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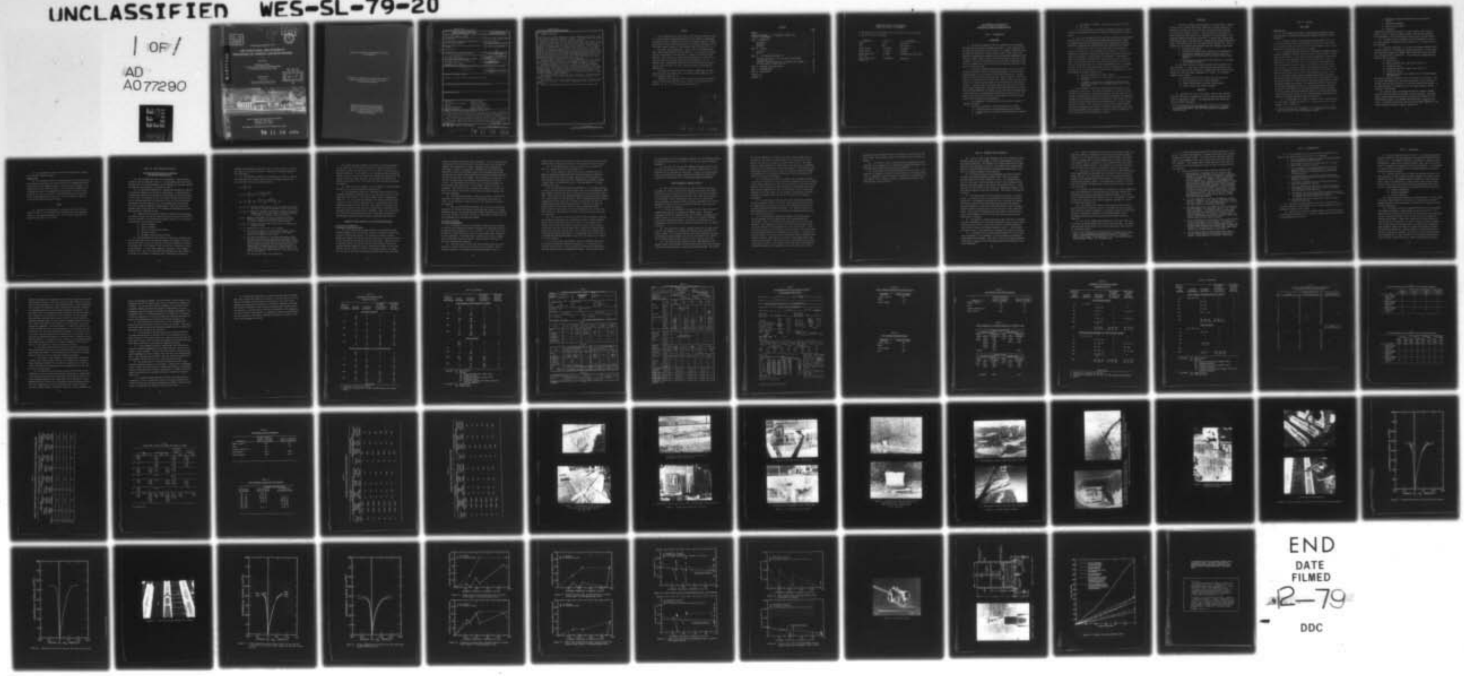

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THE STRUCTURAL AND DURABILITY PROPERTIES OF VARIOUS CONCRETE REPAIRS

by

Carl E. Pace

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U. S. Army Engineer Waterways Experiment Station
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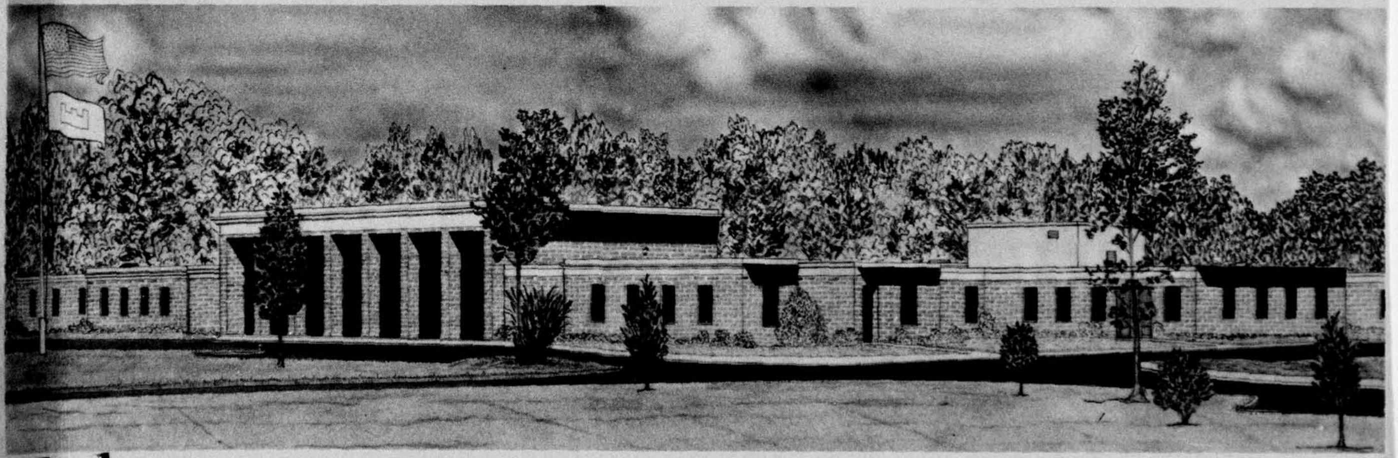
September 1979

Final Report



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Many old concrete structures exist and are in need of repair. The structural deterioration will accelerate with advancing age and progressively diminish their service lives. Methods of evaluation and repair are necessary.

Durable concrete can be produced and placed; therefore, the main problem is to have a durable interface between the old and the new concrete. The bonding of epoxy resin, cement mortar, latex polymer mortar, and latex polymer mortar plus fiberglass fabric was tested in a freezing and thawing environment subjected (Continued)

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20. ABSTRACT (Continued)

to conditions of complete submergence, one-half submergence, and stress conditions. Many surfaces are subjected to abrasion. The latex polymer was tested to determine if it helped to increase abrasion resistance.

These tests showed that for early ages of repair water will collect at the interface of the old and new concrete and when the water concentration is sufficient and freezing occurs, the overlay will be debonded. The epoxy bond exhibited a constant number of specimen failures with cycles of freezing and thawing. The concrete-to-concrete bonding had more specimens fail at early intervals of freezing and thawing than in later intervals, indicating that as similar characteristics develop between the repair and the aged concrete, less water collected at the interface. All four bonding types had about the same final percent failures in the freezing and thawing environment, which in all probability suggests that the failures due to water collecting at the interface for early ages of repair are essentially comparable.

Specimens which were subjected to freezing and thawing plus stress showed more failures than the unstressed specimens. The specimens which were one-half submerged showed no failure in the freezing and thawing environment.

Epoxy bonding should not be used in a freezing and thawing environment where there is a possibility of water collecting at the interface. The latex polymer showed a considerable decrease in shear strength with cycles of freezing and thawing. The concrete-to-concrete bonding to a dry interface is an acceptable bonding. The fiberglass fabric is a promising material to be added in thin overlays to prevent cracking.

The stressing of the specimens at various intervals of freezing and thawing had an adverse effect on the durability of the shear strength of the repaired interface.

Any eccentricity of the load causing shear at the repair interface produces tension on the interface. Tension was a predominant factor in shear stress failures.

A concrete overlay should be placed on a surface which is surface dry.

PREFACE

This investigation was performed by the Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES), as implemented by WESVT DF dated 1 October 1977, subject, "In-House Laboratory Independent Research (ILIR), FY78 and FY79," for the Assistant Secretary of the Army (R&D), under Project No. 4A161101A91D, Task 02, Work Unit 121 08.

The report was prepared by Dr. Carl E. Pace, Structures Branch (SB), Engineering Mechanics Division (EMD), SL. Mr. Martin Rohn helped prepare the specimens, including fabric. Messrs. Willard Lee, James Eskridge, Frank Stewart, and John Oak helped prepare the concrete mixture and also cast, prepared, and tested the specimens. Mr. Roy Campbell made a significant contribution in his discussion on condensing the data collected. Mr. Dale Glass supervised the freezing and thawing tests.

The study was conducted under the general supervision of Messrs. Bryant Mather, Acting Chief, SL; J. M. Scanlon, Chief, EMD, SL; and J. E. McDonald, Chief, SB, SL.

Commanders and Directors of WES during the preparation and publication of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

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

Multiply	By	To Obtain
inches	25.4	millimetres
feet	304.8	millimetres
pounds (mass)	0.4535924	kilograms
pounds (force)	4.448222	newtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals

THE STRUCTURAL AND DURABILITY PROPERTIES OF VARIOUS CONCRETE REPAIRS

PART I: INTRODUCTION

Background

1. The Corps of Engineers (COE) is responsible for maintaining and improving our nation's navigable waterways. In this capacity COE has constructed many concrete structures. For example, navigation locks and dams have been built for many years and are a vital link in this country's transportation network as well as providing significant recreation facilities. Many of these structures are now old and are in need of repair. The COE is responsible for the operation, maintenance, and repair of substantially all of the major lock and dam structures it has built over the past years.

2. There are 50 power-producing dams without locks and 241 lock and dam structures of which 16 are power-producing. Of the 66 power-producing dams, 34 (52 percent) are more than 20 years old. Seventy percent of the 241 locks and dams are more than 20 years old, with more than half (55 percent) over 40 years old. Many of these concrete structures do not contain concrete which is air-entrained nor were they constructed using the latest technology which will allow them to effectively resist weathering. Many have already deteriorated to the point where continued exposure with advancing age will allow accelerated deterioration which will progressively diminish their service lives. The major repairs are costly and should be performed in the most durable manner with the most effective materials.

3. A few examples of deteriorated locks and dams are given in Figures 1 through 7.

4. The repair procedure is best developed in four phases.

   a. A condition survey, including sampling and testing.

   b. A final analysis, evaluation, and development of remedial action.

c. Development of designs, repair plans, and specifications.

d. The repair.

5. It is very important to perform a systematic analysis of deteriorated or distressed structures to determine the problems and remedial action.

6. The first two phases have already been systematically developed. Currently the U. S. Army Engineer Waterways Experiment Station (WES) is forming evaluations and recommending repair, maintenance, and rehabilitation procedures for existing structures throughout the country.

7. It may be very costly if the evaluation is delayed until repair is uneconomical, and a replacement is necessary. The cost of building new structures, especially large ones, has become so exorbitant that it is difficult to obtain funds for replacement. This makes it essential to maintain and repair the structures at the most economical time. In many cases, especially for gravity structures, a structure's life can be extended many years if the deteriorated surface is repaired. At times in the past, the repairs have not been performed until the structure is in a state where it is apparent that something must be done. The reasons for delaying repairs are:

a. Costs and complexity of repair efforts.

b. Systematic guidelines for the repair of old structures do not exist.

c. In general, proven repair techniques and materials and efficient equipment for performing repairs have not been identified.

8. New equipment, materials, and techniques for repair are developing at a rapid rate. This rapid development is relatively recent, and many of the materials and repair procedures have not stood the test of time. The adequacies of repair materials and procedures are being proclaimed by various manufacturers and contractors. Most claims are from intuition or from limited and short-term experiences. Very few claims have been verified. This verification requires that detailed studies be made and information consolidated as guidance concerning repair materials and procedures. This guidance can then be used in planning the repair of many structures throughout the country.

Objective

9. Concrete technology has progressed to the point where a durable concrete can be produced and placed; therefore, the main problem is to bond the new concrete to the old and have a durable interface between the overlay and original concrete. This then indicates that good repairs (especially with concrete) are dependent on the performance of the interface between the new and old concrete. In this study overlays were made using an epoxy resin (Material 1), cement mortar, polymer (Material 2) mortar, and polymer mortar plus fiberglass fabric (Material 3). The performance of the interface was evaluated under the following conditions:

- a. Various bonding agents.
- b. Freezing and thawing effects (CRD-C 20-76, Procedure A*).
- c. Freezing and thawing plus stress effects to give comparable rates of deterioration at areas of stress concentration.
- d. Various degrees of saturation while exposed to a freezing and thawing environment.

10. For many surfaces, the repair material must have good abrasion resistance. In this study, limited testing was performed to see how well the latex polymer (Material 2) affects abrasion resistance when using silica sand and bauxite aggregate as a filler. The specimens tested were as follows:

- a. Polymer modified silica sand mortar (two specimens).
- b. Silica sand mortar (one control specimen).
- c. Polymer modified bauxite mortar (two specimens).
- d. Bauxite mortar (one control specimen).

Approach

11. Specimens were cast in two stages. Half of the specimens were cast and cured to represent the old concrete and half were cast later to represent the repair. The specimens were then tested and the test results evaluated.

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* U. S. Army Engineer Waterways Experiment Station, CE, "Handbook for Concrete and Cement," Aug 1949 (with quarterly supplements), Vicksburg, Miss.

PART II: TESTING

Test Plans

Original plan

12. The original test plans for evaluating the bonding of overlays subjected to freezing and thawing and stress conditions are given in Table 1.

13. Forty-two regular freezing and thawing specimens (3-1/2 by 4-1/2 by 16 in.*) were cast in two placements (Figure 8) and then cured in a fog room. Three specimens were cut from each member and their ends ground plane and parallel for effective testing.

14. Limestone aggregate concrete of approximately 4800-psi, 28-day ultimate compressive strength was used for the first placement to represent the aged concrete. The concrete mixture proportions, coarse aggregate data, and fine aggregate data are given in Tables 2, 3, and 4, respectively. One-half plus 1/8 in. of the depth of each member was cast and allowed to cure in a fog room for 78 days. This assured that the properties of the first placement had stabilized such that changes would be negligible and the concrete would represent old concrete. The 28-day stress-strain curves for the first placement are given in Figure 9. The 100-day (age at which specimens were started in freezing and thawing cycles) stress-strain curves for the first placement concrete is given in Figure 10. The top surface was then scraped (Figure 11) and the bonding agents were applied. The same concrete mixture as was used in the first placement was used for the second placement of specimens for both the epoxy (Material 1) bonding and concrete overlay bonding. The 22-day (age at which specimens were started in freezing and thawing cycles) stress-strain curves for the second placement epoxy bonding and concrete-to-concrete bonding are given in Figure 12.

15. A disadvantage of a concrete overlay is that the new concrete has low tensile strength and may crack. Cracks can occur due to many reasons, some of which are:

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* *A table of factors* for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

a. Reflective cracking from beneath and up through the overlay.

b. Drying and shrinkage.

c. Temperature gradients.

d. Overstress.

A significant consideration would be to add a fabric in the concrete overlay to give it tensile strength, thereby reducing the cracking, water penetration, and resulting deterioration of the concrete overlay.

16. The third group of specimens tested the bonding of an overlay which included a fiberglass fabric (Material 3) to increase its tensile strength.

17. From past experience, it is known that polymer modified mortar is highly durable in a freezing and thawing environment. In this study tests were planned using the polymer modified mortar with the inclusion of a fiberglass fabric (Material 3). The overlay was constructed from bottom to top as follows:

a. Aged concrete.

b. Polymer modified neat cement slurry (Table 5).

c. Fiberglass fabric.

d. Polymer modified neat cement slurry (Table 5).

e. Fiberglass fabric.

f. Topping of modified neat cement slurry and selected aggregate (Table 6).

The tensile strength of Material 1 has been tested to be 1750 psi. This is a great improvement over the tensile properties of plain concrete. In this study the shear resistance at the bond interface was tested. If the bond resistance is adequate, it will be a good system to prevent cracking in the overlay.

18. The last group of specimens was made by casting a polymer modified mortar directly onto the aged concrete specimens. The 22-day (age at which specimens were started in freezing and thawing cycles) stress-strain curves of the polymer modified mortar are given in Figure 13. The mixture proportions and the cube strengths (100-day) of the mortar are given in Tables 7 and 8, respectively.

19. The specimens for each of the above conditions were planned to be tested as shown in Table 1.

Changed plan

20. The specimens which were being subjected to freezing and thawing testing were checked at 56 cycles and due to the damage and failure of specimens at the bonding interface, the test plan was changed. The changed test plan is given in Table 9. The plans were changed because a significant number of specimens failed during the test and if they continued to fail at the same or a more accelerated rate, there would not be enough specimens for testing at various freezing and thawing cycles to give good statistical results.

