>
</tr>
<tr>
<td>Sand</td>
<td>37</td>
</tr>
<tr>
<td>Mineral filler</td>
<td>5.8</td>
</tr>
<tr>
<td>Sulphur</td>
<td>12</td>
</tr>
<tr>
<td>Sulphur concrete modifier polymer</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
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</table>

The slump or workability of the mix may be adjusted by adding slightly more or less sulphur and sulphur concrete modifier polymer, keeping the sulphur / sulphur concrete modifier ratio less than 10 to 1 by weight.

The hot mix may be transported in ready-mix concrete trucks equipped with heaters and insulation or in oil-jacketed mixer-transporters. The working temperature range of the mix is 125-150\(^\circ\)C (250-300\(^\circ\)F). The mix may be held at this temperature for many hours without deterioration.
PLACEMENT AND FINISHING

The mix may be poured into forms with or without steel reinforcement. Forms may be constructed of wood (lightly oiled), steel, aluminium or other composite materials.

Standard concrete vibration is used to consolidate the mix in the forms. Hand trowels and bull floats may be used for finishing, in addition to heated vibrating screeds.

There are no toxic emissions from the mixing, handling or placement of Sulphur concrete when proper techniques are employed.

A useful guide for mixing and placing sulphur concrete has been published by the American Concrete Institute (8).

REINFORCEMENT

Where reinforcement is required, conventional steel rebar or wire mesh is generally used. Due to the very low water absorption of Sulphur concrete, corrosion of embedded steel has been negligible unless the product becomes cracked so as to permit water to penetrate to the steel. In highly corrosive areas the rebar may be coated with a high temperature and chemically resistant coating as an extra precaution.

Fibrous reinforcement, such as chopped glass fibre, also may be incorporated in the mix to increase tensile strength, flexural strength and impact resistance. It is, of course, unnecessary to use the alkali-resistant glass fibre commonly used in portland cement concrete.

Conventional prestressing and post-tensioning techniques are also usable.

EXAMPLES OF EXISTING APPLICATIONS IN MINERAL PROCESSING AND CHEMICAL MANUFACTURING PLANTS

Sulphur concrete has been used in these applications primarily for corrosion-proof floors, grade beams, foundations, tanks, sumps, pump bases and containment areas. Bechtel Engineers, Brown & Root, Cominco Engineering Services Ltd., and Fluor
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Daniel along with other consulting engineers, have been specifying sulphur concrete for use in such corrosive environments for years.

Chemical Plants

One of the first commercial applications in Canada in a fertilizer plant was the use of Sulphur concrete to replace a section of concrete floor, a pump base, and gutters in the basement of an ammonium sulphate plant in Warfield (near Trail), British Columbia, in 1978.

This area was suffering from serious concrete corrosion resulting from continuous drips of hot, saturated ammonium sulphate solution. The corrosive drip has continued but the Sulphur concrete has shown no evidence of corrosive attack in over 20 years.

As a vote of confidence in the performance of the original Sulphur concrete, the owner specified Sulphur concrete for a modernization and expansion project in this plant in 1991. The scope of this project included an expansion to the plant, plus the replacement of all floors, pump and tank bases, and trenches inside the existing plant that were not previously constructed using sulphur concrete. This area also shows no signs of deterioration in 10 years.

Metal Refineries

In 1980, a 930 m² (10,000 ft²) floor and drainage canal were installed with Sulphur concrete for a new Solvent Extraction Electro-Winning (SX-EW) copper refinery cell house near Miami, Arizona. This area has been subjected to a continuous spray of 15-17% sulphuric acid since that time with no corrosive damage.

In 1983, Sulphur concrete was again selected for a 1,675 m² (18,000 ft²) floor and drainage canal for an SX-EW plant in Tyrone, New Mexico. Again there has been no chemical attack due to acid.

In early 1991, Fluor Daniel specified Sulphur concrete for a SX-EW Copper Refinery in Morenci, Arizona. Sulphur concrete was chosen for this project after another acid resistant concrete had failed. Again, all exposed concrete in the acid portion of the plant was poured using Sulphur concrete.

Secondary Containment

In 1986, Sulphur concrete was used as a corrosion-proof secondary containment lining for a concrete catch basin under a sulphuric acid plant in a Calgary fertilizer manufacturing complex. This project involved placing 10 cm. (4 in.) lining on the floor, walls, piers, pile caps, trench and sump for the containment and recycling of
93% sulphuric acid. Due to mechanical problems in the start up of the plant, the basin was flooded with this acid for some time, but it showed no ill effect.

