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REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

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REHABILITATION OF PERMEABLE BREAKWATERS AND JETTIES BY VOID SEALING: SUMMARY REPORT

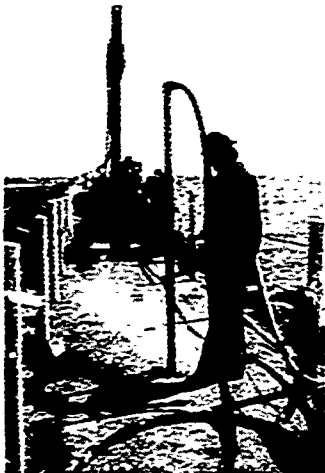
by

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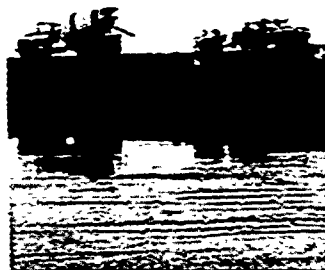
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CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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COVER PHOTOS:

TOP — Drilling sealant holes at Port Everglades, FL.

BOTTOM — Placing sealant at Buhne Point, Humboldt Harbor, CA.

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<p>→ Many Corps breakwaters and jetties have become permeable to sand transport and wave transmission, a condition that results in increased Operations and Maintenance dredging costs and increased risks and delays to navigation. It is apparent that significant first-cost savings could be realized by applying to coastal projects those grouting techniques and sealing procedures developed in civil and mining engineering for closing voids and fractures, instead of the more expensive method of applying layers of chinking and armor stone to the existing structure. However, the longevity of such grouts and sealants placed in voids in the interior of rubble-mound structures exposed to wave and current conditions is not well known. The term "sealant" is used in this report to describe any material that closes voids in rubble-mound structures and includes grouts as well as very stiff, aggregate-containing cementitious and asphalt materials.</p>					
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→ This problem is

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The overall problem under investigation was logically separated into two distinct parts. One part required an evaluation of the effectiveness of materials already being used. The second part entailed the development of guidance on sealant hole drilling, quantities to inject, techniques of injection, and knowledge of material properties to effectively create the needed barrier with the optimum combination of drilling effort and sealant quantities. This research investigated three different aspects pertaining to sealing voids in rubble-mound structures with grouts and concrete sealants: (a) large-scale laboratory investigation for evaluating the effectiveness of sealant injection into such structures, and bioassay tests of materials with potential for adverse environmental effects; (b) long-term time-dependent durability exposure testing of sealant specimens in three different prototype environments (cold region: Treat Island, MA; moderate region: Duck, NC; near-tropical region: Miami, FL); and (c) precise monitoring of the sealing and resulting effectiveness of a prototype rubble-mound jetty (Port Everglades, FL).

Specific objectives of the large-scale laboratory investigation included (a) construction of a rubble-mound physical model at a scale sufficiently large that deviations from similitude would be negligible; (b) preparation and injection into the model two types of cementitious sealants (WES Mixture and Buhne Point Mixture), two types of chemical sealants (Sodium Silicate-Cement Mixture), recording for each the quantities, location of injection, pumping rates, and gel times of the materials; (c) providing specific descriptions of materials by precise recording of components and proportions, and obtaining determinations of standard parameters for the respective materials; and (d) recording spread, shape, competency, and continuity of the hardened sealants upon disassembly of the structure. Sealants to be evaluated were selected based on their (a) potential to be easily pumped; (b) having a short, controllable set time; (c) ability to resist dilution and dispersion; and (d) chemical stability and structural integrity, once set.

The sealant durability time-dependent tests were formulated to determine how the sealant materials would endure under actual field conditions. Effects of environmental exposure to waves, currents, freezing and thawing, wetting and drying, abrasion biological influences, and chemical reactions are being evaluated. A monitoring effort of indefinitely long duration was established to determine the performance with time of sealant materials in the field environment. Representative samples of each sealant material evaluated in the physical model rubble-mound structure were cast as specimens and placed in locations with varied climatic conditions. Since the specimen exposure is direct and unconfined, the tests may actually be more severe and extreme than if the materials were placed inside a structure.

The voids in the Port Everglades, FL, south jetty were sealed with sodium silicate-cement sealant such that it would function as a terminal groin to the John U. Lloyd State Park beach fill. The sand layer beneath the jetty and the voids within the structure which were filled with sand were stabilized with sodium silicate-diacetin sealant. A monitoring plan to ascertain the effectiveness of the sealing project through a field evaluation was conducted by the US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, with the cooperation of Broward County, the State, and the contractor.

The use of synthetic materials such as those utilized in these investigations continues to draw scrutiny from various environmental advocacy groups. The US Army Corps of Engineers is in full agreement with such concerns and recognizes the health, safety, and water quality aspects associated with such materials. The Corps is committed to fully understanding all environmental consequences associated with their utilization and will adhere to all standards, specifications, and safeguards pertaining thereto.

→ Keywords: Coastal engineering; sealing compounds; voids; Sand/erosion/transport; Sodium silicates/cements; Asphalt; Dredging;

→ Navigation/hazards; wear ways; Florida.

PREFACE

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Coastal Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32375, "Rehabilitation of Permeable Breakwaters and Jetties by Void Sealing," for which Mr. David P. Simpson, Ms. Julie D. Rosati, Ms. Joan Pope, and Dr. Lyndell Z. Hales of the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES), were the Principal Investigators. Mr. John H. Lockhart, Jr. (CEEC-EH) was the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr. (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-OM) and Dr. Tony C. Liu (CECW-ED) serve as the REMR Overview Committee; Mr. William F. McCleese (CEWES-SC-A), WES, is the REMR Program Manager. Mr. D. Donald Davidson, Wave Research Branch, CERC, is the Problem Area Leader.

The work was performed at WES, and this report was prepared by Mr. Simpson, Ms. Rosati, Dr. Hales, and Messrs. Thomas A. Denes and Jeffrey L. Thomas, CERC, under the general supervision of Dr. James R. Houston, Chief, CERC; Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC; Mr. H. Lee Butler, Chief, Research Division (RD), CERC; and Mr. Thomas W. Richardson, Chief, Engineering Development Division (EDD), CERC; and the direct supervision of Dr. Stephen H. Hughes and Mr. Bruce A. Ebersole, former Chief and Chief, respectively, Coastal Processes Branch (CPB), RD; and Ms. Pope, Chief, Coastal Structures and Evaluation Branch (CSEB), EDD.

Valuable assistance was provided throughout all phases of this investigation by other WES laboratory personnel, without whose guidance and advice this research effort could not have been concluded successfully. Acknowledgment is extended to Messrs. Allen F. Kimbrell and Perry A. Taylor, Rock Mechanics Application Group, Engineering Geology and Rock Mechanics Division, Geotechnical Laboratory (GL), and Mr. Nelson Godwin, Engineering Investigation, Testing, and Validation Group, Pavement Systems Division, GL; Messrs. John A. Boa, Jr., Donald M. Walley, and Billy D. Neeley, Concrete and Grout Unit, Concrete Technology Division (CTD), Structures Laboratory (SL); Messrs. Henry T. Thornton, Jr., and Daniel E. Wilson, and Ms. Linda S. Mayfield, Evaluation and Monitoring Unit, CTD, SL; and Dr. Henry E. Tatem,

Contaminant Mobility and Regulatory Criteria Group, Ecosystem Research and Simulation Division, Environmental Laboratory.

The first milestone report arising from this research study, "State-of-the-Art Procedures for Sealing Coastal Structures with Grouts and Concretes," was prepared in 1989 by Mr. Simpson, Research Hydraulic Engineer, CPB. The second milestone report, "Laboratory Techniques for Evaluating Effectiveness of Sealing Voids in Rubble-Mound Breakwaters and Jetties with Grouts and Concretes," was prepared in 1989 by Messrs. Simpson and Thomas (formerly Research Hydraulic Engineer, CSEB). The third milestone report, "Field Evaluation of Port Everglades, FL, Jetty Rehabilitation," was prepared in 1990 by Ms. Rosati, Research Hydraulic Engineer, CPB (formerly Research Hydraulic Engineer, CSEB), and Mr. Denes (Research Hydraulic Engineer, CSEB). Long-term exposure durability monitoring of sealant specimens is continuing and will be reported in final form subsequently. This summary report contains preliminary results from the long-term exposure testing and a synopsis of knowledge gleaned from Simpson (1989), Simpson and Thomas (1989), and Rosati and Denes (1990).

Commander and Director of WES during the publication of this report was COL Larry B. Fulton, EN. Technical Director of WES was Dr. Robert W. Whalin.



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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:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
cubic feet	0.028317	cubic metres
cubic yards	0.7645549	cubic metres
cups	0.0002366	cubic metres
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
gallons (US liquid)	3.785	litres
gallons (US liquid) per minute	0.0630833	litres per second
inches	25.4	millimetres
knots (international)	0.5144444	metres per second
miles (US statute)	1.609347	kilometres
ounces (US fluid)	0.02957353	cubic decimetres
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per cubic yard	1,186.552725	kilograms per cubic metre
yards	0.9144	metres

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

REHABILITATION OF PERMEABLE BREAKWATERS AND JETTIES

BY VOID SEALING: SUMMARY REPORT

PART I: INTRODUCTION

Background

1. When many coastal breakwaters and jetties were erected, the service of the structure was considered satisfactory if the inlet or entrance was stabilized and wave energy was merely reduced in the harbor. Today, however, increasing ship drafts have pushed to the limit the practical ability to maintain navigable depths by periodic dredging at locations where deteriorated structures permit shoaling material to pass through such structures. With increased competition worldwide among ports, the need to provide reliable depths, and to minimize Operation and Maintenance expense, has been accentuated.

2. Many US Army Corps of Engineers (USACE) breakwaters and jetties have become permeable to sand transport and wave transmission, a condition that results in increased Operation and Maintenance dredging costs and increased risks and delays to navigation. The permeability of some coastal structures to the movement of shoal material and to the transmission of wave energy is severe enough to have serious economic consequences. Economic losses resulting from permeabilities of coastal breakwaters or jetties include decreased efficiency of ship operation due to light-loading for transiting a shoal area in a navigation channel and limitations on port development due to insufficient reduction in wave energy by such structures. Causes of the permeability may be wave damage to armor and concomitant loss of core material, differential settling of rubble material below a monolithic cap, or the use of only large blocks to construct the original section.

3. Whatever the cause, the engineering problem facing a coastal planner or engineer is to economically rehabilitate a coastal rubble-mound structure by permanently closing the large voids in a specified zone of its interior, where the void size may be on the order of a metre in diameter. It is apparent that significant savings could be realized by applying to coastal projects those sealing procedures developed in civil and mining engineering as a method of closing voids and fractures. In order to refine the methods and materials

presently available for such applications and to provide field guidance in this promising type of rehabilitation, the Repair, Evaluation, Maintenance, and Rehabilitation Research Program work unit "Rehabilitation of Permeable Breakwaters and Jetties by Void Sealing" was initiated in FY86 by the US Army Engineer Waterways Experiment Station (WES).

4. Before the actual initiation of any grouting, concreting, or sealant placement techniques, a thorough foundation and hydraulic investigation must be conducted to assess potential settlement and wave wash effects. Many rubble-mound coastal structures are designed to dissipate wave energy and prevent overtopping (based upon the voids that exist within the structure). Whenever an evaluation is made that considers sealing to repair such a structure exposed to a severe wave climate, an engineering analysis should also be conducted to determine how sealing may affect wave overtopping, dissipation, reflection, and subsequent stability of the structure.

Terminology

5. Grout is defined by Engineer Manual (EM) 1110-2-3506 (Headquarters, US Army Corps of Engineers (HQUSACE) 1984) as a mixture of cementitious or noncementitious material, with or without aggregate, to which sufficient water or other fluid is added to produce a flowing consistency. Throughout the present report, the term "sealant" is used to describe any material that closes voids in rubble-mound structures and includes grouts as well as very stiff, aggregate-containing cementitious and asphaltic materials. The distinction is purposefully made for the following reasons: (a) the tendency to call any material pumped or tremied down a hole to close voids a "grout" is incorrect and could result in poor communication between those involved in design and others in construction, and (b) a contractor who is unfamiliar with this unique type of problem would have difficulty trying to apply typical grouting materials and techniques to highly porous coastal rubble-mound breakwaters and jetties. Sealant competency refers to the ability of sealants to harden into a mass sufficiently adequate to fill cavities and interconnect with adjacent cavities, thereby creating a continuous barrier.

Purpose of the Study

6. Sealing of permeable structures (almost exclusively rubble-mound) by filling significantly large voids is a concept not routinely considered by coastal engineers. However, the basic underlying technology necessary for closing such large voids and for stabilizing sand within a structure has been developed previously in the grouting field for sealing cracks and fissures in rocks or dam foundations. While specific guidance did not exist for sealing breakwaters and jetties by those means, adaptation of this technology and promotion of the use of cementitious, chemical, and asphaltic products in coastal structures to reduce wave penetration and sand infiltration were initiated by WES in 1986. Figure 1 provides field evidence of sand transport



Figure 1. Prototype field evidence of sand transport through rubble-mound breakwater or jetty

through a rubble-mound breakwater or jetty. A schematic of a structure sealing operation is shown in Figure 2. This investigation has developed and conveyed state-of-the-art knowledge in this area to appropriate Corps and other personnel charged with field application responsibility for performing such sealing measures.

7 The overall problem under investigation was logically separated into two distinct parts. One part required an evaluation of the effectiveness of materials already being used. The second part entailed the development of guidance on sealant hole drilling, quantities to inject, techniques of injection, and knowledge of material properties to effectively create the needed

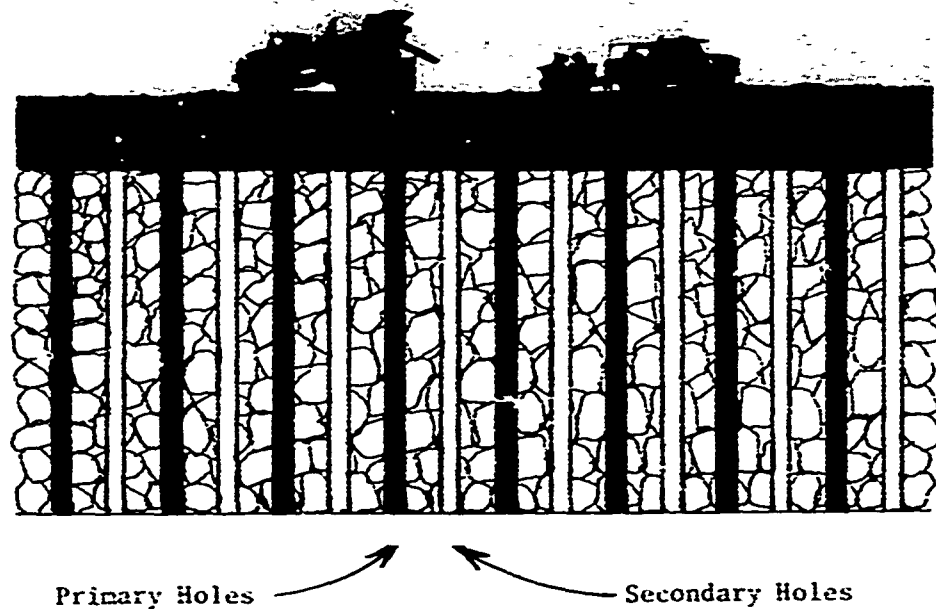


Figure 2. Schematic of rubble-mound structure sealing operation. Primary holes are sealed first; then secondary holes are sealed to complete closure of all interconnecting structure voids

barrier with the optimum combination of drilling effort and sealant quantities. This research investigated three different aspects pertaining to sealing voids in rubble-mound structures with grouts and concrete sealants:

(a) large-scale laboratory investigation for evaluating the effectiveness of sealant injection into such structures and bioassay tests of materials with potential for adverse environmental effects; (b) long-term time-dependent durability exposure testing of sealant specimens in three different prototype environments (cold, moderate, near-tropical); and (c) precise monitoring of the sealing and resulting effectiveness of a prototype rubble-mound jetty (Port Everglades, FL).

Purposes of laboratory investigations

8. The specific objectives of the laboratory investigations were to:
 - a. Obtain quantitative measurements and qualitative descriptions of the injected materials after they had solidified inside the rubble-mound structure, by the construction of a rubble-mound physical model at a scale sufficiently large that deviations from similitude would be negligible.
 - b. Prepare and inject into the model two types of cementitious sealants, two types of chemical sealants, and one asphalt concrete, recording for each the quantities, locations of injection, pumping rates, and gel times of the materials.

- c. Provide specific descriptions of materials by precise recording of components and proportions and obtaining determinations of standard parameters for the respective materials.
- d. Record spread, shape, competency, and continuity of the hardened sealants upon disassembly of the structure.
- e. Perform abbreviated bioassay tests to bracket toxicity effects on the laboratory animal *Daphnia* by levels of concentrations of the sealant materials.