Tests

21. The tests were performed in accordance with the plans presented in Table 9. The specimens were evaluated after each indicated period of freezing and thawing cycles. The indicated specimens were tested if they were still testable.

PART III: TEST RESULTS AND ANALYSIS

Specimen Bond Failures Due to Freezing and Thawing Conditions Only

22. The specimens were cast in two placements. Their material properties are as presented in Part II. The specimens were then started (22 days after the second placement) in the sequence of testing, freezing and thawing, and stressing, as outlined in Table 9.

23. The specimens scheduled for freezing and thawing were removed from the test chamber at 56 cycles for observation. It was found that a substantial number had failed due to the freezing and thawing process. If the failure of specimens in the test chamber continued or accelerated as the testing progressed, too few would be left to test and give good experimental results; therefore, all the specimens were incorporated into the freezing and thawing testing program. Table 10 depicts the specimens which had failed due to the freezing and thawing process only when observed at specified cycles.

24. Observation and general statements concerning the percentage of failures during freezing and thawing cycling can be made from Table 10. A better analysis of the freezing and thawing failures is to draw conclusions based on the following variables:

a. Type of bonding.
b. Type of exposure.
c. Cycles of freezing and thawing.
d. Specimens tested.
e. Specimens failed during stressing.

25. The specimens which were failed by testing or stressing could not be placed back in the freezing and thawing test chamber; therefore, they did not have a chance to experience continued freezing and thawing and perhaps fail in the chamber. This fact has to be taken into account in the analysis. It takes large numbers of specimens to give smooth trends in data. This test program had 126 specimens, but that number is still small in relation to obtaining smooth experimental variations.

Although the experimental variations are not smooth, when all variables are taken into account, the data are adequate to establish trends and draw conclusions.

26. The following formulas and terminology were used to take the above variables into account and calculate percentage failures after each interval of freezing and thawing cycles.

$$C_1 = \frac{F_1}{N_1} \text{ x } 100$$

$$C_2 = C_1 + \frac{F_2}{N_1} \text{ x } 100 + \frac{K_1 \; F_2/N_2 \text{ x } 100}{N_1}$$

$$C_3 = C_2 + \frac{F_3}{N_1} \text{ x } 100 + \frac{(K_2 + K_1 - K_1 \frac{F_2}{N_2})}{N_1} \frac{F_3}{N_3} \text{ x } 100$$

F_1, F_2, F_3 = Specimen failures after the first, second, and third interval of freezing and thawing cycles, respectively.

N_1, N_2, N_3 = Number of specimens remaining in freezing and thawing chamber after the first, second, and third intervals of freezing and thawing cycles, respectively.

K_1, K_2 = Number of specimens kept out of freezer for the next interval of freezing and thawing cycling because they were either tested or failed while being stressed.

C_1, C_2, C_3 = Percent failures after each interval of freezing and thawing cycling.

27. An explanation of the formulas is as follows.

a. For the first interval of freezing and thawing cycling, the percent failures are just a ratio of the number failed to the number in the freezer.

b. For the second interval of freezing and thawing cycles, the percent failed is the percent which failed the first interval plus the percent which failed the second interval plus the percent of those which would have failed if left in the freezer but did not have the opportunity due to being tested or having failed while being stressed. The term assumes that the failure rate for those which were tested or failed while being stressed is the same as those left in the freezer.

c. The same concepts apply for obtaining C_3.

28. Using the above formulas, the percent of specimen failures in the freezer at 44, 79, and 179 cycles is presented in Table 11. The percent failures in the freezer at 56, 91, and 191 cycles are presented in Table 12. The different sets of specimens (those checked and tested at 44, 79, and 179 cycles and those checked and tested at 56, 91, and 191 cycles) are shown separately because they were observed and tested at different cycles. The results are then combined in the plots and analysis.

29. Table 13 gives a summary of the percentage of specimens which failed at the various freezing and thawing cycles.

30. The phenomenon whereby the specimens failed in bond due to freezing and thawing conditions only is very important because it indicates that the interface of the overlay should create a minimum discontinuity. If the overlay and bonding do not have the same characteristics as the old concrete being repaired, a discontinuity will exist creating a barrier to water transfer. This causes a concentration of water at the interface, and when this concentration is sufficient and freezing occurs, the overlay will be debonded. This is not surprising, but it has not been demonstrated how the various type of bonding or environmental conditions either enhance or eliminate this process.

Analysis of Bond Failures Due to Freezing and Thawing

Unstressed and submerged freezing and thawing specimens

31. The freezing and thawing failures of the unstressed epoxy bonded specimens (Table 10 or Figure 14) were, in general, uniform with cycles of freezing and thawing. The concrete-to-concrete bonding (Table 10 or Figure 15) had more specimen failures in the early intervals of the freezing and thawing cycles than in the later. The failures for the polymer concrete-to-concrete and the fabric-polymer concrete-to-concrete bonding (Figures 16 and 17, respectively) seemed to have less failures than the epoxy and concrete-to-concrete bonding. The sample size of each of these last two groups was smaller than either the epoxy

bonded or concrete-to-concrete bonded specimens. All four systems seemed to have about the same final percent failures, which in all probability suggests that failures due to water collecting at the interface for early ages of repair is essentially comparable for each bonding type. The fabric incased in the polymer mortar at the interface had tensile strength and as a result fewer specimens failed during freezing and thawing than for the other type bonding. This resilience also showed up in the shear strength tests; the specimens underwent greater strain at failure. More specimens failed (Table 14) at low shear strengths for the specimens which had fabric at the interface than for the other specimens. This indicated that specimens were damaged, but due to the fabric they did not come apart in the freezer but stayed together with low shear strengths.

32. The general conclusion is that at early ages, a similar discontinuity was formed with all types of bonding and caused water to collect at the interface, either by entry at the interface or through the specimen.

33. Due to less failures during the later cycles of freezing and thawing of the concrete-to-concrete bonded specimens, there is a strong indication that as the repaired concrete develops characteristics similar to the old concrete, less water collects at the interface; hence there is less debonding due to freezing and thawing.

Freezing and thawing plus stressed specimens

34. In general, there was a substantial increase in the specimen failures in the freezing and thawing environment for specimens subjected to repeated stress (Figures 14, 15, 16, and 17). The stress effect was obtained by cycling 10 times 50 percent of the average shear strength of the test specimens. The average shear strength used was that obtained from the specimens which were tested at that particular interval for which the stressing was conducted.

35. The test results clearly show that stressed areas will deteriorate at a faster rate than areas which are not stressed. This is important because in a freezing and thawing environment it can be

expected that a repair will deteriorate more rapidly in an area of stress, and in general, these will be the more critical areas in the structure.

36. The specimens which seemed to be affected the least were those of concrete-to-concrete bond (Figure 15).

37. If the repair for concrete-to-concrete bonding (after its physical properties become stabilized) has characteristics similar to those of the concrete which is being repaired, the discontinuity at the interface of the repair will have substantially decreased, causing a lesser effect on deterioration due to freezing-thawing or freezing-thawing plus stress.

38. For new structure concrete placement, it is very important not to have the freshly placed concrete freeze until it has reached about 4000-psi strength, at which time the void spaces will not be critically saturated. The interval of time between placement and freezing is more critical for a repair than for a new structure. This is apparent from this testing program because the repair had a strength of about 4000 psi when the freezing and thawing cycling began and still a substantial number of repairs failed at the repair interface from freezing and thawing. Water collects in pore space near the discontinuity, and it takes time for the water at the interface to diffuse into the pore space away from the interface.

39. The concrete-to-concrete bond was 22 days old before freezing and thawing cycling began, and a substantial number of these specimens failed in the freezer during the early cycling. The failing in the freezer did not stop until about 91 cycles, at which time the repair was 41 days old; this indicates that even a concrete-to-concrete repair should be at least 41 days old before it is allowed to be subjected to a freezing and thawing environment. Epoxy bonding should not be used in a freezing and thawing environment where water can collect at the interface of the repair.

40. The specimens (approximately one-half submerged) which were in the same freezing and thawing environment did not experience any failures in the freezer. These specimens also experienced considerably less deterioration than the submerged specimens. This indicates that

the environment for the half-submerged specimens for the standard freezing and thawing testing is not as severe as that for the totally submerged specimens.

41. The fact that the one-half submerged specimens did not fail in the freezer brings up a question. Under what conditions will a discontinuity at the interface be important? It must be a condition where there is a possibility of water transfering through the concrete and collecting at the interface in a freezing and thawing environment.

Shear Strength of Bonded Interface

42. One of the main objectives of this particular study was to determine the effect of freezing and thawing and freezing and thawing plus stress on the durability of the interface of the repair subjected to various degrees of specimen saturation. This study was successful in that general trends established certain effects as significant. Table 14 presents the specimen numbers and shear strengths of the tested specimens at various cycles of freezing and thawing. These data are plotted on Figures 18 through 21.

43. For the epoxy bonding (see Figure 18), the shear stress decreased with exposure to freezing and thawing cycles. The half-submerged freezing and thawing cycling did not affect the durability or shear strength of the repair nearly as much as the totally submerged freezing and thawing environment. Stress had a predominant role in affecting the acceleration of environmental deterioration of the repair interface.

44. For concrete-to-concrete bonding (Figure 19) the same trend existed. The exposure to freezing and thawing cycling decreased the shear strength. For the specimens which were half submerged, there was an increase in shear strength. The stress environment of the overlay had an adverse effect on the durability of the repaired interface.

45. The repair whereby fiberglass fabric was embedded in the polymer mortar at the bonded interface exhibited much less shear strength than did the epoxy bonding or concrete-to-concrete bonding. The reason

for this was observed to be that it was hard to keep enough mortar on all faces of the fabric for good bonding. The failures were at the fabric face, and in all cases it was deficient in mortar. The shear stress is still adequate for normal repair, but there was a predominant decrease in shear strength with continued exposure to freezing and thawing cycling. As in the case of epoxy or concrete-to-concrete bonding, the bonding with the inclusion of fiberglass fabric was adversely affected by the stress environment.

46. Polymer mortar created a bond which was comparable to epoxy or concrete-to-concrete, but as the exposure continued, the shear strength of the repair decreased more than either the epoxy or concrete-to-concrete bonding. Even though the stressed specimen for the polymer mortar bond had a shear strength greater than that subjected to only freezing and thawing, the two data points are not enough to conclude that the shear strength at the bonded interface was not affected by the stressed environment.

47. The freezing and thawing test method, having the specimens totally submerged in water, is a severe test and was indicated as such by comparison with specimens which were half submerged and located in the same freezing and thawing environment. The specimens which were half submerged and located in the freezing and thawing environment had very little deterioration.

48. The freezing and thawing environment with the specimens totally submerged or half-submerged may not be representative of the exposure much of the repair may be subjected to in the field environment. This suggests that the results of those tests may or may not be an indication of how specimens will fail in the field. If the collection of water at the interface is not as severe as for these tests, the discontinuity may not be detrimental to the repair. In general, it would be helpful if for various field conditions (these conditions could represent baseline conditions) it was known to what degree water will collect at an interface. From these tests it is apparent that if there is an excess of water at the interface, the repair will be debonded by freezing and thawing. How applicable this is in relation to a real

environment situation where the water is behind or below the wall and has to travel some distance to get to and collect at the interface is unknown.

49. *It is best to stay on the safe side and assume that a discontinuity at an interface in a freezing and thawing environment is undesirable and to minimize this as much as possible.*

50. These tests only considered repairs of an early age. It is important to consider later ages of repair because it is good practice if at all possible to allow the repair to age until its properties are very similar to the repaired concrete to decrease the effect of the discontinuity at the interface.

PART IV: ABRASION TESTS AND RESULTS

51. As part of this study, abrasion tests were performed on some specimens using the latex polymer as used in the examination of interface repair properties. The abrasion of a polymer modified silica sand surfacing (same materials as used for the polymer mortar bonding specimens) and a polymer modified bauxite surfacing was determined in relation to a control specimen for each material.

52. The mixture proportions and aggregate test data are given for the silica sand surfacing in Tables 4 and 7 and for the latex modified bauxite surfacing in Tables 15 and 16. Two specimens were cast for each, and a control specimen was cast for each using the same materials and proportions except without the polymer (Table 8). Cubes were cast for each (Table 8) and tested for compressive strength at the same time the abrasion tests were performed. The results are presented in Table 8.

53. Various surfaces of locks and dams are subject to abrasive action. The abrasion action is accelerated if the concrete has been subjected to environmental deterioration such as freezing and thawing. Good quality concrete will resist high velocity water flow without excessive abrasion but will not resist high velocity water flow which contains abrasive materials such as rocks, pieces of steel, and other debris. The filling and emptying ports and tunnels, overflow dam surfaces, stilling basins, and lock floors are some surfaces which are susceptible to abrasion.

54. The repairs of surfaces which have been subjected to abrasion have been performed by not only using conventional concrete but by using fiber-reinforced concrete, epoxy resin concrete, polymer-impregnated concrete, steel plates, and polymer modified concrete. These repairs are expensive and in many cases their performance has been unsuccessful.

55. To determine the best materials and methods for use in abrasion environments, it is necessary to perform research and establish these materials and methods. This type of study is now being conducted at WES under a program titled "The Maintenance and Preservation of Concrete Structures."

56. A new test method is being used to perform these tests.* The apparatus consists of essentially a drill press, an agitation paddle (Figure 22), a cylindrical steel container which houses a disk-shaped concrete specimen, and 70 steel grinding balls of various sizes (ten 1-in.-diameter balls, thirty-five 0.75-in.-diameter balls, and twenty-five 0.50-in.-diameter balls). The overall test setup and a detailed cross sectional view are given in Figures 23 and 24, respectively.

57. The water in the container is circulated by the immersed agitation paddle which is powered by the drill press rotating at approximately 1200 rpm. The circulating water, in turn, moves the abrasive charges (steel grinding balls) on the surface of the concrete specimen producing the abrasion effects. The average water velocity on the surface of the specimen as measured by a blunt nose Pitot tube is approximately 6 ft/sec.

58. Briefly, the test consists of placing an 11-3/4-in.-diameter by 4-in.-thick specimen in the watertight steel container, adding steel grinding balls and water, mounting the agitation paddle on the drill press, and operating the drill press for 72 hr. The specimen is weighed at each 12-hr interval. The relative abrasion resistance of concrete is evaluated by weight loss.

59. The abrasion test results for the silica sand and bauxite mortar are given in Tables 17 and 18. The weight loss versus abrasion time in hours is given in Figure 25. The bauxite mortar is heavier than the silica sand mortar; therefore, the effective weight loss for the bauxite mortar relative to the silica sand mortar is shown in Figure 25.

60. The overall weight loss decreased for both the silica sand mortar and the bauxite mortar when latex polymer was added. The weight loss decreased by 58 percent for the silica sand mortar and 48 percent for the bauxite mortar.

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* Tony C. Liu, "Maintenance and Preservation of Concrete Structures; Report 3, Abrasion-Erosion Resistance of Concrete," Technical Report C-78-4, Report 3 (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

61. A latex polymer does increase the abrasion resistance of the mortar. The harder the aggregate, the smaller the weight loss as demonstrated by the bauxite mortar. The tests that are now being conducted study various aggregate types, water-cement ratio, additives, and surface treatment. The research that is being conducted is that which is necessary for determining materials which are best for abrasion resistant surfaces.

62. Certain observations were made during the abrasion tests.

- a. The maximum size of aggregate in the concrete being eroded relative to the size of the material causing the abrasion is an important factor in abrasion resistance of a concrete surface. For example, there is more paste area (in general, soft relative to the aggregate) for concrete made of large aggregate, and small balls or debris can contact the paste without or with different support conditions from surrounding aggregate. Also, when holes develop which are large relative to the balls or debris, the balls or debris can become trapped and not continue to move over the concrete surface, which causes a different mechanism of wear. This can account for certain specimens having an abrasion time at which the weight loss decreases significantly.
- b. It is very important to not have entrapped air in the concrete. Pinholes in the concrete accelerate abrasion. The concrete must be well consolidated from top to bottom for best results in an abrasive environment.
- c. The weight loss is not the significant factor in an abrasive environment; the significant factor is the effective depth of abrasion. This requires that the unit weight of the material be obtained and an effective depth of abrasion determined. For example, a substance twice as dense as another would have to have twice the weight loss to have equal effective abrasion depths.
- d. Due to centrifugal force the balls produce abrasion mainly on the outside edge of the specimens. This makes the boundary conditions at their outside edge important. If spaces between specimens and container vary, uncompatible results will be obtained due to the outside edges being exposed to a varying contact by steel balls.
- e. For specimens which are eroded deeper than others, a thinner outside edge will be developed which will be subject to being broken off instead of eroded away.