In 1990, during a plant upgrading, Simplot Chemicals in Brandon, Manitoba added containment around two sets of Urea Ammonium Nitrate Solutions pumps. These were constructed of Sulphur concrete, while the existing concrete bases we left in place. Since that time the concrete bases have been replaced (using portland cement concrete) and have continued to deteriorate, while the Sulphur concrete remains intact.

In November 1992, Sulphur concrete was used to construct a secondary containment basin for two nitric acid storage tanks for a gold mine in Marathon, Ontario. In addition to chemical resistance, two of the benefits of using Sulphur concrete for this application were:

a) the ability to pour in below freezing conditions without the need for heating and hoarding, and
b) the reduced construction schedule since a Sulphur concrete project is complete almost immediately after pouring. If the containment basin would have been poured using Portland Cement Concrete, it would have been necessary to cure the concrete for 28 days prior to the installation of a liner or acid brick, and then the liner or acid brick would have to be installed before the area could be put into service.

This containment area was inspected as late as this year (2001) and shows no signs of acid attack.

Rehabilitation of Corroded Concrete Structures

A Canadian sulphuric acid manufacturing plant built in 1975 had experienced a number of acid spills that resulted in acid permeating the soil. By 1980, the concrete foundations were found to be so badly corroded that structural failure was predicted within 18 months.

To save the structure from collapse, soil was removed from around all foundations and the corroded concrete was removed. New forms were installed to permit pouring Sulphur concrete around the existing prepared foundations. The Sulphur concrete served to reinforce the foundations and prevent further acid attack.

Precast Applications

In addition to these cast-in-place applications, Sulphur concrete has been used to manufacture precast beams and other shapes to replace other construction materials
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such as coated steel and fibreglass where these materials have failed.

A set of precast Sulphur concrete Pump Support Beams we installed over a sulphuric acid tank at Cominco in Trail, BC in 1990 replacing the pervious fibreglass beams. These beams continue to be unaffected by the chemicals and structurally sound today (2001).

SOME ADDITIONAL SULPHUR CONCRETE APPLICATIONS

Pipeline Weights

Sulphur concrete has been used in many other applications where the performance of Portland Cement Concrete has not been acceptable. As an example, the Foothills Pipeline chose Sulphur concrete for 6400 tonnes of weights used in the construction of its 107 cm (42 in.) natural gas pipeline that crossed Alberta and part of southeastern Saskatchewan in 1981. Many thousands Sulphur concrete pipeline weights were used to provide negative buoyancy for river and swamp crossings. The main concern here was the uncertain performance of sulphate resistant portland cement concrete when exposed to the high levels of sulphates and organic acids present in the soil and swamps of this area.

Insulator Blocks

A further example would be the hundreds of insulator blocks that have been made to provide electrical isolation between components in acidic metal refineries.

Hazardous Waste Containment & Disposal Systems

Considerable interest is currently being shown by both Canadian and United States' authorities in using Sulphur concrete for hazardous waste handling systems and for encapsulation of hazardous and low level radioactive waste. Sulphur concrete is suitable for these applications due to its extreme corrosion resistance, and its impermeability.

Sewer Pipe

Sulphur concrete appears to have great potential for the manufacture of sewer and industrial pipe, manholes and other appurtenances due to its resistance to corrosion by hydrogen sulphide and sulphuric acid, its impermeability and high strength.
ECONOMIC CONSIDERATIONS

Compared with portland cement concrete, sulphur concrete is generally more expensive. The price difference in part is due to the cost to mobilize and set up the required equipment and the relatively small volumes of Sulphur concrete required on a given project. Naturally, the larger the job the lower the cost is likely to be. Form work and placement of sulphur concrete generally cost about the same as that for portland cement concrete.

However, in making a cost / benefit comparison of Sulphur concrete versus portland cement concrete, one must consider the total cost of the completed project, including coatings, linings, or acid brick which may be required to protect the portland cement concrete. In most heavy industrial applications, the cost to install Sulphur concrete is less than the total cost to install and protect portland cement concrete for the same application. Also, since Sulphur concrete is chemical resistant throughout, a sulphur concrete installation will be far more durable and less subject to attack or damage in the long term.

