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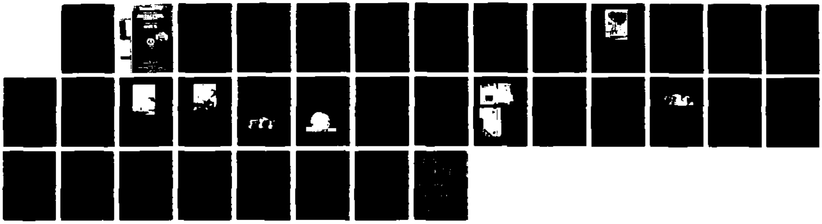

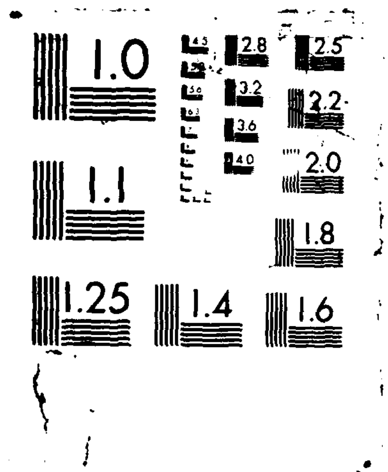
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[illegible] REPAIR OF DETERIORATED [illegible] IN HYDRAULIC STRUCTURES: LABORATORY STUDY

by

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Presented are the results of a laboratory-scaled test program conducted to evaluate the effectiveness of (a) pressure injection, and (b) polymer impregnation repair techniques for use in in situ repair of cracked concrete hydraulic structures. In general, the test results indicate that pressure injection can be used to effectively restore the integrity of air-dried and water-saturated cracked concrete. Polymer impregnation can be used to improve the quality of the concrete surrounding the crack network. However, its effectiveness in sealing the crack network is dependent upon the viscosity of the impregnant being used. The two methods can be used in conjunction to effectively repair and improve the overall quality of the structure to be rehabilitated.

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PREFACE

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32308, "In Situ Repair of Deteriorated Concrete," for which Mr. James E. McDonald is principal investigator. This work unit is part of the Concrete and Steel Structures Problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The Overview Committee of HQUSACE for the REMR Research Program consists of Mr. James E. Crews, Mr. Bruce L. McCartney, and Dr. Tony C. Liu. Technical Monitor for this study was Dr. Liu.

This study was sponsored by the Waterways Experiment Station (WES) and conducted by the Brookhaven National Laboratory (BNL) under the auspices of the Department of Energy under Support Agreement No. WESSC-86-01. This report was prepared by Messrs. R. P. Webster and L. E. Kukacka, Process Sciences Division, BNL. The study was performed under the general supervision of Mr. Bryant Mather, Chief, Structures Laboratory (SL), and Mr. John M. Scanlon, Chief, Concrete Technology Division (CTD), and under the direct supervision of Mr. James E. McDonald, Research Civil Engineer, CTD. Program Manager for REMR is Mr. William F. McCleese, CTD.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
centipoises	0.001	pascal-seconds
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet per second	0.3048	metres per second
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

IN SITU REPAIR OF DETERIORATED CONCRETE IN HYDRAULIC STRUCTURES: LABORATORY STUDY

PART I: INTRODUCTION

Background

1. Over the last 75 to 80 years, the use of portland-cement concrete in hydraulic structures, such as dams, spillways, lock chambers, and bridge support columns and piers, has been very extensive in the United States. The U.S. Army Corps of Engineers estimates that it now operates and maintains 536 dams and 260 lock chambers at 596 sites (Scanlon, et al. 1983). Of these, more than 40% are more than 30 years old and 29% were constructed prior to 1940. In addition, nearly half of the 260 lock chambers will reach their 50-year design lives by the turn of the century. Periodic inspections of these facilities show that a large number of the older structures require significant maintenance, repair, and rehabilitation.

2. Repairs to many such structures involve removal of the deteriorated concrete and replacement with new concrete, to varying extents. Considerable savings in time and cost for the rehabilitation of highly deteriorated concrete structures could be realized if methods and materials could be developed to repair such structures without extensive removal of the deteriorated concrete. To this end, Brookhaven National Laboratory (BNL), under contract to the U.S. Army Corps of Engineers, has carried out a program entitled "In Situ Repair of Deteriorated Concrete in Hydraulic Structures." The results from Phase One of this program have been documented in a report to the Corps of Engineers (Webster and Kukacka, 1987).

3. The objectives of Phase One of the BNL program were to (a) identify the forms of deterioration most prevalent in concrete hydraulic structures, and (b) identify existing methods and materials commonly used for the repair and rehabilitation of concrete structures. This information then was evaluated to determine the applicability of the various repair methods and materials to the in situ repair of concrete hydraulic structures.

4. According to a survey initiated in 1982 by the U.S. Army Corps of Engineers (McDonald and Campbell, 1985), the three most common problems encountered in the Corps' civil works concrete hydraulic structures were (a) cracking, (b) seepage, and (c) spalling. These three problems accounted for 77% of the 10,096 deficiencies identified during a review of available inspection reports. Concrete cracking was the most frequent, accounting for 38% of the total defects. In situ repair procedures may not be readily applicable for seepage problems; however, they seem to be suited to repairing deterioration due to cracking and spalling.

