

Machine Application of Polymer Concrete for Highway Repairs

by Danny Marsh, W. J. Simonsen, and D. W. Fowler

Synopsis: Polymer concrete has been used for years to repair portland cement concrete. A monomer system is mixed with well-graded aggregate and placed in the repair area. After the monomer cures, a strong durable material is produced which bonds well to portland cement concrete.

Special mixing and placing equipment was developed for a large pavement repair job in Houston. Longitudinal cracks, longitudinal lane-shoulder joint separations, spalls, punch-outs, and other types of damage were repaired.

Keywords: concrete pavements; concrete slabs; costs; cracking (fracturing); equipment; joints (junctions); methyl methacrylate; patching; polymer concrete; precast concrete; repairs; safety.

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INTRODUCTION

Polymer concrete made with methyl methacrylate (MMA) monomer was used to make pavement repairs in Houston. Specialized equipment was developed by the contractor for mixing and placing the monomer and polymer concrete. Repairs included sealing longitudinal cracks, filling spalls, punch-outs, lane-joint separations, and bonding of precast portland cement concrete slabs.

Materials

Monomer -- The monomer system was a blend of the chemicals shown in Table 1. The MMA and TMPTMA were bought in bulk quantities and delivered to a central location near the jobsite where the manufacturer of the DMT blended all three chemicals together in their proper proportions. The monomer was then transferred to a large holding tank until needed.

A total of 46,000 gallons of monomer were used in this project. Of the polymer concrete used, 45 percent was for sealing 137,000 lineal ft. of random longitudinal cracks and spalls. Another 45 percent was used to seal 51,000 lineal ft. of longitudinal lane-joint separations, 9 percent was used to repair punch-outs and blow-ups and one percent was used to place precast concrete slabs

Aggregates -- Due to the width of lane separations needing repair, the maximum coarse aggregate met the following grading requirements:

Retained on 3/4 in. sieve	0%
Retained on 1/2 in. sieve	0 - 10%
Retained on 3/8 in. sieve	30 - 60%
Retained on No. 4 sieve	85 - 100%
Retained on No. 8 sieve	0%



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Fine aggregate met the following grading requirements:

Retained on 3/8 in. sieve	0%
Retained on No. 4 sieve	0 - 5%
Retained on No. 8 sieve	0 - 20%
Retained on No. 16 sieve	15 - 50%
Retained on No. 30 sieve	35 - 75%
Retained on No. 50 sieve	70 - 90%
Retained on No. 100 sieve	90 - 100%
Retained on No. 200 sieve	97 - 100%

Aggregate proportions depended on the type of repair. For longitudinal separations, full depth repairs, and precast slabs, the coarse aggregate was mixed with the fine aggregate at a one to one ratio (by weight). Cracks and spalls were repaired using fine aggregate alone.

Because the moisture content of the aggregates (at the time of placement) was limited by specifications to a maximum 0.5 percent by weight, keeping the aggregates dry became a major concern. To meet the 0.5 percent specification for dryness, the coarse and fine aggregates were blended at a 50:50 weight ratio and dried in a kiln at about 245°F. A special bag with a bottom discharge chute, making the material easier to unload, was selected for transporting the aggregate to the job site (Fig. 1). The bags held 2500 lbs of premixed aggregate.

Table 1. Formulation for Monomer System

<u>Chemicals</u>	<u>Function</u>	<u>Percent by Weight</u>
Methyl Methacrylate (MMA)	primary monomer	95
Trimethylolpropane trimethacrylate (TMPTMA)	cross-linking agent	5
N,N-dimethyl-p-toluidine (DMT)	promoter	6*
Benzoyl Peroxide (BzP (40% dispersion)	initiator	2* (pure BzP)

*DMT and BzP adjusted for ambient temperature to result in a pot life of about 20 minutes; five percent of BzP, which was in the form of a 40 percent concentration in dispersion form, was used.

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Steel Fibers -- Three percent by weight of steel fibers were added to the polymer concrete to increase the ductility and toughness of the polymer concrete in large mass repairs, such as lane-joint separations and full depth repairs. Loose, uncollated steel fibers with hooked ends having a length of 30 mm and a diameter of 0.5mm were used.

Thickener -- Polymethyl methacrylate (PMMA) powder at the rate of three percent by weight of the total aggregate was added to the polymer concrete to minimize evaporation and drainage of the monomer and to improve the workability.

DEVELOPMENT OF EQUIPMENT

With the limited existence of proven equipment for field applications, one of the major risks and concerns of the contractor in bidding the job was the development of equipment that could make polymer concrete to meet the requirements of the four polymer bid items and, at the same time, produce polymer concrete in a continuous production-like manner. Because of time constraints specified by the SDHPT for completing the project and because of the different volumes of polymer concrete needed to make each repair two different machines were developed. One machine, the smaller mixer, was capable of delivering the monomer system at a maximum output rate of 1 gal/min. for repairing cracks and spalls where dry aggregates were first placed by hand and injected with monomer later (Fig. 2). The other machine, the large unit, could deliver up to 10 gal. of monomer and mix it with all the PC components, thus yielding up to a maximum of 4 cu. ft. of PC/min.

The Large Unit -- This unit was used for repairing longitudinal separations and full depth repairs, and for bonding precast slabs. Components of the large unit included a 1500-gal. monomer supply, a high-volume air compressor, 9 cu. yd. aggregate supply bins, a feeding system for steel fibers, a PMMA powder metering system, a supply and metering system for BzP, and the mixing pumps and mixing augers which delivered the uncured PC into the repair (Fig. 3).

In order to facilitate production, a boom truck was used to transfer the bags of blended aggregate to the storage compartments on the trailer (Fig. 1). The transfer caused only a minimal disruption in production. The aggregate was fed by gravity into a hopper. The self-powered hopper had an auger which provided accurate metering of the blended material (Fig. 5). Using a mixing auger, the modified rig metered and mixed the different materials with the monomers at rates up to 12 cu. yd/hr. The advantage of using this machine was its modular design.

Two air-powered, direct displacement piston pumps, were used to pump and mix the monomers (Fig. 5). The large pump (10 gal/min.) was used to pump and mix the monomer directly into the

mixing auger. The smaller pump (3 gal/min.) was used to apply mixed monomer directly on the repair for keeping the already-placed polymer concrete saturated. This was necessary because the low-viscosity monomer often ran off or leaked out of the repairs. Additionally, in case of a malfunction in the large pump during production, the smaller pump could be easily switched over to the mixing auger.

Since the MMA, TMPTMA, and DMT blend coming from the monomer tank was colorless and the initiator, BzP, was also colorless, a blue dye was added to the BzP. When the monomer was injected into the screw auger machine the operator could easily determine by the color if the monomers had been properly mixed.

Because of the high flammability of the monomer, certain safety precautions were taken by equipping the large mixer:

- 1) A perforated CO₂ pipe lined the inside of the main screw auger. The CO₂ could be turned on quickly by the operation in case of fire
- 2) A sink and hand-held shower were installed for use as an emergency eye and body wash station
- 3) Fire extinguishers were placed at various locations around the machine and truck.

Building and rigging a comparably equipped machine would cost about \$85,000, excluding the truck and the air compressor.

Small Mixing Machine -- A smaller monomer mixing and dispensing machine was needed for repairing cracks and minor spalls (Fig. 2). Because of the smaller quantities of monomer used, the MMA, TMPTMA, and DMT were blended and stored in 55-gal. drums. The air compressor to run the hydraulic injection system pump was stationed on a flat bed truck along with a silicone pump which was used in conjunction with another construction item. A small hydraulic injection system pump similar to the small pump used on the large machine was used to mix and blend the monomers. This small pump also had mixing guns and modifications similar to the other pumps. The aggregate bin was designed for a one-to-two-day supply of aggregate and was situated at the end of the trailer for easy discharge. Building and rigging the smaller machine cost about \$25,000, excluding the truck and air compressor.

REPAIRS

Longitudinal Lane-Joint Separations and Lane-Shoulder Separations -- The joints at the edge of the concrete pavement adjoining an asphalt median or shoulder were required to be cut to a depth of 8 in. and cleaned of all loose material. Furthermore,

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the pavement joint face had to be cleaned by wire brushing or scraping with hand tools or power tools, sandblasting, or other applicable techniques. Unknown to the contractor and the State Department of Highways and Public Transportation, some of the 8-in. thick continuously reinforced concrete pavement had been slip-formed with a keyway, making it difficult to clean and fill the joint according to the specifications.

It was decided that a rock saw (Fig. 6) could remove the keyway and also serve to saw-cut the asphalt and clean the face of the pavement. An added benefit, the use of the rock saw reduced labor costs without significantly reducing production. Due to using the rock saw, the separation trench was a uniform 3 in. wide and 8 in. deep (Figure 7).

A problem that was not anticipated was the tremendous amount of water that drained from beneath the pavement into the trench even after many days without rain. Because water prevented the bond between PC and concrete, great care was taken to dry the edge joint, especially the face of the pavement. Some water in the bottom of the joint actually prevented the monomer from leaking out. Compressed air was used to blow the water out of the edge joint.

Large butane heaters were then used to dry the face of the concrete. Because of the problem with water infiltration, the water removal and drying operation had to be performed just ahead of the polymer concrete placement.

The polymer concrete was placed in the trench using the large polymer concrete machine (Fig. 8). The surface was wetted with additional monomer (Fig. 9) and then finished to insure adequate saturation at the surface. The cost of cleaning the joint and placing the polymer concrete in the lane-joint and lane-shoulder separations was approximately \$9.05 per lineal foot. Fig. 10 shows the finished joint.

Full-Depth Repairs -- Punch-outs are full-depth failures of the concrete pavement resulting from intersecting transverse and longitudinal cracks (Fig. 11). Blow-ups are defined as cracking and heaving of concrete pavement, usually located at pre-formed transverse joints, caused by thermal expansion. Ninety percent of all full-depth failures in this job were punch-outs (Fig. 12). Transverse saw-cuts were made on each side of the failure one lane in width. The cuts were 2 in. deep to provide a neat repair edge and to prevent the steel reinforcing from being cut. The concrete within the repair area was then removed with air hammers.

After preparation was completed, the large polymer concrete machine was used to place polymer concrete in the full-depth repair (Fig. 13). As the area was being filled with polymer concrete the second smaller pump was activated to replenish monomer.

losses due to evaporation and leakage into cracks and voids. Once the surface was saturated it was screeded smooth. The surface was kept saturated with monomer until polymerization occurred. A mixture of concrete sand with three percent (by weight) PMMA powder was sprinkled over the entire repair area to prevent slick spots from occurring after polymerization and to reduce further evaporation. The entire area was allowed to cure two hours before traffic was allowed over the repair.