PART V: RECOMMENDATIONS

63. It is recommended that further testing be performed, and in light of the previous tests the following is recommended:

a. Use as a minimum the same three types of bonding systems as were used in the previous tests.

b. The testing should start at three intervals of repair age (28 days, 48 days, 90 days).

c. It is desirable to use large specimens but due to the number necessary for reliable results, it is almost mandatory to use small specimens as was done in this testing program.

d. The exposed edges of the bonded interface should be sealed in order that water can only get to the interface through the concrete.

e. The number of specimens for each bonding type and for each testing should be doubled.

f. Control specimens (not subjected to freeze and thaw or environmental effects) should be tested for comparison with deteriorated specimen tests.

g. The general test plans using control specimens subjected to freezing and thawing and specimens subjected to freezing and thawing plus stress should be the same.

h. The bonding surface for concrete-to-concrete bonding should be surface dry.

64. With this testing program, the analysis of data should accurately determine the most durable type of overlay bonding in relation to time and exposure after repair.

65. The concrete-to-concrete bonding seemed to have less failures as the overlay had time to cure. This is a significant effect and should be established with certainty.

PART VI: CONCLUSIONS

66. Many old concrete structures exist. The structural deterioration may accelerate with advancing age and progressively diminish their service lives. A systematic evaluation, development of remedial actions, development of repair plans and specifications, and a repair are necessary for economical and progressive structure performance. To accomplish the repair, efficient, effective, and economical materials and repair procedures must be available.

67. Durable concrete can be produced and placed; therefore, the main problem is to have a durable interface between the overlay and the repaired concrete. The bonding which was evaluated in these tests was that of epoxy resin (Material 1), cement mortar, latex polymer (Material 2) mortar, and latex polymer mortar plus fiberglass fabric (Material 3). The bondings were tested in freezing and thawing subjected to:

- <u>a</u>. Complete submergence.
- <u>b</u>. One-half submergence.
- <u>c</u>. Stress conditions.

68. Many surfaces are subjected to abrasion action. In this study the latex polymer (Material 3) was used in a silica sand and bauxite mortar along with control specimens to determine how it helped increase abrasive resistance.

69. One hundred twenty-six specimens were tested in the freezing and thawing environment. Each specimen was 3-1/2 by 4-1/2 by 5 in. They were cast in two pours; the first pour was allowed to cure 100 days, and the second pour allowed to cure 22 days before the freezing and thawing testing began. These tests showed that for early ages water will collect at the interface of a repair and when the water concentration is sufficient and freezing occurs, the overlay will be debonded. Many specimens failed from only the freezing and thawing environment. The epoxy bond exhibited a constant number of specimen failures with cycles of freezing and thawing. The concrete-to-concrete bonding had more specimens fail at early intervals of freezing and thawing than in later intervals, indicating that as similar characteristics develop

between the repair and the aged concrete (at least 41-days age of similar characteristic repairs), less water collects at the interface and hence, there is less debonding due to freezing and thawing. Latex polymer and latex polymer plus fiberglass fabric bonding also exhibited a tendency for debonding failures in the freezing and thawing environment. The bond where fabric was included has some resilience and resisted debonding although it was weakened in shear strength. All four bonding types had about the same final percent failures in the freezing and thawing environment, which in all probability suggests that the failures due to water collecting at the interface for early ages of repair are essentially comparable. For aged repairs (> 41 days) the concrete-to-concrete bonding may have less discontinuity at the interface and will be superior in a freezing and thawing environment. It is best to stay on the safe side and assume that a discontinutiy at an interface in a freezing and thawing environment is undesirable and to minimize this as much as possible. The material for an overlay in a freezing and thawing environment should be matched as closely as possible to the material which is to be repaired to reduce discontinuity effects.

70. Specimens which were subjected to freezing and thawing plus stress showed more failures than unstressed specimens in the freezing and thawing environment. The specimens which were one-half submerged showed no failure in the freezing and thawing environment.

71. The initial shear strengths of the epoxy bond, concrete-to-concrete bond, latex polymer bond, and latex polymer plus fiberglass fabric bond were 500, 300, 475, and 200 psi, respectively. After 191 cycles of freezing and thawing the shear strengths were 325, 200, 170, and 125 psi, respectively.

72. The epoxy and latex polymer produce good bond and will be satisfactory in a non-freezing and thawing environment (a justification of the extra expense should be considered) if the bonding retains its shear strength capacity as the repair ages (15 to 100 years). Epoxy bonding should not be used in a freezing and thawing environment where there is a possibility of water collecting at the repair interface. The latex polymer showed a considerable decrease in shear strength with

cycles of freezing and thawing. For this reason a latex polymer is not recommended for use in repairs subjected to a freezing and thawing environment. The concrete-to-concrete bonding to a dry interface is an acceptable bonding, and from the results of these tests, it is the recommended type of bonding for freezing and thawing environments. The fiberglass fabric is a promising material to be added in thin overlays to prevent cracking if it can be saturated with cementitious mortar to prevent weak bonding and if the project justifies the extra cost.

73. For overlays over an inch thick, it is recommended that dowels and reinforcing wire or bars be used in the overlay. The dowels and reinforcing are inexpensive insurance against overlay cracking and debonding of the overlay at the interface.

74. The stressing of the specimen at the various intervals of freezing and thawing had an adverse effect on the durability of the shear strength of the repaired interface. These tests results were for early ages of repair and do not show conclusively how the bonding types will behave with time in a freezing and thawing environment.

75. It was observed during the testing that when there was an increase in exposed aggregate at the bonded interface, there was a decrease in shear strength. This was true even when the surface with the exposed aggregate was more irregular than that with less exposed aggregate. This indicates that the paste could not penetrate and bond into the aggregate surface as well as it could into the old paste.

76. Any eccentricity of the load causing shear at the repair interface produces tension on the interface. Tension was a predominant factor in shear stress failures; if tension was present on an interface, it would reduce the shear strength significantly. In some cases where small eccentricities were present, the shear strength was reduced to almost zero.

77. A concrete overlay should be placed on a surface which is surface dry. This is because the voids at the surface should not be filled with water at the time of placement but should be such that the mortar can penetrate into them and create a better bond.

78. The abrasion resistance of concrete specimens was increased when latex polymer was added to the mixture. With the addition of latex polymer the weight loss decreased by 58 percent for the silica sand aggregate surfacing and 48 percent for the bauxite aggregate surfacing. The abrasion resistance of the concrete surfacing also increases with the increase in concrete quality and with the hardness of the aggregate. Increased abrasion resistance due to aggregate hardness was demonstrated by less abrasion of the bauxite aggregate surfacing in relation to the silica sand aggregate surfacing.

Table 1

Specimens to be Tested in Shear

Original Test Plan

Cycles of Freezing and Thawing	Control Specimens	Surrounded by Water*	Surrounded by Water and Subjected to Stress**	With Water Opposite Overlay Side Only*
Epoxy Bonding (Damp)				
0	1	--	--	--
	10	--	--	--
	19	--	--	--
50	2	6	--	27
	18	14	--	30
	20	21	--	39
100	--	7	--	31
	3	15	--	40
	11	22	--	36
200	4	8	25	32
	12	16	28	41
	--	23	37	35
300	5	9	26	33
	13	17	29	34
	--	24	38	42
Concrete Overlay Bonding to a Dry Concrete Surface				
0	43	--	--	--
	46	--	--	--
	55	--	--	--
50	44	51	--	70
	47	59	--	75
	56	64	--	81
100	45	52	--	71
	48	60	--	76
	--	65	--	80
200	49	53	63	72
	57	61	68	77
	--	66	73	84
300	50	54	69	83
	58	62	74	78
	--	67	82	79

(Continued)

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* Subjected to freezing and thawing.

** Subjected to stress at 0, 50, 100, and 200 freezing and thawing cycles.

Table 1 (Concluded)

Cycles of Freezing and Thawing	Control Specimens	Surrounded by Water	Surrounded by Water and Subjected to Stress	With Water Opposite Overlay Side Only
		Resin Bonding, Polymer Mortar Plus Fabric†		
0	87	--	--	--
	96	--	--	--
	105	--	--	--
50	--	93	--	--
	--	102	--	--
100	94	88	--	--
	103	97	--	--
	--	106	--	--
200	--	89	85	--
	--	98	91	--
	--	107	100	--
300	95	90	86	--
	--	99	92	--
	104	108	101	--
		Resin Bonding††		
0	111	--	--	--
	120	--	--	--
	126	--	--	--
50	--	--	--	--
100	--	113	--	--
	--	122	--	--
200	114	112	109	--
	123	121	117	--
	--	125	118	--
300	--	115	110	--
	--	--	116	--
	--	124	119	--

† Specimen: (a) Aged concrete
(b) Overlay
  (1) Polymer modified neat cement slurry
  (2) Fiberglass fabric
  (3) Polymer modified neat cement slurry
  (4) Fiberglass fabric
  (5) Topping of modified neat cement slurry and selected aggregate

†† Specimen: (a) Aged concrete
(b) Polymer mortar

Table 2

Concrete Mix Proportions Limestone Aggregate Concrete

JOB NAME Durability of Concrete Repairs		**CONCRETE MIXTURE PROPORTIONS** (WORK SHEET) (CRD-C 3)	DATE 6-12-78
JOB. NO. 1	MIXTURE SER. NO. 1		INITIALS

PORTLAND CEMENT TYPE SER. NO. ADDITION BRAND AND MILL RC 705 II	POZZOLAN SER. NO. TYPE SOURCE	A. E. ADMIX: SER. NO. NAME NVR Lab stock AMOUNT % ML
OTHER CEMENT SER. NO. BRAND AND MILL	CHEMICAL ADMIX SER. NO. % ML NAME	

FINE AGGREGATE	COARSE AGGREGATE
TYPE Natural SER. NO. SOURCE WES-1 S-4 (50)	TYPE Limestone SER. NO. SOURCE Vulcan Materials Co. SIZE 3/4 in.

MATERIALS

MATERIAL	SIZE RANGE	BULK SPECIFIC GRAVITY	UNIT WEIGHT (SOLID), LB/CU FT	ABSORPTION, PERCENT	TOTAL MOISTURE CONTENT, PERCENT	NET MOISTURE CONTENT, PERCENT
CEMENT		3.15	196.56			
F. AGGREGATE		2.63	164.11	0.4		0.5
C. AGGREGATE (A)		2.72	169.73	0.4		0.3
C. AGGREGATE (B)						
C. AGGREGATE (C)						
C. AGGREGATE (D)						
POZZ/OTHER CEMENT						

PROPORTIONS

MATERIAL		CALCULATED BATCH DATA (1 CU YD) SOLID VOLUME CU FT/BATCH	SAT. SURF DRY BATCH WT, LB	FACTOR	ACTUAL BATCH DATA 5.0 CU FT SAT. SURF DRY BATCH WT, LB	WATER CORRECTION, LB	ACTUAL BATCH WT
CEMENT		2.630	517.0 (13)	.185	95.6		95.6
F. AGGREGATE		7.419	1217.5		225.2	+1.1	226.3
C. AGGREGATE (A)		11.603	1969.4		364.3		364.3
C. AGGREGATE (B)							
C. AGGREGATE (C)		(11)					
C. AGGREGATE (D)		(10)					
POZZ/OTHER CEMENT							
WATER		3.728	232.65 (3)		43.0 (1)	-1.1	41.9
AIR		1.620					
TOTAL	AIR FREE	(5)	(4)		(2)		
	YIELD	27.000 (14)					

MIXTURE DATA

SLUMP 2-1/2, 2-1/2 IN.	AIR CONTENT (D) %	MIXING WATER F	TH CF LB/CU YD
REMOLD EFF DROPS	AIR CONTENT (E) %	AMBIENT F	ACT CF 517.0 LB/CU YD
TH UW LB/CU FT	AIR CONTENT (F) 5, 5, 6.5 %	CONCRETE F	W/C 0.45 WT
ACT UW LB/CU FT	BLEEDING %	S/A 39 PERCENT VOL.	

WES FORM NO. 476
REV MAR 1972

(OVER)

Table 3

Coarse Aggregate Data for Limestone Concrete

MEMO	JOB	COARSE AGGREGATE WORK SHEET	DATE	INIT
CORPS OF ENGINEERS, USAE		SOURCE Vulcan Materials, Co. Calera, AL	MTRL Crushed Limestone	
PROCESSING			P. O. DRAWER 2131 JACKSON, MISSISSIPPI	
PROJECT Laboratory Stock		NO. CL-2G-1(3)	DATE 9-1-77	SAMP. BY

	SIEVE SIZE	IND WT RET, GRAMS	IND, % RET	CUM, % RET	CUM, % PASS.	SPEC, % PASS.
SIEVE	6-IN.					
ANALYSIS	5-IN.	CL-2 G-1 (3)				
	4-IN.		4-3/4			
	3-IN.					OCE
	2-IN.					Guide
CRD-C 103	1-1/2-IN.					
DATE 8-31-77	1-IN.	0	0	0	100	100
	3/4-IN.	318	2.5	2.5	98	90-100
INIT	1/2-IN.	6856	54.2	56.7	43	--
	3/8-IN.	3728	29.5	86.2	14	20-45
	NO. 4	1626	12.9	99.1	1	0-5
	PAN	117	0.9	——	——	——
	TOTAL	12645	100.0	——	——	——

	SIZE	GRAD, %	WT, LB	-2.40, LB	-2.40, %	SAMP., %
LOW SPECIFIC GRAVITY	2-IN.					
PARTICLES	1-1/2-IN.		2 RR Cars			
CRD-C 129	1-IN.	RCC	26 Aug 1977			
DATE	3/4-IN.					
INIT	1/2-IN.					
TOT %	3/8-IN.					
	NO. 4					

SPECIFIC GRAVITY	SSD, LB (B)	4549	W + T, LB	4890	T WT, LB	2012
CRD-C 107	WIW, LB (C)	2878	WW (B – C)	1671	B/B – C	2.72
ABSORPTION	ODW, LB (A)	4530	B – A, LB	19	B – A, %	0.4
CRD-C 107	DATE		INIT		CHECK	

	SIZE	S WT, g	NO. PCS	SP W, g	SP NO.	WT, %	NO., %	SAMP., %
SOFT PARTICLES	2-IN.+							
	1-1/2-IN.							
CRD-C 130	1-IN.							
DATE	3/4-IN.							
INIT	1/2-IN.							
TOT %	3/8-IN.							