CONCLUSIONS

1. Sulphur concrete is an acid and chemical resistant concrete for use in aggressive chemical environments where portland cement concrete and other building materials typically fail and have proven to last in harsh chemical environments for over 20 years.

2. The use of Sulphur concrete modifier polymer provides a simple and effective method of modifying sulphur for sulphur concrete manufacture.

3. The sulphur concrete made with Sulphur concrete modifier polymer and known as Sulphur concrete has performed well in many aggressive environments for over 20 years.

4. Sulphur concrete is a more durable, cost effective alternative to portland cement concrete protected with acid brick or chemical resistant linings.

5. Field experience with sulphur concrete is increasing rapidly and increased attention must now be given to developing standards and specifications for its use.
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REFERENCES


<table>
<thead>
<tr>
<th>TABLE I TYPICAL PHYSICAL TEST RESULTS OF SULPHUR CONCRETE</th>
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<tr>
<td>Test Description</td>
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<tr>
<td>Compressive Strength</td>
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<td>Tensile Strength</td>
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<td>Modulus Of Rupture</td>
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<td>Modulus Of Elasticity</td>
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</table>

Note: This table gives test results as compared to typical portland cement concrete using 3/4" (19mm) washed gravel with approximately 60% fractured face. It should be noted that the relationship of compressive strength to modulus of elasticity could, if desired, be varied with special additives.
Testing a Polymer Concrete Coating for Dry and Wet Concrete and Clay Brick Wastewater Facilities

by J. Liu and C. Vipulanandan

**Synopsis:** Deteriorating sewer facilities require rapid in-situ rehabilitation and using coating as a corrosion protection is one method currently being adopted. Hence, applicability and performance of coatings under dry and wet conditions must be investigated. Performance of a polymer concrete coating was evaluated using a combination of full scale and laboratory tests. The polyester based polymer concrete coating had a density of 1.75 g/cm$^3$ (109 lb/ft$^3$) and a hardness in the range of 38 to 45 (Barcol hardness). Full-scale test on coating applicability and performance on concrete substrate was performed under a hydrostatic pressure of over 103 kPa (15 psi) of water, simulating the groundwater condition. Coated concrete cylinders and clay bricks with holidays (pinholes) were used to study the chemical resistance under acidic environments to represent the worst sewer and accelerated test conditions (ASTM G 20). Bonding strength between the coating and the concrete and clay brick substrates were determined using the modified ASTM D 4541 and ASTM C 321 tests. Performance of the polymer concrete coating material was studied for over 3 years and the results are analyzed to determine the performance of the polymer concrete coating.

**Keywords:** bonding test; chemical test; coating; hydrostatic test; modeling; polymer concrete
Cement concrete and clay bricks have been widely used in the construction of wastewater facilities such as wet wells, holding tanks, manholes and sewer pipelines. Many municipalities are discovering that cement concrete and other structures in the wastewater collection and treatment facilities are subjected to microbial induced deterioration and the concrete are degrading rapidly (1-2). Concrete surfaces are more difficult to prepare and protect than metal surfaces. There are several methods in practice to control the degradation of concrete in wastewater facilities (3). The primary goal of in-situ rehabilitation is to return these facilities to its original working conditions. Coating is one method currently being adopted but the effectiveness of this method for rehabilitating concrete lift stations and sewer treatment facilities is still in question.

Sewer facilities are generally wet and experience hydrostatic pressure under normal service conditions. Application of coating materials on to concrete surfaces is considered a challenge and must be evaluated (4). The surface moisture will depend on the porosity of the concrete and hydrostatic pressure due to the groundwater table. Coatings can debond and blister if the hydrostatic pressure exceeds the tensile adhesion of the coating material. Bonding between the concrete surface and the coating material is another important factor that
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must be evaluated to determine the performance of the coating. Chemical resistance of coated concrete to acidic corrosive environment is also very important. Several coating materials were studied by the Los Angeles County and the results showed that only a low percentage of coatings performed well under their testing conditions (5-7). Hence, to select good coating materials for protecting the wastewater structures and collection facilities, a series of tests must be developed to evaluate the performance of coating in a reasonable period of time.

Since several factors in the field can affect the performance of a coating it is important to identify the factors through controlled experiments where important variables are studied one at a time. In this study, a testing program has been developed for evaluating coating materials for rehabilitating and protecting concrete surfaces.