The cost of material for this type of repair was up to 20 percent less than the cost of some of the other materials: magnesium phosphate, magnesium polyphosphate, and commercially-available two-component polymer concrete. Another advantage of using polymer concrete in this type of repair was that the set time could be adjusted and thus could be placed at any temperature by adjusting the amount of BzP or DMT.

Limits in the specifications allowed other materials to be placed only when the temperature was below 85°F. The only material used in this project that was less expensive than the polymer concrete was type III portland cement concrete (PCC). However, while polymer concrete needed only two hours or less to cure, the type III PCC needed up to 10 hours to obtain 3000 psi compressive strength, depending on the temperature. In high density traffic areas the higher price of PC can be offset by the higher cost of traffic control caused by the longer curing.

Precast Concrete Repair Slabs -- The use of precast slabs required removing deteriorated sections of continuously reinforced concrete pavement and replacing it with a precast portland cement concrete slab. Polymer concrete was used to fill the joint between the precast slab and the existing concrete pavement. Plans called for the precast slab to be 7-1/2-in. thick. For the remaining 1/2 in. beneath the slab, the contractor had the option of selecting a poured grout bed or pumping fly ash grout underneath the precast slab. Eleven areas were selected for repair by placement of precast slabs. All sites but one were to be 6 ft. long by a full 12 ft. lane wide, however, the dimensions were verified in the field. Because the actual thickness of pavement at each specific location could not be determined, the slabs were precast 7-1/4 in. thick instead of the planned 7-1/2-in. The slabs were precast at a site near the job and cured for seven days. The areas to be repaired ranged in size from 6 ft. by 12 ft. to 20 ft. by 12 ft.

A supporting frame with leveling jacks was fabricated to install the precast slabs. After the saw cuts were made and the old concrete removed, the supporting frame was attached to the lifting points of the precast slab (Fig. 14). A 27-ton motor crane was used to place the slab.

Instead of using the 1/2-in. grout bed under the precast slab as shown on the plans, the contractor elected to use polymer concrete. Reasons for substitution were:

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- 1) With the possibility of the grout setting up before the slab was in its final position, substituting polymer concrete allowed 15 to 20 minutes before polymerization occurred.
- 2) No additional equipment was required
- 3) Since grout was not used in the joints between old and new concrete, there was additional savings in time and on formwork and cleanup.
- 4) An increase in production was obtained.

Specifications called for a sheet of plastic to be placed over the base to prevent leakage, however, the monomer dissolved the plastic film; so, to prevent leakage, the contractor used clay to fill cracks and voids in the corners and at the edges. Once the precast slab was in position and leveled as required, the gaps around the slab were filled with polymer concrete (Fig. 15). After 2 hours of curing, traffic was allowed over the repaired area.

All eleven precast slabs were in place within seven days. By substituting the polymer concrete for the grout under the slab, the repairs were made more quickly.

Longitudinal Cracks -- The specifications for preparing a longitudinal crack (Fig. 16) required making a vertical groove at least 3/4 in. wide by 3/4 in. deep, centered along the existing crack. In cases where the existing crack was wider than 3/4 in. the crack was routed so that the sides were vertical. The groove was prepared using a crack cutter manufactured by McDonald Air Tool Corporation. Other machines were tried but none would make a vertical groove as well as the crack cutter without spalling the edges of the concrete. Other methods included using a random saw cut machine, but the water needed to run the saw cut machine proved to be a major problem. After the prepared crack had been air blasted, a small amount of monomer was poured into the undisturbed portion of the crack (below the prepared crack) until it would accept no more.

For the smaller mixer, the fine aggregate was loaded into a specially-designed hopper for easy discharge into the prepared crack. The crack was filled with the fine aggregate to a level approximately 1/2 in. above the pavement surface and approximately 1/2 in. on both sides of the crack, assuring a tightly sealed crack and a good bond. The monomer mixture was then poured over the aggregate until it was completely saturated. The aggregate was then tamped and screeded level with the adjacent concrete. If required, the crack was then saturated again with monomer before adding a mixture of concrete sand with three percent (by weight) PMMA powder, sprinkled liberally over the crack. The PMMA powder helped to reduce evaporation of the monomer. The crack was then covered with polyethylene and cured for two hours before allowing traffic over the repair.

For many of these repairs, most of the time involved in making the repair was in the preparation. In the case of cracks and spalls, 10 to 12 crack cutters were required to keep the small polymer concrete machine busy.

Early experience on the job indicated that for polymer concrete crack repairs to be durable, the cracks need to be opened to a depth of 1 to 2 inches instead of the 3/4 in. which was specified. A 1 in. to 2 in. depth would provide a greater concrete surface area for bonding to the polymer concrete. For reliable crack repair, monomer must be allowed to totally saturate the area adjacent to the crack at the surface. This requires additional monomer, but it is necessary to provide a good bond.

CONCLUSIONS

Based on the experience during this project, the full-depth repairs of all types and the precast slab repair method were very successful and are cost competitive with most current fast repair stems now being used.

The ability to continuously mix and place polymer concrete with these machines helped the versatile polymer concrete to compare very favorably with any other rapid setting material product. However, in order for polymer concrete to become more acceptable and cost effective in concrete pavement repairs, some improvements are needed:

- 1) A monomer that is not flammable
- 2) A monomer that does not have such a noxious odor; and
- 3) Most important of all, a monomer which is compatible with water.

Application costs could be significantly reduced if labor for preparing the repair area can be decreased and if aggregates would not have to be dried and bagged.

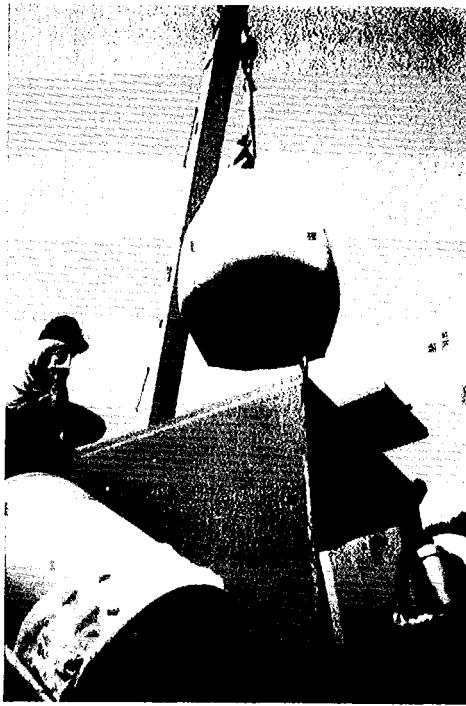


Fig. 1--Nylon bag for transporting aggregate

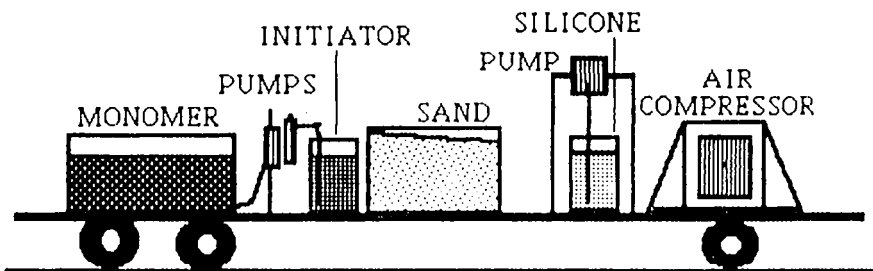


Fig. 2--The small mixer: trailer mounted equipment

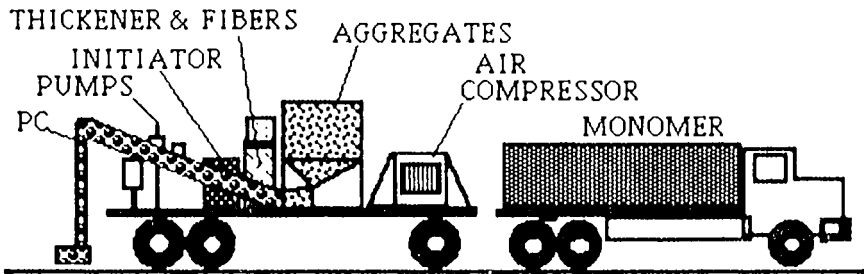


Fig. 3--Diagram of large mixing machine

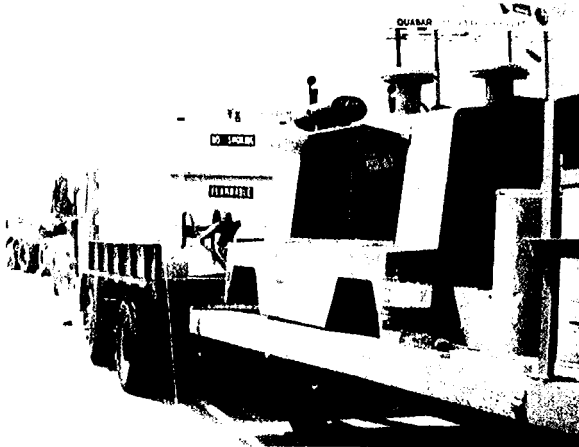


Fig. 4--Equipment for mixing polymer concrete for longitudinal separations and full-depth repairs--monomer tank and air compressor