LOS ANGELES ABRASION	NO REV		GRAD		S WT, g		R WT, g	
CRD-C 117	P WT, g		% LOSS		DATE		INIT	
$MgSO_4$ F-477 CRD-C 115	NO. CYC		% LOSS		DATE		INIT	
F & E F-833 CRD-C 118	GRAD		F & E, %		DATE		INIT	
CL & FP WORK S CRD-C 142	GRAD		CL & FP, %		DATE		INIT	

WES FORM NO. 445
REV JAN. 65

Table 4

Fine Aggregate Data for Limestone Concrete

FINE AGGREGATE WORK SHEET

Serial No.:______ Memo No.:______ Date: 1-9-69 Init.______

Job No.______ Tested For:______

Source: American Sand and Gravel Co., Hattiesburg, MS

Processing Before Test: None 2 RR Cars Combined

Date Rec'd.:______ Sampled By:______ Type Mtrl: Natural

CRD-C 108
Bulk Sp Gr; Date 1-9-69 Init:______

	Run 1	Run 2
Flask No.	5	
Flask vol, ml (V)		
Wt, Flask+Ag+Water, g	965.0	
Wt Flask + Ag, g	655.0	
Wt Water added, g		
Temp correction, (C)	25 (C)	
Water added (W)		
Sp Gr $\left(\frac{500}{V-W}\right)$	- 2.63	

$$\frac{500}{500 + 655 - 965}$$ Avg ______

CRD-C 108
Absorption: Date:______ Init.______

	Run 1	Run 2
SSD wt, g	500.0	
O.D. wt, g	497.8	
Moist. wt, g	2.2	
Absorption	0.4	
Avg	0.4	

CRD-C 121
Organic Color:______
Date:______ Initials______

CRD-C 116
Mortar-Making Properties: Date Made:______ Init.:______ Cement Type:______
Date, 3-Day Test:______ Init.:______ Date, 7-Day Test:______ Init.:______
Flow, %, Test Sand______ Std Sand:______ Lb, Test Sand______ Std:______

	Strength, lb			psi	Strength, lb			psi
Sand	3D-1	3D-2	3D-3	Avg	7D-1	7D-2	7D-3	Avg
Test								
Std								

Strength ratio, % - 3-Day______ 7-Day______

CRD-C 103
Sieve Analysis: Date: 1-9-69 Init.:______

Sieve	Wt	%	Cumulative Per Cent			
Size	Ret.	Ret.	Ret.	Pass.	Spec.	Pass.
No. 4	7.6	1.9	1.9	98.1	100	
No. 8	42.0	10.3	12.4	87.6	80	90
No. 16	54.0	13.2	25.6	74.4	65	75
No. 30	89.1	21.8	47.4	52.6	30	60
No. 50	112.5	27.5	74.9	25.6	12	20
No. 100	75.9	18.6	93.5	7.0	2	5
No. 200	23.5	(5.7)	98.8	1.2		
Pan	5.0	(1.2)	100.0	0.0		

CRD-C 104
Fineness Modulus:______
Spec. F. M.______

CRD-C 105 Date: 1-9-69
Decantation: Init:______
Orig. OD wt, g 408.0
OD wt aft Dec, g 403.0
Wt loss, g 5.0
% loss 1.2

CRD-C 115______
Magnesium Sulfate Soundness:
Date:______ Init:______
% Loss:______ Cycles:______

CRD-C 118
Clay Lumps, %______
Date:______ Init.______

WES Form 466 (Revised Aug 1962)

Table 5

Latex Polymer Modified Neat Cement Slurry

Material	Parts by Weight
Cement, Type II	100
Water	20
Latex Polymer	30

Table 6

Latex Polymer Modified Mortar

Material	Parts by Weight
Cement, Type II	100
Water	18
Latex Polymer	30
Sand	306

Table 7

Mix Design, Silica Sand Surfacing

Material	Polymer Modified Silica Sand Mortar (parts by weight)	Silica Sand Mortar (parts by weight)
Cement, Type II	100	100
Water	18	48
Polymer (Material 2)	30	--
Sand (Table 4)	306	307

Table 8

Cube Strengths For Abrasion Specimens at 100-Days Age

Silica Sand Mortar					
Polymer Modified			Nonmodified		
Speci-men	Cube	Compressive Strength	Speci-men	Cube	Compressive Strength
PSS-1	PSS-1	5860	CSS-1	CSS-1	Void
PSS-2	PSS-2	7520		CSS-2	7510
	PSS-3	7320		CSS-3	8540
	PSS-4	7510			
	PSS-5	7020			
	PSS-6	7240			
Average		7078			8025

Bauxite Mortar					
Polymer Modified			Nonmodified		
Speci-men	Cube	Compressive Strength	Speci-men	Cube	Compressive Strength
PB-1	PB-1	4970	CB-1	CB-1	4600
PB-2	PB-2	4500		CB-2	4950
	PB-3	5230		CB-3	4700
Average		4900			4750

Table 9

Specimens to be Tested in Shear

Changed Test Plan

Cycles of Freezing and Thawing	Control Specimen	Surrounded by Water*	Surrounded by Water and Subjected to Stress**	With Water Opposite Overlay Side Only*
		Epoxy Bonding (Damp)		
0	1, 10, 19	--	--	--
44		2, 20, 18,	--	--
56		6, 14, 21	--	27, 30, 39
79		3, 11	--	--
91		7, 15, 22	--	31, 36, 40
179		4, 5, 12, 13	--	--
191		8, 9, 16, 17, 23, 24	25, 26, 28, 29, 37, 38	32, 33, 34, 35, 41, 42
		Concrete Overlay Bonding to a Dry Concrete Surface		
0	43, 46, 55	--	--	--
44		44, 47, 56	--	--
56		51, 59, 64	--	81, 70, 75
79		45, 48	--	95, 104
91		52, 60, 65	--	71, 76, 80
179		50, 49, 57, 58	--	--
191		53, 54, 61, 62, 66, 67	63, 68, 69, 73, 74, 82	72, 77, 78, 79, 83, 84

(Continued)

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* Subjected to freezing and thawing.

** Subjected to stress at 0, 56, 91 , and 191 freezing and thawing cycles.

Table 9 (Concluded)

Cycles Freezing and Thawing	Control Specimens	Surrounded by Water	Surrounded by Water and Subjected to Stress	With Water Opposite Overlay Side Only
		Resin Bonding, Polymer Mortar Plus Fabric[†]		
0	87, 96, 105	--	--	--
44		94, 103	--	--
56		93, 102	--	--
79		95, 104	--	--
91		88, 97, 106	--	--
179		--	--	--
191		89, 90, 98, 99, 107, 108	85, 86, 91, 92, 100, 101	-- --
		Resin Bonding[††]		
0	111, 120, 126	--	--	--
44		123, 114	--	--
56		--	--	--
79		--	--	--
91		112, 113, 122, 125	--	--
179		--	--	--
191		115, 121, 124	109, 110, 116 117, 118, 119	--

[†] Specimen: (a) Aged concrete
(b) Overlay
(1) Polymer modified neat cement slurry
(2) Fiberglass fabric
(3) Polymer modified neat cement slurry
(4) Fiberglass fabric
(5) Topping of modified neat cement slurry and selected aggregate

[††] Specimen: (a) Aged concrete
(b) Polymer mortar

Table 10

Cycles of Freezing and Thawing at Which Specimens Were Observed to Have Failed While in the Freezing and Thawing Process

	Freezing and Thawing Cycles																						
Specimen	Epoxy Bond							Specimen	Concrete-to-Concrete Bond							Specimen	Polymer Concrete with Fiberglass Fabric Bond						
	0	44	56	79	91	179	191		0	44	56	79	91	179	191		0	44	56	79	91	179	191
1								43								85							
2								44								86							
3								45								87							
4								46								88							
5								47		X						89							
6								48		X						90							
7								49								91			X				
8								50				X				92							
9								51								93							
10								52								94							
11				X				53								95							
12						X		54								96							
13						X		55								97							
14								56								98							X
15								57		X						99							X
16							X	58		X						100							X
17							X	59			X					101							
18		X						60			X					102							
19								61			X					103							
20								62			X					104							
21								63								105							
22					X			64								106							
23								65								107							
24							X	66								108							
																	Polymer Concrete-to-Concrete Bonding						
																	0	44	56	79	71	179	191
25					X			67							X	109							
26			X					68			X					110							
27								69								111							
28			X					70								112							
29								71								113							
30								72								114							
31								73								115							X
32								74								116					X		
33								75								117							
34								76								118			X				
35								77								119			X				
36								78								120							
37					X			79								121			X				
38								80								122							
39								81								123							
40								82								124							
41								83								125							
42								84								126							

Table 11

Percent Specimen Failures in the Freezer After 44, 79, and 179 Freezing and Thawing Cycles

Cycles	Situation	Epoxy Bond Regular Freezing and Thawing Tests	Concrete-To-Concrete Bond Regular Freezing and Thawing Tests	Polymer Matrix and Fabric Bond Regular Freezing and Thawing Tests	Polymer Concrete-To Concrete Bond Regular Freezing and Thawing Tests
44	Number of Specimens	9	9	4	2
	Failures in Freezer	1	4	0	0
	Testing Failures	2	2	2	2
	% Failures in Freezer	11	44	0	0
79	Number of Specimens	6	3	2	0
	Failures in Freezer	1	1	0	0
	Testing Failures	1	1	2	0
	% Failures in Freezer	26	63	0	0
179	Number of Specimens	4	1	0	0
	Failures in Freezer	2	0	0	0
	Testing Failures	2	1	0	0
	% Failures in Freezer	63	63	0	0

Table 12

Percent Specimen Failures in the Freezer After 56, 91, and 191 Freezing and Thawing Cycles

Cycles	Situation	Epoxy Bond		Concrete-To-Concrete Bond		Polymer Matrix and Fabric Bond		Polymer Concrete-To-Concrete Bond	
		Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed
56	Number of Specimens	12	6	12	6	11	6	7	6
	Failures in Freezer	0	2	4	2	0	1	1	2
	Testing Failures	3	0	2	0	2	1	0	1
	% Failures in Freezer	0	33	33	33	0	17	14	33
91	Number of Specimens	9	4	6	4	9	4	6	3
	Failures in Freezer	1	3	0	2	0	0	0	1
	Testing Failures	2	0	2	0	3	0	4	0
	% Failures in Freezer	11	83	33	67	0	17	14	56
191	Number of Specimens	6	1	4	2	6	4	2	2
	Failures in Freezer	3	0	1	0	2	1	1	0
	Testing Failures	3	1	3	2	4	3	1	2
	% Failures in Freezer	56	83	50	67	33	38	57	56

Table 13

Summary of Specimens Which Failed in the Freezer at the Different Freezing and Thawing Cycles

	Epoxy Bond		Concrete-To-Concrete Bond		Polymer Matrix and Fabric Bond		Polymer Concrete-To-Concrete Bond	
Cycles	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed	Regular Freezing and Thawing Tests	Freezing and Thawing Environment, Stressed
44	11		44		0		0	
56	0	33	33	33	0	17	14	33
79	26		63		0		0	
91	11	83	33	67	0	17	14	56
179	63		63		0		0	
191	56	83	50	67	33	38	57	56

Table 14

Specimen Number, Ultimate Shear Strength, and Average Shear Strength

	Epoxy			Concrete To Concrete			Latex Polymer Mortar Plus Fiberglass Fabric		Latex Polymer Mortar	
	Sub	Sub-Stress	$\frac{1}{2}$ Sub	Sub	Sub-Stress	$\frac{1}{2}$ Sub	Sub	Sub-Stress	Sub	Sub-Stress
0	10-495* 19-489* 492			43-347* 55-242* 46-349* 312			87-182* 96-215* 105-212* 203		111-473* 120-484* 126-467 475	
44	2-349			44-319 56-289 304			94-143 103-128 136		114-389 123- 18 204	
56	6-450 14-381 21-128 320		27-341 30-496 39-535 457	51-382 64- 17 200		70-364 75-358 81-387 370	43-127 102-145 136			
79	3-360			45-186			95- 17 104- 74 46			
91	7-394 15- 45 220		31-603 36-328 40-478 470	52-405		71-428 76-401 80-427 419	88-166 97- 19 106-186 124		112- 70 113-307 122-222 125- 89 172	
179	4-320 5-391 356			49-416						
191	8-333 9-363 23-275 324	29-187	32-549 33-565 34-429 35-419 41-545 42-418 488	53-111 54-129 66-346 195	69-214 82-350 282	72-537 77-538 78-602 79-500 83-447 84-532 526	89- 42 90-104 107- 20 108- 75 62	85-37 86-19 101-51 36	124-5	110-124 117- 84 104

*Not submerged (sub).

Table 15

Mix Design, Bauxite Surfacing

Material	Polymer Modified Bauxite Surfacing (parts by weight)	Bauxite Surfacing (parts by weight)
Cement, Type II	100	100
Water	18	48
Polymer (Material 2)	30	--
Fine Bauxite	187.5	187.5
Coarse Bauxite	187.5	187.5

Table 16

Sieve Analysis, Coarse and Fine Bauxite

Sieve Size (US Sieves)	% Retained on Each Sieve: Coarse Bauxite (6 by 12 Mesh)	% Retained on Each Sieve: Fine Bauxite (12 Mesh by Down)
No. 6	0 to 5	
No. 8	25 to 35	
No. 10	35 to 50	0 to 5
No. 16	20 to 30	15 to 25
No. 20	0 to 10	25 to 35
No. 40	0 to 5	12 to 22
No. 60		15 to 25
No. 100		0 to 10
No. PAN	0 to 4	0 to 4

Table 17

Abrasion Test Results of Bauxite Mortar Overlay

Two Specimens Overlay of Polymer Modified Bauxite Mortar							Control Specimen Overlay of Bauxite Mortar			
Abrasion Time (hr)	Specimen Weights (Grams)		Weight Loss (Grams)		Average Weight Loss (Grams)	Accumulated Average Weight Loss (Grams)	Abrasion Time (hr)	Specimen Weight (Grams)	Weight Loss (Grams)	Accumulated Average Weight Loss (Grams)
	PB-1	PB-2	PB-1	PB-2				CB-1	CB-1	
0	11721	11946					0	9944		
			45	40	43	43			86	86
12	11676	11906					12	9858		
			48	23	36	79			88	174
24	11628	11883					24	9770		
			57	53	55	134			86	260
36	11571	11830					36	9684		
			48	37	43	177			90	350
48	11523	11793					48	9594		
			55	47	51	228			80	430
60	11468	11746					60	9514		
			47	59	53	281			111	541
72	11421	11687					72	9403		

Table 18

Abrasion Test Results of Silica Sand Mortar Overlay

Two Specimens Overlay of Polymer Modified Silica Sand Mortar							Control Specimen Overlay of Silica Sand Mortar			
Abrasion Time (hr)	Specimen Weights (Grams)		Weight Loss (Grams)		Average Weight Loss (Grams)	Accumulated Average Weight Loss (Grams)	Abrasion Time (hr)	Specimen Weight (Grams)	Weight Loss (Grams)	Accumulated Average Weight Loss (Grams)
	PSS-1	PSS-2	PSS-1	PSS-2				CSS-1	CSS-1	
0	11358	10936					0	9838		
			52	57	55	55			167	167
12	11306	10879					12	9671		
			63	73	68	123			158	325
24	11243	10806					24	9513		
			77	101	89	212			234	559
36	11166	10705					36	9279		
			51	93	72	284			242	801
48	11115	10612					48	9037		
			130	109	120	404			271	1072
60	10985	10503					60	8766		
			136	121	129	533			210	1282
72	10849	10382					72	8556		