OBJECTIVES

The objective of this study was to evaluate the performance of a polymer concrete coating (polyester based) for use on dry and wet concrete and clay brick. Specific objectives are as follows: (a) to evaluate the applicability and performance of the coating on a concrete surface under hydrostatic pressure of 103 kPa (15 psi); (b) to evaluate the acid resistance of coated concrete and clay brick with and without holidays; and (c) to determine the bonding strength of the coating materials to concrete and clay brick over a period of time.

MATERIALS AND TESTING PROGRAM

Material

A polymer concrete coating material was used to coat dry and wet concrete and clay bricks. Some properties of the pure coating are listed in Table 1.

Testing Program

(1) Full Scale Test

(a) Hydrostatic Pressure Testing

In order to simulate hydrostatic backpressure on concrete structures due to the ground water table, it was decided to use concentrically placed concrete pipes to develop the necessary full-scale testing conditions (8-9) (Fig.1). This was achieved by using 900 mm (36 in.) inner pipes and 1600 mm (64 in.) outer pipes with two concrete end plates. Steel elements were used to support the entire set-
up. Inner concrete pipes were representing a concrete surface under hydrostatic pressure and coating a pipe surface represented most of the difficult conditions encountered in coating structures such as lift stations. The total area available for coating was 14 sq. meter (150 sq. ft.). Based on federal regulations, 900 mm (36 in.) diameter pipe was the smallest pipe in which a coating applicator can be allowed to operate within the concrete pipe. Pressure chamber used for the full-scale test was designed and built by Hanson (formerly Gifford-Hill & Company), Houston Division, which was representing the American Concrete Pipe Association.

_Dry test:_ Coating was applied to new 900 mm (36 in.) diameter concrete pipe at the Hanson concrete pipe yard in Houston. The coated pipe was then placed in the pressure chamber for hydrostatic pressure testing.

_Wet test:_ The 900 mm (36 in.) concrete pipe was installed in the test chamber and pressurized at 103 kPa (32 ft of water head) for at least four weeks before applying the coating. The coating was applied after water jet blasting the concrete surface. The coating was yellow in color. Application temperature was 65°F.

(b) Measurements

_Visual Inspection:_ The coated surfaces were visually inspected regularly and information on blistering, spalling, discoloring and cracking were noted and photographed.

_In-Situ Bonding Test (ASTM D 4541, CIGMAT CT-2):_ In-situ bonding tests on the coating materials were performed at the end of the hydrostatic test. A 51 mm (2 in.) diameter core drill was used to core into the concrete surface and isolate the test area and a metal piece was glued to the coating with an epoxy. After 24 hrs. of curing, the test was performed using a hydraulic loading system to determine the bonding strength and the type of failure.

_Water Vapor Emission Test (ASTM E 1907):_ Water vapor emission rate of coated concrete pipes was measured according to ASTM E 1097.

(ii) Laboratory Test

(a) Bonding Strength

Bonding strength (pull-off strength) between the concrete and clay brick and the coating material was determined over a period of three years.

_ASTMD 4541(CIGMAT CT-2):_ In this test 51 mm (2-in.) diameter circular area was used for testing (Fig. 2 (a)). Coated concrete blocks/clay bricks were cored
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using a diamond core drill to predetermined depth to isolate the coating. A metal fixture was then glued to the isolated coating section using a rapid setting epoxy.

*ASTM C 321 (CIGMAT CT-3)*: In this test the coating was sandwiched between a pair of rectangular concrete block/clay brick specimens and then tested for bonding strength (Fig. 2 (b)). Both dry and wet specimens were used to simulate the dry and wet coating conditions. The bonded specimens were cured under water up to the time of testing. Compared to *ASTM D 4541* test, this is an easier test to perform since no coring or gluing of metal fixture is required.

(b) Holiday Test - Chemical Resistance  (*ASTM G 20, CIGMAT CT-1*)

In order to study the chemical resistance *ASTM G 20* test was modified to use with coated concrete and clay brick materials. As shown in Fig. 3 the specimens were immersed in a selected test reagent to half the specimen height in a closed bottle so that the specimens were exposed to the liquid phase and vapor phase. This method was intended for use as a relatively rapid test to evaluate the acidic resistance of coated specimens under anticipated service conditions. In this test, 76 mm (3-inch) x 152 mm (6-inch) cylindrical cement concrete specimens and 76 mm x 152 mm clay bricks were used. Dry and wet specimens were coated on all sides and tested. For the test two radial holes were drilled into the specimen approximately 15 mm deep. In this test the changes in (1) weight of specimen and (2) appearance of specimen were measured at regular intervals. The test reagent was 3% sulfuric acid solution ($pH = 0.45$; representing the worst reported condition in the wastewater system) for this study. Control tests were performed with no holiday.