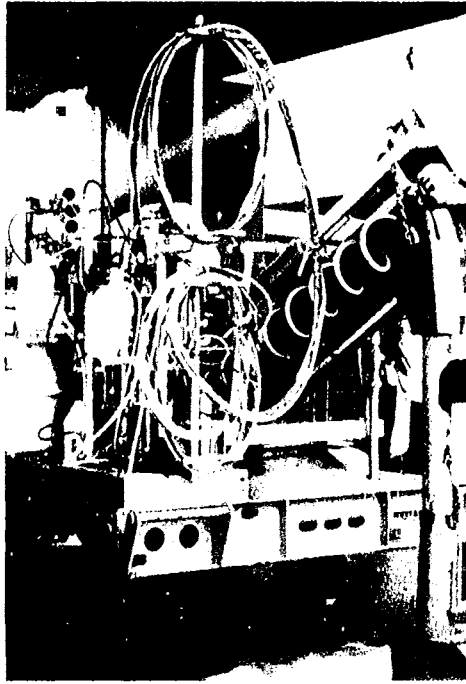


Fig. 5--Auger for blending polymer concrete

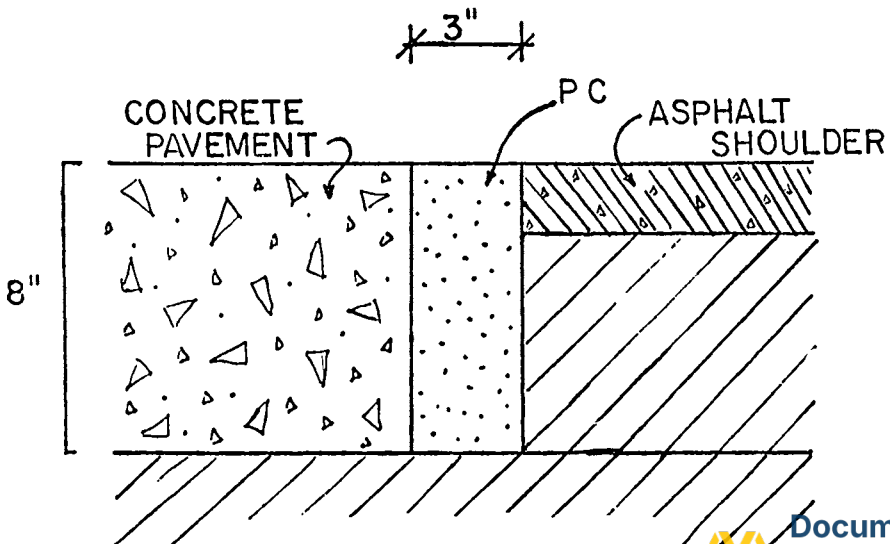


Fig. 6--Diagram of edge joint separation repair



Fig. 7--Tungston carbide-toothed rock saw used to cut trench at longitudinal separation



Fig. 8--Placing polymer concrete in trench cut lane joint separation



Fig. 9--Finishing polymer concrete



Fig. 10--Placing polymer concrete in full-depth repairs

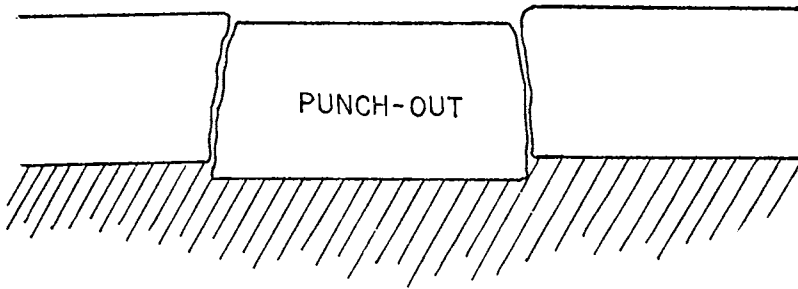


Fig. 11--Punch-out

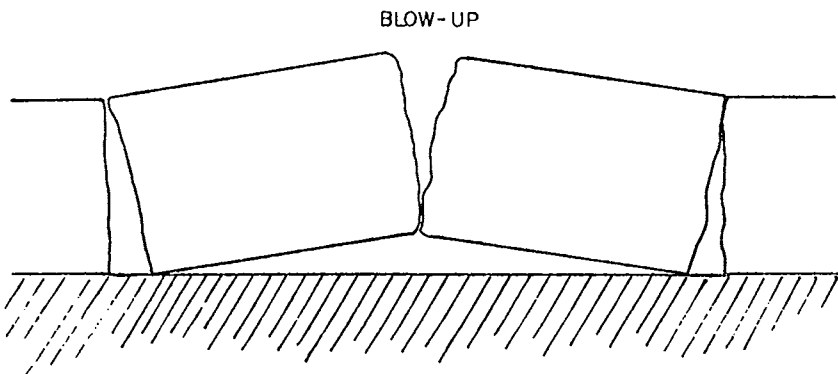


Fig. 12---Blow-up



Fig. 13--Finished joint separation



Fig. 14--Setting precast slab in place



Fig. 15--Filling joints with polymer concrete



Fig. 16--Preparing longitudinal cracks for repair

Corrosion Resistant Pipe Liners — Polymer Concrete

by Albert O. Kaeding

Synopsis: Processes are described for centrifugally applying polymer concrete (PC) liner to straight pipe, for casting the PC liner in pipe fittings, and for closure of field joints. Physical properties of the PC liner materials were measured. Compressive strengths of up to 165.8 MPa (24,045 psi) and splitting tensile strengths of 23.5 MPa (3408 psi) were measured at ambient temperature. Compressive strengths of 24 MPa (3490 psi) and splitting tensile strengths of 2.5 MPa (366 psi) were measured at about 150°C (302°F). Cost of piping a geothermal plant with PC and PC-lined steel pipe is calculated to be \$1.21 million, which compares favorably with a similar plant piped with alloy steel piping at a cost of \$1.33 million. Life-cycle cost analysis indicates that the cost of PC-lined steel pipe would be 83% of that of carbon steel pipe over a 20-year plant operating life.

Keywords: bonding; centrifugal casting; compressive strength; corrosion resistance; costs; permeability; pipe joints; pipe linings; pipes (tubes); polymer concrete; splitting tensile strength; thermal shock.

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INTRODUCTION

As a result of a recognized limit to U.S. and worldwide petroleum reserves over the past several years, the U.S. Government and private industry have been researching alternative energy sources. One such source being investigated is the extraction of heat energy from the earth, or geothermal energy.

One of the more serious technical problems encountered in economic utilization of geothermal energy is severe corrosion and scaling of the geothermal fluid piping. As fluid pressure and recovery temperatures are increased (improving efficiency), the potential for high corrosion rates and excessive scaling of the geothermal fluid piping. As fluid pressure and recovery temperatures are increased (improving efficiency), the potential for high salt content also increases. The dissolved solids produce high corrosion rates and excessing scaling of carbon steels and many alloy steels.

Corrosion studies of several different steels exposed to high temperature, high salinity wellhead brine flow in the Salton Sea Geothermal Field were made by the Lawrence Livermore laboratory. A mild steel specimen (AISI 1009) indicated corrosion rates of 1.65 mm/year (65 mil/year) while a chrome moly steel (ASTM A 387-9) indicated 0.13 mil/year (0.5 mil./ year). This test was performed using a six-month exposure. Chrome-moly steels, however, cost about four to six times as much as the carbon steels, substantially increasing plant construction costs.¹ Other studies have related corrosion to construction costs.¹ Other studies have related corrosion to fluid pH and temperature and indicate that the use of expensive special materials is warranted when fluid pH is less than 6.0 and the temperature is about 120°C (248°F).¹

Potential industrial application of geothermal energy using fluids at 40° to 70°C (104° to 158°F) can use various forms of plastic piping which are not subject to corrosion by the fluids. Low temperature space heating, greenhousing, and various other agricultural applications can make use of systems at these temperatures. Various curing and drying applications along with high temperature space heating require fluid temperatures up to 90°C (194°F). Normal plastic piping systems are not recommended above about 70°C (158°F), but fiber-reinforced plastic (FRP) piping is available that can operate at temperatures of 90°C (194°F). Again, corrosion resistance of FRP piping is good.

Above 90°C (194°F), serviceable piping has been limited to metallic types. Many industrial processes require fluid in this temperature range. For electricity generation, fluid temperatures of 140° to 150°C (284° to 302°F) are presently required. Mild and alloy steels are acceptable within the constraints discussed earlier. But, in contrast to plastic, corrosion is a major problem.

The operating limits of various kinds of piping are illustrated graphically in Figure 1. Data for this figure were obtained from product literature of manufacturers producing the various types of pipe. Limits shown for PC-lined steel pipe were taken from data provided by Brookhaven National Laboratory (BNL).

BNL demonstrated that a particular polymer concrete (PC) formulation, shown in Figure 2, was capable of withstanding brine, flashing brine, and steam at temperatures up to 260°C (450°F).² BNL has completed extensive laboratory studies of this material and have long-term test data available.

For high temperature, 250°C (482°F), applications currently requiring chrome-moly steel piping, this PC provides an economical substitute. For operating pressures up to 1000 kPa (145 psig), properly constructed PC pipe can be used.⁴ In pressure regions of 1000 to 4000 kPa (145 to 580 psig), the PC can be applied as a liner to mild steel pipe. For this application, the PC provides corrosion and scaling protection, while the steel pipe contains the fluid pressure.

PC production processes are similar to portland cement concrete production processes, with a few notable exceptions. First, PC cures much more rapidly with initial set occurring in 2 to 4 hours; 80 to 90% of the final strength is obtained within this time. Final set is accomplished in a process oven in approximately 8 hours at 180° to 190°C (356° to 374°F).

Monomer constituents of the mix are tenacious adhesives to most materials. This property is a definite asset in bonding the PC liner to the steel pipe but has the disadvantage of causing the PC to stick to mold materials. Also, the monomeric components are generally classed as flammable liquids which require the use of explosion-proof equipment, nonsparking tools, and various other safety-related procedures and equipment.

Acrylonitrile, a major component of mix, has been classified as a carcinogen by the National Institute of Occupational Safety and Health (NIOSH). Atmospheric vapor levels and personnel exposure are severely restricted by the OSHA standards. Use of specific personal protective gear is required during prototype work. Production equipment designed for total enclosure is warranted for personnel safety in a full scale plant.

Lining carbon steel pipe with PC has been successfully demonstrated by BNL on a laboratory scale. Field trials by BNL have shown that the PC formula described can protect carbon steel from corrosion and lessen the adherence of calcite-type scale when exposed to geothermal fluid and process conditions.²

Because economical, corrosion-resistant piping for geothermal plants is needed, this project was undertaken to demonstrate new materials with potential to fill this need. In order to be a successfully commercial product, PC-lined steel pipe has to meet several criteria. First, the product must be competitive with acceptable alternative materials. Mass production must be possible and the liner must consistently meet certain physical standards. The PC lined pipe must also be suitable for field installation by contractors normally engaged in plant construction and maintenance. Finally, its durability must be demonstrated in full-scale field trials.

CONCLUSIONS AND RECOMMENDATIONS

Successful full-scale application of PC pipe liners has been demonstrated. Plant-scale centrifugal lining of straight pipe, pipe, and formed, cast, and vibrated fitting linings are possible. Equipment required for a full-scale plant is available "off-the-shelf" or may be fabricated readily.

The use of the specified PC liner in carbon steel pipe provides a very economical corrosion-resistant system for high temperature, high pressure applications. The durability of the PC in geothermal fluid environments has been demonstrated by extensive, long-term tests conducted by BNL. Estimates show that if the normal corrosion allowance provided in steel pipe design is replaced by a PC liner, the initial purchase price of the pipe may actually be lower. Life-cycle cost analysis demonstrates even more remarkable cost savings with a projected 26% annual cost reduction.