Purposes of long-term exposure testing

- 9. Objectives of the long-term durability exposure tests included:
 - a. Casting specimens of each sealant type, performing baseline measurements of parameters that will provide an indication of strength variance with time, including pulse velocity (speed of sound pulse through the specimen) and dynamic modulus of elasticity for the cementitious and chemical sealants, and the Marshall stability test for the asphaltic concrete specimens.
 - b. Placing specimens in the prototype environment, exposing the samples to cycles of wetting and drying, freezing and thawing, and chemical and biological degradation in the saltwater environment.
 - c. Placement of samples at two water levels of mean water line (mwl) and below mean lower low water (-mllw), at three exposure sites: Treat Island, ME; Duck, NC; and Miami, FL.
 - d. Periodically retesting to ascertain effects of environmental factors on strength variance with time.

Purposes of monitoring
prototype structure sealing

- 10. The monitoring program included:
 - a. Reconnaissance evaluation, designed to obtain preliminary information so that later phases of the program could be best designed.
 - b. Preconstruction experiment to qualitatively and quantitatively evaluate the presealing condition of the structure.
 - c. During construction observations of the drilling and grouting techniques.
 - d. Postconstruction experiment, which repeated tests during the preconstruction phase so that the degree to which structure sealing occurred could be assessed.

PART II: SEALANTS AND THEIR CHARACTERISTICS

Grouts and Sealants

11. Grouting and sealing voids in coastal structures are two closely related operations, but careful distinctions should be made between them. The term "grouting" implies the injection under pressure of a liquid or suspension into fractures in rock or in a structure or into interstices of smaller particles. The injected grout must eventually form either a gel or a solid within the treated voids, or the grouting process must result in the deposition of suspended solids within those voids. The purpose for sealing voids in rubble-mound coastal breakwaters and jetties is to create a vertical barrier that is impervious to the movement of shoal material or wave energy.

12. Sealing products that have been applied to coastal structures, with one known exception (a sodium silicate solution), are not properly called grouts. Their viscosities cannot be measured with ordinary laboratory viscometers. According to EM 1110-2-3506 (HQUSACE 1984), grout is "a mixture of cementitious or noncementitious material, with or without additional aggregates, to which sufficient water or other fluid is added to produce a flowing consistency." Likewise, grout placement is "the introduction of grout by gravity or pressure into voids; usually accomplished by grouting through pipes placed in the medium to be grouted, or through drilled open holes penetrating the medium." Conventional terminology in the grouting field requires grout to be able, at least, to flow through a Marsh funnel. Materials used in most coastal applications are usually described by their slump and not by time of efflux from a funnel. Techniques for modeling grout flow, whether in physical scale models or by analytical procedures, are not applicable to coarse aggregate concrete, the material most often chosen to seal coastal structures.

13. The importance of terminology is emphasized because this research topic brings together two fields that have had relatively little interaction, those being coastal studies and geotechnical grouting. Use of the term "grout" is minimized or heavily qualified in this report when a sealant for large voids in a rubble-mound structure is intended. Many true grouters, upon hearing the term "grout" applied in this context, may develop an incorrect understanding of the problem and materials the coastal engineer deals with. The coastal engineer, likewise, must know how to communicate with grouters because the concept, basic materials, and some of the equipment are taken from

the grouting industry. The terminology of this report is intended as clarification for coastal engineers.

14. As an alternative to the term "grout," it is proposed to establish the term "sealant" as a generic descriptor of the very viscous materials pumped into the interiors of coastal structures to achieve a purpose similar to that of cavity filling in other environments. Sealant is intended to imply that the injected material may be thick or quick-setting to avoid loss through dilution and dispersion by dynamic forces and to prevent uncontrolled gravity flow as in special preparations of cementitious or asphaltic concrete. The term also includes a true grout that may be used to stabilize sands occupying voids within a rubble structure, an example being sodium silicate gel. Nevertheless, the technology for emplacing sealants in coastal structures was refined over many years by grouters, and the basic ingredients used, though modified for coastal work, were developed by grouters.

15. Grout development and grouting technology have made great advances in the fields of geotechnical and structural engineering. The main purposes have been to stabilize or impart strength to soils or other geologic materials for tunneling or foundation work, termed "structural grouting." Equally important to advances in grouting have been efforts to block the flow of water, as in cases of leakage into an excavation area or out of a containment area, and to minimize seepage and uplift pressures under hydraulic structures, a procedure termed "waterproof grouting."

Sealant Materials

16. There are many sealant materials in existence, with the basic types being suspensions, solutions, and emulsions. Other taxonomic classifications have been attempted, but distinctions become difficult when various constituents are added to obtain particular properties. At the beginning of this century, cement-based sealants were viewed separately from sodium silicate-based (chemical) sealants. Grouping sealants by modes of network formation (such as interlocking crystals for portland cement), neutralization of surface charges (such as in bentonites), and others may be useful. Categorizing chemical sealants by their viscosity is a practice in Europe. Sealants with viscosities close to that of water are termed resins, and those with higher viscosities are termed gels.

17. Examples of the suspension type of sealants are portland cement in association with water and clays in water (i.e., some or all of the ingredients do not dissolve in water). Suspensions may be normal, such as cement-clay mixtures, or thixotropic, such as bentonite. A solution type of sealant is one in which all ingredients go into solution. Colloidal solutions have the solute present in the colloidal state (i.e., in suspension). Chemical sealants may be applied as a "one-shot" solution (e.g., sodium silicate and a coagulant) or a "two-shot" solution (e.g., successive injections of sodium silicate and an electrolyte). Emulsions are two-phase systems in which the dispersive phase comprises minute drops of liquid (e.g., bitumen and water).

18. In coastal engineering practice, a pure portland-cement sealant would rarely, if ever, be used. Admixtures are needed to accelerate the setting time so as to minimize dilution or erosion by water. Because the mixture has such a low water-to-cement ratio, it is more properly called "concrete" than a sealant. Therefore, this report discusses sealants according to chemical, cementitious, and asphaltic types and groups coastal structure sealants as concretes (both cementitious and asphaltic) or gels (e.g., sodium silicate, a true grout).

Properties of Sealants

19. Desirable properties of sealants for coastal work include suitable rheological characteristics with appropriate viscosity, correct setting time, minimum shrinkage, stability, and durability. Viscosity and other rheological properties are important not only for pumping and injection into the structure, but also for penetration into the spaces to be sealed. Rheological properties of sealant suspensions also are important because they determine the minimum pumping pressure required to inject a sealant into a material with specified void dimensions. Thixotropy is a rheological property of some gels and clays, defined such that gels and clays behave as liquids when agitated and set when quiescent. This is a desirable behavior for sealants being pumped, and not impacted by dynamic loading after injection. Conversely, in some applications, it has been found advantageous for a sealant to mobilize shear strength to resist wave forces, yet deform slowly to accommodate settling.

20. The effective rates of injection of sealants in typical coastal applications are determined by permeability of the material being sealed,

injection pressure, and viscosity of the sealant. (Where soils are sealed, the soil shear strength is another determining factor.) Permeability is the measure of fluid flow through voids between solid particles. Reynolds numbers express the ratio of inertial forces to viscous forces. When a sealant is injected into spaces in such a way that the flow is laminar (Reynolds number less than 5), Darcy's law states the velocity, V , is linearly related to the hydraulic gradient, dh/ds , by the coefficient of permeability, k .

$$v = k \frac{dh}{ds} \quad (1)$$

where

h = head drop across the section, ft

s = length of section, ft

21. There are only slight deviations from Darcy's law at Reynolds numbers less than 200 (Bowen 1975). The permeability coefficient is a function of the shape and degree of packing of the solids, the square of a characteristic particle diameter, and viscosity of the fluid (Ippen 1966).

22. At higher Reynolds numbers (turbulent flow) in fully saturated media of grain size more than 1.00 mm, Darcy's law is stated as:

$$v = k \left(\frac{dh}{ds} \right)^\phi \quad (2)$$

where ϕ is the exponent of turbulence, shown by experimental results to be between 0.65 and 1.00 (Tuma and Abdel-Hady 1973).

Viscosity

23. In all fluids, shearing (friction) forces exist whenever motion takes place. These friction forces are due to a property of the fluid called viscosity. Viscosity of a fluid is a measure of its resistance to shear. It is the proportionality between shear stress and rate of strain. This proportionality is linear (constant) for a Newtonian fluid, and nonlinear for a non-Newtonian fluid. Chemical grouts, prior to setting, are non-Newtonian liquids. If a finite force (cohesion) is required before initial deformation

occurs and if the rate of deformation is thereafter linear, the fluid is said to be visco-plastic and offers resistance to both cohesion and viscosity.

Cohesion

24. Stable cement and bentonite-based sealants are examples of visco-plastic liquids, called Bingham liquids. They have properties of both cohesion and viscosity. Cohesion of a mixture is its yield stress, that stress which the applied shear stress must exceed before initial flow occurs. Analysis is possible only of stable mixtures, which by this definition are mixtures having less than 5-percent sedimentation in 2 hr; i.e., less than 50 ml of water standing at the top of a 1,000-ml cylinder filled with the mixture (Lombardi 1985). The percentage of sedimentation of cement-based sealants can be greatly reduced by addition of small amounts (2 to 4 percent) of bentonite. The bentonite is particularly effective for thinner sealants (Deere 1982). The effect of stabilizing a sealant mixture is to increase both the viscosity and cohesion, but especially the cohesion, according to Deere and Lombardi (1985). They showed that viscosity is a factor in the rate at which a sealant flows under pressure, and cohesion is a factor limiting the distance of sealant travel, and therefore, the volume of sealant required to fill a cavity or fissure.

Sealant particle size

25. The size of particles in a grout suspension is an important factor in the effectiveness and ability to seal fractures and granular material. For all the foregone reasons, it is necessary to develop empirical relations in estimating the ability to seal certain materials. Groutability ratios (GR) have been developed for the successful treatment of soils and rock strata, as:

$$(GR)_{\text{soil}} = \frac{(D_{15})_{\text{soil}}}{(D_{85})_{\text{grout}}} > 25 \quad (3)$$

$$(GR)_{\text{rock}} = \frac{(D_{\text{max}})_{\text{fissure}}}{(D_{\text{max}})_{\text{grout}}} > 3 \quad (4)$$

In the preceding, D_{15} and D_{85} are the particle sizes such that 15 and 85 percent, respectively, of the mixtures are finer in size. Figure 3 shows the limiting grain sizes of materials that can be successfully sealed by various types of sealants. Experience with chemical sealants has resulted in a delineation by size ranges of soils according to groutability (Figure 4).

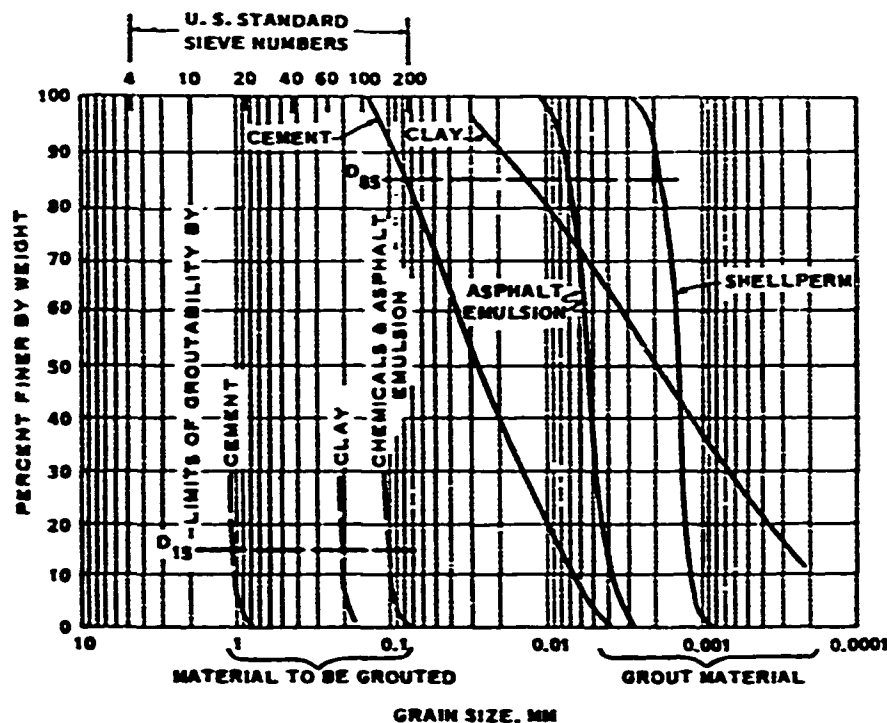


Figure 3. Groutability limits of materials using various grouts, EM 1110-2-3506 (after HQUSACE 1984)

Grout extent

26. According to Deere and Lombardi (1985), grout will spread a radial distance, r , after injection such that:

$$r = 0.62 \left(\frac{Rgt}{n} \right)^{1/3} \quad (5)$$

where

R = ratio of viscosity of water to viscosity of grout, dimensionless

g = rate of grout intake, g/sec

t = gel time, sec

n = soil porosity, ratio of volume of voids to total volume, dimensionless

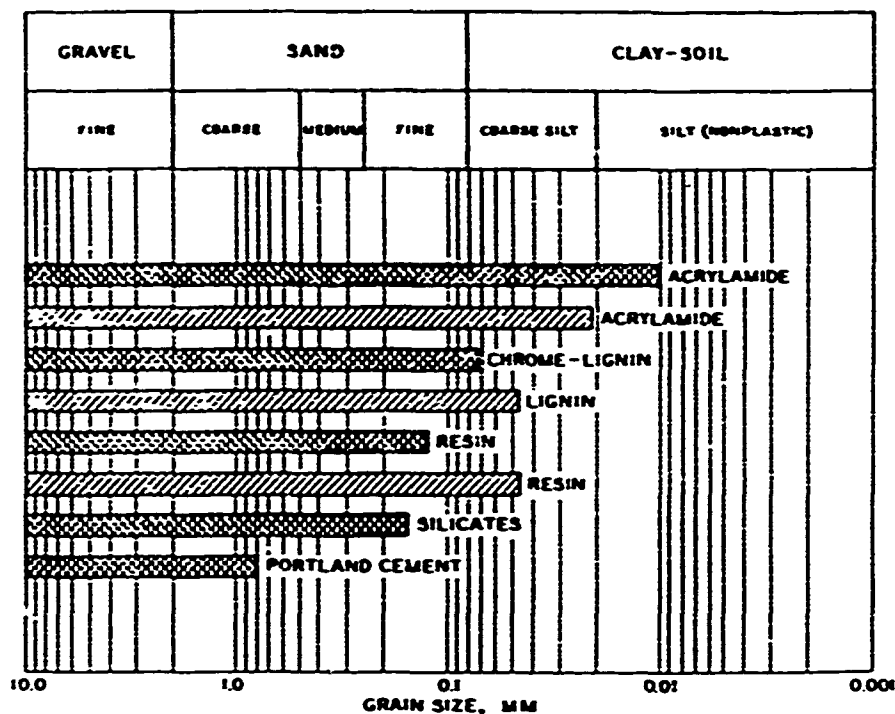


Figure 4. Grain size ranges for chemically groutable soils, EM 1110-2-3506 (after HQUSACE 1984)

Correct setting time

27. Setting time of sealants placed in the coastal environment must be controlled. Sealants tested for resistance to erosion in a flume showed the most important factor was a fast set time (Walley 1976). Admixtures control gel times and set times of sealants over a wide range. Care must be taken so that the sealant does not set in the injecting equipment or in voids in such a way that blockage to other voids occurs and ineffective grouting results.

Minimum shrinkage

28. Volume change of a sealant during setting or curing in typical coastal applications is not as important as in waterproof sealing. The barrier being created does not have to be watertight in order to be successful. Shrinkage would be important if it were so extreme as to not effectively reduce sand or energy transmission through the structure or prevent bonding of particles being grouted.

Stability

29. Permanence of the chemical state of a sealant is important to the success of a coastal sealing project because, unlike some geotechnical applications, creating an impermeable barrier is the structural objective. Should

the sealant fail to meet this objective, the investment represented by the total contract cost would be lost. The sealing material should resist deterioration by chemicals, organisms, sunlight, and air.

Durability

30. Not all sealants are intended to be permanent, however, but sealing jetties and breakwaters to block the movement of sand and wave energy does require the material to have a long service life. When in contact with sediment-transporting water, the sealant must not be easily eroded or dissolved. It must also not be sensitive to cycles of wetting and drying and/or freezing and thawing. In one application for which documentation exists, the cost of the sealing materials was only 20 percent of the project, the rest being mobilization and demobilization, drilling sealant holes, placing sealant, and other costs. It is important, therefore, that the durability of the sealant be considered as significant in economic analyses and specification writing.