5. Three crack-repair techniques and two techniques for repairing spalled concrete were identified as being most applicable for in situ restoration. The methods include pressure injection, polymer impregnation, and the addition of reinforcement. In conjunction with these procedures, thin reinforced overlays and shotcrete were chosen as methods for the repair of spalled concrete and to resurface a cracked structure after it has been repaired. Based upon these findings, BNL developed a laboratory testing program in Phase Two to evaluate two of the crack repair methods: pressure injection and polymer impregnation.

Phase Two Program Objectives

6. The primary objectives of the Phase Two program were to experimentally evaluate and develop new methods and materials for the in situ repair of cracked concrete hydraulic structures using pressure injection and polymer impregnation repair techniques. A laboratory-scaled test program was developed to (a) evaluate the effectiveness of selected injection adhesives to repair air-dried and water-saturated cracked concrete, and (b) evaluate the effectiveness of polymer-impregnation as a means for repairing highly cracked concrete. Four tasks were developed as guidelines for the research program:

Task A. Selection of Monomer Systems.

Task B. Optimization of Impregnation Techniques.

Task C. Evaluation of Physical and Mechanical Properties.

Task D. Optimization of Pressure Injection Techniques.

PART II: PHASE TWO TEST PROGRAM

Laboratory Test Program

7. The primary objectives of the laboratory test program were to (a) experimentally evaluate the effectiveness of selected adhesives to repair air-dried and water-saturated cracked concrete by pressure injection, and (b) evaluate the effectiveness of polymer-impregnation for repairing highly cracked concrete.

8. All tests were done on non-air-entrained concrete specimens. The concrete mixture used contained: portland cement - Type I, fine aggregate - graded silica sand, coarse aggregate - 3/8 in. nominal - graded crushed siliceous gravel, w/c = 0.42. Twenty-eight day compressive strength tests indicated that the concrete had an average compressive strength of 4800 psi.

9. Test specimens used in the program consisted of 3-in. diam by 6-in. long cylinders and 18-in. by 18-in. by 3 1/2-in. thick "cracked" concrete slabs reinforced with wire mesh.

10. The "cracked" slabs were fabricated by casting them individually into sheet metal forms. After the mixture had taken its initial set (3 to 4 hr after being fabricated), the corners of the forms were opened, and the slabs were flexed by hand until cracks began to open up in the surface. Cracks varying in width from hairline to 1/4 in. could be created this way (Figure 1). All slabs were sandblasted prior to being repaired.

Evaluation of Pressure Injection Repair Techniques

Preliminary adhesive evaluation

11. Eight adhesives were selected for evaluation in injection repair procedures; three epoxies, an emulsifiable polyester resin, furfuryl alcohol, a furan resin, a high molecular weight (HMW) methacrylate, and a polyurethane. These materials are described below and are summarized in Table 1.

Figure 1. Typical "cracked" concrete slab.

12. Denepox 40 epoxy is a very low viscosity, two-component epoxy-resin system designed specifically for pressure injection. It also can be used to repair cracks in horizontal surfaces by means of gravity penetration (i.e., ponding). It is a 100% solids resin which is insensitive to the presence of moisture.

Table 1. Injection Adhesives Evaluated.

ADHESIVE	VISCOSITY cP at 25°C	GEL TIME,[a] min
Denepox 40 epoxy (de neef America, Inc.)	40	∿60
Duralith epoxy (Dural International Corp.)	500 - 1000	13 - 18
Flexolith epoxy (Dural International Corp.)	700 - 1000	13 - 18
Altek 78-50ER3 emulsifiable polyester (Alpha Corp.)	50 - 80	∿10
Furfuryl alcohol (QO Chemicals, Inc.)	15	>240
QuaCorr 1001 furan resin (QO Chemicals, Inc.)	450	∿20
PCM-1100 high molecular weight methacrylate (Rohm and Haas Co.)	12 - 15	∿45
Percol S-100 polyurethane (Arnco Co.)	1.3	<2

[a]A 2-ml sample at 25°C.

13. Duralith epoxy is a low viscosity, high-modulus adhesive and mortar binder for repairs of structural concrete. It is a 100% solids, moisture-insensitive, two-component epoxy system suitable for application at temperatures as low as 30°F.

14. Flexolith epoxy is a low viscosity, low-modulus, high early strength epoxy mortar binder for overlays and horizontal patching. It is a 100% solids, moisture-insensitive, two-component epoxy suitable for application at temperatures as low as 30°F.

15. Altek 78-50ER3 is a low viscosity, water-emulsifiable polyester resin which can be cured at ambient conditions using an initiator/promoter system.

16. Furfuryl alcohol is a low viscosity, water soluble monomer produced from agricultural wastes such as corn cobs and oil hulls. It is characterized by low vapor pressure and low flammability.

17. QuaCorr 1001 furan resin is an acid-catalyzed, furfuryl alcohol-based resin system.

18. PCM-1100 is a high molecular weight (HMW) methacrylate developed specifically for use as a topical treatment for concrete pavement and bridge decks. It is a low viscosity, low volatility monomer which can be cured at ambient conditions using an initiator/promoter system.

19. Percol S-100 is a low viscosity, moisture-insensitive polyurethane designed specifically for use as a binder for a rapid setting polymer concrete patching system.

20. The initial evaluation of each adhesive was based upon the results of slant shear bond strength tests (ASTM C 882) using air-dried and water-saturated concrete cylinders. The cylinders were sawed at an angle of 30 deg from the vertical, bonded back together, and then tested in compression. The cut cylinders used to evaluate adhesive bond strength to water-saturated concrete were soaked in tap water for a minimum of three days. They were then wiped to a saturated, surface-dry (SSD) condition with a moist cloth and repaired. The results are summarized in Table 2.