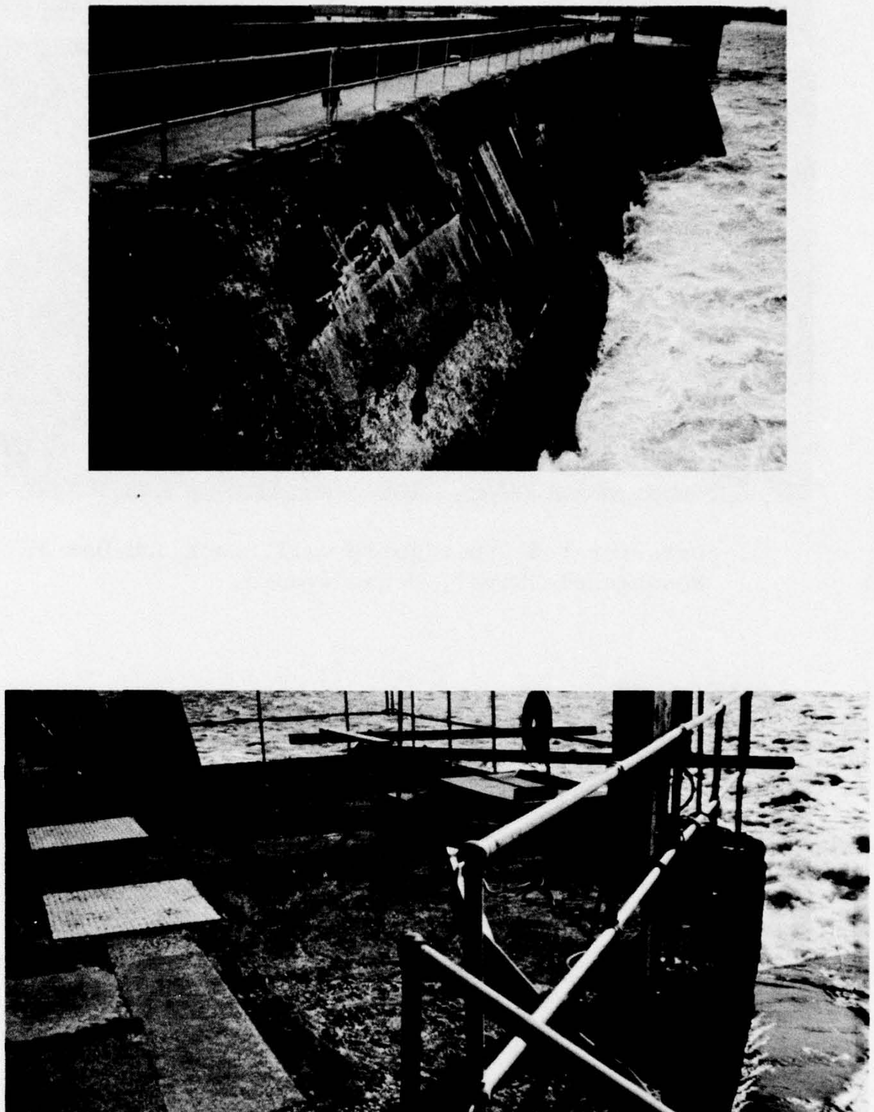
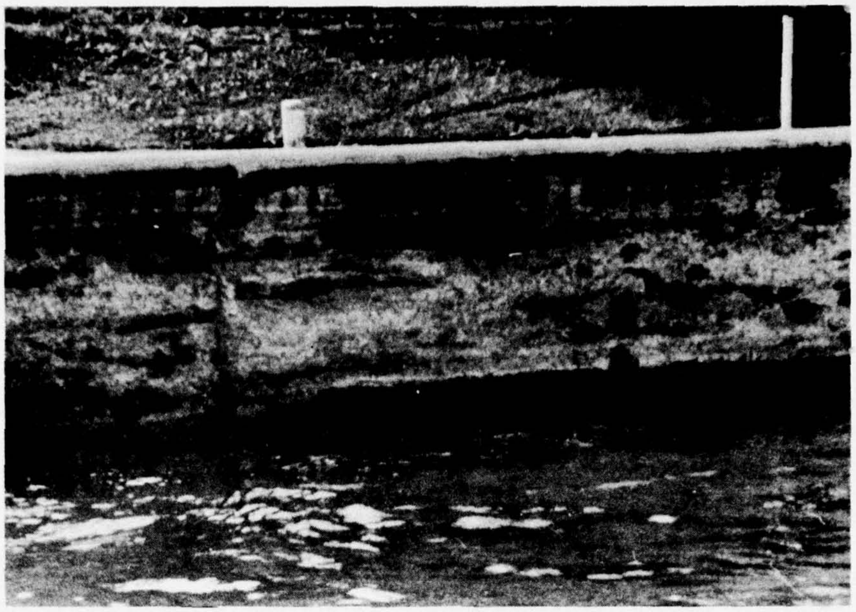
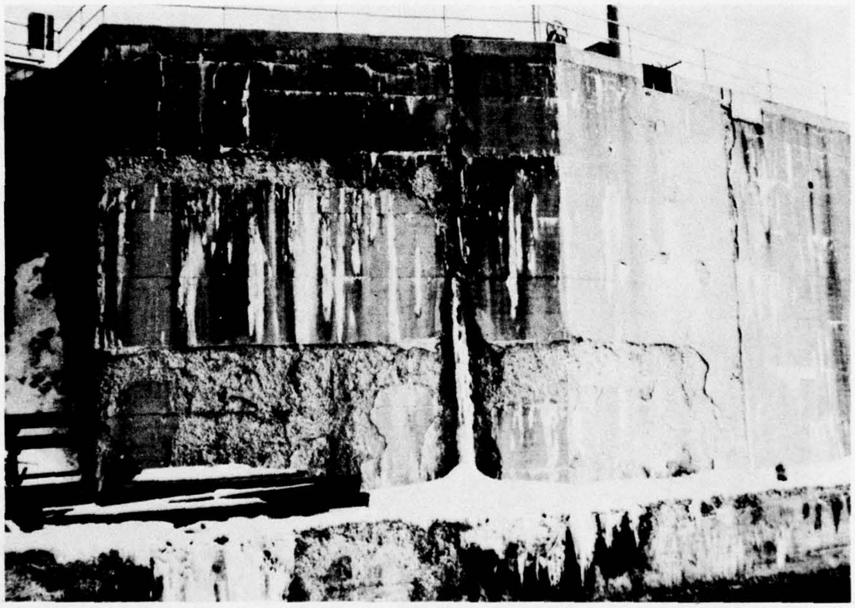


Figure 1. Deteriorated surface concrete, Troy Lock and Dam, Hudson River, Troy, New York

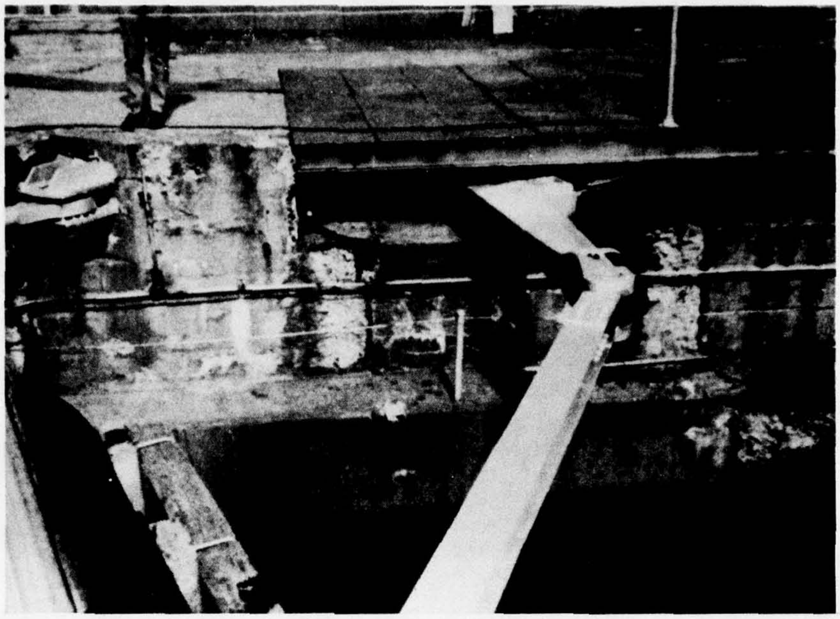


a. Deteriorated upper guide wall, Lock and Dam 3, Monongahela River, Pennsylvania.



b. Deteriorated river side, river wall, Lockport Lock, Joliet, Illinois

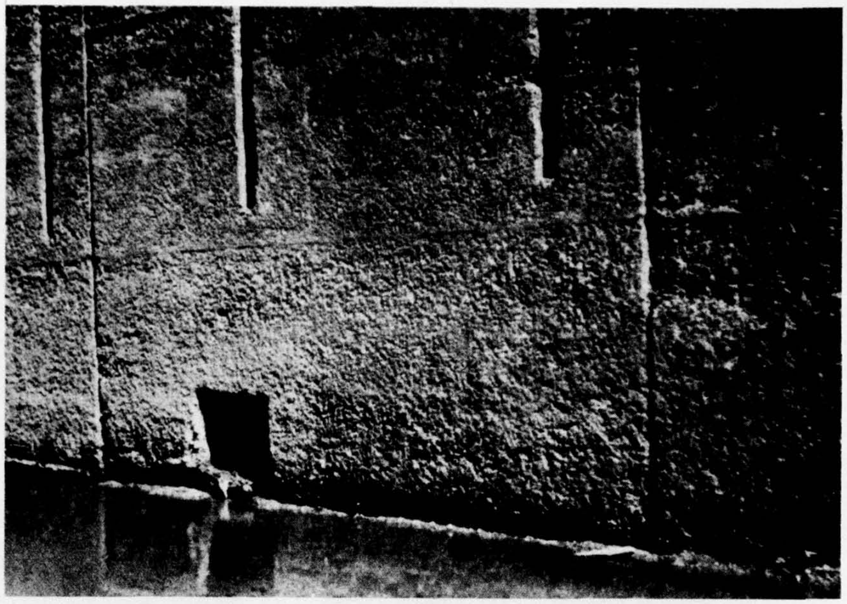
Figure 2. Deteriorated guard and lock walls



a. Emsworth Lock, Ohio River, Pennsylvania

b. Lock and Dam 3, Monongahela River, Pennsylvania

Figure 3. Deteriorated gate anchorage



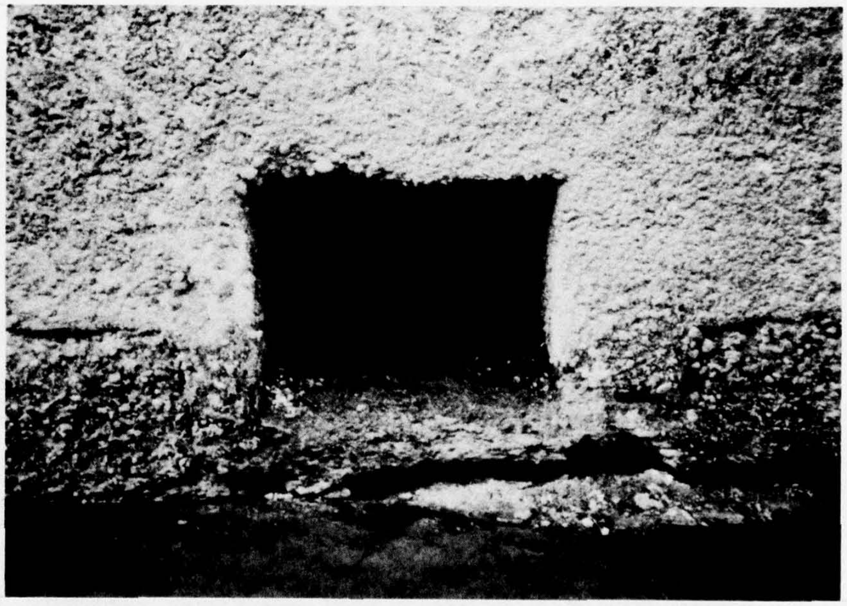
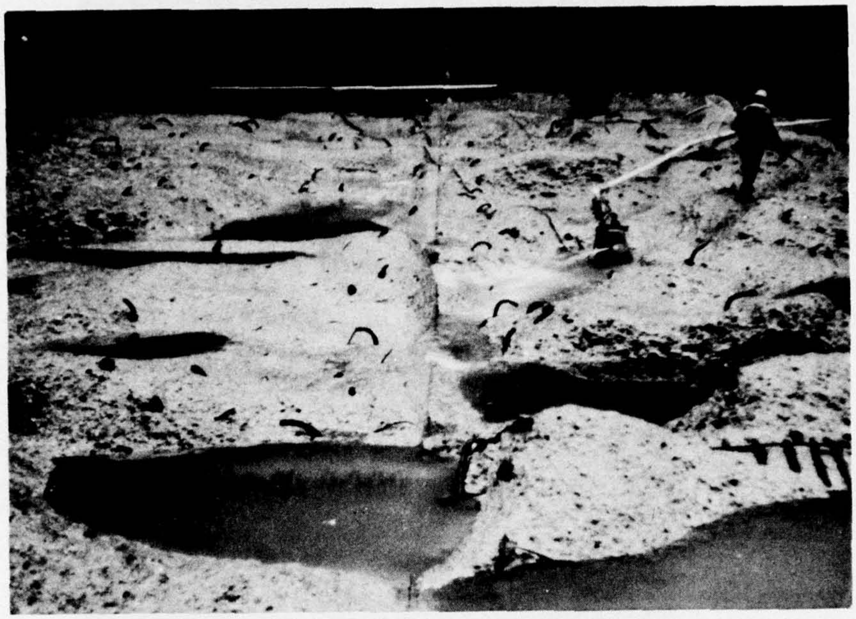
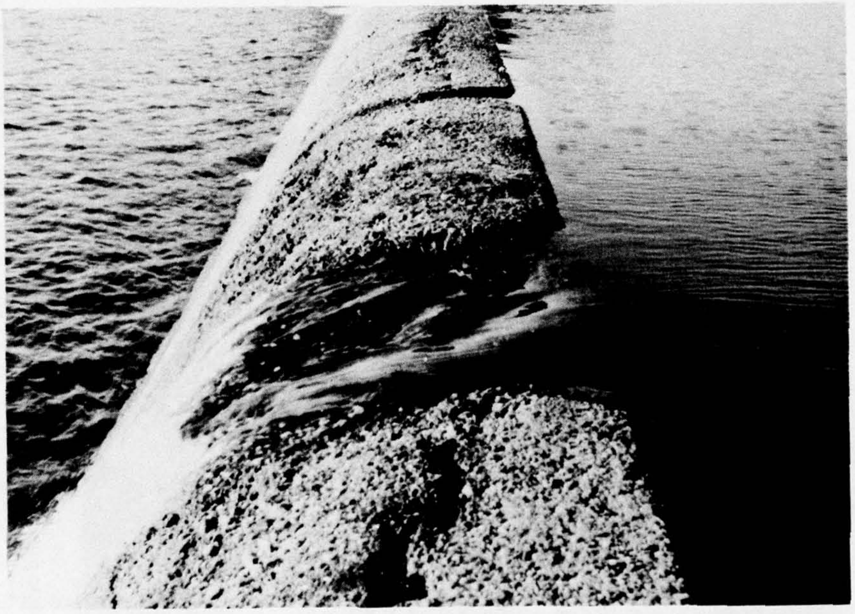


Figure 4. Deteriorated inlet and outlet ports
and undermining of monolith base,
Troy Lock and Dam, Hudson River,
Troy, New York

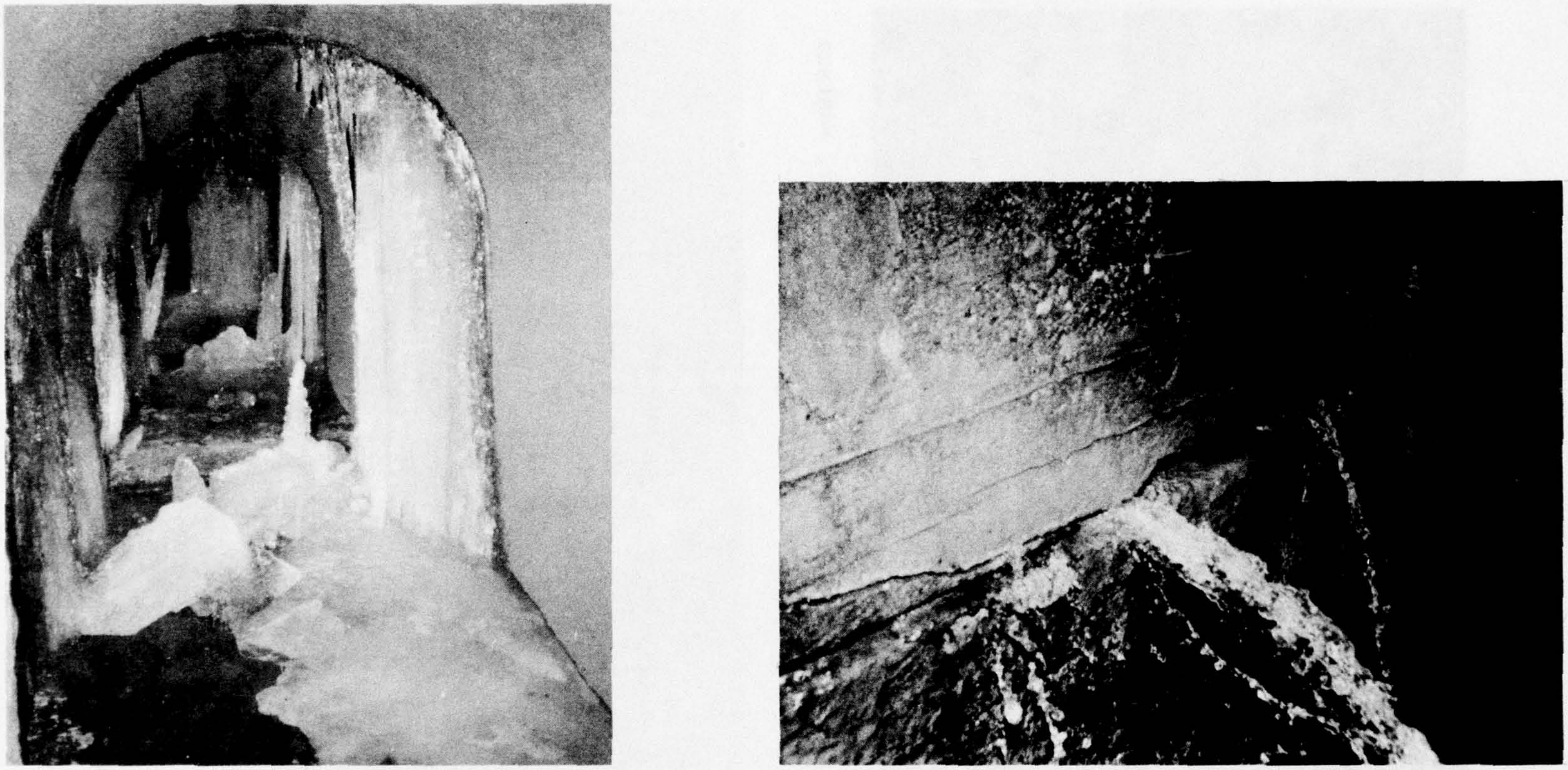


a. Stilling basin erosion, Libby Dam, Libby, Montana



b. Dam surface erosion, Troy Dam, Troy, New York

Figure 5. Eroded concrete surfaces



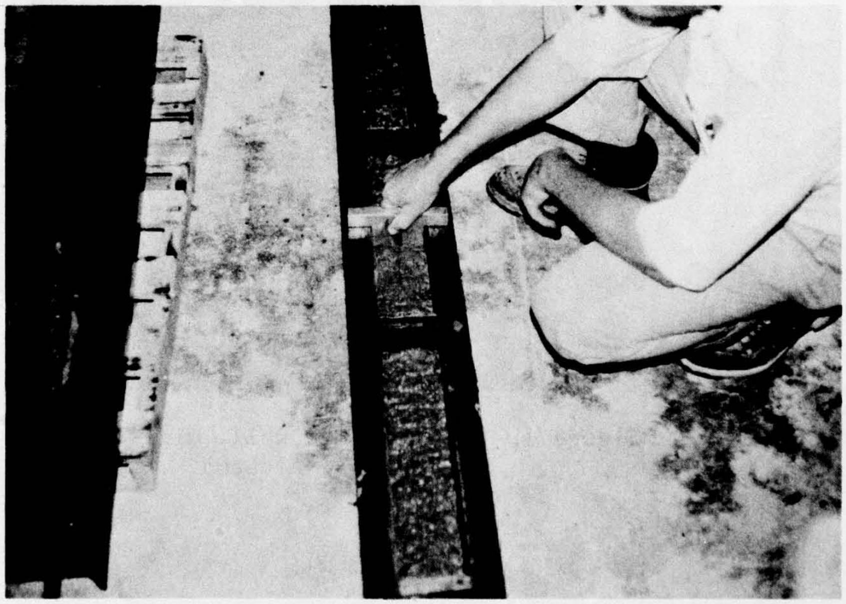
a. Seepage through construction joints and monolith walls, land wall filling, and emptying culverts