RESULTS AND DISCUSSION

**Hydrostatic Pressure Test**

The performance rating criteria are as follow: (i) Overall condition (appearance): good, satisfactory, bad; (ii) Surface texture: smooth, rough; (iii) Blistering: yes, no; (iv) Cracking: yes, no; (v) Change in color: yes, no; (vi) Overall finish (quality of the job): good, satisfactory, bad; Overall Rating: Pass, Satisfactory, Fail.

After twenty-four months of hydrostatic pressure test, the polymer concrete coating had good overall condition under dry and wet concrete surface. The surface textures were smooth and there were no blisters and cracks. The overall finish was good for the coating.

In-situ bonding test results and water vapor emission rates for dry and wet coated concrete pipes are summarized in Table 2.
Liu and Vipulanandan

From the in-situ bonding test results, the bonding strength for the wet application condition was much higher than the bonding strength from the dry application condition. The failure type of the bonding tests for the dry application condition was bonding failure which failure occurred between the coating and the substrate. The failure types for the wet application condition were bonding failure and substrate failure. Bonding test results indicate that the polymer concrete has better bonding with wet concrete surface than with dry concrete surface.

Water vapor emission rate may affect the bonding strength of coatings to concrete substrate. Test results from Suprenant(10) showed that when the water vapor emission rate exceeds 283 μg/(s.m²) (5 lbs/(1000 ft².24 h), the bonding strength for most adhesives drops dramatically. The water vapor emission rates of the polymer concrete under both dry and wet application conditions were all lower than the value.

Discolored spots were observed on wet coated coating surface. The formation of the spots may be because the polymer concrete is not a homogenous material and the excessive water vapor evaporates from these areas. If this situation exists in the field, corrosive liquids will penetrate through these areas. Failures may occur first in these areas.

Bonding Test (Laboratory)

Failure types of the bonding tests are characterized as follows (1) concrete and clay brick failure – Type 1, (2) coating failure – Type 2, (3) bonding failure – Type 3, and (4) Bonding and concrete/clay brick failure – Type 4. Type 1 is the most preferred.

(i) Concrete Substrate

Variations of bonding strength for the polymer concrete to the concrete substrate are in Fig. 4 under wet and dry conditions. Failure Type 1, 2, and 3 were observed in modified ASTM D 4541 and ASTM C 321 tests (Fig. 4). The predominant failure type was Type 3 where failure occurred at the interface of the coating and concrete substrate. Bonding strength from both ASTM D 4541 and ASTM C 321 test did not change up to three years of testing. The results from ASTM D 4541 test showed that most of the failure strengths for both dry coated and wet coated concrete were lower than 200 psi. On the other hand, nearly all bonding strength from ASTM C 321 test were higher than 200 psi. The reason may be because of the way the specimens prepared. For modified ASTM D 4541 specimens (Fig. 2 (a)), coating film directly contacted with the curing agent (water). Water can easily penetrate through coating film into concrete. Soluble salts were dissolved into the water and changed the structure of the
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coating-substrate interface. On the other hand, for ASTM C 321 test specimens (Fig. 2 (b)), the curing agent had no significant effect on the coating-substrate interface.

Test results from the laboratory bonding tests and the in-situ bonding test indicate that the polymer concrete had better bonding strength with wet concrete surface than with dry concrete surface (Fig. 4 and Fig. 5).

In Fig. 5, the results from ASTM D 4541 tests are compared to the ASTM C 321 tests. From Fig. 5, 79% of the bonding strength from ASTM C 321 test were higher than that from the ASTM D 4541 test.

(ii) Clay Brick Substrate

Variations of bonding strength of the polymer concrete to the clay brick substrate are in Fig. 6 under wet and dry conditions.

The predominate failure type from ASTM D 4541 test and ASTM C 321 test for dry and wet coated clay bricks was Type 1 where the failure occurred in the substrate (Fig. 6 (a) and (b)). Most of the failure strengths were higher than 200 psi. This indicated that the polymer concrete had good bonding strength with clay bricks. The bonding strength during the testing period remained mainly unchanged.