21. In general, the tests indicate that each adhesive bonds better to air-dried concrete than to water-saturated concrete as shown by the reduction in bond strength between the two. The adhesives which exhibited the highest bond strength to air-dried concrete were the Duralith, Flexolith, and Denepox 40 epoxies, with bond strengths of 3205, 2968, and 1985 psi, respectively. The adhesives which exhibited the highest bond strength to water-saturated concrete were the Denepox 40 epoxy and the Altek polyester with bond strengths of 1110 and 700 psi, respectively. Overall, Denepox 40 epoxy and Altek polyester exhibited the least reduction in strength from air-dried to water-saturated concrete.

Table 2. Slant Shear Bond Strength Test Results.[a]

ADHESIVE	Air-Dried Concrete		Water-Saturated Concrete	
	Bond Strength, psi	Failure Zone	Bond Strength, psi	Failure Zone
Denepox 40 epoxy	1985	CJ[b]	1110	J
Duralith epoxy	>3205	C[c]	255	J
Flexolith epoxy	>2968	C	402	J
Altek 78-50ER3 polyester	1302	CJ	700	J
Furfuryl alcohol	1166	J	0[e]	—
QuaCorr 1001 furan resin	49	J[d]	0[e]	—
PCM-1100 HMW methacrylate	856	J	280	J
Percol S-100 polyurethane	745	CJ	49	J

[a]ASTM C 882, Type I, Grade 1 resin system. [b]CJ = concrete and joint. [c]C = concrete only. [d]J = joint only. [e]Resin did not cure.

22. Because of the low bond strengths exhibited by the QuaCorr 1001 furan resin to both air-dried and water-saturated concrete and the low bond strengths exhibited by the furfuryl alcohol and the Percol S-100 polyurethane to water-saturated concrete, they were not considered further as injection adhesives.

Repair of cracked concrete by injection

23. Laboratory tests were done to evaluate the effectiveness of selected adhesives to repair highly deteriorated, cracked concrete by injection, using 18 by 18 by 3 1/2 in. thick slabs. Air-dried and water-saturated slabs were repaired. Crack widths at the surface of the slabs varied between <0.1 and 5 mm.

24. The injection procedure used to repair the slabs was as follows:

a. Sandblast the slab to remove surface laitance.

b. Clean out cracks with compressed air.

c. Glue injection ports to the surface of the slab.

d. Coat the surface and sides of the slab with a gel epoxy to seal the surface of the cracks and prevent leakage of the injected adhesive.

e. Take pre-injection pulse velocity measurements.

f. Inject slab.

g. Take post-injection pulse velocity measurements.

h. Core slab, run splitting tensile strength tests on sections cut from the cores.

25. The water-saturated slabs were soaked in water for a minimum of three days between steps 2 and 3. They were then patted dry to a SSD condition before the injection ports (1-in. diam wooden dowel into which a hole had been drilled) were glued to the surface. Because of the small quantities of materials used to repair the slabs, all the injection work was done by hand using plastic syringes (Figure 2).

26. The effectiveness of the repairs was evaluated by visual examination of cores removed from each slab, by means of pre-injection and post-injection ultrasonic pulse velocity measurements, and by splitting tensile strength tests done on discs cut from the cores removed from the repaired slabs.

27. Ultrasonic pulse velocity measurements were made with a Pundit Portable Ultrasonic Tester (Figure 3) and are summarized in Table 3. Pre-injection and post-injection measurements were taken at three spots located along the height of the slab, approximately at the quarter points.

28. Splitting tensile strength tests (ASTM C 496) were done using discs cut from 3-in. diam cores taken from the repaired slabs. The discs were generally cut from the top 1 1/2 to 2 in. of the cores. Thickness of the discs was limited by the reinforcing mesh located near the midpoint of the cores. Splitting tensile strength test results are summarized in Table 4.

Table 3. Summary of Ultrasonic Pulse Velocity Data.

ADHESIVE	ULTRASONIC PULSE VELOCITY MEASUREMENTS, ft/sec[a]							
	PRE-INJECTION				POST-INJECTION			
	A[b]	B[b]	C[b]	AVG	A	B	C	AVG
AIR-DRIED CONCRETE								
Altek 78-50ER3 polyester	13,759	7,884	13,741	11,795	14,619	13,580	14,352	14,184
Flexolith Epoxy	10,490	7,474	12,405	10,123	13,905	14,036	14,727	14,223
Duralith Epoxy	11,714	10,489	11,714	11,306	14,543	14,267	14,977	14,596
Denepox 40 Epoxy	11,070	10,101	7,118	9,430	14,563	14,354	14,102	14,340
PCM-1100 HMW Methacrylate	10,678	9,675	11,917	10,757	14,323	14,948	14,971	14,747
WATER-SATURATED CONCRETE								
Altek 78-50ER3 polyester	13,741	14,230	14,630	14,200	14,513	14,713	14,630	14,619
Flexolith Epoxy	11,194	11,111	10,870	11,058	15,000	15,000	15,151	15,050
Duralith Epoxy	13,274	11,858	13,100	12,744	14,493	14,354	14,218	14,355
Denepox 40 Epoxy	12,110	10,714	10,273	11,032	14,971	15,000	14,748	14,906
PCM-1100 HMW Methacrylate	NR[c]	11,135	14,477	12,806	NR	14,040	14,812	14,426

[a] Uncracked concrete had a pulse velocity of 14,000 to 15,000 ft/sec.
[b] A, B, and C are reading locations at selected points along the height of the slab.
[c] NR = No reading taken.