b. Leakage through construction joint in entrance shaft to dam tunnel

Figure 6. Troy Lock and Dam, Hudson River, Troy, New York

Figure 7. Cracked lock wall, Oliver Lock, Tuscaloosa, Alabama

a. Consolidation of first placement



b. Finishing of first placement

Figure 8. First placement of specimens to evaluate overlay performance

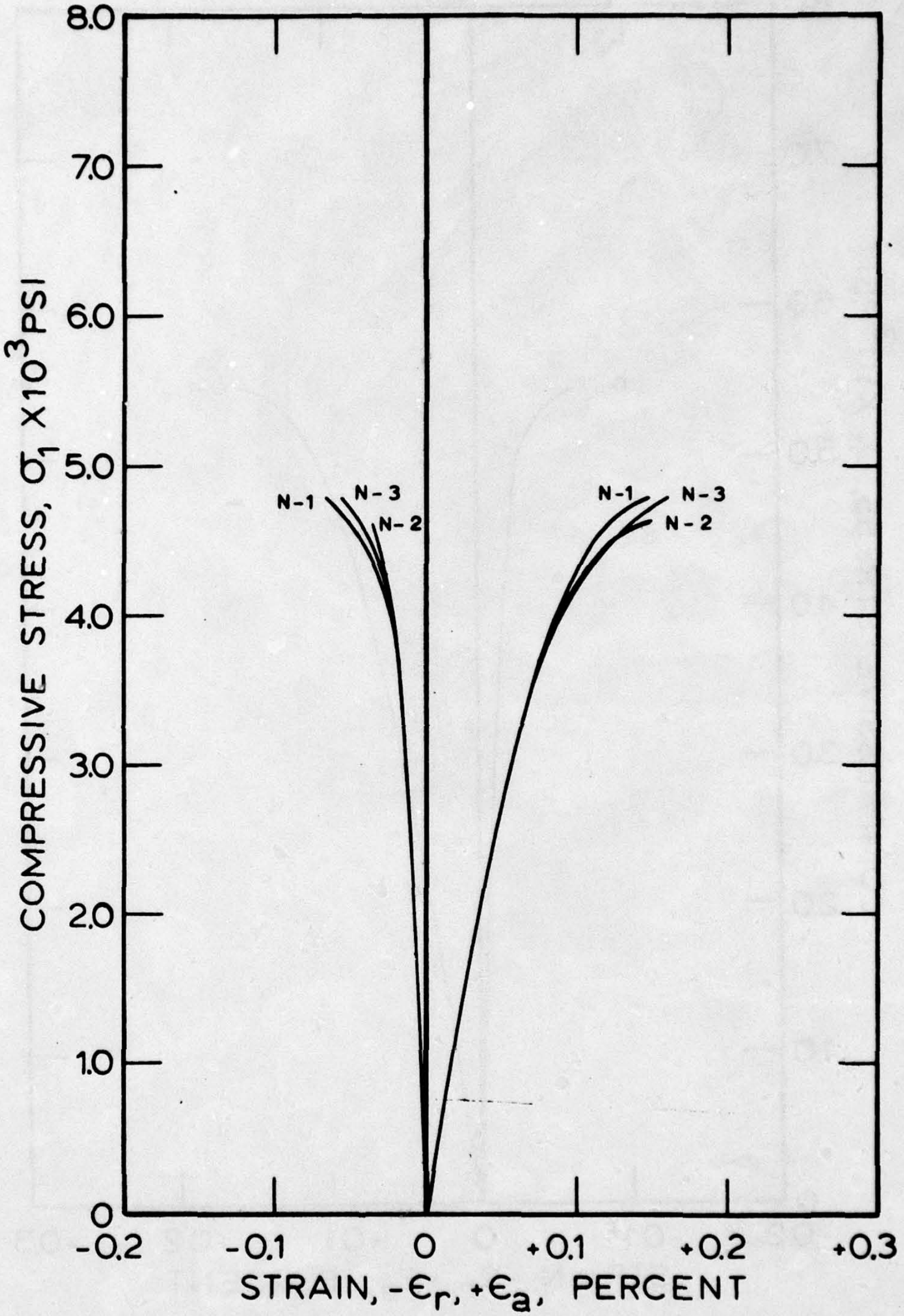


Figure 9. Stress-strain curves for the first pour concrete

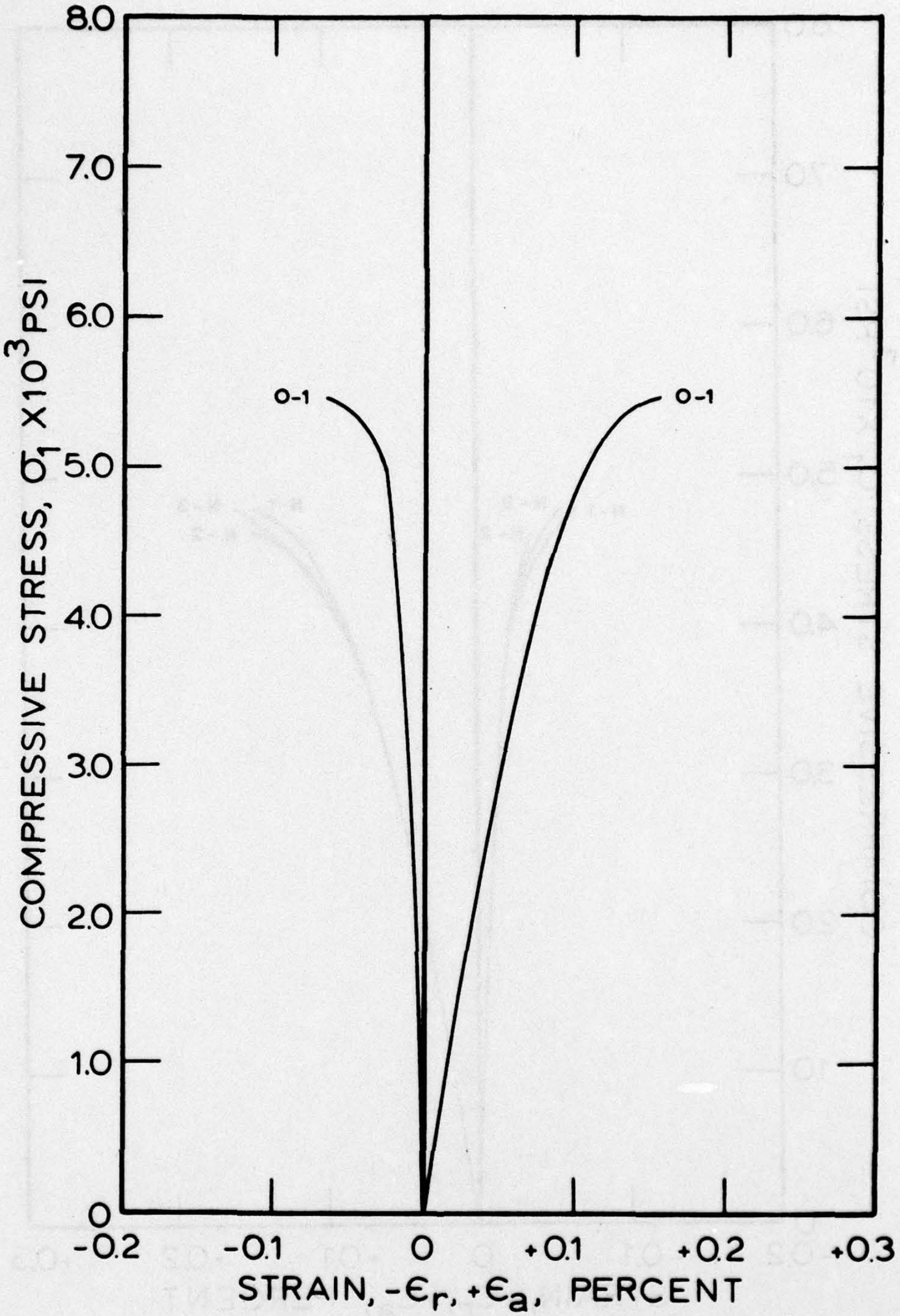


Figure 10. 100-day stress-strain curves for the first pour concrete

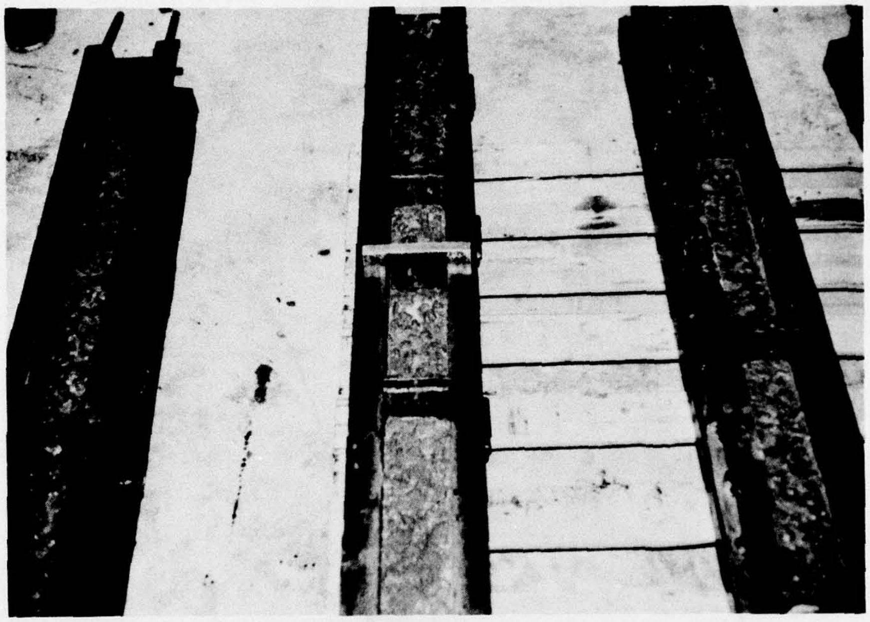


Figure 11. First pour surface proposed for overlay

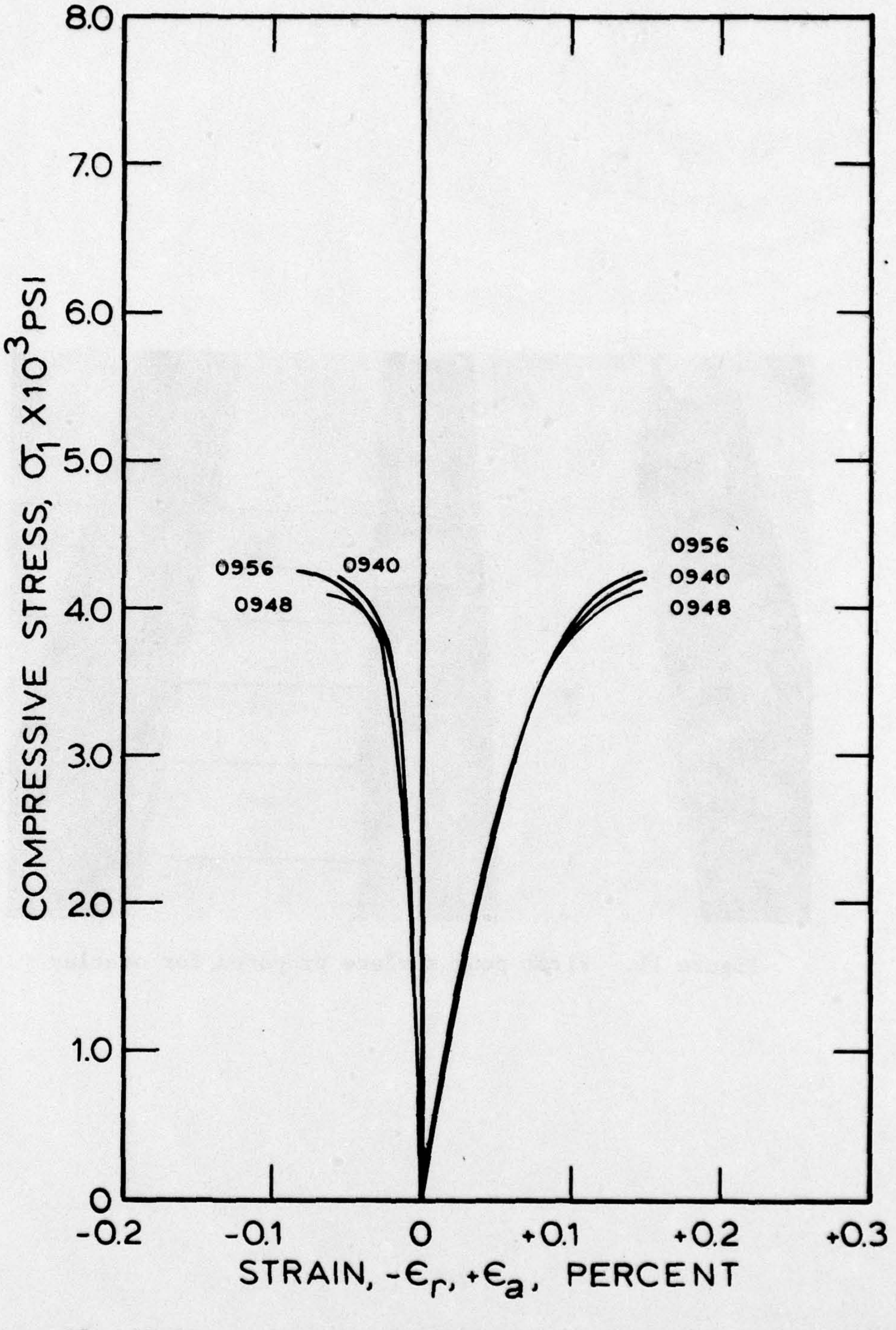


Figure 12. 22-day compressive stress-strain curves for the concrete to be used in second pour epoxy bonding and concrete overlay bonding