The results from ASTM D 4541 tests are compared ASTM C 321 tests in Fig. 7. The results also showed that the bonding strength from ASTM C 321 test were higher than from ASTM D 4541 test.

Chemical Resistance Test

When coated concrete and clay bricks were immersed in acidic solutions, the performance of coated concrete was different from coated clay brick. When coated concrete absorbed acidic solution, concrete will react with the sulfuric acid and expand, but clay brick will not react with the acid solutions.

(i) Coated Concrete

When coated concrete specimens are immersed in sulfuric acid solutions, acid will penetrate through the holiday, coating film and interface (exposed at the holidays) and react with the Ca(OH)₂ and other complexes in the cement (8). Based on pH and sulfate concentration in the specimen, gypsum and/or ettringite is formed. Ettringite expands and causes coating cracking, blistering, and spalling. Failure types observed when sulfuric acid attacked on coated concrete specimens
The relationships of weight change versus time for coated specimens are shown in Fig. 8. The weight increase of the dry coated specimens with and without holidays in 3% sulfuric acid were more than 0.5% after 200 days. Small cracks were observed on the coating surface. All of the dry coated specimens were failed after 400 days because the length of the cracks exceeded 25 mm (1”) and the weight increases of the specimens exceeded 1% (Fig. 8 (a)). On the other hand, although the weight increase of the wet coated specimens with holidays were similar with the dry coated specimens in the test period, there were no failures on the wet coated specimens with and without holidays after 400 days of immersion (Fig. 8 (b)). The wet coated specimens without holidays exhibited good ability to resist solution penetration. The weight increases was about 0.5% for the wet coated specimens without holidays after 400 days of immersion (Fig. 8 (b)). The reason that the dry coated specimens failed faster than the wet coated specimens in 3% sulfuric acid may be: (1) dry concrete specimens were rich in free Ca(OH)₂, when the concrete was immersed in sulfuric acid, it quickly reacted with H₂SO₄ and formed gypsum and ettringite. Large expansion of the reacted concrete caused the coating film cracked. (2) In water saturated specimens, the pores are filled with water and hence acid will be diluted in the pores which will reduce the concentration of sulfuric acid and slow down the degradation of the concrete specimens. (3) Bonding test results showed that the polymer concrete had poor bonding on dry concrete surface. If there were defects (such as holidays) on coating surface, acid would penetrate through coating film much fast. Because of the poor bonding between polymer concrete coating and concrete substrate, acid penetrated along the interface of the coating film and concrete. This increased the contact area of the coating film and the concrete substrate. Cracks occurred at the weak area because of the expansion of the reacted concrete.

Fig. 9 shows the percent passing of coated and uncoated specimens in 3% sulfuric acid. For uncoated specimens in 3% sulfuric acid, failure was defined by 2% weight loss, and all specimens failed in 7 days. For coated concrete specimens in 3% sulfuric acid, coating failures for dry and wet coated concrete started after 200 days and 500 days respectively. The time-to-failure factor (K) is defined as the ratio of the failure-time of the coated specimens to the failure-time of the uncoated specimens in the same solution. As shown in Fig. 9, the ratios are as follows:

For 100% passing:  
- Dry condition: \( K_{100} = \frac{t^D_{2}}{t_i} = \frac{200}{7} = 29 \),
- Wet condition: \( K_{100} = \frac{t^W_{2}}{t_i} = \frac{500}{7} = 71 \).
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For 50% pass

Dry condition

\[ K_{50} = \frac{t_{50}^D}{t_3} = \frac{300}{7} = 43. \]

Wet condition

\[ K_{50} = \frac{t_{50}^W}{t_3} = \frac{700}{7} = 100. \]

Hence, by coating the concrete the lifetime of the concrete in 3% sulfuric acid without any failure can be extended by more than 29 and 71 times for dry and wet coated concrete respectively. Test results indicate that after 200 days for dry coated concrete and 500 days for wet coated concrete, the coated concrete sewer facilities exposed to 3% sulfuric acid must be inspected for possible failure of the coating and maintenance purposes.

(ii) Coated Clay brick

The variations of weight increase with time for coated clay bricks in 3% sulfuric acid over a period of three years are shown in Fig. 11.