For this project, eight 305 mm diam. by 1.5 m long (12 in. by 5 ft.) straight pipe segments, four 305 mm (12 in.) elbows and two 305 mm (12 in.) tees were lined with a 9.53 mm thick (0.375 in.) PC liner. These units will be installed in an operating geothermal energy plant for in-service durability evaluation. In addition, several 142 mm diam. (6 in.) pipe segments were lined with both bonded and unbonded PC liners for testing purposes. Mechanical properties, permeability, bond strength, and thermal shock durability were measured and determined to be acceptable for the intended service. Variations of standard ASTM testing procedures were used whenever possible. Where special tests were deemed appropriate, they were developed and are described in this report.

Mechanical test strengths of the PC at elevated temperature were much lower than those reported by BNL in earlier reports. While two possible causes for this were considered and tested, strength improvements were not obtained. Additional study and testing is suggested to determine causes for elevated temperature strength loss and remedies determined which may be incorporated in future lining production specifications.

Three filed jointing methods were described and tested which will provide satisfactory finished installation. The most economical method entails direct butt welding of the pipe spools in the field and then field grouting the liner joint. This method uses a PC slurry containing ACN, an extremely hazardous organic chemical. Additional research is recommended to eliminate the need to use this material on construction sites, and preferably, to eliminate all field grouting with a more dependable (and still economical) field joint. Because of the hazards described herein associated with field grouting, the use of the more expensive flanged joint with a gasket is recommended at this time.

Replacement of the normal corrosion allowance, added to steel pipe walls in design, with a PC lining is suggested to obtain the most economical piping system. Use of the PC-lined carbon steel pipe should be adequate in all cases where the use of high alloy steel piping was indicated for corrosion resistance.

While work of this project was directed at geothermal fluid piping applications only, cross-over applications in many other industries faced with similar corrosion problems are possible. By addressing these other potential uses, sufficient market for the output of a PC lining plant of the scale suggested will be available sooner. This would permit earlier construction of a lining plant to make this product available on a commercial scale to developing geothermal energy industry.

PROJECT PILOT PLANT

Three special pieces of process equipment were required for the pilot plant to prepare and install the PC liner: a PC mixer, a pipe spinning machine, and a process curing oven. In addition, other equipment requirements included monomer and chemical handling facilities, aggregate storage and batching equipment, batching scales, and ventilation equipment. In-plant and off-the-shelf equipment was used.

A. The PC Mixer. For the small quantities required for each trial run, a paddle-type batch mixer was used. The mixer used a polyethylene drum capable of holding approximately 30 kg (65 lb) of PC. A steel mixing paddle was lowered into the mix and driven at 115 rpm using a 746-W (1 hp) explosion-proof motor with a right-angle drive. The mixer also had a pneumatically actuated raising and lowering mechanism to remove the mixer paddle from the batch. The drum diameter was 30 cm (12 in.) and the height was 37 cm (14.5 in.).

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B. The Pipe Spinning Machine. The machine consists principally of a rigid base frame, a driving shaft with a variable speed motor, and an idler shaft. Each shaft has a set of steel trunions which support the pipe during spinning.

Vertical guards and braces provide a safety confinement for the pipe while it is spinning. A rod was passed through holes in the top of the guards, above the pipe being spun, to contain the pipe during the high rpm phase of the spinning.

The spinning machine was constructed with several features which permit considerable flexibility in the placement process. The driving shaft is powered by a direct-coupled variable speed dc motor so that radial acceleration is continuously adjustable from 0 to 500g. The trunions on both shafts can be changed to different diameters. This permits spinning pipes with a large variety of diameters.

All rotating components of the spinning machine must be carefully balanced. Spring-mounted and dampened containment rollers above the pipe should be included on a production machine to assure safety during spinning. Stationary portions of the machine must have a mass at least twice that of all rotating components to further assure stability.

Accessories include a direct reading optical tachometer and motor speed controls.

C. The Process Curing Oven. Secondary curing was done with a batch oven constructed for the project. The oven's internal dimensions were 2.4 m (7 ft. 10 in.) wide by 0.9 m (3 ft.) high by 0.6 m (2 ft.) deep. The oven was equipped inside with pipe rests to support the pipes and with three 1500-W heating elements, each controlled by a thermostatic controller with a probe in the oven. It also had an internal circulating fan to distribute the hot air evenly throughout the oven. The shell of the oven was insulated with 6 inches of high-temperature insulation. The entire front of the oven was removable for loading and unloading specimens. The oven was supplied with fresh air to limit styrene vapor buildup.

LINING PROCESSES

A. Straight Pipe Lining. All straight pipe liners were applied centrifugally using the equipment described previously. Each 1.5 m long (5 ft.) by 304.8 MM (12 in.) pipe section was sandblasted prior to lining. Prewedged 6.0 kg. (13.2 lb.) PC batches were mixed and placed inside the pipe. The end caps were then attached and the pipe was spun, first at 115 rpm to distribute the material and then at 1700 rpm for 2 minutes to compact the PC. It was found that even when the PC was prepared with 9 wt % monomer content, a fluid slurry of monomer and cement remained in the pipe after compaction. Approximately

0.5 kg (1.1 lb) of this slurry was drained from the pipe immediately after spinning. Actual polymer content of the finished liner was determined to be 4.45 wt % based on loss on ignition tests. A 4 to 8 hour primary cure at ambient temperature was carried out with the end caps left in place. Even with the end caps on, some monomer depletion occurred at the surface, leaving a 1.6 mm (1/16 in.) or less, layer of dry fines over the inside surface of the pipe, as shown on Figure 3.

The pipe was then placed in the secondary curing oven where the temperature was raised to 180°C (374°F) over a period of 3 hours. This temperature was maintained for 8 hours, after which the pipe was cooled to ambient conditions inside the closed oven.

B. Elbow and Tee Lining. Initially, an attempt was made to line the elbows and tees by troweling on a PC mortar. This process had been successfully demonstrated with a portland cement mortar. While trowel application of a portland cement mortar could be duplicated, successful application of a PC mortar could not be achieved. The PC formulation specified was modified within limits permitted by BNL during these attempts. Mixes with low (<10 wt %) monomer content would not properly wet out the pipe surface resulting in loss of bond during curing. Mixes with higher monomer contents would sag on overhead and vertical surfaces before primary cure occurred, even when small amounts (0.2 wt %) of thixotropic agents were added.

After the work to develop a trowel-on liner was completed, efforts were made to develop a disposable inside mold and also to prepare a removable core. Both methods were successfully applied.

The disposal molds were made up of paraffin-impregnated paper or cardboard. After casting and initial curing of a liner, the mold was peeled off the inside surface. Removal can be facilitated by heating the pipe to the melting point of the paraffin. This method has good potential for production operations, as individual liners are inexpensive and easy to use. Special forming mandrels are required to make up the elbow molds, however, so trials were made only on tees.

Removable and reusable cores were made of fiberglass with a paraffin separating layer.

Before each use, the fiberglass cores were coated with a 0.65 cm. (0.25 in.) layer of paraffin to facilitate removal after casting. This core was then inserted into a sandblasted fitting and fiberglass end spacers were applied. PC was then placed into the fitting. Compaction was accomplished by attaching a vibrator to the fitting. After the primary cure was completed, the fitting was heated to melt the paraffin parting layer and the core was removed.

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Tees were lined in a manner similar to that used on the elbows illustrated except that a two-part core was used. This resulted in a sharp-edged turn being formed at the intersection of the two core segments. This sharp edge must then be ground to a suitable radius before secondary curing.

C. Field Jointing Methods. Methods to provide liner continuity in the field were also studied. Six different basic configurations were examined, and three were tested. To be considered satisfactory, a joint procedure must provide impermeable continuity under field conditions.

Two of the methods considered required shop fabrication at each pipe end and some form of compressible gasket to seal the liner ends at the time of field installation. The first method was conventional forged steel pipe flanges. Flanged joints are very adaptable to lined-pipe installation. Initially, this was the preferred method of jointing. Installation is simple and positive. A seal is provided by compressing a gasket into the joint space as the joint is assembled in the field. Since the mating flange faces are machined, the PC liner must be ground and dressed to provide a suitable gasket land.

The other prefabricated joint consisted of a steel coupler which is field welded to steel retainer rings on the pipe spools. Details of this joint are shown in Figure 4.

One of the expected drawbacks to field welding was the damage that might be done to the PC liner immediately adjacent to the weld line by the welding heat. The advantage of the welded coupler joint is the separation and shielding between the welding point and the pipe liner. This method was tested and thermographs were taken to determine the maximum temperature encountered at the steel-liner interface. A thermo-couple probe was embedded at the interface, approximately 2.5 cm. (1 in.) to the side of the weld line. The maximum temperature recorded was about 155°C (311°F), which is within the operating temperature limits of the PC liner.

This joint is installed by inserting the pipe ends in the coupler and hydraulically closing the joint to compress a molded gasket which is on the inside of the coupler. The standard coupler is supplied with an elastomeric gasket unsuitable for use at high temperature, but the manufacturer stated that another gasket material was available which would provide service at the required temperatures.³ This method of assembly is used commonly in plastic-lined pipelines and also for jointing cement-lined pipe in some oil field recovery piping.

Since relatively low temperatures were encountered in the coupler welding tests, a similar test was conducted for direct butt-welded joints. Thermographs were again taken and the results are shown in Figure 5. The maximum temperature recorded was about 170°C (338°F) after the third welding pass.  The highest

single pass temperature rise was 95°C (170°F). If the weld line were cooled to ambient temperature between passes, relatively low peak temperatures within the PC may be anticipated.

After welding, the joint was sawed to examine the PC-steel interface. Delamination was noted approximately 1.3 cm (0.5 in.) to each side of the weld line.

Field closure of the PC liner must be performed to provide liner continuity. This was done by inserting an inflatable bladder at the joint and sealing it to the liner by inflating it. A PC slurry was then injected into the joint and allowed to polymerize, completing the joint. The PC slurry used consisted of 33% Type III portland cement, 33% silica flour, and 34% of the specified monomer. This procedure is illustrated in Figure 6. Drawbacks to this closure method include the need to leave the bladder in place until initial polymerization has taken place (1 hour) and the possibility of voids and cracking in the slurry. Another is the need to handle a PC mixture in the field.

MATERIALS PROPERTIES TESTING

The steel shell of the pipe can be expected to carry all or most of the mechanical stresses, high compressive and splitting tensile strengths were not of primary concern, but were measured for purposes of quality control. Liner impermeability was required to assure protection of the steel pipe from the brine. Bond strength between the PC and the steel pipe is important, since a securely bonded liner is less likely to crack during thermal cycling in service.