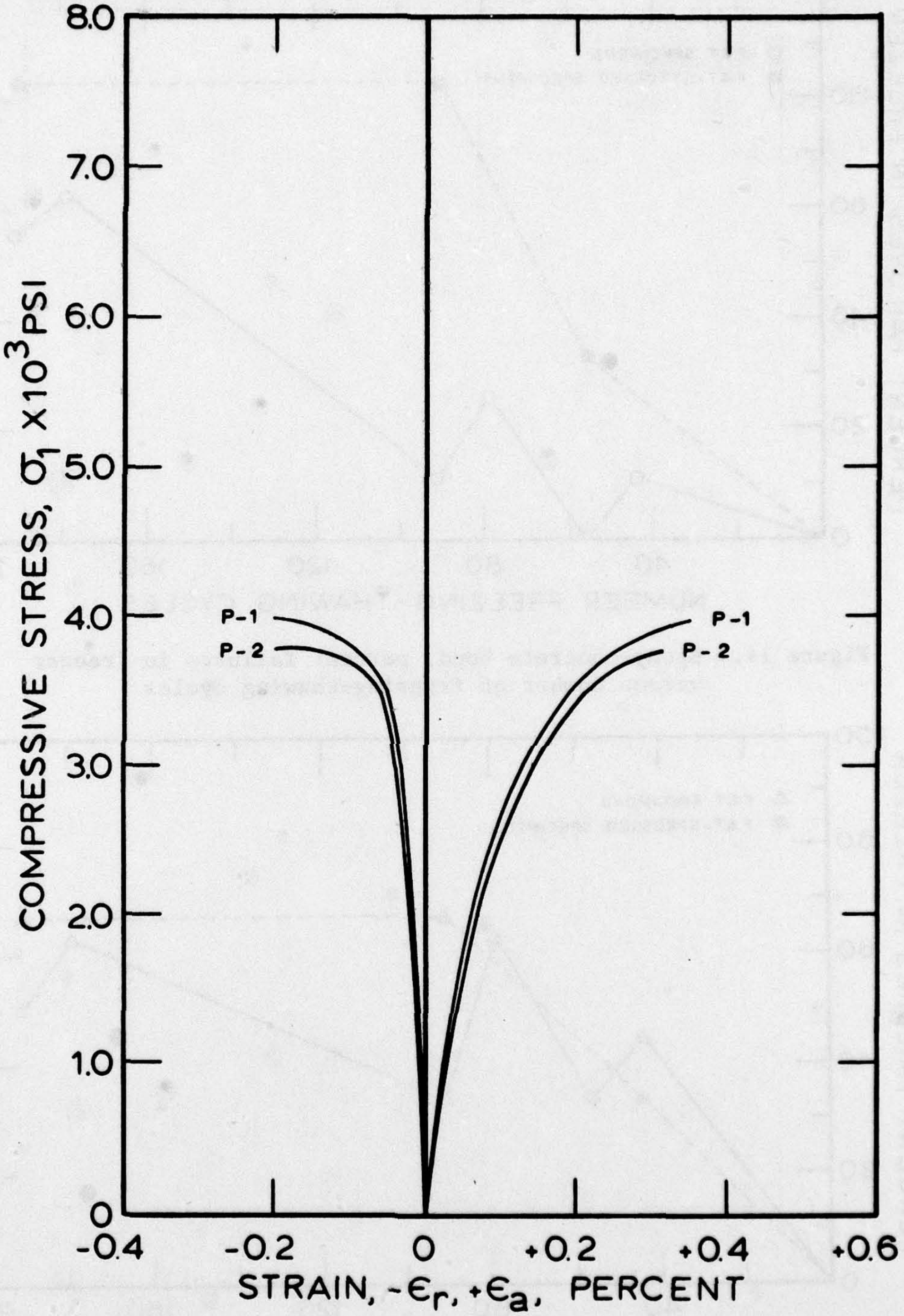


Figure 13. 22-day compressive stress-strain for the second pour polymer modified mortar

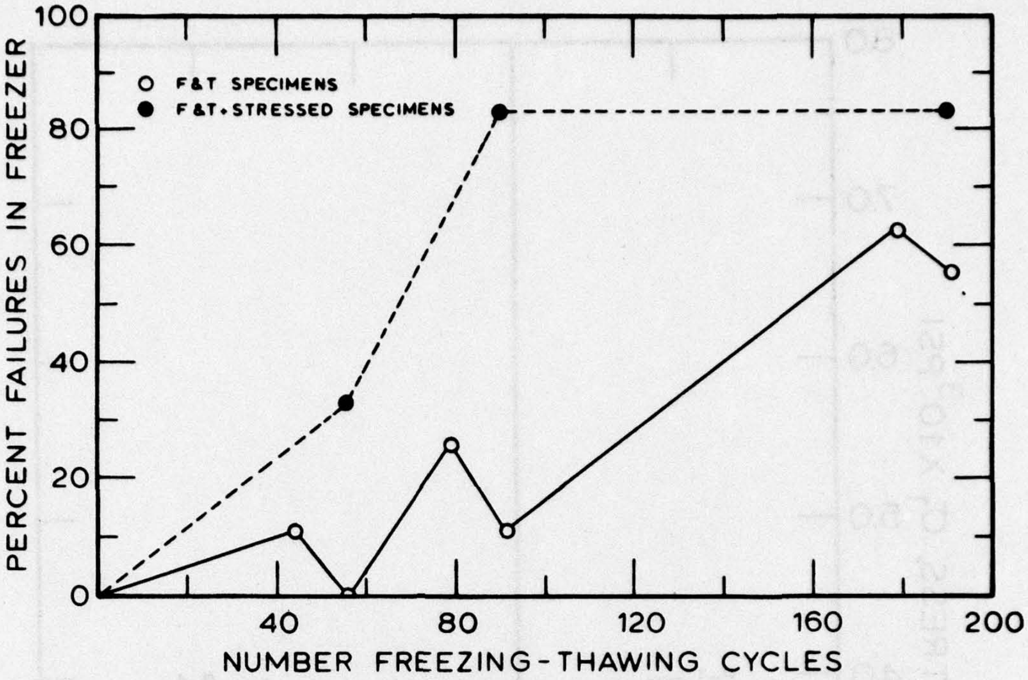


Figure 14. Epoxy-concrete bond, percent failures in freezer versus number of freezing-thawing cycles

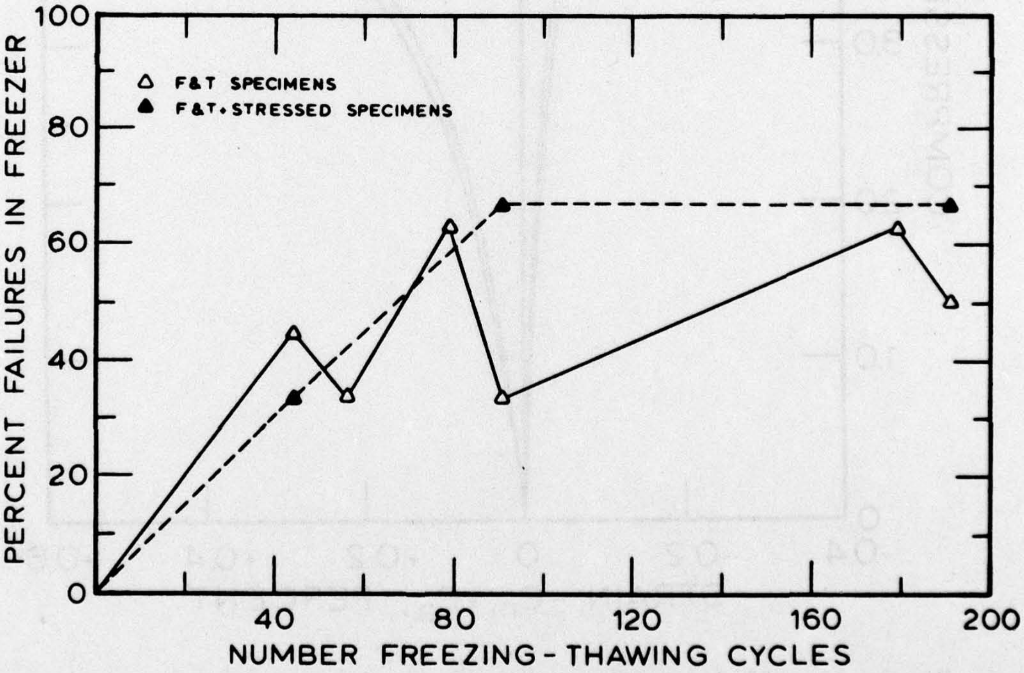


Figure 15. Concrete-to-concrete bond, percent failures in freezer versus number of freezing-thawing cycles

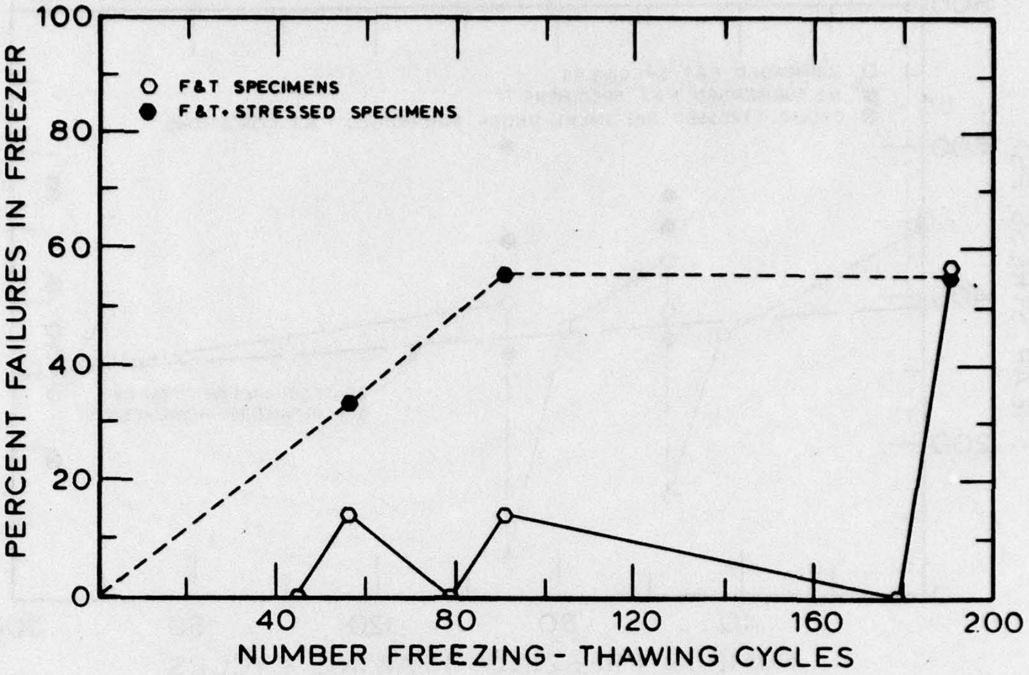


Figure 16. Polymer-concrete bond, percent failures in freezer versus number of freezing-thawing cycles

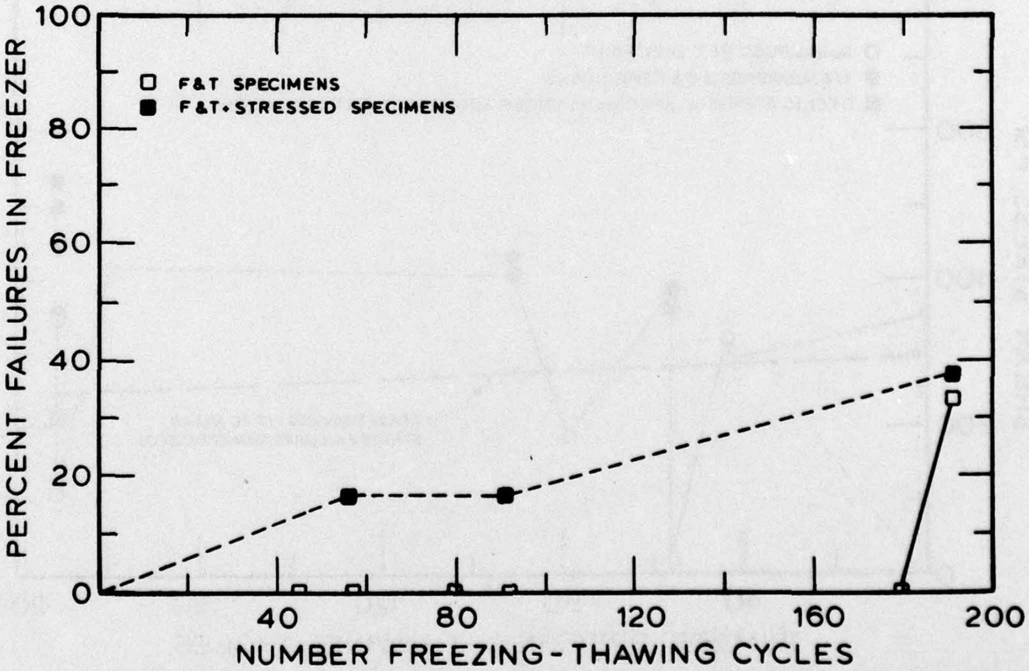


Figure 17. Fabric plus polymer-mortar bond, percent failures in freezer versus number of freezing-thawing cycles

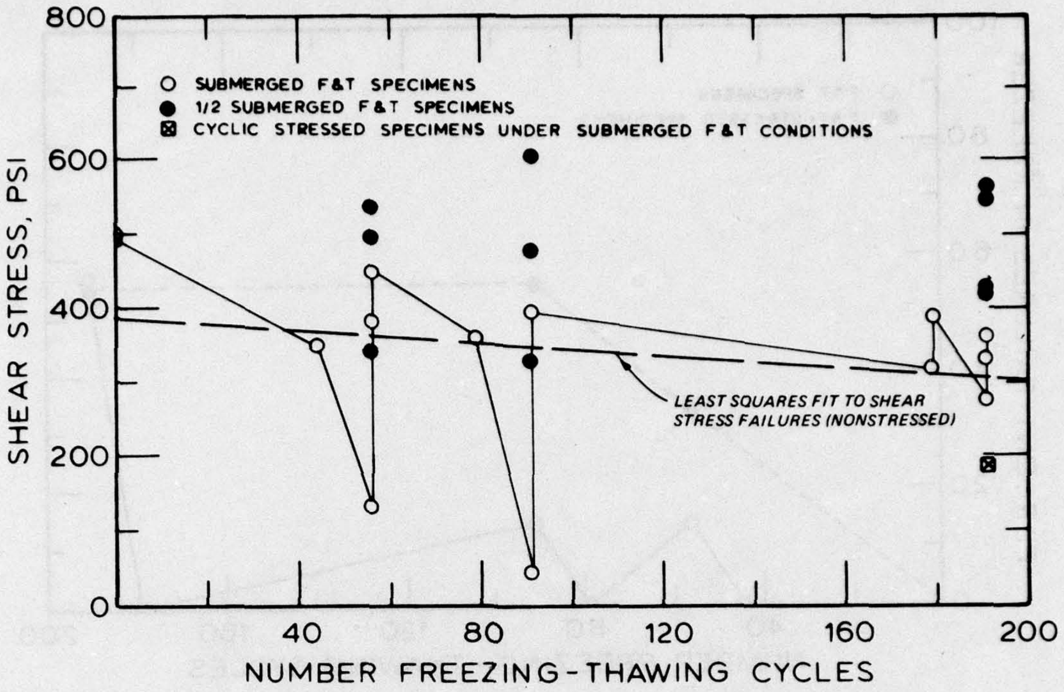


Figure 18. Shear stress versus freezing-thawing cycles, epoxy bonding

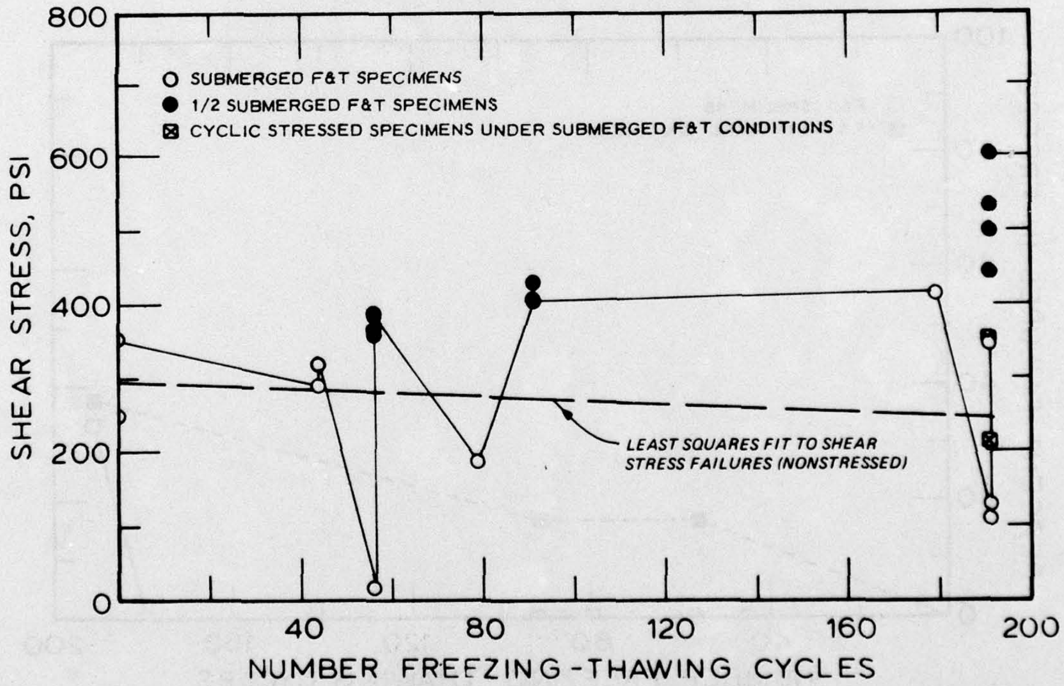


Figure 19. Shear stress versus freezing-thawing cycles, concrete-to-concrete bonding