Figure 2. Repair of slab by injection using a plastic syringe.

29. The results of the ultrasonic pulse velocity tests indicate that each of the adhesives was effective in restoring the integrity of the slabs, regardless of whether the slabs were air-dried or water-saturated. The average post-injection pulse velocities of the repaired slabs were all within the range measured for sound, uncracked concrete, i.e., between 14,000 and 15,000 ft/sec. Ultrasonic pulse velocities for sound, uncracked water-saturated concrete are approximately 2% lower than those values measured for sound, uncracked, air-dried concrete.

30. A visual examination of the cores indicated that with the exception of those slabs which were repaired with the PCM-1100 HMW methacrylate, approximately 95% of the crack network within each slab was filled with

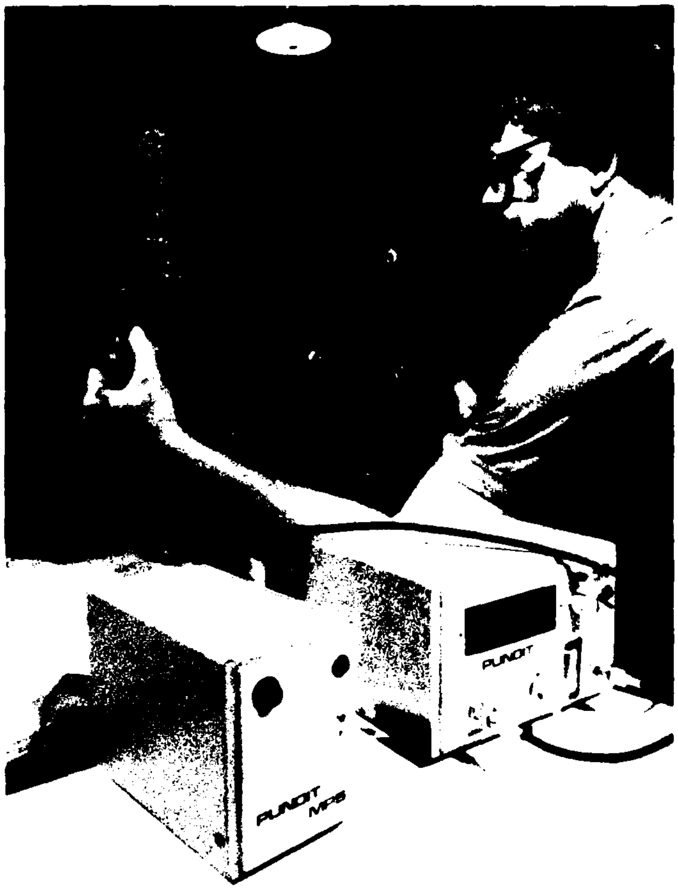

Figure 3. Ultrasonic pulse velocity test.

adhesive (Figure 4). The crack network within the slabs repaired with the PCM-1100 contained only 50 to 80% adhesive. Drainage of adhesive from the crack network within these slabs probably was due to the low viscosity and long gel time of the system.

31. The results of the splitting tensile strength tests indicate that each of the adhesives can restore the structural integrity of both air-dried and water-saturated cracked concrete. In fact, all adhesives exhibited a higher splitting tensile strength for the wet repairs than for the dry repairs. Denepox 40 exhibited the highest strength for both the dry and wet repairs. The air-dried slabs repaired with Denepox 40 epoxy exhibited a splitting tensile strength of 923 psi while the value for the water-saturated

Table 4. Splitting Tensile Strength Test Results for Slabs Repaired by Injection.

ADHESIVE	AIR-DRIED CONCRETE		WATER-SATURATED CONCRETE	
	SPLIT TENSILE STRENGTH, psi[a]	FAILURE ZONE	SPLIT TENSILE STRENGTH, psi	FAILURE ZONE
Altek 78-50ER3 polyester	430	Concrete	524	Concrete and crack
Flexolith Epoxy	500	Concrete	591	Concrete and crack
Duralith Epoxy	595	Concrete	652	Concrete and and crack
Denepox 40 Epoxy	923	Concrete	703	Concrete and crack
PCM-1100 HMW Methacrylate	410	Concrete	435	Concrete and crack

[a] Uncracked, air-dried concrete had a splitting tensile strength of 616 psi.

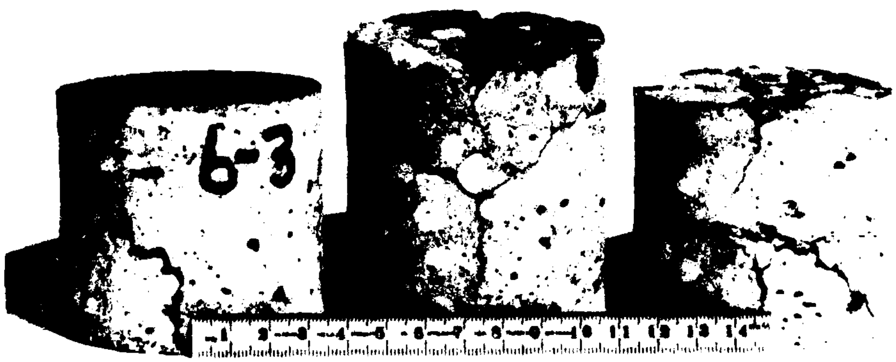

Figure 4. Cores removed from slabs repaired by injection.

slabs was 703 psi. Concrete used as the control had an average splitting tensile strength of 616 psi. After testing, an examination of the disc cross-sections indicated that failure of the samples generally occurred in a zone outside the filled cracks (Figure 5).