A. Compressive Strengths. Although the liner will not be required to withstand high physical stresses, it must maintain its integrity while conducting high temperature flowing brine. PC formulations with the same ingredients in mix ratios similar to those used for this project have been tested by BNL. Samples exposed to flowing brine at 135°C for 18 months did not exhibit any appreciable deterioration. Specimen strength increased to approximately 200% of its initial value (88.5 MPa) (12,835 psi) during the exposure. This increase is attributed to gradual hydration of the portland cement when immersed in the hot brine.

After exposure, compressive strength of 136 MPa (19,735 psi) was measured at 150°C (302°F) test temperature. Before exposure, the compressive strength of a similar formulation was about 55 MPa (7,980 psi) at 150°C test temperature.²

PCR prepared samples of the liners using the material ratios indicated. After curing, compressive strengths were measured, using methods similar to ASTM C-39, on cylindrical specimens, 76.2 mm diam. by 142.4 mm long (3 x 6 in.), at temperatures varying from ambient to 260°C (500°F). The results of the tests are shown in Figure 7. While ambient temperature strength is

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were higher than reported by BNL, 165.8 MPa (24,045 psi) versus 88.5 MPa (12,836 psi), they were only about 44% of the reported strength at 150°C. At a test temperature of 260°C, compressive strengths of 3.9 to 6.4 MPa (566 to 926 psi) were measured. This is approximately 40 to 65% those reported by BNL at this temperature.²

In an attempt to determine if inadequate secondary curing may also be affecting compressive strengths determined by PCR, curing times were extended and additional measurements taken. Ambient temperature strength improvements were noted when the curing time was extended from 4 to 7 hours. Additional curing time, up to 113 hours, showed no additional improvement at ambient temperature. At 260°C (500°F), there was a gradual strength improvement as the curing times were extended.

After curing 15 180°C (378°F) for 66 hours, a strength of 6.1 MPa (844 psi) was determined compared with 3.6 MPa (519 psi) after only 4 hours at curing temperature. In another series, only a 3% improvement was noted for a 113-hour vs. a 4-hour cure. This improvement is not statistically significant, as sample variability was + 15% at this test temperature.

Two different forms of benzoyl peroxide (BP) were used for initiating polymerization. One form, BP-40, contained 60% of an organic plastisizer. Since this is a significant portion of the total mix, a series of comparison tests were made to determine if the plastisizer might be affecting the elevated temperature strengths: No such effect was apparent in the results and it therefore appears that the two peroxides may be used interchangeably.

B. Splitting Tensile Strength. Splitting tensile strengths were also measured on 76.2 mm diam by 142.4 mm long (3 x 6 in.) cylinders at temperatures varying from 21°C (70°F) to 260°C (500°F) using methods described in ASTM C 496. Again, while ambient temperature strengths were 23.5 MPa (3,415 psi), a significant loss in elevated temperature strengths was noted, down to 2.5 MPa (366 psi) at 160°C (320°F). PCR cured all samples in this series at 180°C (374°F) indicated oven temperature. An odor of ammonia was emitted by broken samples, indicating conversion of monomer to polymers, but conversion may not have been complete.⁴

Elevated temperature compressive and splitting tensile strengths measured should be adequate for the proposed service since high physical stresses will not be applied to the liner. Another factor considered was a noticeable decrease in the brittleness of the PC when tested at elevated temperatures. Considerably more deformation occurred prior to failure which would permit the PC to yield and transfer the load to the steel pipe wall. In addition, as the portland cement hydrates in service, compressive strengths will increase, improving service durability further.

C. Permeability. Since the purpose of the liner is to provide a barrier between the geothermal fluid carried in the pipe and the mild steel shell, the permeability coefficient of the lining material is important. Permeability was measured on samples that represent material as placed in the elbows and tees and on materials representative of the centrifugally applied pipe lining. The difference in the two materials was in the method of compaction of the liner. The elbow and tee liners were compacted using vibration applied to the steel shell during and after filling. Compaction of the straight pipe liner was by the centrifugal force applied during spinning.

For the tests on the elbow and tee lining material, cylindrical specimens, 76.2 mm diam by 142.4 mm long (3 by 6 in.), were cast and vibrated using the lining material.

A 76.2 mm (3 in.) disk, about 10 mm (0.4 in.) thick, was sliced out of the cylinders for testing. The permeability coefficient was calculated, using Darcy's Law, to be 22×10^{-12} cm/sec (817×10^{-12} in./sec). Earlier tests on PC that visually exhibited a large number of voids had a permeability coefficient of 28×10^{-12} cm./sec. (11×10^{-12} cm. sec.), while samples with few visible voids had a coefficient of 13×10^{-12} cm./sec. (5.1×10^{-12} insec.)⁵ The permeability of normal portland cement concrete is 5.12×10^{-10} cm./sec. or about 23 times more permeable.⁶

Specimens representative of centrifugally applied lining were prepared by spinning 142 mm diam (6 in.) pipe sections, removing the liner from the steel shell, and slicing off 142 mm long (6 in.) segments. These samples were then tested under a constant head of 42.8 m (142 ft.) H₂O. Usable data were not obtained from this test since a watertight joint between the apparatus and the pipe could not be obtained. After several trials the test procedure was abandoned. Data and results from the permeability tests are shown in Figure 8.

D. Bond Strength and Thermal Shock. Bond strength between the PC liner and the steel pipe was also tested. Sections of 153.4 mm diam (6 in.) pipe, centrifugally lined with PC, were loaded in a compression testing machine as shown in Figure 9. Bond strengths were found to be about 3315 kPa (510 psi) at ambient temperature. Similar specimens were subjected to 5 and 10 thermal shock cycles to determine the effect of rapid temperature change on the bond strength. Results shown in Table 3 indicate that 5 cycles of 256°C (460°F) temperature change decreased the bond strength to 35% of its initial value and 10 cycles decreased the bond strength to 22% of its initial value. Results of these tests were extremely variable, with strengths of 345 and 1220 kPa (50 and 177 psi) resulting after 10 cycles. Debonding near the specimen ends is suspected, resulting in a very large end effect. Continuous pipe runs should be able to redistribute the stresses developed more readily and consequently should have higher bond strength. BNL reported bond

strengths of 10.3 MPa (1508 psi) after 90 days' exposure to 280,000 ppm flowing brine at 235°C. No deterioration of the PC or loss of bond to the steel was apparent after the exposure.⁷ These results indicate that bond strengths should improve with immersion time as the compressive strength did and that end effects are less for greater segment lengths.

E. Cost of PC Lined Steel Pipe. A probable market or selling price for PC lined pipe was calculated.⁸ The average selling price for the liner alone was found to be \$87.10 per meter (\$26.55 per ft.) based on an analysis at a full scale pipe lining plant.

Figure 11 shows a comparison of materials and installation costs for a wide variety of corrosion-resistant piping. Systems operating at 70°C (160°F) and 1.03 MPa (15 psig) or less could be assembled with any of the materials listed. At temperatures above 70°C (160°F), only those materials marked with an asterisk (*) could be used.

Three different PC-lined carbon steel piping systems are listed. All are based on schedule 40 pipe. The "butt welds" entry is based upon 35 field-made butt welds and includes sealing each joint with a PC slurry after welding. Flanged joints and a joint using the Flexweight coupler are also listed. These two listings are based on substituting the respective joint for each of the 35 joints listed as field welds for the "butt welds" entry. As shown, the cost of PC-lined pipe compares very favorably with the majority of other corrosion-resistant piping methods.

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REFERENCES

1. McCright, R. D., Frey, W. F., and Tardiff, G. E., Localized corrosion of steels in geothermal steam/brine mixtures, Geothermal: Energy for the Eighties, Transactions, Volume 4, Geothermal Resources Council, ISSN #0193-5933, ASBN #0-934412-54-5, Davis, California, 1980.
2. Kukacka, L. E. et al., Alternate Materials of Construction for Geothermal Applications, Progress Report No. 18, BNL 51036, 1979.
3. Schmigle, B. J., and Hemm, K. W., Testing of Flexweight Corporation's Perma Couples for Williams Brothers Engineering Company, Tulsa Division, North American Rockwell, 1974.
4. Schroeder, J. E., Design and Fabrication of Polymer Concrete Pipe for Testing in Geothermal Energy Processes, Final Report, Lindsey Industries Project Report, BNL 486337-S, 1981.
5. Kaeding, A., Design and Fabrication of Polymer Concrete-Lined Pipe for Testing in Geothermal Energy Processes, Progress Report No. 3, April-June 1981, BNL 529117-S, 1981.
6. Design and Control of Concrete Mixtures, Twelfth Edition, Portland Cement Association, Skokie, Illinois 1979.
7. Kukacka, L. E. et al, Alternative Materials of Construction for Geothermal Applications, Progress Report No. 17, BNL 50979, 1978.
8. Kaeding, A., Design and Fabrication of Polymer Concrete-Lined Pipe for Testing in Geothermal Energy Processes,

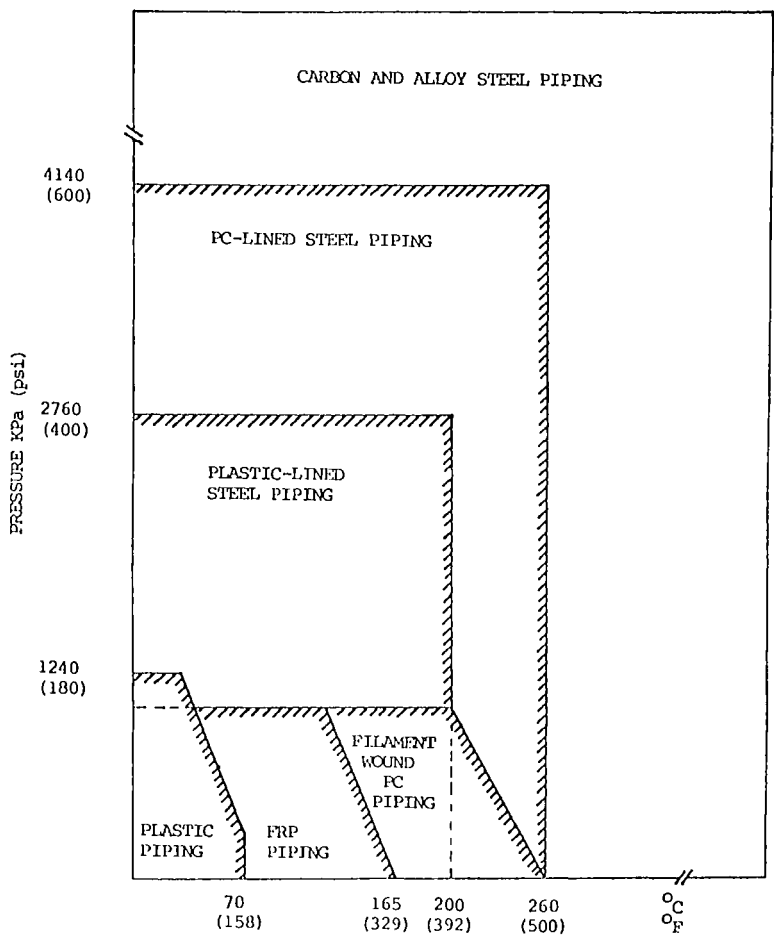


Fig. 1--Temperature and pressure operating limits for various piping materials

FIGURE 2

HIGH TEMPERATURE RESISTANT
POLYMER CONCRETE FORMULATION

Monomer portion (12 wt. % of total mix)