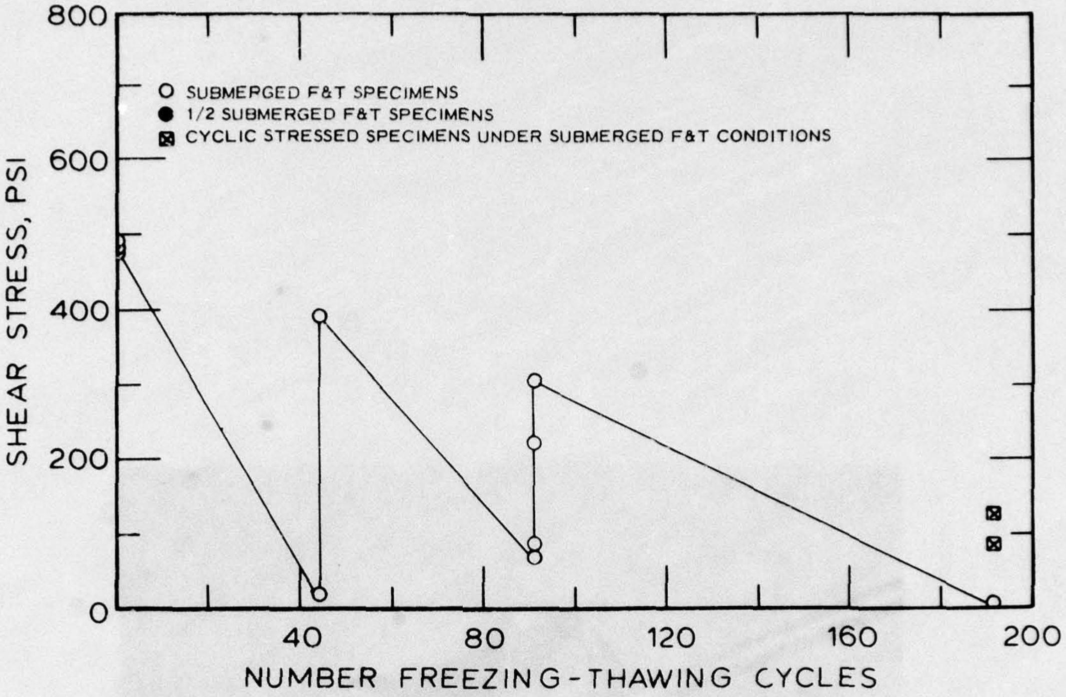


Figure 20. Shear stress versus freezing-thawing cycles, polymer-mortar bonding

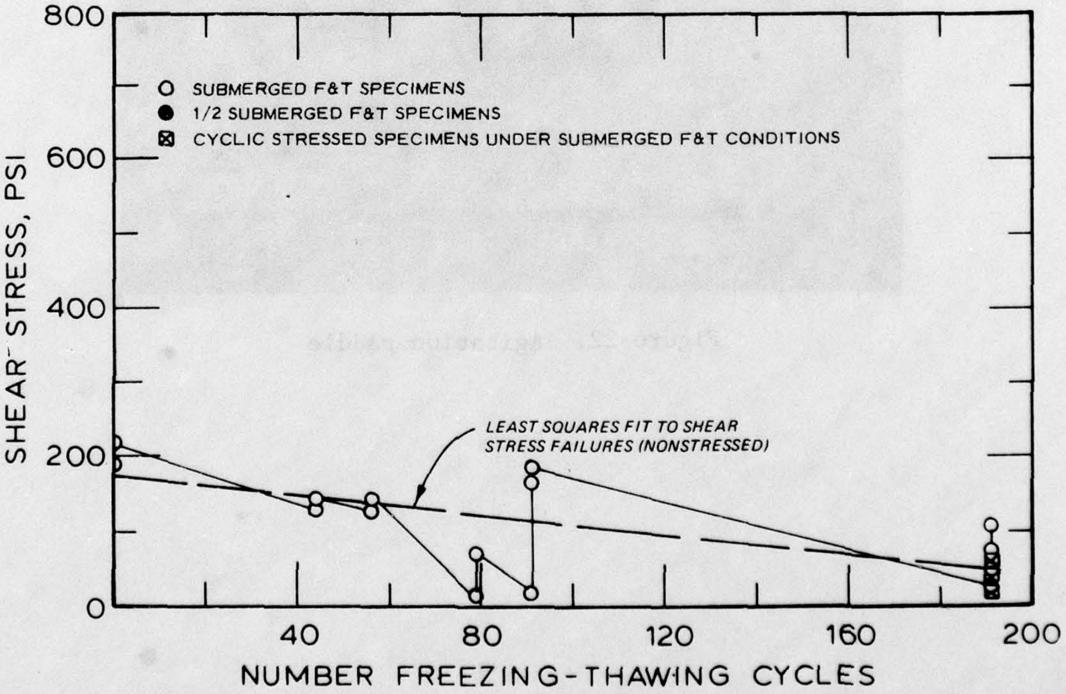


Figure 21. Shear stress versus freezing-thawing cycles, polymer-mortar plus fiberglass fabric bonding

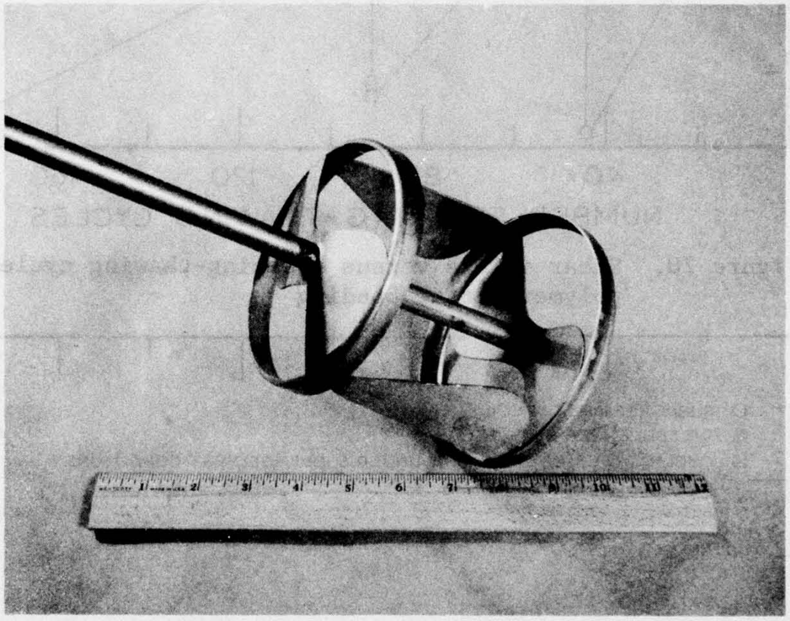


Figure 22. Agitation paddle

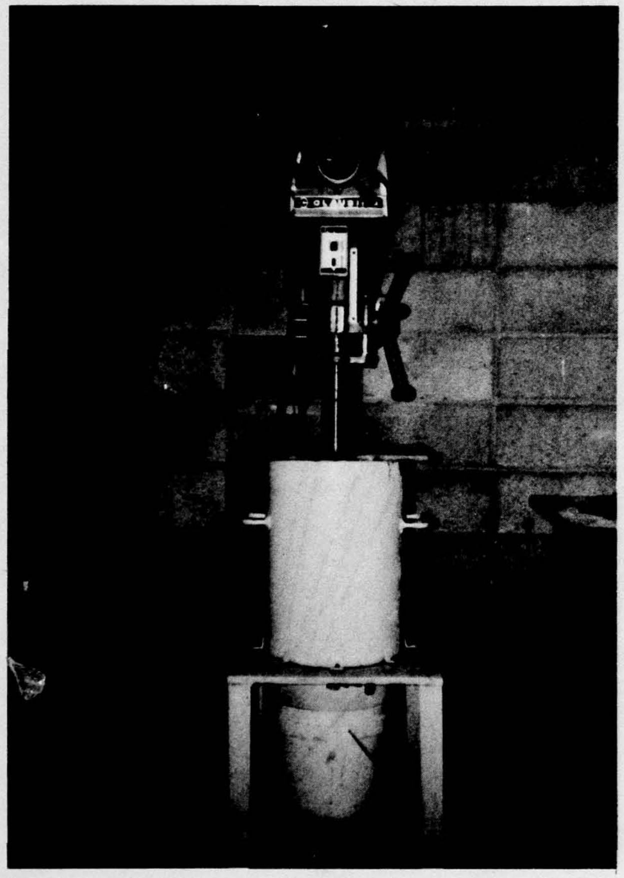


Figure 23. Test setup - overall view

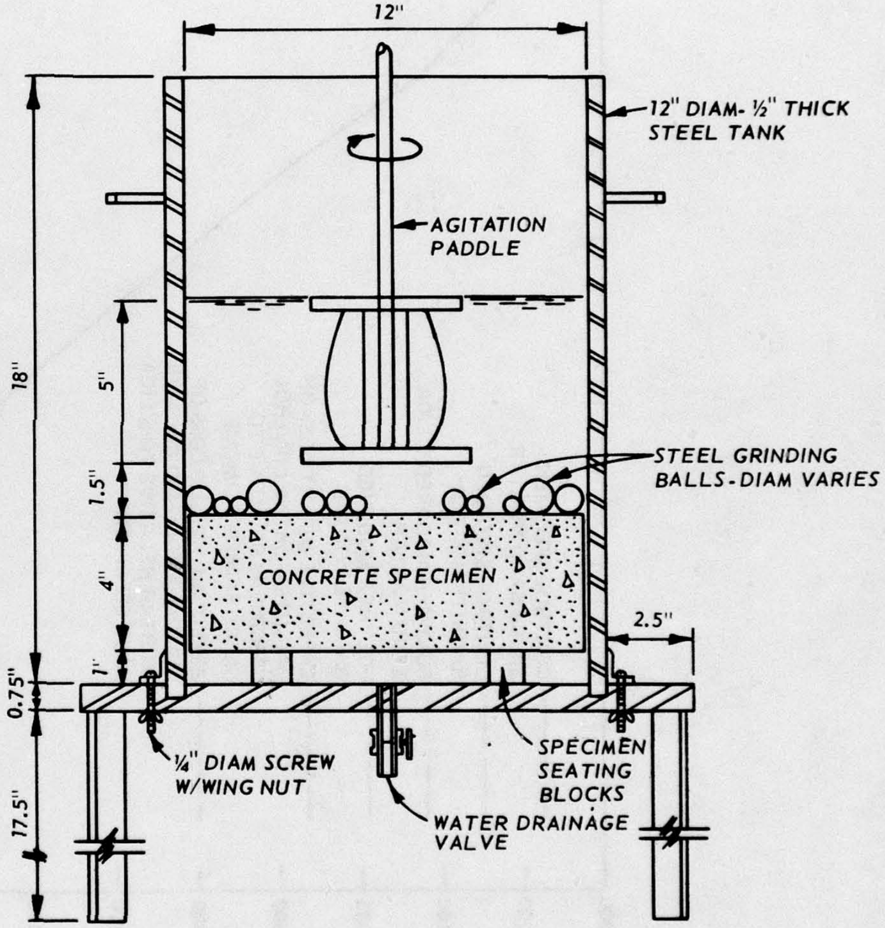


Figure 24. Test setup - details

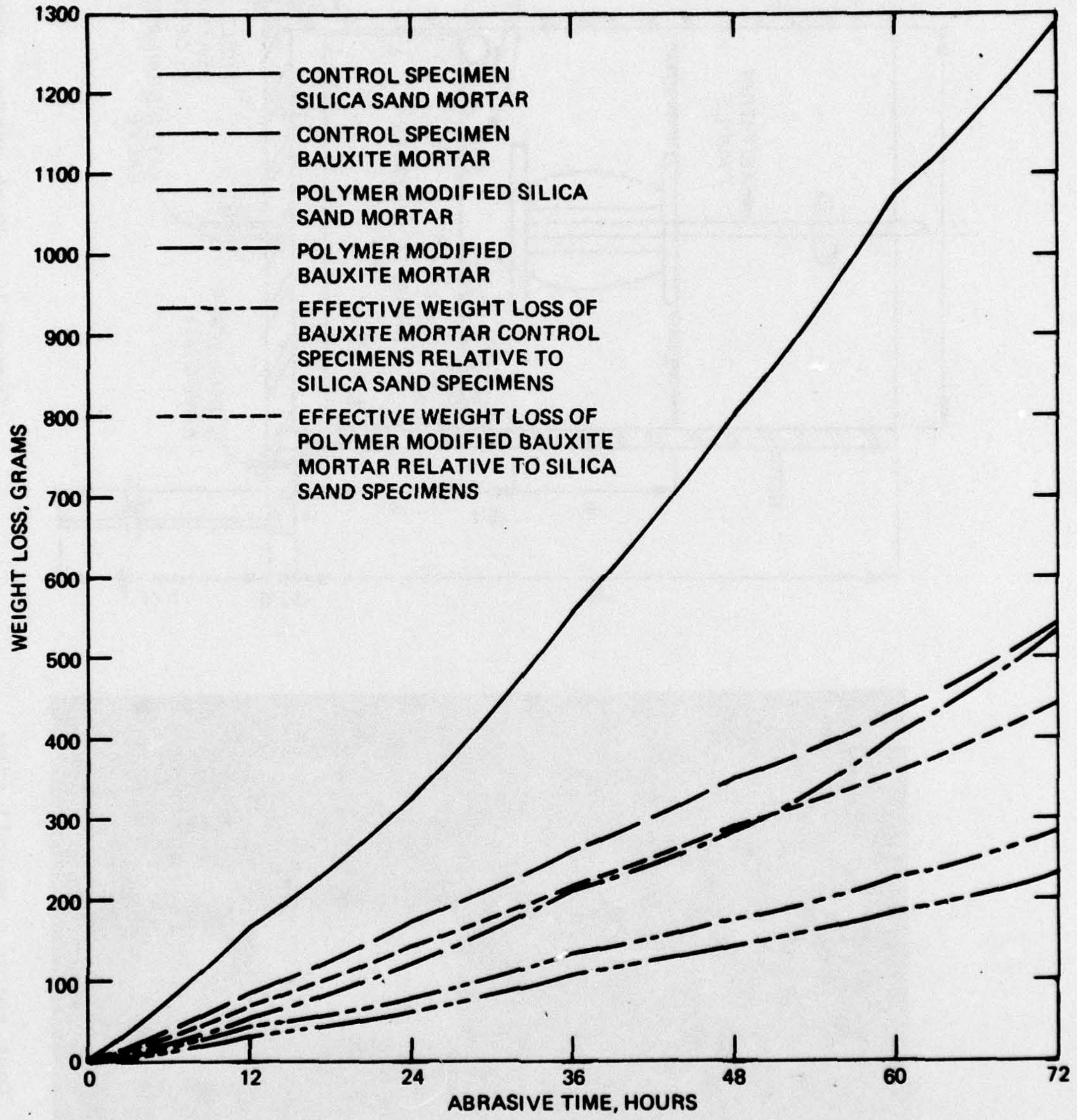


Figure 25. Weight loss versus abrasive time

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Pace, Carl E
The structural and durability properties of various concrete repairs / by Carl E. Pace. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
25, [36] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; SL-79-20)
Prepared for Assistant Secretary of the Army (R&D), Department of the Army, Washington, D. C., under Project No. 4A161101A91D, Task 02, Work Unit 121 08.

1. Abrasion. 2. Bond (Concrete to concrete). 3. Bonding. 4. Concrete deterioration. 5. Concrete durability. 6. Concrete repair. 7. Concrete structures. 8. Freeze-thaw durability. 9. Freeze-thaw tests. 10. Shear strength (Concrete). I. United States. Assistant Secretary of the Army (Research and Development). II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; SL-79-20.
TA7.W34m no.SL-79-20