32. Results of the slant shear, splitting tensile strength, and pre-injection and post-injection ultrasonic pulse velocity tests showed that the most promising injection adhesive is Denepox 40 epoxy. The most promising non-epoxy adhesive is Altek 78-50ER3 emulsifiable polyester. Tests were conducted, therefore, to verify the ability of these two resins to repair water-saturated, cracked concrete.

33. One water-saturated, cracked concrete slab was repaired by injection with each adhesive. The slabs had been soaked in water for 11 days to ensure complete saturation of the concrete. In addition, the crack network

Figure 5. Splitting tensile strength test specimen after failure.

of each slab was fully injected with water several times before it was repaired to evaluate the ability of each adhesive to displace water present within the crack network. The ultrasonic pulse velocity measurements and splitting tensile strength results are summarized in Table 5.

34. Both adhesives seem to be equally effective in repairing highly saturated slabs. The average post-injection pulse velocities were measured to be between 14,000 and 15,000 ft/sec. The splitting tensile strengths measured for the slabs repaired with Altek polyester and Denepox epoxy were 76% and 82% of the control values measured for the uncracked controls. Visual examination of the cores removed from each slab showed that the cracks contained 90 to 100% adhesive, indicating that both adhesives are capable of displacing water.

Table 5.

A. Ultrasonic Pulse Velocity Test Results

ADHESIVE	PULSE VELOCITY, ft/sec[a]					
	PRE-INJECTION			POST-INJECTION		
	A[b]	B[b]	AVG	A	B	AVG
Altek 78-50ER3	13,224	14,360	13,792	14,501	14,524	14,513
Denepox 40	14,360	14,524	14,442	14,863	14,692	14,778

[a] Uncracked concrete had a pulse velocity of 14,000 to 15,000 ft/sec.
[b] Test locations located at third points of slab height.

B. Splitting Tensile Strength Test Results

ADHESIVE	SPLITTING TENSILE STRENGTH, psi
Altek 78-50ER3	501
Denepox 40	539
———	660[a]

[a] Average of a total of six control cores removed from uncracked areas within each slab.

Evaluation of Polymer Impregnation Repair Techniques

Impregnation monomers

35. Four monomer systems were selected for evaluation for use in polymer impregnation repair techniques; they were furfuryl alcohol, PCM-1100 HMW methacrylate, and two methyl methacrylate (MMA)-based systems. The furfuryl alcohol and PCM-1100 HMW methacrylate were evaluated as sealants/impregnants for horizontal surfaces and the two MMA-based monomer systems as impregnants for vertical surfaces.

Polymer impregnation of vertical surfaces

36. Most of the impregnation on vertical surfaces was performed using a MMA-based monomer system consisting of 83 wt% MMA, 5 wt% trimethylolpropane trimethacrylate (TMPTMA) cross-linking agent, and 12 wt% polymethyl methacrylate (PMMA). To this system was added 1% A-174 silane coupling agent, 1% surfynol 440 surfactant, and 1% Luazo-79 2-t-butylazo-2-cyanopropane initiator by weight of the monomer mixture. This monomer system has a viscosity of 5 to 6 cP at 75°F.

37. All vertical impregnations were done using a soaking jacket which was braced against the face of the slab (Figure 6). The soaking jacket was made of 0.05 in. thick stainless steel sheet with a 0.5 in. thick stainless steel spacer around the edge of the jacket. A closed-cell polyurethane was used as a gasket material to seal the soaking jacket to the face of the slab. The sides and back of all slabs were coated with a gel epoxy to prevent leakage of monomer during soaking.

38. The impregnation process consisted of a monomer soaking time of 4 hr at atmospheric pressure. Then the monomer was drained from the impregnation jacket, the jacket was removed, and the slab was placed inside an enclosure into which steam was injected. The slabs were steam cured for a minimum of 2 hr at an ambient temperature of 80° to 95°C, after which they were cured in an oven at 100°C for 12 hr. Oven curing shortened the steam curing cycle and ensured complete polymerization of the monomer.

A. Laboratory set-up for vertical impregnation studies.

B. Close-up of slab inside impregnation soaking jacket.

Figure 6.

39. One series of tests was done using oven-dried, air-dried, and water-saturated slabs to evaluate the degree of dryness necessary to obtain good impregnation results. The oven-dried slabs were kept at 110°C for a minimum of 2 days to ensure removal of free-water from the concrete. The slabs were cooled for 12 hr at 24°C prior to impregnation. The water-saturated slabs were soaked for 1 wk prior to being impregnated. Evaluation of each slab was based upon visual examination and pre-impregnation and post-impregnation ultrasonic pulse velocity and splitting tensile strength tests.

40. A visual examination of the surface of each slab suggested there was no polymer present in the cracks at the surface, regardless of the initial degree of dryness of the concrete. Crack width at the surface varied between 0.1 and 8 mm. An examination of the cores also revealed very little polymer in any of the cracks throughout the depth of each slab. However, a close examination of the core cross-sections removed from the oven-dried concrete showed a darkening of the concrete surrounding the cracks, indicating that there might be some polymer present (Figure 7). Thermogravimetric analysis (TGA) of powdered samples removed from this area indicated a polymer loading of ∿10 wt% in the oven-dried concrete, ∿3 wt% in the air-dried concrete, and <1 wt% in the water-saturated concrete. Since there was a lack of visible evidence of polymer within the crack network, one of the oven-dried slabs was injected with Denepox 40 epoxy after being impregnated.