Styrene	52.6 wt. % (of monomer)
Acrylonitrile (ACN)	34.4 wt. % (of monomer)
Trimethylopropane trimethacrylate (TMPTMA)	8.6 wt. % (of monomer)
Silane A-174	1.0 wt. % (of monomer)
Benzoyl peroxide (BP)	1.9 wt. % (of monomer)
Di-tert-butyl peroxide (DTBP)	0.5 wt. % (of monomer)
Dimethyl analine (DMA)	1.0 wt. % (of monomer)

Aggregate portion (88 wt. % of total mix)

Blended silica sand	70.0 wt. % (of aggregate)
Type III portland cement	30.0 wt. % (of aggregate)

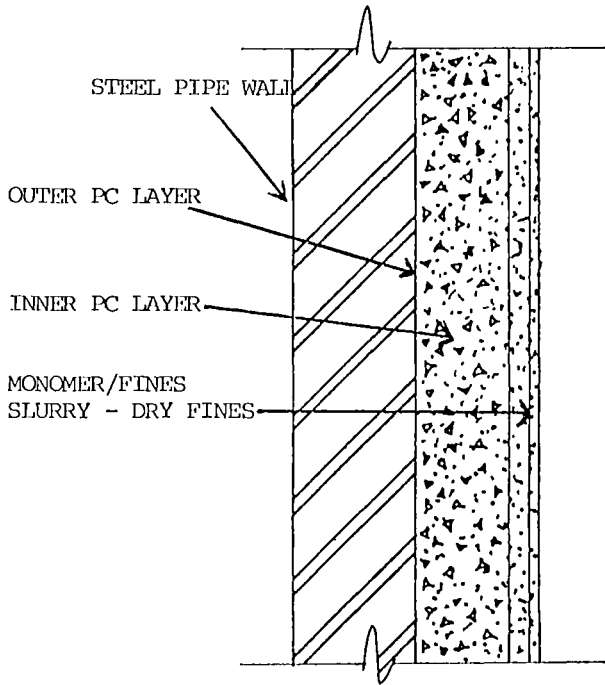


Fig. 3--Section through centrifugally applied pipe lining

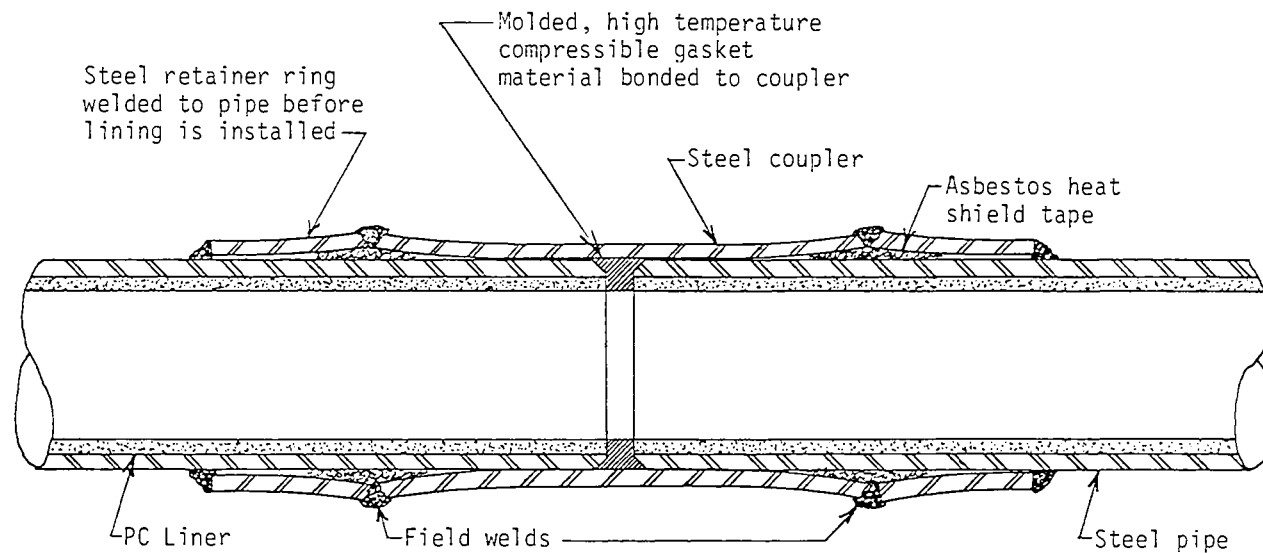


Fig. 4--Field jointing coupler

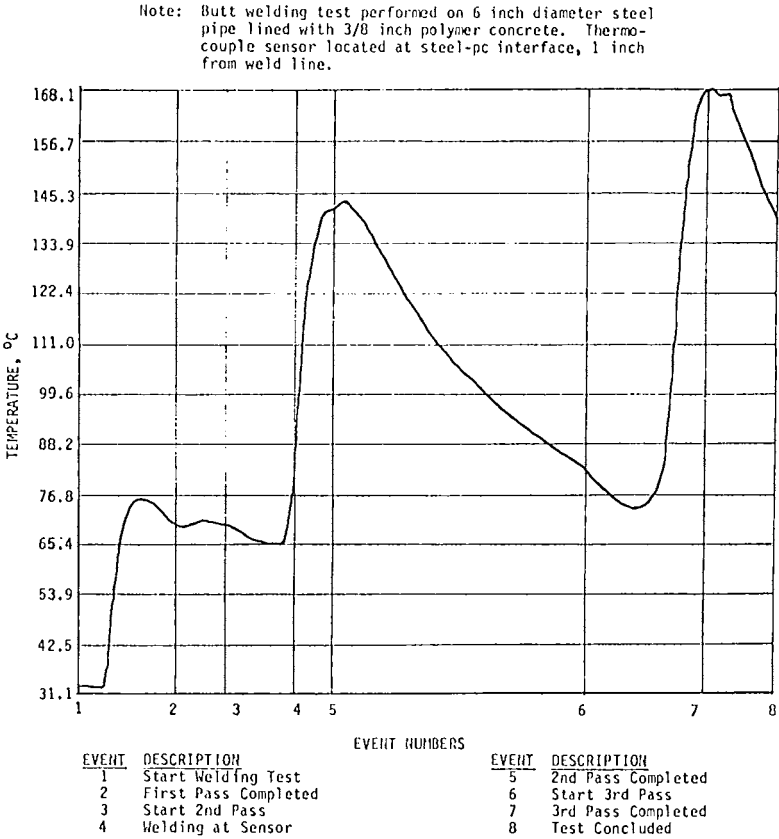


Fig. 5--Welding thermograph: direct butt weld

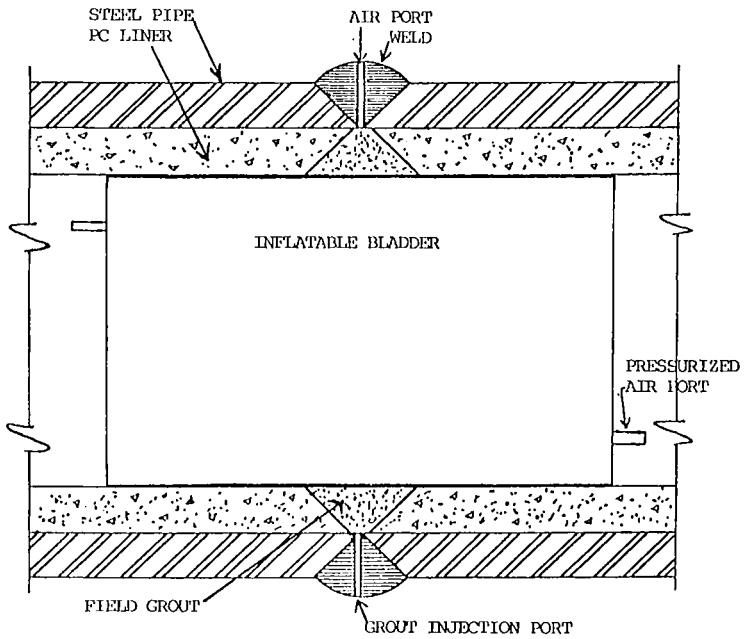


Fig. 6--Field jointing detail

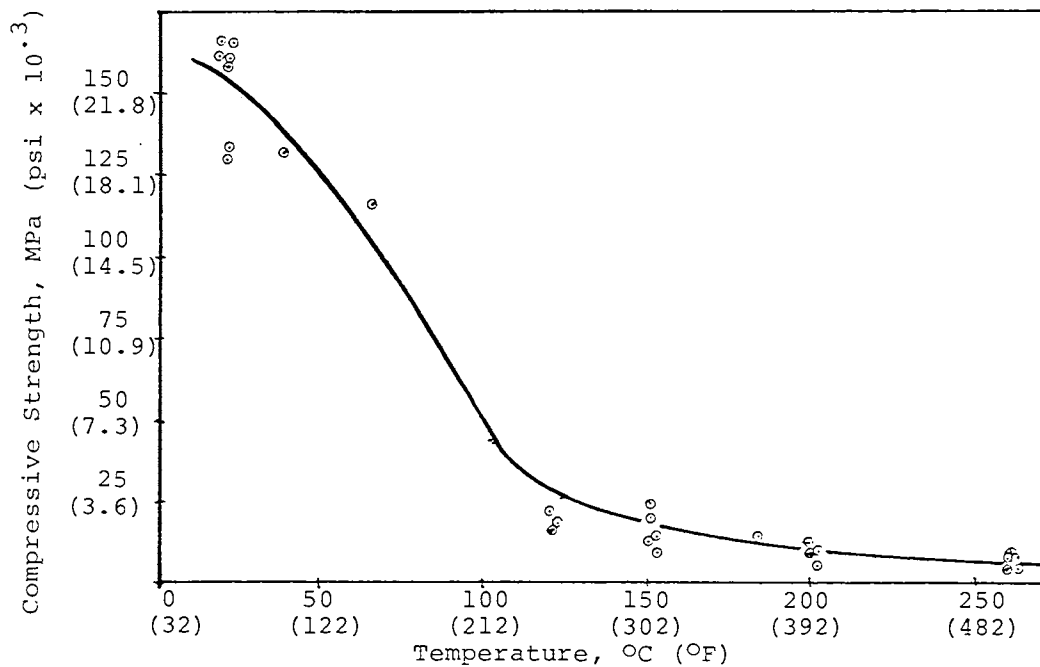


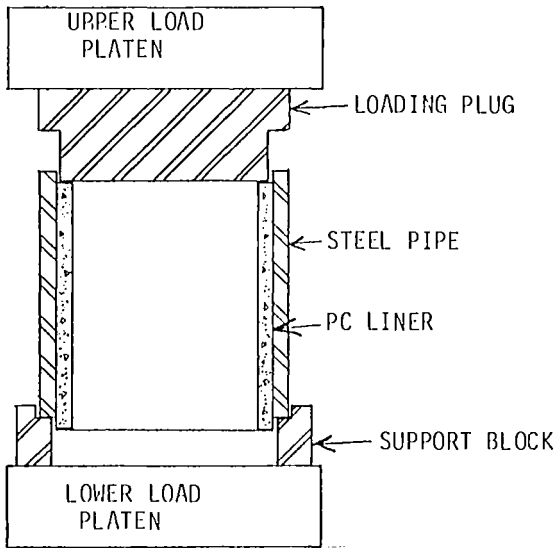
Fig. 7--Compressive strength of PC vs. test temperature of sample

FIGURE 8
Elbow and Tee Liner Permeability

7/62 cm. diam (3 in.) disk specimens

Test No.	Thickness cm.	Avg. Vol. flow, cc/sec	Density kg/m ³	Permeability coefficient, cm/sec
1	1.11	1.94×10^{-6}	2355	13.32×10^{-12}
2	1.19	3.04×10^{-6}	2329	22.38×10^{-12}
3	0.95	4.74×10^{-6}	2231	27.86×10^{-12}
4	0.95	16.30×10^{-6}	--	37.80×10^{-12} *

* The permeometer is suspected of leaking during the test.



$$F_b = \frac{P}{3.14dL}$$

Where: F_b = Bond Strength
 P = Initial Breakout Force
 d = ID of Steel Pipe
 L = Length of PC Liner

Fig. 9--Bond strength testing method

FIGURE 10
Results of Thermal Shock Tests

Test No.	No. Cycles	Specimen Length cm. (in.)	Temperature Range		dT °C	Bond Stress kPa (psi)
			Upper °C(°F)	Lower °C(°F)		
1	0	15.24 (6.0)	control	specimen ambient	256	3392 (492.0)
2	5	19.82 (7.8)	260(500)	4(40)	256	2581 (374.3)
3	5	16.76 (6.6)	260(500)	4(40)	256	777 (40.2)
4	5	19.05 (7.5)	260(500)	4(40)	256	683 (99.0)
5	10	19.82 (7.8)	260(500)	4(40)	256	1220 (177.0)
6	10	16.00 (6.3)	260(500)	4(40)	256	345 (50.0)

FIGURE 11
Comparative Cost of Piping

Piping Materials	Material Cost,\$	Field Labor Cost,\$	Total Installed Cost Cost/ft	Ratio
*Sch 40 carbon steel	4,914	10,973	62	1.00
*PC-lined carbon steel, butt welds	9,907	11,935	87	1.40
*PC-lined carbon steel, couplers	12,972	12,300	100	1.63
*PC-lined carbon steel, flanged	16,032	13,640	119	1.92
Vinyl ester FRP	11,411	12,540	86	1.39
Rubber-lined Sch 40 Steel	18,097	13,640	99	2.16
*Sch 10 aluminum	5,143	9,680	105	1.69
*Sch 40 aluminum	6,679	10,423	105	1.69
*304-L SS, Sch 10	8,487	10,434	106	1.71
Polypropylene-lined steel	15,231	13,640	106	1.71
Polypropylene-lined steel	15,231	13,640	106	1.71
Saran-lined steel	16,710	15,070	114	1.84
*316-L SS, Sch 10	12,833	10,423	121	1.95
*304-L SS, Sch 40	15,634	11,220	139	2.24
Kynar-lined steel	29,979	13,640	158	2.55
*316-LSS, Sch 40	23,030	11,200	165	2.66
*Glass-lined steel Sch 40	32,480	22,605	201	3.24
FEP-lined steel	45,725	13,640	215	3.47
PTFE-lined steel	46,591	15,070	222	3.58
*Alloy 20, Sch 10	33,193	10,973	225	3.63
*Nickel, Sch 10	57,971	11,330	323	5.21
*Alloy 20, Sch 40	64,093	11,935	349	5.63
*Hastelloy C-276, Sch 10	93,103	11,330	421	6.79
*Nickel, Sch 40	112,354	12,375	562	9.06
*Hastelloy C276, Sch 40	171,824	12,375	704	11.35

* Based on a 400 ft. long complex plant piping plan.

Polymer Impregnation and Polymer Concrete Repairs at Grand Coulee Dam

by W. Glenn Smoak

Synopsis: Polymer impregnation and polymer concrete were used to repair the concrete roadway over the Bureau of Reclamation's Grand Coulee Dam. The equipment, materials, and processes used on this project are discussed in depth. The report includes data on the costs of the project.

Keywords: concrete dams; concrete pavements; costs; equipment; impregnating; polymer concrete; repairs.

W. Glenn Smoak has been employed by the Bureau of Reclamation since he received his BSCE degree from Clemson University in 1965. He has been very active in concrete polymer materials research since 1969.

INTRODUCTION

On July 16, 1933, a ceremony was held at Grand Coulee Dam site to mark the turning of the first shovel of earth beginning dam construction. The dam was completed in 1942, forming a huge reservoir that extends 151 mi (242 km) to the Canadian border. Electric power generation capacity of the Grand Coulee complex, including the new Third Powerplant, exceeds 6 million kW (21.6 million MJ), making it the largest single hydroelectric power generating complex in the Nation. The dam is the key feature of the Bureau of Reclamation's Columbia Basin Project, which currently provides irrigation water to over 500 000 acres (2023 km²) and is authorized by Congress to ultimately irrigate over 1 million acres (4046 km²). It is estimated that the completion cost of the Columbia Basin Project is \$3 billion. Over 97 percent of this cost will be repaid by water and power revenues.