Cementitious Sealants

31. To the present time, cementitious mixtures have been the most often used method of sealing voids in coastal structures. The chemical and physical properties of these suspensions should be understood by one desiring to utilize a cement-based sealant.

Portland-cement sealants

32. Portland cements are the most common hydraulic cements. Portland cements are categorized into three types, depending upon their ability to (a) resist sulfate attack, (b) develop early strengths, and (c) generate heat during hydration. EM 1110-2-3506 (HQUSACE 1984) provides a complete discussion of these types.

33. Pozzolan is a siliceous (or siliceous with aluminous) material added to portland cement to react with calcium hydroxide in the presence of water to form compounds having cementitious properties. There exist three classes of pozzolans, with fly ash (finely divided residue of coal combustion) being the most commonly used pozzolan for sealants. Fly ash may be used as a filler or as an admixture to improve pumpability. The maximum amount of fly ash to be used in sealant mixtures generally is around 30 percent by weight of the cement before strength levels of the sealants are adversely impacted.

34. An admixture is any material other than water, fine aggregate, and hydraulic cement added to sealants immediately before or during its mixing to alter its chemical or physical properties to a desired characteristic during its fluid or unhardened state. Admixtures are principally accelerators, retarders, water reducers, fluidifiers, and expansion-producing materials (e.g., aluminum powder).

35. Accelerators provide for early stiffening and setting of sealant mixtures, and the most widely used is calcium chloride (CaCl). Calcium chloride may be safely used in amounts up to 2 percent by weight of the cement and, in some specific cases, could be used in amounts larger than 2 percent. Dissolving calcium chloride in the mix water is a recommended way to add it to the cementitious mixture. This accelerator may aggravate sulphate attack and alkali-silica reaction. In high concentrations, it acts as a retarder. It should not be used when the sealant is in contact with steel. Other accelerators include certain soluble carbonates, silicates, and triethanolamine.

36. Retarders are used to offset the undesirable accelerating effects of high placement temperatures and to prolong sealant injection or placement time. A retarder may be required for temperatures above 70° F.* The most commonly used retarders are lignosulfanic acid salts, hydroxylated carboxylic acid salts, and other organic chemicals.

37. Water reducers may be used to increase the pumpability of cementitious mixtures by increasing their fluidity or to increase their strengths by allowing a reduction in the water content of the mixtures while at the same time maintaining the same degree of fluidity.

38. Aluminum powder is sometimes used in portland-cement mixtures to produce shrinkage compensation, or a slight-to-moderate amount of controlled expansion prior to the final setting of the mixture. The amount and rate of the expansion is largely dependent on the temperature of the mixture, the alkali content of the cement, and the type, fineness, and particle shape of powder comprising the cement. Laboratory or field trial mixtures, using mixing water which will be used on site, are mandatory prior to the use of aluminum powder in project work. Aluminum powder as a shrinkage-compensating agent in sealants is feasible only when a very thick sealant is used. Thinner sealants allow escape of the hydrogen bubbles prior to set. Also, fineness and

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 6.

particle shape affect the time of onset and duration of reaction. All of these parameters must be optimized for this type of admixture. Additionally, mixing the powder with dry cement will help blend the two materials without cutting into the time available to mix and apply the sealant.

39. Fluidifiers in cementitious mixtures inhibit early stiffening, hold fine particles in suspension, produce a controlled amount of expansion prior to initial setting, and improve pumpability. The principal ingredients are usually a gas-generating additive, a retarder, and a dispersing agent. Fluidifiers such as rock flour, pumicites, diatomites, and bentonites usually require an increase in amount of mixture water.

40. Fillers, or extenders, are various types of materials used in cementitious mixtures to replace various amounts of cement for economic reasons and will probably be limited to sealing very large voids. Where sand has infiltrated into rubble or where graded materials exist as a core within larger stone, void size will probably not allow filler material. It should be noted that use of fillers tends to increase the setting time of the mixtures. In the case of high water content mixtures containing fillers, excess mixture water may result in ingredients coming out of suspension before hardening occurs, causing shrinkage and strength loss, particularly if silts and clays containing organic materials are used. Accelerators and water-reducing admixtures should be considered when fillers are used.

41. Fine mineral fillers include rock flour, clay, fly ash, silt, diatomite, pumice, barite, and others. Bentonite is a montmorillonite sodium base clay often called gel. Its utilization has increased in recent years, as it improves the pumpability of mixtures and tends to maintain ingredients in suspension until hardening. Bentonite also acts to reduce shrinkage and prevent bleeding but, if it is used as a filler, it increases mixture water demand and decreases strength. Kaolin is another type of clay used in sealants to improve pumpability, injectivity, and economy but does not exhibit gel-swelling properties. Attapulgite is a third type used in a seawater environment because of its satisfactory performance in high saline conditions.

42. Deere and Lombardi (1985) summarized some effects of additives on properties of sealant slurries. They reported,

. . . (a) decreasing the water-to-cement ratio increases both the viscosity and the cohesion, but increases the cohesion proportionately more, (b) adding bentonite increases both the viscosity and cohesion, but increases the cohesion proportionately more,

(c) adding a fluidifier (Interplast, Intracrete, or Rheobuild) decreases the viscosity and, probably to a lesser extent, the cohesion, and (d) for the same Marsh flow value, a sealant with a fluidifier will be denser and have a greater 28-day compressive strength than one with bentonite. Bentonite should, therefore, be used only to increase the cohesion and limit the travel distance (its action is contrary to that of a lubricant). . . .

43. Caution must be used when mixing bentonite, cement, and water to prevent phase change of sodium bentonite to calcium bentonite. It is necessary to hydrate the bentonite before allowing it to come in contact with cement or even a cement-contaminated mixer (Albritton, Jackson, and Bangert 1984). Deere (1982) recommended that the bentonite be premixed with water and aged for at least 2 hr before adding it to the slurry. The amount of premixed water is assumed to be around 15 percent of the total mixture water.

44. Ordinary sand is the most common coarse sealant filler and is usually screened to a desired gradation. Two parts of sand to one part of cement by weight is the practical upper limit of sand content in a sealant mixture, unless mineral fillers or admixtures are used. Sand containing as much as 25 percent of fines passing the No. 100 sieve can be pumped successfully at 1-to-3 ratios of cement to sand by volume or weight. Many other coarse fillers are available for cases where sealant strength is not a consideration.

45. Mixing water should be free from large concentrations of impurities such as dissolved sodium or potassium salts, alkalis, organic matter, mineral acid, sugars or sugar derivatives, and silts. If suspected of containing impurities, water obtained from natural sources "onsite" must be tested according to American Society for Testing and Materials (ASTM) specifications using standardized procedures of Method CRD-C 400 (WES 1949) in Handbook for Concrete and Cement. Water acceptable for drinking is generally acceptable for use as the mixture water for sealants. Seawater can also be used if the level of dissolved sodium salts in the seawater is not unacceptably high.

46. The water-to-cement ratio in sealant mixtures influences strength and workability as well as pumpability, viscosity, penetration, grout intake, setting time, and pumping pressures, all of which influence the effectiveness and economics of the sealing job. The volume basis for cement sealants is commonly used in the field for convenience because it eliminates batch weighings when precision weighing of constituents is not essential.

47. The volume of fluid sealant actually produced by any combination of properly proportioned materials is equal to the absolute volume of cement plus the sum of the absolute volume of filler material, significant amounts of admixtures, and volume of water. The absolute volume of one 94-lb sack of cement is considered to be 1.0 cu ft. (Actually, the absolute volume is 0.956 cu ft for cement having a specific gravity of 3.15.)

48. Mixtures with a high degree of fluidity, usually containing no sand and only cement, water, and small amounts of modifiers that do not appreciably alter the fluidity characteristics of the mixtures, are referred to as slurries. They may also be referred to as self-leveling, level-seeking, thin cement, neat cement, or highly fluid sealants.

Ultrafine cement sealants

49. Ultrafine-ground cement is a constituent of a commercially available sealing material that has promising characteristics for coastal engineering applications. Microfine Cement, a company which markets ultrafine cement, claims the product can penetrate fine sand and is strong and durable with a 4- to 5-hr set time. Fifty percent of Microfine Cement's particles are less than 4 μ . This compares with 10, 15, and 22 μ for colloidal, high early, and ordinary portland cement, respectively (Clarke 1984). As with ordinary portland cement, ultrafine cement may be combined with sodium silicate to give 1- to 3-min gel times. Ratios of particle size of an ultrafine cement and ordinary portland cement were examined by Karol (1985), who found that the average penetration difference between ordinary portland cement and ultrafine-ground cement may not be as great as previously indicated.

50. A literature review of the subject of sealant injection under conditions of flowing ground water (Walley 1976) yielded the consensus that short gel and set times, no matter whether the sealant is a suspension or solution type, are all important for a successful sealant application in a region of flowing water. Walley (1976) tested freshly injected sealants of 35 different mixtures for resistance to erosion and dilution by flowing water in a flume. He concluded that the most significant properties of sealants (i.e., low viscosities, high fluidity, pumpability, and ease of placement) are factors that work against sealant retention in flowing-water environments. The study indicated that the most efficacious sealants in flowing water are those that either develop a comparatively high viscosity soon after deposition or already possess this property when deposited. After being subjected to flowing water in the flume for 1 hr, two grouts that maintained 60 percent or more of their

original volume were those with Chemcomp Cement (a proprietary, shrinkage-compensating cement) and Reg Set Cement (a proprietary, extremely fast-setting, hydraulic cement) as the main cementing agents.

Chemical Sealants

51. Chemical sealing technology has expanded greatly in the last few decades in response to specialized needs for high penetrability, high strength, and precisely controlled set times. Many chemical sealants exist, although they may be grouped into the two specific categories: (a) precipitated sealants and (b) polymerized sealants. The only chemical sealant that appears to be suitable for stabilizing sand within jetty voids is sodium silicate, one of the precipitated grouts. Other sealants have been considered, such as acrylamides, lignins, and resins, but appear undesirable from toxicity and economic standpoints. Some of the very exotic sealants may be useful, however, in special applications. For example, a petroleum-based sealant that reacts with water as a catalyst might be useful in limited amounts (due to expense) where water velocities are a problem.

Precipitated sealants

52. Sodium silicate is the basic chemical for a variety of silicate sealing processes. In the coastal environment, such chemical sealants may be used when a design specifies that sand which fills voids within a structure be stabilized. In the presence of appropriate reactants, sodium silicate sealants form a gel that fills voids and binds particles of the material being sealed. A variety of grades of sodium silicate and any of several reactants can be used. The choice is determined by the gel time, strength, and permanence desired of the sealant. The strength and permanence of sodium silicate-cement sealant and sand sealed with sodium silicate are presently being evaluated by a series of long-term durability tests at three field exposure sites.

53. The various sodium silicate sealing systems form colloidal silica when the alkaline silicate solution is mixed with an acid or a salt of an acid. The colloids form a gel if the concentration of silica in the silicate solution is greater than 1 to 2 percent by volume. Reactants include chlorine ammonium salts, bisulfates, bicarbonates, sulfur dioxide, and sodium silicofluoride. Sodium silicate also reacts with salts of some metals, such as calcium, magnesium, aluminum, zinc, lead, titanium, and copper. Sodium

silicate may be injected either with the reactants in a single-solution process or separately as part of a two-solution process.

54. The silicate solution concentration that may be used in sealing can vary from 10 to 70 percent by volume, and in systems using amide (a metallic derivative of ammonia in which the $-NH_2$ group is retained, e.g., potassium amide, KNH_2) as a reactant, the amide concentration may vary from less than 1 to greater than 20 percent by volume. A low concentration of silicate in a one-solution system causes the sealant mixture to have a low viscosity. With increases in concentration above 60 percent, the increase in viscosity may be highly significant. Sealants containing 35-percent or more silicate by volume are resistant to deterioration by freezing and thawing and by wetting and drying. Sealants containing less than 30 percent silicate by volume should be used only where the sealed material will be in continuous contact with water or for temporary stabilization.

55. The one-solution process permits better control of the radius and completeness of sealant penetration because of the controlled gel time. In the one-solution process, the reactant solution is diluted with water and mixed thoroughly; then it is introduced into the sodium silicate solution. Reactants commonly used include sodium bicarbonate, formamide, sodium aluminate, calcium chloride, dilute hydrochloric acid, and copper sulfate. Combinations of two or more reactants are sometimes used in the one-solution process. Often formamide is the principal reactant causing gelation, and sodium aluminate is an accelerator that speeds up the reaction. At temperatures below 100° F, the effect of the accelerator becomes increasingly important.

56. The two-solution process involves the injection of one solution containing sodium silicate followed by a separate injection of one solution containing reactants. The second solution can be introduced through the injection line used for the sodium silicate solution, or it can be introduced through a separate injection line and hole simultaneously with or following the injection of the sodium silicate solution. The most commonly employed reactant for the two-solution process is calcium chloride. Other reactants are magnesium chloride, aluminum sulfate, and gel-forming gases such as carbon dioxide. The reaction between the silicate and reactant solution or gas is almost instantaneous.

57. Since it is expected that sealing in coastal engineering practice will involve drilling through stone or concrete to reach a rubble interior, a major disadvantage of the two-solution system is the additional drilling and

labor involved in separate injections, since drill holes are not normally large enough to accommodate two physically separated supply pipes. Pumping the second solution through the same hole after injection of the first solution will almost certainly ensure that the two solutions will not become mixed. Other disadvantages include (a) the limited radius of sealing that might be obtained since the reaction is so rapid, and (b) the possibility of forming partially grouted pockets as the mixing of the chemicals cannot be controlled below the surface. Regardless of the process used, the sealing radius depends upon pumping rates, permeability of materials being sealed, and concentration of chemicals.

58. Common silicate sealant systems consist of sodium silicate as the gel-forming material, formamide as the reactant, and one of the following as accelerators: (a) calcium chloride, (b) sodium aluminate, or (c) sodium bicarbonate. Since formamide has the potential of being a health hazard, diacetin (glycerol diacetate) may be substituted for this chemical. Excessive amounts of accelerators may result in undesirable flocculation or formation of local gelation, producing variations in both the gel and setting times that may tend to plug injection equipment or restrict penetration, thereby resulting in a poorly sealed area. The accelerator is usually dissolved in water at the desired concentration before the addition of other reactants, and the subsequent combination of this mixture with the silicate solution forms the liquid sealant. Sealants formed using the chloride or aluminate accelerators tend to be more permanent than sealants containing bicarbonate.

59. A silicate sealant system that has successfully sealed jetty voids consists of sodium silicate (17-percent solution by volume) in water combined in a 1-to-1 ratio with a 14-percent solution of portland cement and water (using the absolute volume measure of cement). The set time of this sealant is on the order of a few minutes. Increasing the cement volume shortens the set time significantly.

60. The Malmberg System is based on the production of a silicate acid gel by the mixing of a solution of sodium silicate with a solution of the salt of a weak acid. Based on a precipitant, this system differs from other similar two-solution systems, and it differs from other acid reaction systems by maintaining an alkaline pH.

61. Reactants used in this system include acid, alkali, or ammonium salts of weak acids such as sulfurous, boric, carbonic, and oxalic acid. Specific salts include sodium bisulfate, sodium tetraborate, sodium

bicarbonate, potassium-hydrogen oxalate, potassium tetraoxalate, and sodium aluminate. The proportioning of the sodium silicate to the total volume of sealant in the Malmberg System can vary from 10 to 75 percent by volume, with most work being done in the 20- to 50-percent range. The liquid silicate may be used as a diluted stock solution or mixed with water during the reaction with the acid salt stock solution.

62. This system has a small corrosive effect on light metals such as aluminum; however, the effect is not strong enough to warrant anything other than conventional equipment in mixing and pumping.

63. A two-pump proportioning system is desirable when working with a fast gel time. For gel times longer than 20 min, batch mixing can be employed. Compressed air bubble mixing or violent mixing that introduces air should not be used because of the reaction between the solutions and carbon dioxide. Gel time can be accelerated by either (a) decreased sodium silicate concentration, (b) increased acid salt concentration, (c) increased temperature, (d) increased acidity of the materials being sealed, or (e) presence of soluble salts such as chlorides, sulfates, and phosphates in the material being sealed.

Polymerized sealants

64. It is doubtful that polymerized sealants will be used in coastal applications for reasons of toxicity and economics, especially in rubble-mound void sealing operations. Hence, the following is presented only briefly to acquaint the coastal engineer with these specialty products.