41. The pulse velocity data, summarized in Table 6, indicate that despite the fact that little polymer was seen within the crack network, there was improvement in the pulse velocities of each slab after impregnation. The oven-dried slabs exhibited the highest post-impregnation pulse velocities while the water-saturated slabs had the lowest. The pulse velocity of the oven-dried concrete was further improved by injecting the crack network with epoxy after impregnation. Post-impregnation epoxy injection appears necessary if a structure is impregnated with a low viscosity monomer since low viscosity monomers, which are required if penetration of the concrete pore structure is to be obtained, will drain from the larger cracks before they can be polymerized.

Table 6. Ultrasonic Pulse Velocity Data for Slabs Repaired by Polymer Impregnation.

CONDITION OF SLAB	PULSE VELOCITY MEASUREMENTS, ft/sec[a]											
	Pre-Impregnation				Post-Impregnation				Post-Injection			
	Reading Location											
	A	B	C	AVG	A	B	C	AVG	A	B	C	AVG
OVEN DRIED	12,865	13,505	8,885	11,752	14,068	14,130	13,921	14,040	—	—	—	—
OVEN DRIED	12,268	12,517	13,300	12,695	14,070	13,792	13,541	13,801	14,844	14,895	15,046	14,928
AIR DRIED	8,582	8,485	11,628	9,565	13,021	13,308	13,889	13,406	—	—	—	—
WATER-SATURATED	6,161	13,285	5,830	8,425	11,839	11,879	11,616	11,778	—	—	—	—

[a]Uncracked concrete had a pulse velocity of 14,000 to 15,000 ft/sec.

Figure 7. Cores removed from slab repaired by impregnation and injection (darkened areas around cracks indicate polymer impregnated concrete).

42. The results of the splitting tensile strength tests indicate that despite the lack of visual evidence of polymer in the crack network there is enough polymer within the network to bond the cores together (Table 7). The average splitting tensile strengths of the discs removed from the oven-dried slab varied between 303 and 726 psi, while those removed from the air-dried concrete averaged 488 psi. The higher strengths obtained for discs cut from the lower portions of the cores from the oven-dried slab are probably due to the fact that the monomer did not drain as readily from the interior of the slab as it did from the surface. The water-saturated concrete slab had a splitting tensile strength of 286 psi.

43. A comparison of the splitting tensile strengths of the slab which was impregnated and then injected with epoxy and for slabs which only were injected with epoxy indicates that impregnation of the concrete surrounding the cracks resulted in a 24% increase in strength. This comparison demonstrates that the two methods can be used in conjunction to effectively repair and improve the quality of highly cracked concrete.

44. Because of the lack of visible evidence of polymer within the crack network, two air-dried slabs were impregnated with a thickened MMA-based monomer system in an attempt to eliminate drainage and fill the crack network. The monomer system consisted of 67 wt% MMA, 5 wt% TMPTMA, and 28 wt% PMMA. To this mixture was added 1 wt% each A-174 silane, surfynol 440 surfactant and Luazo 79 initiator. The system has a viscosity of 65 cP at 24°C.

Table 7. Splitting Tensile Strengths for Slabs Repaired By Polymer Impregnation.

CONDITION OF SLAB	SPLIT TENSILE STRENGTH, psi[a]	LOCATION OF TEST SPECIMEN	FAILURE ZONE
OVEN DRIED (Impregnation Only)	303	Top 1.5 in. of core	Crack
	726	Bottom 2 in. of core	Crack and Concrete
OVEN DRIED (Impregnation and Injection)	1142	Top 2 in. of core	Concrete
AIR DRIED (Impregnation Only)	488	Top 2 in. of core	Crack, some white polymer noted on face of crack after failure
WATER-SATURATED (Impregnation Only)	286	Top 2 in. of core	Crack, some white polymer noted on face of crack after failure
AIR DRIED (Injection Only)	923	Top 2 in. of core	Concrete

[a]Sound concrete had a splitting tensile strength of 616 psi. Highly cracked concrete has a splitting tensile strength of 0 psi. Split tensile strengths are an average of three to five specimens.

45. The first slab was impregnated for 10 min at an overpressure of 15 psi. Original plans called for impregnating the slab for 1 hr; however, the soaking time was reduced to 10 min because of excessive leakage of monomer through the seals of the impregnation jacket. The slab then was steam-cured for 3 1/2 hr at 97°C. Evaluation was based upon pulse velocity measurements and splitting tensile strength test results.

46. The results of these tests indicated that the slab had an average pre-impregnation pulse velocity of 10,203 ft/sec, an average post-impregnation pulse velocity of 13,446 ft/sec, and an average splitting tensile strength of 333 psi. The splitting tensile strength is ∿31% less than that of the air-dried slab impregnated with the low viscosity MMA-based system. A visual examination of the crack network, however, revealed that it contained about 30 to 40% polymer. This is a significant increase over the amount of polymer found in the crack network of the slab impregnated with the low viscosity system. The higher strength exhibited by the slab impregnated with the low-viscosity system is probably the result of the monomer's having penetrated the concrete around the crack network, thereby strengthening it, as opposed to only filling the network.