After some 40 years of service, the concrete roadway over the dam was showing the effects of exposure. This roadway is over 1 mi (1.6 km) long and has often been used to transport loads that exceed the capacity of the adjacent highway bridge across the Columbia River. In addition to the numerous hatches, access parts, and electrical service outlets, the roadway also contains the embedded rails that form the tracks for the dam gantry cranes. In some locations, the clearance between the crane wheels and the roadway concrete is less than 3/4 in (19 cm).

In 1978 the Grand Coulee Dam Project Office requested the advice and assistance of the Bureau's Denver Office Division of Research in determining a suitable roadway repair program. Inspection of the roadway revealed that the concrete deterioration consisted of shallow surface spalling over much of the roadway surface and deep delaminations primarily at the transverse joints. It was determined that the deterioration in no way affected the safety of the dam, but unless repaired in a timely manner the deterioration would accelerate and ultimately necessitate replacement of the roadway concrete. Such an endeavor would have been extremely expensive. The existence of the crane rails and various other features in the roadway ruled out the use of conventional concrete repair techniques such as an asphalt overlay. Due to the magnitude of the needed repair, it was obvious that the duration of the work would include periods of high summer and very cold

winter temperatures. As a result of these limitations, a two-phase repair procedure utilizing concrete polymer materials was developed. In the first phase of the repair, the entire roadway and part of the pumping plant parking area, 19 600 yd² (14 980 mi²) of surface area, was sandblasted and polymer impregnated. Following impregnation, the deeply delaminated areas were excavated to sound concrete and backfilled to original grade and finish with acrylic polymer concrete. The objectives of the repair program were to repair existing damage, reduce or prevent future deterioration, and restore the appearance of the roadway.

The polymer impregnation process results in significant improvements in durability primarily through reduction in permeability. There is also an increase in compressive and tensile strength properties, though these were not considered directly significant in this application. Acrylic polymer concrete is essentially impervious, rapidly develops a good bond to sound concrete, and appears to have thermal properties compatible with conventional concrete. In this application, the rapid curing characteristics of polymer concrete (1/2 to 2 hours over a wide temperature range) were particularly important because of the below freezing temperatures that would be encountered during the last half of the construction period.

To accomplish the desired repair program, construction specifications were prepared and a contract awarded under competitive bidding procedures to Butler Sealants, Inc., of Seattle, Washington. The construction period extended from May to December 1982.

POLYMER IMPREGNATION

The polymer impregnation or surface impregnation process (as developed at the Bureau's Engineering and Research Center) consists of four basic steps, as follows:

1. Sandblasting the surface to remove oils, other contaminants, and shallow areas of deteriorated concrete.
2. Drying with heat to remove moisture to the desired depth of impregnation.
3. Application of a methyl methacrylate based monomer system.
4. Thermal-catalytic polymerization of the monomer system within the concrete matrix.

Accomplishment of these basic steps, though seemingly simple, requires careful selection of equipment, materials handling procedures, supply logistics, and personnel scheduling.

IMPREGNATION EQUIPMENT AND FACILITIES

The contractor utilized a 15-ft (4.6-m) wide by 260-ft (79.2-m) long heating enclosure for the drying, impregnation, and polymerization steps. The enclosure consisted of a structural steel channel base covered with 22 heating panels, each 15 ft (4.6 m) wide by 12 ft (3.6 m) long. The heating panels formed a weatherproof cover over the base unit. Each heating panel contained nine electric infrared heating elements rated at 7.5 kW each. Three heat control units, each capable of controlling up to eight heating panels, were used to accomplish temperature control. Temperature adjustment was accomplished by setting an interval timer for each heat panel. The timer determined the percentage of each 30-second interval that the heating panel elements were on. It was not possible to adjust the heat elements individually, i.e., the nine elements in any panel were all on or off simultaneously. It was possible to vary the on-off interval for each of the 22 panels.