Figure 11 shows that the solution uptake by wet coated clay bricks without holidays was reduced by the coating under 3% sulfuric acid immersion condition. On the other hand, the solution uptake for dry coated clay brick without holidays increased much faster than the wet coated clay bricks without holidays. Fig. 11 also shows that the holiday sizes did not play an important role on solution uptake for all the specimens with holidays under both 3% sulfuric acid immersion condition. That is, once the holiday is formed on the coating surface, the solution uptake will increase fast and will not relate to the holiday sizes.

There were no failures observed on dry and wet coated clay bricks in 3% sulfuric acid.

MODELING THE WEIGHT INCREASE IN COATED CONCRETE

Weight increase in coated concrete indicates the degree of deterioration of the concrete when immersed in sulfuric acid. Modeling the weight increase of coated concrete can lead to predict the service life of the coated concrete structure when it is in immersion services. The physical model of liquid penetrating through coating film is shown in Fig.12.

In the modeling, the coating film was treated as a plane sheet. The distribution of the degree of saturation of the coating film (S) can be obtained under the boundary condition \( x = 0, \ S = S_0^{CT} \) and \( x = \ell, \ S = S_i^{CT} \).
\[
\frac{S - S_0^{CT}}{S_i^{CT} - S_0^{CT}} = \frac{x}{\ell}
\]  

(1)

where \( S_0^{CT} \) degree of saturation of coating film on the outer surface 
g(solution)/g(solid),

\( S_i^{CT} \) degree of saturation of coating film on the interface 
g(solution)/g(solid),

\( \ell \) coating film thickness cm.

The rate of mass transfer \( F \) (g liquid/s) through a plane sheet under steady state is 
given [Crank, 1975]

\[
F = -D_{CT} \frac{\rho_{CT}^* dS}{dx},
\]

(2)

where \( D_{CT} \) mass transfer coefficient of the coating film cm²/s,

\( \rho_{CT}^* \) density of the coating g/cm³.

Assume that the degree of saturation on the interface varies with time \( t \) can be 
represented by the exponential function:

\[
S_i^{CT} = S_0^{CT} (1 - e^{-\beta_{CT}^* t}),
\]

(3)

where \( \beta_{CT}^* \) is a coating material related parameter.

The amount of solution \( (W_i) \) passing through coating film from time \( 0 \) to \( t \) can 
be obtained as following:

\[
W_i = \frac{2\pi R h \rho_{CT}^* S_0^{CT} D_{CT}}{\beta_{CT}^* \ell} \left(1 - e^{-\beta_{CT}^* t}\right)
\]

(4)

Equation (4) is the film mass transport equation to predict the weight change in 
coated concrete after different times of immersion.

The effect of pinhole sizes on liquid uptake of coated substrate can be taken into 
account by adding a parameter \( \xi \) which is a function of pinhole sizes to Equation 
(4). The parameter \( \xi \) is defined as

\[
\xi = 1 + \frac{d_h}{k_1 + k_2 d_h},
\]

(5)

where \( d_h \) pinhole diameter, cm;
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$k_1, k_2 = \text{constant.}$

Hence, Equation (4) is modified as follows:

$$W_t = \xi \frac{2\pi R \rho^{\alpha}}{\beta^{\alpha}} S_0^{\alpha} \frac{D_{CT}^{\alpha}}{t} \left[ 1 - e^{-\beta^{\alpha}t} \right].$$  \hspace{1cm} (6)

The ultimate degree of saturation $S_0$ can be obtained from the experiments. Fitting Equation (6) to the weight change of coated concrete, the mass transfer coefficient $D_{CT}$, parameter $\beta^{CT}$ of coatings and the holiday effect parameter $k_1, k_2$ can be obtained. The weight change of coated concrete at different immersion time can be predicted by Equation (6).

The parameters in Equation (6) are listed in Table 3 and Table 4. The prediction of weight increase of coated concrete is shown in Fig. 13. From Fig. 13, the model prediction is in good agreement with the experiment data.

CONCLUSIONS

A combination of full-scale and laboratory tests were used to evaluate the performance of a polyester based polymer concrete coating material for dry and wet concrete and clay brick. A model was developed to predict the weight change in the coated concrete in acidic solutions. Based on the experimental results and model prediction, following observations are advanced:

1. Hydrostatic Test: The polymer concrete coating had good overall performance on dry and wet concrete surfaces under a hydrostatic pressure of 103 kPa (15 psi). The coating surface texture was smooth and there were no blisters and/or cracks after twenty four months of testing. Discolored spots were observed on the coating, which was applied under wet conditions. The overall finish was good.