65. Acrylamides. The most widely used acrylamide chemical sealant consists of acrylamide and methylene bisacrylamide mixed in proportions that produce stiff gels from dilute water solutions when properly reacted. Several reactants and mixtures of reactants may be used, but commonly a system of beta-dimethylaminopropionitrile (DMAPN), ammonium persulfate (AP), and potassium ferricyanide (KFe) is employed. The activator for the reaction is DMAPN, while KFe acts as an inhibitor and is used to control the reaction. Injection is by a one-solution process with the AP solution being added to the solution containing the other chemicals just before the injection. Gel time can be controlled from a few seconds to several hours by proper proportioning of all ingredients. The viscosity of the solution approaches that of water, and the solution retains its low viscosity for approximately 95 percent of its fluid life. The gel is stable under nondehydrating conditions, but will lose water and shrink if allowed to dry. If the gel is allowed to dry, it will (within

limits) slowly swell again to its original volume upon sustained contact with water and exhibit its original physical properties. Excessive drying will destroy the gel.

66. Lignins. Lignin, a by-product of the sulfite process of making paper, when combined with a commercial grade chromium compound such as sodium dichromate, forms an insoluble gel. Viscosities and gel times are controllable over a range that makes the lignins capable of being injected into materials as small as fine sand. One- and two-component systems of lignosulfonates are commercially available. The reactants are premixed in the lignin-base material in the one-solution system. Gel times of these precatalyzed lignosulfonate systems are easily adjusted by changing the quantity of water. Closer control of gel time is possible with the two-component systems. Reactants are mixed separately as with a proportioning system, and the total chemical sealant is not combined until immediately prior to injection. Lignin sealants thicken rapidly during the gel-forming period so that its pumping life is approximately one-third the total time required for complete gelation in typical applications. When injected into saturated materials, lignin sealants can be expected to take longer to set.

67. Various reactants used with lignin-based sealants include sodium bichromate, potassium bichromate, ferric chloride, sulfuric acid, aluminum sulfate (alum), aluminum chloride, AP, and copper sulfate. The bichromates have been the most widely used and, apparently, are the most satisfactory. Acidity affects gel time, and field tests are recommended to determine the suitability of lignin sealants before large quantities are placed. The precatalyzed lignosulfonate is incompatible with portland cement and should never be used as an admixture in cement sealant or vice versa.

68. Resins. Resin sealants are normally two-component systems made up of solutions of resin-forming chemicals and a catalyst or hardener that combines to form a hard plastic. Injection is by the one-solution process. The principal resins used as sealants are epoxy and polyester resins. The viscosities of resins are generally higher than those of other sealants, although they can be formulated to have low viscosities. They retain their initial viscosity throughout the greater part of their fluid life and pass through a gel stage just before complete hardening. A large amount of heat is generally given off by resins during curing. The length of time from mixing to hardened stage can be adjusted by varying the amount of the hardening reactant, by

adding or deleting filler material, and by controlling the initial temperature.

- a. Epoxy resins. A flexible stabilizer is sometimes incorporated into one of the components of epoxy resins to increase the ability of the hardened sealant to accommodate movement. A filled system is one in which another ingredient, generally an inert material such as sand, has been added. An unfilled system refers to the original system. For both filled and unfilled systems, tensile strengths generally range in excess of 4,000 psi, elongation may be as much as 15 percent, and flexural strength in both filled and unfilled systems is generally in excess of 6,000 psi. Considerably higher strengths have been reported in some instances with filled systems. Compressive strengths greater than 10,000 psi are attainable.
- b. Polyester resins. Factors influencing the rate of curing include resin volume, ambient temperature, catalyst selection, and heat dissipation. Viscosity can also be controlled through choice of catalyst. Promoters are sometimes used to accelerate the setting of polyester resins. Shrinkage occurring during hardening may range up to 10 percent. Compressive, tensile, and flexural strengths are appropriate for structural sealing and far exceed strengths needed for sealing coastal structures. A polyester resin used in dry fractured rock gels in 15 to 20 min and becomes solid in about 90 min at ambient temperatures ranging from 60° to 80° F.

Asphaltic Sealants

69. Bitumen is the binding material in asphaltic mixtures. It forms a physical bonding with the aggregate or with the sealed material and is chemically inert. Binding to cold, humid aggregate (termed cold mixture) is possible only with chemical additives. Bituminous mixtures are categorized by the amount of bitumen relative to the interstitial spaces of the coarse material with which it is mixed. Most experience with asphaltic sealants has been in Western Europe, and particularly in The Netherlands.

70. In exactly filled mixtures, the volume of bitumen is approximately the same as the volume of voids. Asphalt concrete is an example of an exactly filled mixture and must be compacted when placed. In underfilled mixtures such as lean sand asphalt and Fixtone, the properties of the aggregate dominate. Underfilled mixtures are permeable to water. Examples of overfilled mixtures are mastic asphalt and overfilled stone asphalt.

71. Mastic asphalts are poured hot and used as a solid impervious layer or as a penetration mixture. The reach of penetration is proportional to the fourth power of a characteristic diameter of the voids being filled and is a

function of velocity of injection and rate of cooling. Penetration depth is controlled by varying the ratio of particle size in the mixture to the particle size of stones being penetrated. For underwater sealing, van Garderen and Mulders (1983) suggested maintaining a ratio $(D_{15})_{\text{stone}}/(D_{85})_{\text{mixture}}$ of 10 to 20, where D_{15} and D_{85} are the particle sizes at which 15 percent and 85 percent, respectively, of the material are finer. For above-water placement, the ratio should be 5 to 10. Such ratios will yield a penetration depth of a two-stone thickness.

72. In using asphalt concrete, much attention must be paid to the amount of compaction. The steeper the slope, the less energy for compaction can be supplied. Although the obtainable stability of the mixture may permit a steeper slope, the maximum slope on which asphalt concrete is applied in The Netherlands is about 1 to 1.7 (vertical to horizontal) because of the mechanical stability limitations of the subsoil.

73. Stone asphalt, another of the exactly filled types, was developed in constructing the breakwater at IJmuiden, the outer harbor of Amsterdam. An impervious 6-ft-thick layer was laid on a slope of 1 to 2 above water without artificial compaction. To avoid experiencing creep, a mixture employing two stages was developed. A mastic asphalt was first produced and then mixed with predried rock weighing 20 to 150 lb (8- to 17-in.-diam stone). Special mixing equipment had to be used because standard equipment processes aggregate only up to 2- to 2.5-in.-diam stone.

74. The procedure in the preceding paragraph is the basis of development of the underfilled mixture called Fixstone. This mastic asphalt is made (by weight) from approximately 60-percent sand, 20-percent filler, and 20-percent bitumen. This mixture is then combined at a ratio of 4 to 1 with crushed stone or gravel.

75. Lean sand asphalt, an underfilled mixture, can be made from dredged sand mixed with 2-to 6-percent bitumen by weight. The grains are coated with a thin film, which is susceptible to breakdown by ultraviolet radiation and oxidation. Lean sand asphalt is usually not artificially compacted. The void ratio remains 35 to 40 percent, so the permeability is about the same as that of sand alone.

76. After cooling, sand asphalt behaves like soft sandstone under short-duration loadings and like loose sand under long-duration loadings. It withstands erosion by currents exceeding 9 ft/sec (Mulders et al. 1981). Experience has shown it to be chemically stable for at least 30 years, which

is the extent of field experience. Since petroleum residues represent a food source for some biota, the material is not entirely resistant to biological agents; however, that material untouched by biological activity remains chemically stable. The extent of degradation by ultraviolet radiation and oxidation of rich asphalt and sand mixtures is presently being determined by long-term durability tests at the Miami, FL, exposure station.

77. Sulkje (1969) modified the widely used Burger Model for sand asphalt when he developed a rheological model for bitumen consisting of a Hooke body in series with a Kelvin body. Sand asphalt was considered to possess a visco-plastic behavior and was modeled by adding a Bingham body. The visco-plastic component is dominant for shear strains greater than 4 percent and is presented by Mulders et al. (1981) as:

$$\tau = \tau_i(\sigma_o, \epsilon) + \eta \frac{d\epsilon}{dt} \quad (6)$$

where

τ = shear stress, lb/ft²

τ_i = internal shear resistance, lb/ft²

σ_o = isotropic stress, lb/ft²

ϵ = total shear strain, dimensionless

η = apparent coefficient of viscosity, lb-sec/ft²

t = time, sec

78. When sand asphalt is isotropically (perpendicularly) loaded, the coating is first squeezed from between the grains. Under deviatoric (distortion) loading, bitumen shears between particles before being squeezed out. This results in a gradual buildup of internal resistance due to an increasing amount of grain-to-grain contact. At shear strains in the range of 9 to 16 percent, the internal resistance approaches that of sand.

79. According to Equation 6, high strain rates do not lead to failure as much as would be expected from considering only the low angle of friction, but they mobilize increased viscous resistance. The term $d\epsilon/dt$ is important to the rheology of sand asphalt. Values for internal shear resistance, the failure limit, apparent coefficient of viscosity, and the dependence of strain on shear were obtained from test results using a type of triaxial cell termed a Dutch Cell (Mulders et al. 1981). Creep, $\Delta\epsilon$, is defined by the formula:

$$\Delta\epsilon = (\tau - \tau_i) \frac{\Delta t}{\eta} \quad (7)$$

The symbols have been previously defined.

80. All mixtures to be used should have a record of successful prior applications under conditions similar to those of the proposed project, or they should be tested either in a laboratory or in a test section in the field. This testing entails using in the evaluations the actual materials that will be used in the prototype application.

PART III: SEALING TECHNIQUES AND EQUIPMENT

81. Prior to the 1950's, dam construction expanded, and larger and higher dams were built. Deeper grout holes had to be used; hence light-weight diamond drills were designed. The necessarily higher pressures needed for injection promoted the development of positive displacement pumps suitable for efficient cement sealant handling. Later, other pump types were designed. Since the 1950's, great advances have been made in developing chemical sealants with specialized characteristics of injectability, exactly controlled set times, compressive strengths, impermeability, and others.

Sealing Techniques

82. In the typical coastal structure sealing operation (excluding some asphaltic applications), drilling is necessary and expensive. Because of the linear aspect of the usual sealant placement in coastal applications, the drill hole pattern is normally a single line. The split spacing method should be employed for greater economy. By that method, a series of primary holes are drilled, with center-to-center distances greater than that estimated for the final hole pattern. Sealant is injected into the primary holes, and the grout intake (volume of sealant placed) per vertical foot rise of the injector nozzle is determined. The occurrence of sealant loss from the sides of the structure, as well as any appearance of sealant in any adjacent ungrouted hole, should be ascertained. A 10-ft spacing has been used previously in sealing a jetty to prevent sand passage and was found to be an acceptable spacing for the primary holes. Because hole spacing is dependent on project conditions, a test program should be undertaken before writing large contracts. The next series of holes, the secondary holes, are centered on the same line as the primary holes, but are spaced midway between the first holes. The secondary holes are sealed; then the decision must be made as to whether drilling and sealing a third set of holes is required. On one Corps sealing project, a final 2.5-ft hole spacing was required to seal the structure.

83. The order in which holes should be filled depends on field conditions. If the sealant intake into a hole seems excessive or if it is obvious that sealant is being lost to areas not intended to be filled, consideration should be given to decreasing the sealant's set time or advancing to the adjacent hole and filling the lower part of it. After that, the next level of the

first hole would be filled and so forth. In such an operation, the field engineer must balance the increased labor costs with the savings in sealant. The prime objective, however, is to achieve adequate closure of the voids.

84. In a typical civil or mining engineering sealing application, the medium to be grouted is either soil or rock. However, in coastal engineering applications, the usual case is that sand must be stabilized and voids in the rubble-mound structure must be closed from the same bore hole. Therefore, methods for treating soils as well as rock will be included. The types of sealant treatments known as barrier curtain creation, cavity filling, soil sealing, and riprap sealing are described from a coastal engineering frame of reference.

Barrier curtain sealing

85. Barrier curtain sealing was developed to control seepage under dams or other structures. It often consists of multiple lines of sealed holes. To prevent sand from flowing through a coastal structure, theoretically a two-dimensional, vertical barrier is all that is required, and a single line of sealed holes in communication with each other should accomplish that. Minimum acceptable depths and maximum spacings should be specified. However, specifications should be flexible enough to add additional lines of sealant holes at any location or alter depth and spacing of holes as determined necessary in the field. Final depths or heights should not be based on precedent alone, but on the elevations at which sand could be expected to move under design conditions.

Cavity filling

86. Cavity filling is one of the least standardized types of grouting (i.e., sealing abandoned coal mines). Air- or water-filled cavities of large, open joints can successfully be sealed with concrete. The extent of a cavity is not known after the penetration of a single sealant hole, but an accurate rule of thumb is that the void space is 30 percent of the rock size in old, well-settled structures. When a cavity is encountered in drilling, the hole should be sealed before continuing into the structure. A coarse aggregate concrete may be used for cavity filling and for economy and effectiveness in achieving the desired dimensions of the injected mass.

Soil sealing

87. Soil sealing methods were first developed to stabilize, reduce settlement of, and arrest water movement through unconsolidated granular materials ranging from sand-size particles to, and including, fine gravels. Beach

sands are the typical "soil" materials encountered in sealing coastal structures, and injectability of the sealant mix into the local material should receive much attention. With the proper sealant and proportions determined, methods for soil sealing are summarized (Headquarters, Department of the Army 1970) as:

- a. Casing. A casing may be drilled, jetted, or pushed to the full depth to be treated, and then withdrawn as sealant is pumped into the soil. The escape of sealant up the contact surface of the casing and the soil may be a problem. This method is used extensively in chemical sealing at shallow depths.
- b. Sealant sheath. In this method, a flush-joint sealant pipe is sealed in place, using a special brittle sealant that prevents leakage up the outside of the pipe. The sealant pipe is withdrawn a short distance, leaving a brittle sealant sleeve below the pipe. Sealant is pumped into the soil through cracks produced by the pressure of the sealant in the brittle sealant sleeve below the end of the sealant pipe.
- c. Pierced casing. A patented soil sealing method has been developed in which the casing is sealed in the drill hole, using a special sealant. The casing can be pierced at any selected point by firing an explosive-impelled projectile from a device lowered into the casing.
- d. Tubes á manchette. In this method, a perforated pipe is sealed into the hole with a special sleeve sealant. The perforations are covered with short sections of a rubber sleeve (manchettes) on the outside of the pipe that act as one-way valves. Perforated sections of the pipe are placed opposite injection locations. A double packer is used to control the treatment location. The pressure on the sealant pumped into the hole between the confining packers causes it to push past the small rubber sleeves covering the perforations, rupture the sleeve sealant, and enter the soil. This device is suitable for injecting cement, clay, or chemical sealants. The same holes and the same rubber-sleeved vents have been used in some cases for the injection of each of these sealants separately, and in rotation, into a soil. This procedure permits economical treatment of soil containing large voids with an expensive chemical sealant by first filling the large voids with less costly cement sealants.

Riprap sealing

88. Stability of unconsolidated riprap may be improved by sealing. Riprap sealing may be accomplished above and below water in providing slope protection for revetments, shoreline stabilization, levee facing, and similar projects. Riprap sealing applications normally consist of the gravity or pump placement of sanded cement sealants into the voids existing in riprap. The mixtures may contain three to four parts as much sand by weight as cement. For steeper slopes, more viscous sealant is required. The sealant is usually

filled to approximately one-half to three-fourths of the depth of the voids and, where possible, topped out by brooming and curing by conventional methods.

Sealing Equipment

Drill rigs

89. In the selection of a drill rig, site considerations and job drilling and sealing requirements dictate the type and size drill rig to be used. Drilling from the crest of a jetty is usually best accomplished using a crawler or wheel unit. Hole diameter should be kept as small as necessary to inject sealant, for reason of economy, yet large enough that a reasonably straight hole can be drilled. The two basic types of drills are percussion drills and rotary drills.

90. Percussion drills. Percussion drills are used for drilling in solid rock. Percussion drills are operated by air- or hydraulic-driven hammers. The best-known types are the jackhammer, the drifter, and the wagon drill. Jackhammer drills are only suitable for shallow work and, due to their light weight, are usually held in position by hand. Drifter-type drills are designed for tripod, bar mounts, or jumbo attachments. The commercially available wagon drill is composed of a drill head mounted in leads that are supported on a track, wheel-mounted, or skid-mounted chassis.

91. The drill proper consists of a hollow steel rod that is fitted with a fixed or detachable bit on one end and a shank on the other. Most percussion drills both rotate and reciprocate in normal drilling action. The shank fits loosely into the chuck at the forward end of the machine, where it is struck by a hammerlike piston actuated by compressed air or hydraulic fluid. The bit remains in close contact with the rock at all times during drilling except during the slight rebound caused by impact of the hammer. Cuttings or sludge materials are removed from the hole by air or water that passes through the machine and down the hollow steel drill rod to the bottom of the hole. This material then rises up the hole to the surface.