The monomer system storage and mixing facility was located at a remote site adjacent to the dam. This facility consisted of a 10 000-gal (378.5-m³) underground storage tank, a small air-conditioned storage building, and a second small storage building containing an electric freezer for initiator storage. Safety procedures such as suitable electrical grounds and explosion-proof design, as recommended by the materials manufacturers, were followed at the storage facility. Excess initiated monomer not used on the roadway was bulk polymerized at the storage site prior to disposal. The monomer system was batched and mixed in a truck-mounted tank and transported from the storage area just prior to application. Upon arriving at the dam roadway, a dispersing hose and handheld spray bar were attached to the truck tank and used to apply the monomer system to the concrete surface. Shortly after the contractor began polymer impregnation operations, he found it advantageous to construct a second enclosure base. Using this second unit, he was able to treat two roadway areas simultaneously, i.e., while one area was cooling, he used the second base and the heat panels to dry another area.

Prior to drying, a layer of sand was spread over the concrete surface to reduce thermal shock to the concrete and act as a reservoir for the monomer system while it penetrated the concrete surface. This sand was supplied by the Bureau from its local pit. No grading of this sand was necessary.

From the time of monomer application until the completion of the polymerization step, the surface was covered with mylar film to prevent monomer evaporation and reduce the fire hazard within the enclosure. The excellent durability of the mylar allowed it to be reused for this purpose numerous times.

Electric power for the contractor's operation was supplied by the Bureau. The contractor provided a transmission cable and

transformer as part of a trailer-mounted substation to utilize the electric power. The contractor also provided an excellent system of portable outdoor lights to permit his operations to continue after dark.

Temperatures were continuously monitored within the enclosure with multipoint digital and analog thermocouple recorders. The use of these recorders was shared by Bureau and contractor personnel.

POLYMER IMPREGNATION FIELD APPLICATION

Over 50 setups were required to polymer impregnate the dam roadway. A typical sequence of operations was as follows:

The enclosure base was pulled into position with a truck and sand was spread and leveled. After the thermocouples were epoxied to the concrete surface, a crane was used to place the 22 heat panels on the base and to position the 3 heat control units. The various electrical connections were made and the drying heat cycle began. Drying was continued for a period of 8 hours after the concrete surface was heated to 250 °F (121 °C). After drying the concrete was allowed to cool until the maximum temperature 1 in (25 mm) below the surface was 100 °F (38 °C). Depending on ambient temperature, this cooling required 12 to 36 hours. The rate of temperature change during both drying and cooling was not allowed to exceed 100 °F (55 °C) per hour. During the cooling cycle, the heat panels were removed and used to dry another area.

The monomer system, composed of 95 percent methyl methacrylate (MMA), 5 percent trimethylolpropane trimethacrylate (TMPTMA) and initiated with 0.5 to 1.0 percent of 2,2-azobis(2,4 dimethylvaleronitrile), all by mass, was then applied to the sand at a rate of 0.4 lb/ft² (2.0 kg/m²) and allowed to soak for 6 hours. The mylar film was placed over the monomer-saturated sand immediately after monomer application. During the impregnation soak period, the heat panels were replaced over the base in preparation for polymerization.

Polymerization was accomplished by reheating the concrete to 165 °F (74 °C) and maintaining that temperature for 5 hours. The heat panels were then moved to the other base unit to complete its treatment process. Cleanup involved removal and disposal of the impregnation sand. Two-inch (50-mm) diameter cores were removed from the roadway and split, as in a splitting tension test, to determine the depth of impregnation. Depending on the porosity of the concrete, polymer penetrations of 1/2 to 1 in (12 to 25 mm) were achieved.

PROBLEMS IN THE FIELD

As was expected, there were minor problems, primarily due to lack of training and experience, during the early phases of the project. These were soon worked out, and the project began to run smoothly. One problem that was particularly bothersome involved the impregnation sand sticking to the concrete surface. It was determined that the contractor's heating system was far more effective than those previously used for this type work. The expected monomer loss to evaporation was not occurring. Ultimately, the specified monomer application rate of 0.8 lb/ft^2 (3.9 kg/m^2) was reduced to 0.4 lb/ft^2 (2.0 kg/m^2), and the bonded sand problem was solved.

On several occasions, rainstorms during the cooling cycle wet the dry concrete and necessitated a repeat drying cycle. Improvements were made in the enclosure weatherproofing to reduce this situation.

POLYMER CONCRETE REPAIR

After the polymer impregnation operation had moved sufficiently far across the dam to provide working space, the contractor began excavation and repair of the delaminated zones of the roadway. The depth of these delaminations varied from 2 in (50 mm) to about 18 in (457 mm). The volume of the excavations averaged 1 to 3 ft^3 (0.03 to 0.08 m^3) with the largest about 5 ft^3 (0.14 m^3).

The material used for these repairs was a commercially available acrylic polymer concrete and was delivered to the job-site in bagged units weighing 77.5 lb (35 kg) each. Conventional mortar mixers with about 3 ft^3 (0.8 m^3) capacity were used to mix the polymer concrete. All repairs were placed, consolidated, and finished using conventional concrete vibrators, wood screeds, and trowels. If an excavation was deeper than 6 in (152 mm), the polymer concrete was placed in two lifts. The first lift was placed from the bottom of the hole to just above the top of the reinforcing steel. After this lift had cured, the surface of the polymer concrete was wiped clean with the polymer concrete monomer system and the topping lift placed and finished. The quantities of dry materials used in a polymer concrete mix were as follows:

Polymer concrete powder	-	155 lb (70 kg)
Coarse aggregate - 1/2 to 3/4 in (12 to 19 mm)	-	80 lb (36 kg)
Fine aggregate - 1/4 to 1/2 in (6 to 12 mm)	-	53 lb (24 kg)

If the polymer concrete were to be used in a two-lift repair, the bottom lift was mixed with 1.52 gal (5.75 L) of the acrylic monomer system, and the top or finishing lift was mixed with 1.66 gal (6.25 L). The wetter finishing mix was also used in excavations that were less than 6 in (152 mm) deep and thus repaired with a single lift.

The perimeters of all excavations were sawcut to provide vertical edges. After excavation, the concrete and any exposed reinforcing steel were thoroughly sandblasted and then coated with an acrylic resin primer supplied with the polymer concrete. The primer was allowed to cure prior to placing the polymer concrete.

Inclement weather during the fall and winter months of the construction period was the most significant problem encountered during the polymer concrete repair. Rainwater or melted snow filled the prepared repair areas and necessitated drying, repeat sandblasting, and priming. In some instances, very low ambient temperatures slowed the mixing and curing rates of the polymer concrete and required the use of heaters to obtain reasonable production. These problems, however, were much less severe than would have been encountered with conventional concrete repair techniques.

RESULTS AND COSTS OF THE REPAIR PROGRAM

The roadway repair project was essentially completed in December 1982, 7-1/2 months after startup. Over 19 000 yd² (14 525 m²) of concrete surface was polymer impregnated, and 101 yd³ (77.2 m³) of polymer concrete was placed to repair delaminations and spalls. The appearance and riding qualities of the roadway have been significantly improved. Frequent inspections of the repairs indicate they are performing excellently to date. Only a very few hairline width perimeter cracks were evident immediately following polymer concrete polymerization. The frequency or extent of these has not increased since completion.

The total cost of the roadway repair was \$1.4 million. Polymer impregnation was accomplished at a cost of \$42.50/yd² (\$50.80/m²). Polymer concrete repair of the delaminations including excavation, materials, labor, and profit cost \$5,000.00/yd³ (\$6,540.00/m³). These costs do not include electric power or impregnation sand provided by the Bureau.

Shear Transfer Behavior in Concrete and Polymer Modified Concrete Two-Layered Systems with Application to Infrastructure Rehabilitation and New Designs

by Edward G. Nawy

Synopsis: Research is reported on the shear transfer between normal concrete and polymer modified concrete. The experimental program was designed to verify the general theory of shear transfer mechanism for concrete and to evaluate the necessary constants of the theoretical expressions. The general theory presented covers structural members with (i) no shear reinforcement, (ii) moderate shear reinforcement and (iii) high shear reinforcement. Four groups of specimens were tested. Group A specimens were used to investigate the relation between intrinsic bond shear transfer capacity and the strength of the composite materials (PMC and concrete). No transverse steel was used in these specimens. Group B specimens contained various amounts of shear reinforcement at the shear interface. Group C specimens were cast monolithically using ordinary concrete to serve as control specimens. Group D were control specimens made up of cast-in-place concrete over precast concrete. They were designed to evaluate the "apparent cohesion" of such elements, for the purpose of comparison with Group A specimens.

The investigation will also present the extension of application of the theory to two-layered beams. Results of tests of 16 simply supported beams will be presented, where the principal parameter is the variation of the top PMC layer thickness. The major aspects to be presented are the load-deflection and cracking behavior, the mode of failure of the beams, the contribution of PMC to the strength of the composite beam, the initiation and progress of slip in the interface of the two layers, frictional shear resistance of the unreinforced concrete-PMC interface, and the effect of using shear reinforcement to prevent any slip and shear failure.

Keywords: beams (supports); bond (concrete to concrete); composite construction (concrete to concrete); cracking (fracturing); deflection; loads (forces); polymer-portland cement-concrete; shear properties; shear stress.

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INTRODUCTION

The problem of shear transfer in concrete structures arises when shearing loads must be transmitted across a definite and often weak plane. Typical situations are encountered in corbels, non-monomolithic joints in concrete and composite elements where concrete is cast in place over a precast member.

Since the early fifties several researchers have studied this problem. It is generally recognized that the shear transfer capacity in concrete elements can be attributed to any of the following: friction at the shear plane, interlocking action of the aggregates, dowel action of any reinforcement, and bond forces (apparent cohesion) at the shear plane. However, there continues to be a great deal of debate regarding the relative importance of the various parameters.

Of the many expressions for shear transfer capacity (1-12), the simplest and the most widely used has been that based on the shear friction hypothesis of Birkeland and Birkeland (1). This expression with minor modification (9) has been incorporated in the ACI code. While the expression is useful in estimating shear transfer capacities, its very formulation ignores "apparent cohesion" (bond) and dowel action resistance.

A general theory on shear transfer mechanism is presented, verified by tests (13, 14, 15). The discussion covers any two-layered systems and is extended to the behavior of two-layered beams and their mode of failure.

Tests on sixteen simply supported beam specimens had the principal variable parameter the variation in the thickness of the top polymer modified concrete layer. An expression is developed for evaluating the horizontal shear stress at the interface of the two-layer system in beams. The experimental results indicate that even without reinforcement dowel action, the two-layer system in beams has considerable reserve strength in shear. Friction and interlock well beyond the normal allowed values.