2. Bonding Test: The polymer concrete coating had good bonding strength with wet concrete surface than with dry concrete surface condition. In-situ bonding strengths were comparable with the laboratory ASTM C 321 test results.

3. The polymer concrete coating had good bonding strength with both dry and wet clay brick surfaces during the three years of testing.

4. Chemical Test: The dry coated concrete specimens with and without holidays in 3% sulfuric acid failed in 400 days of immersion because of large blisters or cracks on the coating surface. All wet coated concrete
specimens passed the test in the same period of time. Testing coated concrete specimens with holidays (pinholes) is considered to represent the critical condition in the field.

(5) The tested polymer concrete coating was more suitable for wet concrete surface than the dry concrete surface.

(6) The prediction of weight change in coated concrete using the film model was in good agreement with the experiment data.

**ACKNOWLEDGEMENT**

This project was supported by the Center for Innovative Grouting Materials and Technology (CIGMAT) under grants from the City of Houston, National Science Foundation (CMS-9526094, CMS-9634685), and various industries.

**REFERENCES**


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Table 1. Properties of the Polymer Concrete Coating

<table>
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<tr>
<th>Coating Material</th>
<th>Density (g/cm³)</th>
<th>Pulse Velocity (m/s)</th>
<th>Hardness</th>
<th>Thickness (mm)</th>
<th>Application Condition</th>
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<td>Polymer concrete</td>
<td>1.75</td>
<td>3165</td>
<td>Barcol 38-45</td>
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<td>dry and wet surfaces</td>
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Table 2  In-Situ Bonding Strength Results and Water Vapor Emission Rates

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<thead>
<tr>
<th>Application Condition</th>
<th>Bonding Failure Strength, MPa (psi)</th>
<th>Failure Type</th>
<th>Water Vapor Emission Rate, μg/(s.m²)(r/b/(1000ft².24h))</th>
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<td>Bonding</td>
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<tr>
<td>Wet</td>
<td>2.14 (311)</td>
<td>Bonding and Substrate</td>
<td>130 (2.30)</td>
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Table 3  Values of k₁ and k₂ of Coated Specimen in 3% Sulfuric acid

<table>
<thead>
<tr>
<th>Coating Condition</th>
<th>k₁</th>
<th>k₂</th>
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<tbody>
<tr>
<td>Dry</td>
<td>1.37</td>
<td>1.50</td>
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<tr>
<td>Wet</td>
<td>0.06</td>
<td>0.56</td>
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Table 4  Parameters for the Model in 3% Sulfuric Acid

<table>
<thead>
<tr>
<th>Surface Condition</th>
<th>Ultimate Degree of Saturation S₉ᵃᶜ (g solution/g coating)</th>
<th>Material Parameter βᶜᵃᶜ</th>
<th>Mass Transfer Coefficient Dᶜᵃᶜ 10⁻¹³ × m²/s (10⁻¹² × ft²/s)</th>
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<td>Dry</td>
<td>0.010</td>
<td>0.012</td>
<td>94.9 (102)</td>
</tr>
<tr>
<td>Wet</td>
<td>0.010</td>
<td>0.016</td>
<td>91.4 (98.1)</td>
</tr>
</tbody>
</table>
Figure 1. Hydrostatic Test Configuration

Figure 2. Bonding Test Setup (a) ASTM D 4541 Test and (b) ASTM C 321 Test
Figure 3. Chemical Tests on Coating Materials for Concrete and Clay Brick

Figure 4. Variation of Bonding Strength with Time for Coated Concrete
Figure 5. Comparison of ASTM D 4541 Tests and ASTM C 321 Tests for Coated Concrete Substrate

Figure 6. Variation of Bonding Strength with Time for Coated Clay Bricks
Figure 7. Comparison of ASTM D 4541 Tests and ASTM C 321 Tests for Clay Brick Substrate

Figure 8. Percentage of Weight Change vs. Immersion Time for Coating Coated Concrete in 3% Sulfuric Acid

(a)

(b)
Figure 9. Percent Passing vs. Immersion Time for Coated Concrete

Figure 10. Average Bonding Strength vs. Failure Time
Figure 11. Percentage of Weight Change vs. Immersion Time for Coating Coated Clay Bricks in 3% Sulfuric Acid

Figure 12. The Distribution of the Degree of Saturation in Coating Film
Figure 13. Comparison of Model Prediction and Experiment Data