92. Rotary drills. Rotary drills can accept a variety of bit types and are capable of retrieving cores. The hole is made by advancing a drilling bit attached to a rotating column of hollow drill pipe. The drill pipe is turned by a motor at speeds ranging from approximately 200 to 3,000 rpm or greater. Pressure on the bit is applied hydraulically or mechanically. Water is forced

through the drill pipe to wash cuttings out of the hole. Drill rigs vary in size from small, lightweight machines capable of drilling holes only a few hundred feet deep to large rigs that can drill holes miles in depth. The small rigs would be used on coastal structures because only shallow holes are needed and portability is important. Rotary drills are practical only for retrieving cores, usually after sealing has been effected, and for examining sealing completeness.

Drill bits

93. The major types of bits used in rotary drilling are diamond bits and hard metal bits. Diamond bits may be core- or plug-type. Both types employ a diamond-studded bit to cut the rock. The bit is cooled, and the hole is continuously cleaned by water or compressed air pumped through the drill rods. The core-type bit consists of a hollow steel cylinder, the end of which is studded with diamonds. The bit is fitted to the lower end of a hollow steel chamber (core barrel) that is rotated rapidly while the bit is held firmly against the rock so that the diamonds cut an annular channel in the rock. The rock that lies within the channel and projects into the barrel constitutes the core.

94. The plug-type bit is available in two varieties. One is the concave type, the head of which is depressed toward the center, and the other is a pilot type, which has a protruding cylindrical element that is smaller in diameter than the main bit head. Noncoring diamond bits have a wide range of usefulness in foundation sealing. However, plug bits are more costly than coring bits for drilling in extremely hard foundations and in badly fractured rock because of greater diamond cost. Since plug bits produce only cuttings, part of the rock encountered is removed as core. The loss of one or two diamonds from the center of a noncoring bit occasionally occurs when shattered rock is drilled and thus renders the bit useless for further cutting. A commercially available bit utilizing polycrystalline diamond blanks has proven very effective. Penetration rates have been obtained that are up to three times greater than tungsten carbide and surface set diamond drill bits.

95. The sizes of diamond bits are standard and are generally known by the code letters EW, AW, BW, and NW. Most diamond-drilled sealant hole sizes are EW or AW in typical civil engineering applications. The dimensions of each size are:

Diamond Bit Sizes				
Code	Size, in.		Size, mm	
	Hole	Core	Hole	Core
EW	1-31/64	27/32	37.7	21.5
AW	1-57/64	1-3/16	48.0	30.1
BW	2-23/64	1-21/32	60.0	42.0
NW	2-63/64	2-5/32	75.7	54.7

96. Wire line bits are another type bit, but would not be used in production drilling for coastal structure grouting. Wire line bits were developed for efficient retrieval of cores, which may be needed for checking the continuity of the barrier sealant curtain.

97. Hard metal bits are made of hardened steel notched to resemble the teeth of a saw and are placed on the core barrel to substitute for a diamond bit. In some soft rocks, this type bit drills a hole much faster, is not easily blocked, and is much cheaper than a diamond bit. The teeth of such bits are often faced with one of the alloys of tungsten carbide, or replaceable inserts of hard alloy are welded into holes cut into the bit blank. The hard alloys can also be used to make a noncoring bit.

98. Roller rock bits are also attached to the bottom of a hollow drill pipe column. The bit is made of toothed rollers or cones, and each one turns or rolls on the rock as the bit rotates with the drill pipe. Cuttings and sludge are washed out of the hole by circulating water or drilling mud through the drill pipe and back to the surface between the drill pipe and the walls of the hole. The roller rock bit is not extensively used for sealant hole drilling because the smallest available size is approximately the same as that of an NW-diamond bit.

99. Drag and fishtail bits are suitable for rock and soil. The cutters, or cutting edges of the blades of the bits, are made of hardened steel or are covered with hard alloys and curve away from the direction of rotation.

100. Drill bit types and the materials in which they are generally used include:

<u>Drill Bit Type</u>	<u>Principal Use</u>	<u>Not Suited For</u>
Diamond core	Rock and concrete	Unconsolidated soils
Plug	Rock	Extremely hard rock, extremely soft rock, unconsolidated soils, and shattered or fractured rock
Hard metal	Soft rock, hard clay, and cemented soils	Hard rock and unconsol- idated soils
Roller rock	Rock	Unconsolidated soils and very hard rock
Drag and fishtail	Soft rock and soil	Hard rock
Percussion	Rock and concrete	Unconsolidated soils

Sealant pumps

101. A great variety of sealant pumps of various makes and sizes is available for the placement of sealant. They may be air, gasoline, diesel, or electrically powered. They may be constant- or variable-speed pumps. Sealant pumps should be carefully selected to ensure a built-in flexibility that provides close control of pumping pressures and variable rates of injection. The pumps should be a type that can be easily and quickly serviced during sealing operations. Pumps for most sealing projects should be of the nonsurging or minimum surging type, which reduces or eliminates the pulsating effect transmitted to a hose, pipeline, drill stem, or sealant hole. Spare pumps and spare parts should be available during all sealing operations. Types of sealant pumps include line-type slush pumps, sidepot-type sump pumps, divided fluid-cylinder valvepot-type pumps, progressive cavity pumps, and centrifugal pumps, as detailed in EM-1110-2-3506 (HQUSACE 1984).

Concrete pumps

102. Concrete pumps are occasionally used to pump sanded and unsanded cement sealants in cases where the consistencies of such mixtures are near minimum fluidity. These mixtures have a standard slump cone consistency ranging between 4 and 8 in. Concrete pumps can easily handle aggregate to a maximum size of 1 in. in diameter and are also capable of pumping sealants containing steel fibers. These units are composed of reciprocating pistons housed at the bottom of a stowing-type hopper. The piston delivers the mixture directly into 4-in.-diam or larger steel pipelines through a swedged head-type coupling. The pumps are normally truck- or trailer-mounted and gasoline powered. They are not used in sealing applications that require

close pressure controls, but they are mainly used in filling large cavities and, at times, are used to deliver concrete to tremies.

Sealant mixers

103. The first consideration in the selection of a sealant mixer is ensuring that it has the desired capacity and that it will produce a homogeneous mixture in a desired period of time. Types of sealant mixers available include vertical tub mixers, horizontal drum mixers, high-speed colloidal mixers (required for mixing ultrafine grout cement), transit mixers, skip-loaded concrete mixers, jet mixing units, and compressed-air tank mixers. EM 1110-2-3506 (HQUSACE 1984) provides details of such mixers.

Agitator holding tanks

104. To provide a high volume and continuous injection of sealant, two mixers are usually set up to alternately discharge into an agitator holding tank. This agitator holding tank has a capacity at least two, and preferably up to three, times the capacity of the mixing system. Tub- or horizontal-type mixers operated at slow speeds are frequently used for agitating holding tanks. Agitator holding tanks may be similar in design to certain tub-type mixers having paddle blades mounted on a vertical spindle and arranged in pitch to force sealant to the discharge end of the tub.

Sealant lines

105. Two primary arrangements of sealant piping are used to supply sealant from the pump to the hole for typical noncoastal applications. The circulating system is compiled of a double line, and one of the lines serves as a return line from the header to the sealant pump. That system is designed for sealing media under pressure, which is not the case for rubble-mound coastal jetties and breakwaters. The single-line system is the simpler of the two arrangements and is the only one appropriate to coastal rubble-mound structures. The system consists of a pipe, hose, or combination of both extending from the pump discharge to the header at the hole collar. The pump speed alone controls the pressure and rate of sealant injection. Hose lines are usually made of reinforced rubber or plastic. The inside diameter of these hoses for most sealant applications ranges from 1 to 2 in.

Valves

106. Valves for sealant lines should be quick-opening, easily regulated, and resistant to corrosion and abrasion. They should be capable of accurately controlling pressures in all positions. When in the full open position, valves should not present a restriction to the flow of sealant.

Diaphragm-type valves have proven to be quite effective. Pressure relief valves should be installed in sealant lines as an added precaution against the creation of excessive pressures, which might rupture lines or other equipment.

Asphalt sealing equipment

107. Portable asphalt heating kettles commonly used by contractors for pavement crack sealing, roofing coatings, and similar applications have served well in heating asphalt for many sealing purposes. Hot asphalt heating should be maintained below the flash point of the asphalt. Reciprocating pumps with ball valves, 1-in.-diam boiler-fed piston pumps, or gear pumps have been used to pump hot asphalt through 1- to 2-in.-diam black iron pipes. Conventional-type cement sealing equipment can be used for asphalt emulsions. A bituminous stone structure is a different concept for the use of asphalt. Mastic asphalt is produced at a large-scale plant, mixed with stones weighing 20 to 150 lb, trucked to the site, and then placed with a crane-operated bucket.

Chemical sealing equipment

108. Sealing equipment has been generally developed by the chemical manufacturers to mix and place particular chemical sealant systems. Conventional sealing equipment may also be used for a number of processes, especially when single batching will meet the job requirements. Closely controlled proportioning systems are frequently recommended for handling two or more components of a given formulated sealant. Details of chemical sealing equipment are contained in EM 1110-2-3504 (HQUSACE 1973).

Casing

109. Casing commonly used on sealing work is steel or plastic tubing. The tubing is lowered into a borehole to prevent collapse of the hole or entry of loose rock and to prevent loss of circulation fluid into permeable zones. Perforated casing is used to isolate zones to be sealed.

Meters

110. An accurate and expeditious method of controlling sealant water content is by using volume-measuring water meters. These meters can be obtained with graduated measurements in either gallons or cubic feet and can usually be read to the nearest one-fourth gallon or one-tenth cubic feet. A meter should be checked for accuracy before it is used and, if necessary, should be calibrated. Meters for measuring quantity of sealant placements may consist of something as simple as a vertically graduated scale or rod gage placed in mixers or agitator trucks, or they may use calibrated spindles placed in the sealant line and geared to counters or strip recorders. These

meters may be designed to measure barrels, cubic feet, gallons, or any specified fraction of these units.

Pressure gages

111. Pressure gages are essential in virtually all types of sealant and pressure testing, and they must be extremely reliable. Emplacing some sealants in coastal structures is accomplished with a concrete pump operating at low pressure. Pressure gages are not critical pieces of equipment in such operations. In sealing at high pressures, however, malfunctioning gages have resulted in damage to structures and equipment as a result of excessive pressures. Gages should be tested for accuracy prior to use and periodically checked during the course of the work. The moving parts of the gage should be protected from dust and grit and from direct contact with the sealant. Diaphragm systems, such as glycerin-filled gage savers, provide an additional degree of protection.

Monitoring Equipment

112. In sealing coastal structures, the specialized monitoring equipment developed in other fields of cementitious, chemical, and asphalt sealing is not absolutely required. However, this does not discount the need for monitoring sealant travel and solidification. The simplest probe can indicate travel of sealant from a filled hole to an adjacent untreated hole. Observation can reveal leakage of the mixture from the sides of a structure into the channel or ocean water. Pressure gages on the sealing equipment can be very effective monitoring equipment when utilized by an experienced observer.

Flow cone

113. The flow cone measurement may be used both in the laboratory and in the field for determining the flow of sealant mixtures. This is done by measuring the time of efflux of a specified volume of sealant from a standard cone. This test is used to ascertain the fluidity of sealant mixtures. The ASTM procedure for testing is provided in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 611. The usual mixtures used for jetty void sealing are thick, contain coarse rock aggregate, and do not flow from a flow cone.

Slurry scales

114. The unit weight of mixtures may be determined by using either the standard American Petroleum Institute approved mud scale balance or by a precisely calibrated unit weight container that ranges in volume from 0.25 to

1.0 cu ft. The calibrated unit weight container has a set of scales graduated to 1/10 lb, with a weighing capacity of at least 250 lb.

Slump cone

115. The consistency of very thick mixtures may be determined by measuring the slump. The cone is a metal frustum that has a base diameter of 8 in., a top diameter of 4 in., and a vertical height of 12 in. The mixture is placed in the cone in three equal layers, and each layer is rodded 25 times. The cone is removed vertically, and the slump of the mixture is measured in inches from the tip of the slump cone to the top of the sealant. This ASTM procedure for testing slump is further described in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 5.

Air content measurement

116. Five fundamental methods may be used for determining the air content of portland cement sealant mixtures: (a) gravimetric, (b) high pressure, (c) micrometric, (d) pressure, and (e) volumetric. These ASTM procedures are described in the Handbook for Concrete and Cement (WES 1949), Methods CRD-C 7, CRD-C 83, CRD-C 42, CRD-C 41, and CRD-C 8, respectively. Methods CRD-C 7, CRD-C 41, and CRD-C 8 apply to the measurement of air in freshly mixed sealant, whereas Methods CRD-C 83 and CRD-C 42 describe the measurement of hardened sealant air content, which is usually determined in the laboratory.

Time-of-setting apparatus

117. The initial and final sets of portland cement sealants are determined by the use of a mechanical device known as the Vicat apparatus. The instrument is designed to measure with respect to time the depth of penetration (or no penetration) of a blunt needle into a small cuplike receptacle containing a sample of the sealant. This test can be conducted in the laboratory or in the field. The ASTM procedure for testing is described in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 614.

PART IV: PLANNING, DESIGN, AND CONTRACTING
COASTAL STRUCTURE SEALING

Determining Need for Structure Sealing

118. Establishing clear, quantitative objectives of the sealing program early in the planning process is essential to success. In the case of suspected sand movement through a rubble-mound structure, it must be shown that deposition results from sand actually passing through, and not around or over, the structure. The speed at which dye released in the water on one side of the structure appears on the other side gives an indication of the ease of sediment through-flow. If the dye appears in less than 1 min through a rubble-mound jetty or breakwater, it may be assumed the structure can facilitate an abundant amount of sediment flow. Hydrographic surveys, strategically scheduled around dredging and meteorological occurrences, will reveal the location, size, and rate of growth of a shoal attributable to transport through a structure. Even though accretionary offsets indicate coastal sediments move predominately in one direction, it is possible for the problem shoal to result from sediment moving locally in the opposite direction because of unique hydrography or a longshore current that has even minor reversals. The existence of topographically depressed areas adjacent to the structure indicates sediment is moving from that location through the structure.

119. The quantity of material moving through the structure which contributes to the shoal must be of such a magnitude that the cost of its elimination is offset by the savings in mobilization, demobilization, and dredging which would otherwise be attributed to it. In instances where a designated disposal area for such material is nearing its capacity, a high priority would be placed on minimizing shoaling material that passes through the structure, thus reducing material that would need to be placed in the disposal area. Alternately, if the shoal developed from sediments moving through the structure does not impair navigation significantly between times when a dredge is ordinarily in the area, the cost-effectiveness of sealing would be questionable. If the service life of the structure is near an end, sealing may not be feasible. Instead, designing for sediment cutoff in the rehabilitation would be more reasonable. Benefits claimed from any sealing efforts undertaken in a deteriorating structure may detrimentally affect the economic justification of a future planned rehabilitation effort.

120. Another factor affecting the determination of need for sealing is the engineering feasibility of accomplishing the job (Baker 1982). If it is inordinately difficult to mobilize drilling equipment, sealing equipment, and supplies to the site, those facts should be recognized early in the planning process. If exposing the equipment to high risks due to, for example, high wave occurrence on a low-elevation structure, those potential costs resulting from such risks should likewise be recognized early.

Determining Extent of Injected Barrier

121. Design conditions must be established for which the barrier sealant curtain is intended to provide protection. Sealing to reduce wave transmission depends on some described excessive wave climate propagating through the structure. Sealing to reduce sediment flow may not be designed to a high wave event, but to the present and final configurations of the accreted sand on one side of the structure and to the channel on the other side.

122. If the structure is being sealed to prevent sand transmission only, the existing sand layer should be stabilized first. After sand stabilization, the top elevation to which the barrier will be constructed should exceed the height to which sediment presently moves or, in the future, probably will move against the structure by currents or waves. The sand layer should also be stabilized to a bottom elevation sufficient to block the flow of sediments moving through the structure from the down-flow side. Sealing probably will not extend below the bottom elevation of the structure unless stabilizing the foundation is an objective. If both sand and wave energy transmission are problems at a site, then void sealing should extend from the top of the stabilized sand layer to approximately mean high water elevation.

123. The length of the barrier of sealant should bracket the locations of sediment permeation or wave transmission. Additionally, the barrier curtain should traverse all locations that may become problem areas due to any changes in bottom elevation or breaker angle resulting from the changed hydraulic characteristics of the sealed structure. A final equilibrium shoreline must not flank a sealed section of jetty.

Preliminary Field Investigations

124. Field conditions of primary importance are rock size and type in the rubble-mound structure section to be sealed. These characteristics offer information about void size and degree of communication with other voids, percentage of voids filled with sand, and voids filled only with water or air. The rate of water movement through the area to be sealed and the pH, salinity, and temperature of the water saturating the media also merit serious consideration when evaluating the potential groutability of the structure.