47. After a new gasket was installed on the impregnation jacket, a second slab was impregnated for 1 hr at an overpressure of 3 psi. With the exception of a small pin-hole sized leak in the epoxy coating, no problems were encountered during the impregnation of the slab. The monomer then was drained from the impregnation jacket. The slab was steam-cured for 6 hr at 85° to 92°C. Evaluation was based upon ultrasonic pulse velocity measurements and splitting tensile strength test results.

48. The slab had an average pre-impregnation pulse velocity of 13,032 ft/sec, an average post-impregnation pulse velocity of 14,372 ft/sec, and an average splitting tensile strength of 641 psi. The splitting tensile strength is ∿31% higher than that measured for the air-dried slab impregnated with the low viscosity MMA-based system and ∿92% higher than that measured for the slab impregnated with the high viscosity MMA-based system. In fact, the strengths are greater than those measured for the control concrete.

However, visual examination of the cores indicate that the crack network contained only 50 to 60% polymer, indicating that the higher viscosity system will also drain from the crack network prior to polymerization.

Polymer impregnation of horizontal surfaces

49. Two highly cracked, air-dried slabs were repaired horizontally by ponding PCM-1100 HMW methacrylate resin on the surface of the slab and allowing it to penetrate into the crack network. This work evaluated the effectiveness of PCM-1100 to seal and repair cracks in horizontal surfaces, the specific application for which the system was developed. The resin was cured using an initiator-promoter system which gave the resin a gel time of approximately 45 min. Tests done using discs cut from cores indicated that the splitting tensile strength of the repaired slabs averaged 553 psi, as compared to a control value of 616 psi. The splitting tensile strength of slabs repaired horizontally was ∿35% higher than the strengths obtained for the concrete repaired vertically using the resin as an injection adhesive. Because of its low viscosity, the resin probably tends to drain slightly from vertical cracks prior to polymerizing. Visual examination of the cores taken from slabs repaired horizontally indicated that the crack network was completely filled with polymer, while cores from slabs repaired vertically indicated some voids within the network.

50. One air-dried slab was impregnated horizontally by ponding furfuryl alcohol (FA) on the surface and allowing it to penetrate. In bulk, the FA system has a cure time of less than 3 min at room temperature; however, in a thin layer such as that which exists within the crack network, it takes in excess of 6 hr to cure.

51. Splitting tensile strength tests run on cores removed from the repaired slab indicated that the slab had a strength of 237 psi, compared to a control value of 616 psi. Visual examination of the cores indicated the cracks were completely filled with polymer and that the concrete surrounding the crack network was impregnated up to a depth of approximately 0.25 in.

PART III: SUMMARY AND RECOMMENDATIONS

52. According to a survey by the U.S. Army Corps of Engineers (McDonald and Campbell, 1985), the three most common problems encountered in the Corps' civil works concrete hydraulic structures were (a) cracking, (b) seepage, and (c) spalling. These three problem areas accounted for 77% of the 10,096 deficiencies identified during a review of available inspection reports. Concrete cracking was observed most often, accounting for 38% of the total deficiencies. While in situ repair procedures may not be readily applicable to repair seepage, they seem to be suited to repairing deterioration due to cracking and spalling.

53. In Phase One of the program, three crack-repair techniques and two techniques for repairing spalled concrete were identified as being most applicable for the in situ repair of concrete hydraulic structures. The repair techniques include pressure injection, polymer impregnation, and the addition of reinforcement. In conjunction with these repair procedures, thin reinforced overlays and shotcrete were identified as methods to be used to repair spalled concrete and to resurface a cracked structure after it has been repaired. Based upon these findings, BNL developed a laboratory-scaled testing program in Phase Two to evaluate two of these crack repair methods: pressure injection and polymer impregnation. The results are summarized in this report.

54. The primary objectives of the laboratory program were to experimentally evaluate (a) the effectiveness of selected adhesives to repair air-dried and water-saturated cracked concrete by means of pressure injection, and (b) the effectiveness of polymer-impregnation for repairing highly cracked concrete.

55. Eight adhesives were selected for evaluation for use in injection repair procedures: three epoxies, an emulsifiable polyester resin, furfuryl alcohol, a furan resin, a high molecular weight (HMW) methacrylate, and a polyurethane. Based upon the results of slant shear bond strength, ultrasonic pulse velocity, and splitting tensile strength tests, the most promising adhesive was Denepox 40, a two-component, very low viscosity epoxy system designed specifically for pressure injection repairs.

56. Air-dried and water-saturated cracked concrete slabs repaired by injection with Denepox 40 epoxy had ultrasonic pulse velocities varying between 14,102 and 15,000 ft/sec, as compared to pre-injection pulse velocities of 7118 to 12,110 ft/sec. Sound, uncracked concrete had a pulse velocity of 14,000 to 15,000 ft/sec. Splitting tensile strengths for air-dried and water-saturated concrete repaired by injection were 923 and 703 psi, respectively, compared to a value of 616 psi for uncracked concrete.

57. The most promising non-epoxy adhesive was the Altek 78-50ER3 emulsifiable polyester. Concrete slabs repaired with this adhesive exhibited ultrasonic pulse velocities varying between 13,530 and 14,713 ft/sec, and splitting tensile strengths of 430 and 524 psi respectively, for air-dried and water-saturated concrete.

58. Tests were done to evaluate the effectiveness of polymer impregnation as a means of repairing cracked concrete. Four monomer systems were tested: PCM-1100 HMW methacrylate, furfuryl alcohol, and two methyl methacrylate (MMA)-based systems. The PCM-1100 HMW methacrylate and furfuryl alcohol were assessed as sealants/impregnants for horizontal surfaces; the two MMA-based monomer systems, as impregnants for vertical surfaces.