125. These factors can be evaluated through results of an experimental contract, in which some selected holes are drilled and investigated. Such work will indicate future ease of drilling, which is not often known because rock type and random surface orientation at depth may present difficulties. Knowledge regarding surface elevation and porosity of sand within the structure is necessary for computing not only volume of sealant but also is required for determining the flow characteristics and set time to specify for the sealant. Whether or not to specify flushing of the hole before sealing in situ sand can be decided in the exploratory program. Estimating the size of between-rock voids may be possible only from the drilling logs, recognizing the limitations of one-dimensional measurements. Data gathered must be correlated and analyzed to be beneficial. Information presented in this document is intended to serve as a guideline only and cannot replace experience of qualified engineers, technicians, and contractors.

126. Factors of pH, salinity, and temperature of the water in which the sealant will be placed, as well as the mix water, are known to affect the stability and durability of the mixture. Knowledge of these factors will lead to more efficient field testing of mixtures. Preliminary testing also should include the pumpability, groutability, and set time of mixtures. There exists no substitute for field testing a mix before specifications are written for the main sealing job.

Sealant Design

127. The main factors affecting a sealant mix designed for filling rubble-mound breakwater or jetty voids include (a) the potential for dilution and dispersion by water movement through the structure during emplacement, (b) the consistency of the sealant and structure materials, (c) size of the

voids needed to be filled, (d) elevation of the sealant application, and (e) permanence of the grout mass. Taken together, these factors constrain the sealant mixture to be highly viscous after emplacement yet fluid enough under low pumping pressure to be placed at a rate much greater than the water flow rate through the cavity, have a fast set time, be durable and stable under conditions of cyclic wetting and drying, and be economical. Because of the many variables of cement and admixture properties, laboratory tests are recommended to determine the characteristics of sedimentation, slurry density, Marsh funnel viscosity, and Vicat needle setting time (Deere 1982).

128. Deere (1982) also notes that a specific procedure must be followed in determining the apparent viscosity using a Marsh funnel and that funnels of different dimensions yield different values. Viscosities of certain sealants have been determined for the most commonly used funnels. Actually, Marsh cone values reflect a combination of rheological properties of the sealant mixture and the boundary roughness of the cone (Lombardi 1985). Actual sealant viscosity can be easily obtained from funnel viscosity if cohesion is known. Lombardi (1985) designed a simple method for determining cohesion and, thereby, viscosity. It consists of a roughened steel plate of known weight and dimensions, which is dipped into the sealant (of known unit weight) and then weighed. This procedure yields the thickness of sealant layer on both sides of the plate and, thus, the cohesion per unit weight.

129. Sealants injected to stabilize sand must have the ability to penetrate the sand mass a distance of a few feet at low pressure. They must have a set time that permits injection yet minimizes loss by dispersion and must be stable in their chemical environment.

Injection Process Planning

130. The thickness of the injected barrier curtain theoretically is of little concern. A two-dimensional barrier curtain of finite small thickness should be just as effective as a barrier of large thickness. Sealant injection, however, results in a three-dimensional sealed space. Optimizing the sealant hole spacing based on drilling costs, sealant intake, subsurface conditions, and material costs is crucial to the economic planning of a sealing program. Experience has proven the alternating hole drilling (primary and secondary) technique to be the best staggered arrangement of placement. Limited field experience with sealing rubble-mound jetties and breakwaters has

shown that good results can be obtained by spacing primary sealant holes on 10-ft centers in a single, straight line on the structure crest. After filling primary holes, secondary holes are drilled and sealed along the same line on 5-ft centers. Sealant intake should reduce considerably with each set of holes. Instances where actual field construction has utilized hole spacing less than 2.5 ft are not known.

131. The contractor should be able to quickly assess and modify the mixture viscosity as it is being injected, but because of the amount of communication of voids with each other, it may not be expedient to fill one hole to the top before pulling out and filling the next hole. Maximum economy may be achieved by staging the filling of adjacent holes.

132. If the sand filling the area to be sealed is clean and well-sorted and the groutability is adequate, sealing of the sand in the structure may be preferred to flushing the sand from the cavity. Otherwise, the sand must be flushed out and replaced with a sealant. Sanded concretes should be used for the sake of economy to fill large voids. The larger voids should be filled first, usually with a cement-sand mixture; then the sands that are to remain should be sealed as a secondary effort.

133. Much work remains to be performed in the area of developing ways of estimating the quantity of mixture needed. In one field application, the net quantity for sealing a rubble-mound jetty was very close to the estimated amount. This occurred when the estimate was based on a theoretical volume 6 ft wide at the design length and height of the sealant barrier curtain, plus a 30-percent factor for voids. The in-place cost should be used in comparing the costs of different sealants. These costs are not only for all actual sealant materials, but also for drilling, pumping, equipment, labor, and supervision. Delays and loss of mixture due to lack of control of viscosity or set time will also affect the final cost. For these reasons, the tendency to consider colloidal solution sealants exceedingly expensive and suspended-solids sealants less costly may not always be correct.

Field Procedures

134. Field procedures are affected greatly by the way specifications are written. In some cases, specifications may be written with the intention of leaving procedural decisions to the field sealing supervisor. That could be an advantage in those cases where it is known which organization will be

designated for field supervision, and the field sealing supervisor in that organizational element is known to be sufficiently experienced. The sealing procedure should be closely supervised by a Corps inspector who is experienced in sealing methodology. A disadvantage of this approach is that some of the design responsibility is removed from the designer and given to the sealing supervisor, who must therefore realize where his field decisions should involve input from the designer.

135. In other cases, specifications may give clear and detailed guidance regarding sealant hole layout, design of slurry, pumping of slurry, etc. The design drawings and the specifications must then show precisely the hole location, mixing design of the ingredients, and every succeeding step through the criteria for determining the adequacy of the sealant spread and continuity. This approach demands that the designer have considerable field experience, since a great deal of the sealing process is as much an art as a science.

136. Once the slurry mixing has begun in the field, the mixture must be checked periodically. It is recommended that the mixture be sampled hourly and that three tests be done on the specimens, including (a) temperature of the slurry, (b) density of the slurry using the mud balance, and (c) Marsh funnel viscosity. An in-line nuclear density gage is also available that can give density values and, by means of correlation, indicate water-to-cement ratio, viscosity, and cohesion. The values will indicate adjustments that might be required in the quality and proportions of the ingredients and in the mixing procedure.

137. If bentonite is used in the sealant, the bentonite should be pre-mixed with about 15-percent water by weight and aged for at least 2 hr before being added to the sealant slurry. This procedure is necessary to prevent a phase change of sodium bentonite to calcium bentonite. When seawater is used as the mix water, attapulgite is recommended over bentonite if clay is to be an ingredient.

138. The most important part of the entire sealing operation is retaining a contractor who is competent in this type work and conscientious enough to understand the indications of what is occurring below the surface and make necessary adjustments. The flow of sealant to adjacent holes or out the sides of a structure must be monitored to adjust the mix or injection procedure.

Quantity Estimates and Specifications

139. In recent jetty sealing efforts, the Corps has not experienced the degree of inaccuracy in estimating the amount of drilling and grouting that is common for dam foundation sealing. Inaccuracies with the latter have resulted in contractual disputes based on claimed differing site conditions. However, coastal engineers are not totally ensured against such difficulties just by the fact that their sealing jobs are in more homogeneous media (rubble masses).

140. Practices recommended to minimize contract problems in foundation sealing are utilized for estimating quantities and writing contract language for coastal structure sealing. One recommendation by George Washington University (1985) is to increase use of Corps drilling and sealing capabilities, particularly for repair work but especially for predesign investigations. A second recommendation is to perform more thorough site investigations on which to base estimates. A third recommendation is to develop better methods of estimating amounts of drilling and mixture quantities (especially mixture quantities). A fourth recommendation concerns the major area that requires improvement, namely contractual procedures. In actuality, all four recommendations should be implemented in combination.

Exploration borings

141. The evaluation of the cores of test borings from the exploration program is fundamental in the initial stages of preparing an estimate of mixture quantities.

Test injections

142. For medium and large projects, probably the most reliable method for estimating sealant intake is to conduct an experimental prototype test program on a specific reach of the structure. The area of the structure chosen for testing should be representative of conditions for the entire project and should be extensive enough to allow adequate estimation of the effectiveness of the sealing program.

"Unit take" estimates

143. A method frequently used during preparation of detailed estimates for rock drilling and sealing programs is called the "unit take" method. In adapting this method to a coastal application, the area to be sealed is divided into horizontal reaches and vertical zones, each having different permeabilities, based on rock size and whether the voids are filled with sand

or unfilled. Estimates are made of the number of primary and secondary holes required to complete each area and zone. Sealant intake in cubic feet per foot of hole is estimated, as well as the reduction in sealant intake for each split and zone. The amount of sealant intake in each series of primary and secondary holes normally should be less than the preceding set of holes and, if multiple lines are used, intake in each line should be less than a previously treated line. Each zone of each hole is assigned an estimated intake in cubic feet of mixture per foot of hole. A typical estimate using this method may resemble the following:

Reach "A"
Sealant Intake, cubic feet per foot of Structure

<u>Line A</u>	<u>Depth</u>	<u>Primary</u>	<u>Secondary</u>	<u>Tertiary</u>
Zone 1	0-10	5.0	2.0	0.5
Zone 2	10-20	3.0	1.5	0.5
Zone 3	20-35	1.0	1.0	0.5

Note: These figures are for illustration only and should not be used for purposes of estimating, as criteria for primary or secondary holes or for completion of grouting.

144. Results of different methods of estimating should be compared and critically evaluated for estimating sealant mixture quantities by personnel experienced in this type of sealing methodology.

Contracting procedures

145. The contract types and provisions used in Corps coastal sealing projects should promote quality work first, because of the assumption of risk by the Corps, and timely completion with appropriate economy second. Different approaches to payment and incentives for quality work are available.

146. Albritton, Jackson, and Bangert (1984), after reviewing dam foundation sealing practices Corps-wide, recommended that service-type contracts rather than construction contracts be considered for sealing dams. Performance specifications, though possessing the potential for saving Government funds in some types of construction, do not seem well suited to subsurface sealing where performance cannot normally be precisely ascertained. Only a complete understanding of the methods used will assure quality of the work. Use of disclaimers with the traditional contracting method is discouraged

because the language used probably would not be accepted by a board or court for overriding the mandated differing site conditions clause or other pertinent contract clauses. Use of a more detailed procedural specification seems impractical because detailed knowledge of subsurface conditions is not available. The sealing supervisor should be free to make field decisions.

147. Two-step formal advertising could be advantageous where time allows and where state-of-the-art techniques are involved. The steps are (a) evaluation of technical proposals from prospective contractors and (b) selection of a contractor based on price competition among those submitting satisfactory technical proposals. Prequalification of potential contractors could also be beneficial if the sealant is separately contracted and if the job is sufficiently complex.

148. Based on the above, the traditional specifications seem to serve the Corps best. Options include paying for contractor effort, for quantities of sealant materials, or for some combination of these two elements. By paying for some measure of effort (as time spent in pumping mixture), the Corps may maintain close supervision over the contractor's methods, the contractor will be assured a reasonable profit, and reimbursement terms are clearly defined. Although the project cost may not be minimized, the contractor loses the incentive to move off holes that take mixture slowly or to claim differing site conditions when the average sealant intake is not precisely as represented in the contract documents.

149. If a sealing program is to be performed along with other rehabilitation or construction work, the sealing work may be part of a general construction contract or may be accomplished under a separate individual contract. Both methods have advantages and disadvantages.

150. Performing the sealing under a general contract eliminates contractual difficulties that might arise from interference between sealing work and other activities. Economy of use of resources is also realized by the contractor if men and equipment can be used on other activities when not pumping sealant mixtures. If the general contractor sublets the sealing work, the Contracting Officer's Representative (COR) is contractually removed from the subcontractor, and it is more difficult to administer and maintain control of the operation.

151. Accomplishing a sealing program under a separate contract allows the sealing specialist to be the prime contractor, but this approach could lead to interference of one contractor with the operations of another. The

sequence of operations must be well planned, and coordination among contractors fully maintained.

Contract specifications

152. Because of the risk of unforeseen site conditions, design changes often become necessary. Causes for disputes between Government and contractor should be minimized. The message in decisions of the Corps of Engineers' Board of Appeals seems to be to promptly acknowledge a differing site condition (ideally at the field level) when there is an overrun or underrun, negotiate a changed unit price with the contractor, and avoid a costly claim (George Washington University 1985).

153. The Differing Site Conditions clause is often a cause of claims by foundation sealing contractors. In attempting to mitigate the problem, the Corps (a) has included language to indicate that the amount of drilling and sealing which will be required is unknown and will be governed by conditions encountered and (b) has used subdivided items to provide for variations in quantities (this method provides for two or more prices for an item). Because of the assumption of risk and because employing proper procedures and properly recording them are the only measures of quality control, the Corps has written specifications requiring the contractor to follow detailed field direction by the contracting officer or his representative. Difficulties may arise in cases where sealing is subcontracted because the Corps then has no contractual relationship with the sealing specialist.

154. The Corps has generally used the firm fixed-price contract, with unit prices for drilling and sealant quantities. That type contract has not served the Corps' interest as well as desired because that type is most appropriate only where the job is fully defined prior to bid.

155. To alleviate the problem caused by the great variance between actual and estimated quantities, the special provision "Variations, Estimated Quantities, and Subdivided Items" has been employed but has been a source of problems itself. The majority of potential claims could be settled amicably at field level if the normal variations in quantity clause were consistently used and if unit prices were negotiated at the project level when quantities were greater than 115 percent or less than 85 percent of the estimated amount (George Washington University 1985).

156. George Washington University (1985) iterated three conclusions from a report on tunneling as representing the appropriate philosophy behind recommended contracting practices:

- a. "It is in the owner's best interest to conduct an effective and thorough site investigation, and then to make a complete disclosure of it to bidders"
- b. "Disclaimers in contract documents are generally ineffective as a matter of law, as well as being inequitable and inexcusable in most circumstances"
- c. "Contracting documents and procedures can provide for resolutions of uncertain or unknowable geological processes or conditions before and during construction, rather than afterwards"

157. Because of the numerous contractor claims due in part to the contract language, George Washington University (1985) recommended:

- a. "Elimination from grouting specifications disclaimers such as:
'The program shown on the drawings and prescribed herein is tentative and is presented for bidding purposes only. The amount of drilling and grouting which actually will be required is unknown and will be governed by conditions encountered.'"
- b. "Inclusion of a statement substantially as follows:
'The program shown in the drawings and prescribed herein is based on currently available information. Conditions encountered during construction may require additions or deletions.'"
- c. "When grouting is subcontracted, add to the specifications a statement substantially as follows:
'The grouting program shall not be modified or curtailed as a construction expediency. It is a required part of design and shall not become secondary to any time or scheduling restrictions.'"

158. These recommendations were a part of others, including contracting procedures, use of Corps sealant capabilities, more thorough site investigations, and improvement in methods of estimating, which the authors of the report stressed should be considered as a whole, rather than separately.

Bid item

159. Mobilization and demobilization are considered a lump sum item and are compensation for assembling all necessary drilling and grouting equipment on the site and removing it therefrom. Payment for this item does not depend upon the amount of drilling and sealing performed. Provisions may be made for partial payment to the contractor after mobilizing the equipment and for payment of the remainder of the item when the work is completed and the equipment removed from the project site.

160. A bid item should be prepared for each type drilling required, including sealant hole drilling, exploratory hole drilling for core recovery, drilling hardened sealant, and others. If more than one size hole is required, separate items are needed for each size. The plans and specifications should indicate clearly the location and extent of the work to be done and should show limiting depths and inclinations, if any, of all holes. It is standard practice for payment to be made on a unit basis per foot of hole drilled, but better overall results may be achieved by paying for some measure of drilling effort with close supervision maintained by the Corps. Water and air required for drilling and sealing, or any auxiliary operations, are not separate pay items. The contractor is expected to recover the cost of furnishing both air and water under one or more of the designated pay items.

161. The pay item for placing sealant should cover labor, use of equipment, and the necessary supplies (other than sealant materials) required to mix and inject the sealant into the holes. The stage-sealing method, if employed, may also include cleaning sealant from the holes at the completion of the sealing stage. Placing sealant is sometimes paid by volume of materials (except water) injected (i.e., cubic feet of solids). An estimate of the quantity of mixture must be made since the actual amount is not known in advance. Payment for injection by the hour may be more satisfactory in many cases and would include labor and use of equipment to inject the sealant into the holes. In cases where it is anticipated that extensive use may be made of very thin mixtures to seal fine materials, an alternative method would be to pay for placement of total volume, including water. This would ensure that a contractor is fairly compensated for long periods required to place small amounts of sealant. It should also be realized that if mixture placement is awarded as a "unit prices item," the possibility exists for contractors to take unfair financial advantage through those provisions.

162. The stage-sealing method is probably not applicable to rubble-mound structures in a coastal environment. This procedure is employed where it is desired to treat each seepage-causing flow separately at successively higher pressures. In sealing jetties, breakwaters, etc., an appreciable increase in pressure and multiple applications at one level will probably result in no additional benefit. A stop-sealing procedure will possibly be more applicable where hole collapse or other problems force two-phase sealing. The sealant should be allowed to set before redrilling the hole. Cleaning the

hole might cause further instability. In certain grouting specifications, redrill costs are usually about one-half the bid price for original drilling.

163. A separate bid item should be provided for each ingredient used in the mixture (except water). Solids are usually measured for payment by the cubic foot or pound, and liquids are usually measured for payment by the cubic foot or gallon. For concrete placement, a sack of cement is considered to contain 1-cu ft volume. This item includes all costs involved in purchasing, handling, transporting, and storing the ingredients as necessary to have it available at the mixing site when needed.

PART V: SUPERVISION AND INSPECTION OF SEALING OPERATIONS

164. Experience of the field personnel is of prime value in a sealing operation. Regardless of how well conceived and designed the sealing program may be, success of the program depends upon the field techniques used and upon good judgment by field personnel. Placement techniques may not be subject to contractor quality control and should be directed by the Corps' field personnel. For this reason, an experienced geologist, civil engineer, or senior technician should be in charge of the sealing program, and he or she should be provided with an adequate staff.

165. The art of sealing consists mainly of being able to satisfactorily treat such subsurface conditions as void sizes, shapes, and interconnections without direct observations. Sealing procedures are subject to many variations, depending on the field techniques and procedures being utilized. Such field variations include drilling, washing, selection and adjustment of mixes, changing injection pressures, flushing the holes and washing the pump system during sealing, intermittent filling of holes, determining the need for additional sealant holes, treatment of surface leads, and maintenance of up-to-date records of drilling, emplacement, and monitoring.

166. When adjustments to contract requirements are made, the designers should participate in the decision. The adjustments may include changing the spacing of primary holes or increasing or decreasing the sealing program.

Drilling Operations

167. Since drilling is a vital and costly part of the sealing program, a record of all pertinent data should be kept by the inspector during drilling operations. Entries in chronological order should be made in field books, should include all data of interest that would assist in the identification of the physical characteristics of the subsurface material examined, and should account for all time spent in drilling. Forms for this purpose should be provided for the inspector to enter data as the work progresses. Identification of material encountered and other pertinent remarks of a geologist, engineer, or senior technician assigned to the project should also be included in the log. A sealing data base microcomputer software package for archiving data obtained during a drilling and sealing operation has been developed by the Corps of Engineers' Computer Applications in Geotechnical Engineering

(CAGE) Committee. The following general information should be recorded, regardless of the data handling method employed:

- a. Hole number.
- b. Drilling time schedule.
- c. Names of drillers and inspectors.
- d. Size of hole and inclination.
- e. Stations or coordinates of hole.
- f. Type and identification number of bit used and make of drilling rig.
- g. Elevations of start and completion of drilling.
- h. Location and cause of core losses, such as blocking of bit, soft material, and other.
- i. Location and nature of filled or open cavities.

168. Comments should be made on the log sheet relative to the drilling speed (penetration rate), drill pressure, and the action of the drill rig, such as jerky, smooth, rough, or steady, and the limits of such action. Particular attention should be paid to the driller if a core is being retrieved, as he may be drilling at a speed too fast to get an acceptable core, or he may be drilling at an excessively slow rate and wearing out soft material.

169. The driller's log column should show the driller's interpretation of the subsurface conditions encountered as drilling progresses. If an inspector is checking a driller's log, he will not normally reinterpret the log. Where a qualified inspector is required to log cuttings or cores, he will make the determination regarding material type, characteristic, etc., based on the official log after obtaining the driller's input on machine action, drilling difficulty, and other pertinent facts. This procedure is true whether the inspector is provided by the Corps or by the contractor.

170. In holes drilled with percussion, plug, or other noncoring bits, much of the data from drilling must be obtained from examination of the drill cuttings and fluid. The inspector should turn in a transcript of his records at the end of each shift.

Sealing Operations

171. When sealing the interior of a structure filled with very fine material, the fines must be washed from the hole. Silt and clay must not interfere with sealant injection. Otherwise, windows could be eroded in the

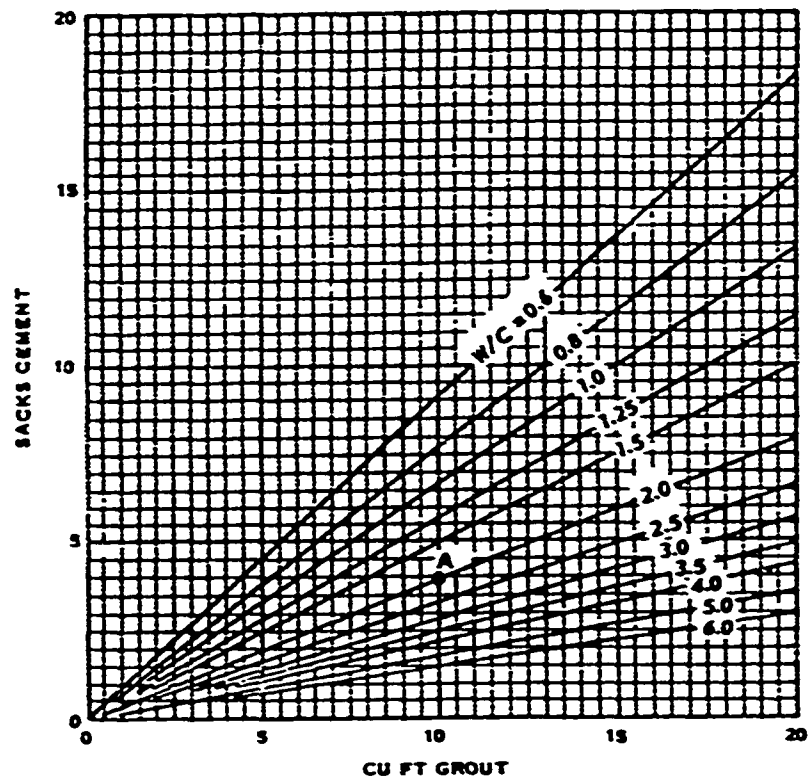
sealant barrier curtain. Open-hole washing is normally done by inserting a small-diameter wash pipe to the bottom of the hole and injecting a jet of water, sometimes in combination with air, to wash out any material in the hole. There will be instances with rotary-drilled holes where it may be determined that the hole is sufficiently cleaned by washing through the drill rods for several minutes after drilling is complete. Sealant should be placed only in an unobstructed hole.

172. Pressure washing a hole consists of injecting water and, in rare cases, air under pressure into the hole through a sealed connection at the collar of the hole. The washing should be continued as long as the rate of water taken continues to increase or as long as muddy water vents from adjacent holes or surface leaks. Air injected in short bursts into the water is a method used to create turbulence and enhance the erosive action of the water. Reversing the direction of washing may also be helpful. Reverse washing will necessitate reconnecting to the original hole and washing it out for a few minutes prior to grout injection. It is important to be constantly aware that excessive pressure can damage the previously placed sealant. Water pressure and air pressure should not exceed the allowable sealing pressure during pressure washing.

173. Pressure washing of holes in rubble-mound breakwaters and jetties should be performed carefully. It may tend to wash all fines from the vicinity of the hole, increasing sealant requirements, and possibly collapsing the hole. Where washing fines out of riprap is intended, the specifications should expressly state that fact. Washing of fines may have to be continued long after water fails to exit at the top of the hole, or at the waterline in most cases.

174. Once the holes in a section of structure have been prepared, sealing may then proceed. The design mixture may need to be modified in the field to achieve desired results. Fluidizers may be added to mixtures to reduce the viscosity. Water-to-cement ratios are normally specified by volume of water and dry volume of cement (i.e., one 94-lb sack of cement is considered to contain 1-cu ft volume). Figure 5 may be used for determining the cement content of various neat cement sealant mixtures.

175. A log sheet of the type shown in Figure 6 should be used to record sealing data. If the hole accepts a few batches of the starting mixture without buildup of material in the hole, thicker mixtures are required; however, thickness limits are imposed by the capabilities of the equipment to pump or



EXAMPLE: 10 CU FT OF 2.0 W/C GROUT (A) = 4.0 SACKS CEMENT.

NOTE: WATER-CEMENT RATIO (W/C) = CUBIC FEET WATER ÷ SACKS OF CEMENT.

Figure 5. Cement content of portland cement sealant mixtures, EM 1110-2-3506 (after HQUSACE 1984)

otherwise handle it. Figures 7 and 8 are for use in measuring portland cement thickening and thinning, respectively. For thickening or thinning, the cement content of a given volume of sealant is first determined. The total cubic feet of sealant is divided by the cubic feet of sealant obtained from a one-sack batch, based on the absolute volume of a sack of cement having approximately 1.0-cu ft volume.

176. Slurry density has been shown (Deere 1982) to be a good index property to check and control water-to-cement ratios. Slurry density may be simply measured in the field using a mud balance. Relatively large changes of bentonite content do not appreciably affect the unit weight of the slurry. Adding excessive amounts of bentonite requires a higher water content to make the mixture pumpable and prevents it from setting up. To this point in discussing sealing operations, open-hole conditions have been assumed. If pressure sealing is performed, some equipment would be different from that

SEALING LOG

PROJECT: South Stone Jetty Repair

LOCATION: West Palm Beach, FL

HOLE No: Station 55+92.5

DATE: 27 June 1985

DIRECTION: Vertical

INSPECTOR: J. Jones

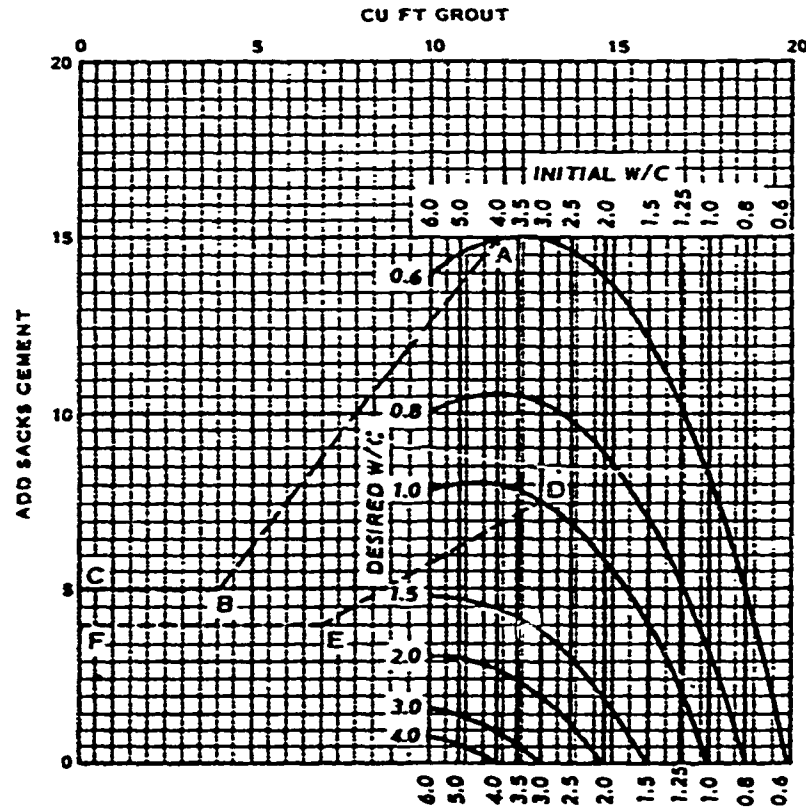
TOTAL DEPTH: 0 - 12 ft (concrete cap of jetty to bottom)

Depth, ft	Gage Pressure lb/sq in.	Silicate Mix No.	Volume of Grout, gal	Time		Pump Time, min	Grout Rate gal/min
				Start	Stop		
11 - 12	15	8	40	1028	1032	4	10
10 - 11	15	8	20	1032	1034	2	10
10 - 11	5	9	20	1037	1041	4	5
9 - 10	5	9	40	1041	1045	4	10
8 - 9	5	9	20	1045	1047	2	10
8 - 9	5	10	20	1049	1051	2	10
7 - 8	5	10	40	1051	1055	4	10
6 - 7	5	10	20	1055	1057	2	10
6 - 7	5	11	20	1100	1102	2	10
0 - 6	--	--	--	--	--	--	--
TOTAL			240				

Figure 6. Sample sealant hole log sheet

discussed previously and would allow the sealer to monitor and adjust the injection rate and pressure at points in the system. With this type sealing, water-to-cement ratios are also closely monitored and may be changed more than once for a single hole as pressure and injection rates vary. It is unlikely, however, that pressure sealing would be performed on a jetty or breakwater. If required, details of pressure sealing may be obtained from EM 1110-2-3506 (HQUSACE 1984).

177. Under open-hole conditions, a maximum pumping rate should be established for injecting sealant to restrain sealant travel within reasonable limits and to have better control of the job. A reasonable pumping rate for most sealing of jetties having voids unfilled by sand is considered to be 1.5 cu ft/min. The specifications should clearly indicate that the rate of injection will be controlled by the COR.



EXAMPLE 1: CEMENT REQUIRED TO THICKEN 4.0 CU FT OF 4.0 W/C GROUT TO 0.6 W/C (ABC) = 5.0 SACKS.

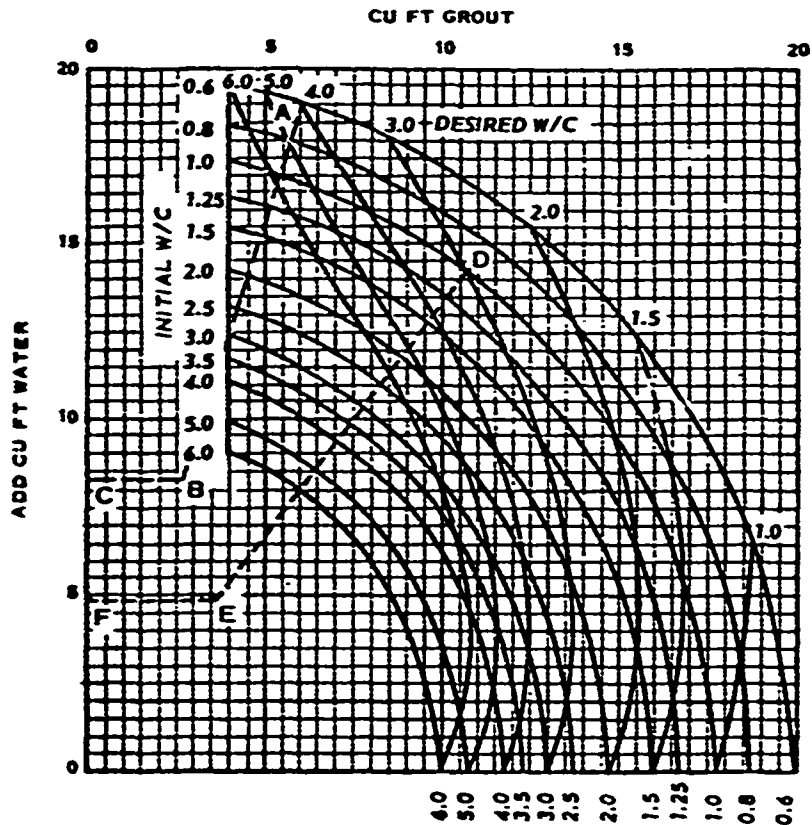
EXAMPLE 2: CEMENT REQUIRED TO THICKEN 7.0 CU FT OF 3.0 W/C GROUT TO 1.0 W/C (DEF) = 4.0 SACKS.

NOTE: WATER-CEMENT RATIO (W/C) = CUBIC FEET WATER ÷ SACKS OF CEMENT.

FOR DETERMINATION OF QUANTITY OF CEMENT TO ADD, LAY STRAIGHTEDGE FROM POINT OF INTERSECTION OF DESIRED WATER-CEMENT CURVE AND VERTICAL LINE REPRESENTING INITIAL WATER-CEMENT RATIO TO POINT 0 AT LOWER LEFT-HAND CORNER OF CHART. READ AMOUNT OF CEMENT TO ADD ON LEFT SIDE OF CHART OPPOSITE POINT WHERE STRAIGHTEDGE INTERSECTS VERTICAL LINE REPRESENTING CUBIC FEET OF GROUT TO BE THICKENED.