59. Oven-dried, air-dried, and water-saturated cracked concrete slabs were impregnated in a vertical position with a MMA-based monomer system with a viscosity of 5 to 6 cP to determine the required degree of dryness necessary for good impregnation results. The vertical impregnation of slabs was accomplished using an impregnation jacket braced against the face of the slab.

60. In general, ultrasonic pulse velocity and splitting tensile strength tests indicated that the best results were obtained when the concrete was oven-dried prior to impregnation. Splitting tensile strengths of repaired slabs varied between 557 psi for oven-dried concrete and 286 psi for water-saturated concrete. Visual examination of cores removed from the repaired slabs, however, indicated that there was very little polymer in any of the cracks throughout the depth of each slab. This lack of polymer was most likely the result of drainage of the low viscosity monomer from the crack network prior to polymerization. Thermogravimetric analysis indicated

the presence of polymer within the pore structure of the concrete surrounding the crack network. Polymer loadings for the oven-dried, air-dried, and water-saturated concrete were ∿10 wt%, ∿3 wt%, and <1 wt%, respectively.

61. Because of the lack of polymer within the cracks, two air-dried slabs were pressure-impregnated with a MMA-based monomer system with a viscosity of ∿65 cP in an attempt to eliminate monomer drainage and fill the network. One experiment was only marginally successful because of excessive leakage of monomer from around the impregnation jacket. The cores removed from this slab showed the crack network contained 30 to 40% polymer; the slab had an average splitting tensile strength of 333 psi. The second slab was successfully impregnated for 1 hr at an overpressure of 3 psi. Examination of test cores indicated that the crack network contained 50 to 60% polymer. The repaired slab had a post-impregnation ultrasonic pulse velocity of 14,372 ft/sec and a splitting tensile strength of 641 psi.

62. One oven-dried slab, which had been impregnated with the low viscosity MMA-based monomer system, was injected with Denepox 40 epoxy in order to fill the crack network and evaluate the compatibility of the two repair techniques. Measurements of the physical properties of the slab indicated improvements in the pulse velocity and splitting tensile strengths over those of slabs which had only been impregnated.

63. A series of tests were performed to evaluate the effectiveness of two monomers, furfuryl alcohol and PCM-1100 HMW methacrylate, to seal and repair cracks in horizontal surfaces. The slabs were repaired by ponding the monomer on the surface of the slab and allowing it to penetrate into the crack network. The slabs repaired with the PCM-1100 had an average splitting tensile strength of 553 psi, while those repaired with the furfuryl alcohol had a strength of 237 psi. In each instance, the crack network was filled with polymer.

64. Based upon our results, the following repair procedures are recommended for use in the in situ repair of concrete hydraulic structures.

65. If the basic quality of the concrete is good, it is recommended that pressure injection repair techniques be used. Tests have shown that pressure injection repair techniques are very effective in restoring the

structural integrity of highly cracked, non-air-entrained concrete. The Denepox 40 epoxy appears to be the most promising of the adhesives evaluated. If an adhesive other than an epoxy is needed or wanted, the Altek 78-50ER3 emulsifiable polyester would appear to be the most suitable.

66. It is recommended that future work in this area include:

a. Laboratory studies to evaluate the durability characteristics, such as resistance to cycles of freezing and thawing of air-dried and water-saturated cracked concrete repaired by injection.
b. The development and optimization of the actual repair techniques to be used in the field.
c. A field demonstration(s) of the repair process.
d. A monitoring program to evaluate the field work.
e. The compilation of information pertaining to the health, safety, and environmental effects of the various chemicals (i.e., adhesives and solvents) used in the repair process.

67. If the basic quality of the concrete is poor, it is recommended that the concrete first be impregnated with polymer to improve its durability characteristics and then pressure-injected to seal the crack network. The two procedures can be used together to effectively repair highly deteriorated cracked concrete.

68. Because of a problem with monomer drainage prior to polymerization, at this time polymer impregnation is not recommended as a repair technique for sealing cracks in vertical surfaces. However, it is an excellent procedure for improving the strength and durability characteristics of low-quality concrete, as documented in the Feasibility Study (Webster and Kukacka, 1987).

69. The proposed repair procedure involves pre-drying the concrete and then impregnating it with a very low viscosity MMA-based monomer system which is subsequently polymerized. The polymer impregnated concrete then is pressure-injected with an adhesive such as Denepox 40 epoxy.

70. A number of variables involving the impregnation procedure need to be studied further before this technique can be effectively implemented. Future research should include:

a. Studies to determine the drying times required to remove moisture from the walls of the crack network at a specified depth from the surface of the concrete.

b. Determination of the impregnation time and pressure, if necessary, to allow penetration of the monomer into the crack network and its subsequent penetration into the walls of the network.

c. An evaluation to determine the applicability of vacuum techniques for drying and impregnating concrete. Balvac/Firstrhyme, a company located in Buffalo, New York, has recently begun repairing concrete structures by a vacuum injection process. Discussions with company personnel could be helpful.

d. Laboratory experiments to evaluate the durability characteristics of concrete repaired utilizing the impregnacion-injection technique.

e. The development and optimization of the repair techniques to be used in the field.

f. A field demonstration(s) of the repair process.

g. A monitoring program to evaluate the field work.

h. The compilation of information pertaining to the health, safety, and environmental effects of the various chemicals (i.e., monomers, adhesives, and solvents) used in the process.

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