Figure 7. Portland cement sealant thickening chart, EM 1110-2-3506 (after HQUSACE 1984)

178. When sealant cannot be built up using the thickest mixes allowed or when it is desirable to prevent the sealant from spreading too far, delays may be used. They may last from a few minutes to several hours. The quantity of material injected per delay should be controlled to fulfill the intended purpose. If the delays are very long and thick material is being used, the hole and pump system should be flushed before each delay. The contractor's efforts should also be allowed to be directed elsewhere during the delay. If the delays are short and the contractor is required to stand by, provisions should be made in the contract for payment of standby time. Intermediate



EXAMPLE 1: WATER REQUIRED TO THIN 2.7 CU FT OF 0.6 W/C GROUT TO 4.0 W/C (ABC) = 8.3 CU FT.

EXAMPLE 2: WATER REQUIRED TO THIN 3.7 CU FT OF 1.0 W/C GROUT TO 3.0 W/C (DEF) = 4.9 CU FT.

NOTE: $\text{WAT_R-CEMENT RATIO (W/C)} = \text{CUBIC FEET WATER} + \text{SACKS OF CEMENT}$.

FOR DETERMINATION OF QUANTITY OF WATER TO ADD, LAY STRAIGHTEDGE FROM POINT OF INTERSECTION OF INITIAL AND DESIRED WATER-CEMENT RATIO CURVES TO POINT 0 AT LOWER LEFT-HAND CORNER OF CHART. READ AMOUNT OF WATER TO ADD ON LEFT SIDE OF CHART OPPOSITE POINT WHERE STRAIGHTEDGE INTERSECTS VERTICAL LINE REPRESENTING CUBIC FEET OF GROUT TO BE THINNED.

Figure 8. Portland cement sealant thinning chart, EM 1110-2-3506 (after HQUSACE 1984)

delays during a single injection period may be required to build up the sealant cone faster.

179. Upon the completion of sealing a hole, any material left in the sump should be wasted. Sealant that is not injected within 2 hr after mixing should be wasted, or sooner if it shows evidence of stiffening.

180. Split-spaced sealant holes may be mandatory, according to the contract specifications, or may be required due to sealant intakes. Split-spaced holes should normally be required on both sides of a hole that takes more sealant than the established minimum for the job. Holes that are

prematurely plugged should be replaced with new holes. The process of split-spacing should continue as long as there is significant reduction of intake with each new series of split-spaced holes or until intakes are not considered to be significant for the particular project.

181. Drilling and sealing should not be permitted in the same section concurrently. After sealing a specified series of holes is completed and the sealant set time has elapsed, the next series of holes may be drilled in the section as required.

182. In extremely hot weather, sealant and sealing materials should be protected from direct sunlight. It is desirable to maintain the sealant at temperatures below 90° F. The higher temperatures accelerate the setting time of the sealant, and this acceleration decreases the working time.

183. Surveillance of the area should be made frequently during sealing to check for surface leaks and to collect monitoring data from other holes. Records should be kept of any evidence of leaks, such as discoloration of the water adjacent to the structure. If the leaks are serious, the accelerator may be modified in the mixture. Sketches of longitudinal sections should be kept up-to-date with drilling, testing, and sealing data. Records should be made of monitoring data to evaluate the ongoing sealing program and for future reference. Sealing effectiveness must be continuously evaluated during the program. Evaluation should be a joint effort between engineering and construction personnel. If problems develop, reaction should be expeditious. Flexibility must be maintained for making changes and improvements as the program progresses.

184. It is worth recalling the observation of Lazarus White (Glossop 1961) on the danger of sealing without proper control: ". . . On excavating . . . very little of it will be found. No one knows where it went; all that one knows is that one has paid for it"

PART VI: FIELD EXPERIENCES

185. The experience of US Army Engineer Division, North Central, indicates that structures designed to be impermeable have in some instances shown some passage of littoral material. The passage of such material has not always resulted in increased maintenance costs, however, since its presence does not always cause a hinderance to navigation. The application of sealants would be recommended for any project where risks to navigation and subsequent increased maintenance costs are realized due to the condition of the structure.

186. The most recent Corps of Engineers experience in sealing voids in permeable jetties and groins occurred when the US Army Engineer District (USAED), Jacksonville, sealed the south jetty at Palm Beach Harbor, FL, in 1984, and the USAED, San Francisco, sealed the Buhne Point groins at Humboldt Bay, CA, in 1985. Subsequent to that time, Broward County, FL, has sealed the south jetty to Port Everglades Harbor, FL, in 1988, and the USAED, Detroit, has completed grouting and rehabilitating the north detached breakwater at Milwaukee Harbor, WI, in 1988. Asphaltic compounds were previously used successfully in Asbury Park, NJ, in 1963, and a breakwater in the Dominican Republic was recently stabilized in 1983 using an asphaltic concrete. Portions of the north and middle jetties at Mission Bay, CA, were sealed with a cement-sand mixture in 1959 by the USAED, Los Angeles. These projects (except Port Everglades Harbor, FL, which will subsequently be discussed in greater detail) are summarized as a means of sharing on-the-job experiences in an area in which little design guidance exists outside these specific Corps Districts.

Palm Beach Harbor, Florida, South Jetty Sealing

187. A major concern regarding the Palm Beach Harbor jetties in 1984 was the passage of sand through the south jetty and into the navigation channel. Since 1978, a shoal had built up each year on the channel side of the south jetty. The shoal was relatively small in quantity (only about 25,000 cu yd), but was very restrictive to the deep-draft vessels using the harbor. Usually each year, the channel shoaled to a depth of about -30 ft mlw, which is 5 ft less than the authorized depth of -35 ft mlw. This development forced some shippers to light-load vessels, thereby significantly increasing their costs. The volume of dredging was relatively small, but a

high unit cost resulted because a dredge was required to be mobilized to remove the shoal each year (USAED, Jacksonville 1984). Elimination of the dredging of the shoal between normal dredging of the inlet would reduce annual cost of maintaining the inlet about \$226,000.

188. The recommended plan was to seal the south jetty from Station (Sta) location Sta 57+50 to Sta 49+50 to form a barrier impervious to sand movement from about elevation (el) -6 to -10 ft mlw up to el 0 ft mlw and then construct a rubble filter that would be protected with armor stone on the seaward side of the south jetty from Sta 49+50 to Sta 44+50.

189. The original plan identified two types of silicate sealants to be injected through the crest of the jetty by way of 2.5-in.-diam casings placed in bored holes spaced no farther than 3 ft apart. Type 1 was a mixture of sodium silicate and sodium aluminate. Type 2 was a mixture of sodium silicate, sodium aluminate, water, and cement. The sealants would be mixed with or injected into the sand, depending on the specific circumstances at a localized portion of the structure. The method of operation would be to bore through the center of the structure to design depths to allow the placing of a 2.5-in.-diam casing. To ensure the formation of a barrier of sealant, the holes would be bored a maximum of 3 ft apart. The sealant would be pumped into the structure by one of two methods:

- a. A 1-in.-diam pipe would be placed in the casing. Then, as a sand-water solution was pumped in to fill all voids prior to injection of the silicate, the casing would be pulled out. The silicate sealant would then be injected into the jetty via the 1-in.-diam pipe.
- b. Existing sand would be washed from the jetty by water pumped through the casing. If the Type 1 sealant option was used, a water-sand mixture would be pumped into the jetty where it would be mixed with the silicate sealant. As the jetty filled, the casing would be removed. If the Type 2 sealant option was used, the silicate sealant and water-cement mixture would be pumped into the jetty, and the casing would be removed as the jetty filled.

190. Since the jetty landward of Sta 53+50 was mostly filled with sand, Method "a" would be applied for sealing this reach of the structure. Seaward of Sta 53+50, Method "b" would be applied. The estimated chemical sealant quantities reflected a 6-ft-wide barrier curtain of sealant extending from about 0 ft mlw to depths of about -10 ft mlw. Only a relatively narrow barrier needed to be provided to seal the structure to sand movement. To

ensure that a continuous barrier would be formed, holes were to be drilled every 3 ft along the center line of that portion of the jetty to be sealed.

191. During the plans and specifications phase of the project, the hole spacing was changed to 5 ft. Sand in the interior of the jetty to depths as great as -10 ft mlw would be chemically grouted with a mixture of sodium silicate, reactants, and accelerators. The void areas of the jetty would be filled with a sealant consisting of cement, sand, water, bentonite, and calcium chloride. The top elevation of the sealed section was changed to the level of the bottom of the concrete cap on the jetty crest.

192. The specified sequence was to seal all voids encountered with the cement-sand sealant. After drilling a hole, an injection pipe was to be inserted into the lower limits of the voids, and the cement-sand mixture would be injected in 1-ft increments as the pipe was withdrawn. The estimated amount of sealant, in order to achieve a 6-ft-wide barrier, was 18 cu ft for each 1-ft increment of height.

193. After the cement-sand mixture had stabilized, chemical sealing of the sands occupying the interior voids would be performed. Holes would be drilled through the cement-sand sealant until sand was encountered below the bottom design elevation of the jetty. An injection pipe would be lowered to the specified bottom limits of the hole, and an estimated 12 cu ft of chemical sealant would be injected for each 1-ft increment of height. The last step was to backfill the drill holes with a cement-sand sealant to the crest.

194. In the field, various sealant compositions were tried. After pumping 18 cu ft of mixture in three holes, the specified cement-sand mixture was judged to have dispersed completely, based on the plume appearance. Viscosity of the mixture was increased by adding bentonite. After 2,044 cu ft of this mixture had been pumped, it appeared that roughly 10-percent effectiveness was being achieved. The sealant that proved most effective was suggested by the contractor, which emphasizes the value of a contractor who is conscientious and experienced in mixing and injecting sealants. The suggested mixture of only cement and silicate was successfully tried in three holes, and a contract modification was issued.

195. During the sealing work, it was found that a better buildup of sealant could be attained by filling in an alternating drill hole sequence. Care was taken so that no mixture extruded from the exterior stones, which would change the hydraulic and wave dissipating performance of the jetty. After the sealing was completed in August 1985, samples were extracted from

exploratory holes, and they showed the intent of the design had been achieved. Hydrographic surveys of the inlet taken since the completion of the project indicate that objectives of the concept are being realized as dredging to specifically remove a shoal from the entrance channel has not been necessary.

Buhne Point, California, Groin Sealing

196. As a part of the Buhne Point Shoreline Erosion Demonstration Project, Phase III, two rock groins were constructed. One was shore-connected and the other was an extension of a groin previously constructed under an earlier phase. Each newly constructed groin exhibited the problem of permeability to sand transport, and a design for injection of concrete was developed (USAED, San Francisco 1985).

197. The design called for drilling 4-in.-diam holes, terminating at 1 ft into the bedding material on which the jetty was constructed. Drilling was accomplished with Schramm Rotary and Chicago Pneumatic Air Track drills. Approximately 90 percent of the holes were drilled with the Schramm Rotary, but because of mechanical difficulties, approximately 30 percent of those holes were drilled with 6-in.-diam widths. The Air Track drilled only 4-in.-diam holes. A total of 6,332 ft of drilling was required.

198. All drilling was done on the jetty center line and was accomplished in three phases. Phase 1 required drilling holes on 10-ft centers, Phase 2 on 5-ft centers between the 10-ft centers, and Phase 3 on 2.5-ft centers between the previous 5-ft centers. The groin extension was drilled on 5-ft centers as part of Phase 1.

199. Sealing was accomplished with a double piston positive displacement pump and a 4-in.-diam line attached to a 3-in.-diam rubber hose that was connected to a 3-in.-outside-diam tremie pipe. The pump and concrete delivery truck were placed on the jetties close to the holes to be filled. The rigid pipe specified in the contract provided assurance that the mixture completely filled the drilled hole and that it could be applied with a small pressure. Since the drilled holes were up to 14.5 ft deep, it was found that the rigid pipe and attached flexible tube became unmanageable as the pipe was withdrawn during filling near the top of the hole. Hence, the tremie pipe was shortened to about 3 ft, and the procedure worked well when the pipe was lowered to the bottom of the 14.5-ft holes by thrusting the pipe and flexible hose down the drilled holes.

200. The mixture required modification since the specified mixture could not be pumped. The mixture was redesigned as shown in the following tabulation, based on the number of pounds of constituents required to develop 1 cu yd of sealant.

<u>Buhne Point, California, Cementitious Sealant</u>		
<u>Component</u>	<u>Specified lb</u>	<u>Modified lb</u>
Coarse aggregate	1,000	1,115
Fine aggregate	1,450	1,655
Cement	705	705
Clay	305	37
Water	500	371
Calcium chloride	15	15
Air	--	0.41

201. The modified mixture had a 5-in. (estimated) slump, which was increased under certain circumstances. The estimated "intake" of sealant in the holes drilled on 10-ft centers in the shore-centered breakwater was 7 cu yd/hole, on the average (holes were 14.5 ft deep). Examination revealed that additional injection was required, and a second set of holes on 5-ft centers was drilled and filled with an average sealant intake of about 5 cu yd/hole. Another examination during high tide and 4-ft seas revealed leaks at el +6 ft mlw and above. An additional set of holes on 2.5-ft centers was drilled and injected. The sealant intake on the last set of holes was about 1 cu yd/hole. A total of 256 holes were drilled between Sta 0+40 and Sta 7+00, with a spacing of 2.5 ft.

202. The existing groin is composed of rubble core construction, and all injection holes were drilled 1 ft into the core, or to a hole depth of 7 ft, and spaced 5 ft apart. After injection with sealant, holes were drilled midway between these primary holes. The sealant intake was similar, being about 1 cu yd/hole on the average for both the holes on 5-ft centers and those on 2.5-ft centers.

203. The groin extension was drilled and sealed in two phases. The first phase involved drilling on 5-ft centers and injecting the sealant. The intake was about 2.5 cu yd/hole. The second phase required drilling on 2.5-ft centers and injecting the sealant. The intake for this phase was about 1 cu yd/hole.

204. After completion of the work, inspection revealed 25 to 30 possible leaks in the total length of sealed jetty (1,200 ft). None are known to exist below el +5 ft mhw or to cause a problem of sand transport in significant quantities.

205. Recommendations of field personnel associated with the sealing work include the following:

- a. Better knowledge is required about mixture performance in prototype field applications.
- b. Drill holes should be at least 6 in. in diameter to facilitate injection operations and visual inspection.
- c. Sand placement adjacent to the jetty should be delayed until all sealing is completed thereby making backwashing of holes easier.
- d. Consideration should be given to sealing the jetty surface on the lee side with a material stiff enough to close the voids, thereby making the coverage of the sealant material easier to evaluate.

Milwaukee Harbor, Wisconsin, North Detached Breakwater Sealing

206. US Army Engineer District, Detroit, successfully rehabilitated the north detached breakwater at Milwaukee, WI, by sealing one element of the structure with sodium silicate-cement sealant and sealing another element with only cementitious sealant (USAED, Detroit 1984). The sodium silicate-cement sealing element consisted of creating two vertical barrier curtains along each side of the breakwater (parallel to the center line of the structure) to serve as forming material for retaining the cementitious sealant element. The purpose of the rehabilitation sealing was for structural purposes only, to reestablish structural stability, and was not precisely for the elimination of penetrating waves or sediment for any future savings due to reduced dredging. This structure was built during the period 1882-1893 and consists of wooden timber cribs filled with rubble-mound stone. At some later date, concrete caps were placed on top of the cribs.

207. Loss of stone out of the cribs as a result of deterioration of the wooden timbers has caused voids up to 4 ft in diameter to develop within the cribs, and settlement and displacement of the concrete caps have resulted. To stop the loss of stone and to restore the functional stability of the structure, 3,800 ft of the north detached breakwater, which is 27 ft wide, has been successfully sealed. The first element consisted of utilizing quick-set

sodium silicate-cement sealant placed along both edges of the breakwater. The quick-set sealant was placed through holes drilled on 4-ft centers. Set time for this sealant was approximately 15 sec. The second element was accomplished after the quick-set sealant had hardened and consisted of placing a low-slump, heavily sanded cementitious sealant through holes drilled on 8-ft centers along the center line of the structure to fill the interior of the cribs between the quick-set sodium silicate-cement sealant walls. To ascertain the viability and practicality of sealing this structure, three different sections of the breakwater were evaluated successively: (a) a prototype test section, (b) a contractor capability demonstration section, and (c) production sealing of the structure.

Sealant designs

208. Sodium silicate-cement quick-set sealant. Along the two barrier curtain locations, the sodium silicate-cement quick-set sealant was placed from the bottom of the concrete cap to the top of the stone in the cribs, to act as a form to prevent the flow of required cementitious sealant outside the cribs. The quick-set sealant consisted of liquid sodium silicate, portland cement, water, and fly ash. The base material for the structural quick-set sealant was liquid sodium silicate, Grade 40, which conformed to ASTM specifications described in the Handbook for Concrete and Cement (WES 1949), Method CRD-D 3400. Portland cement conformed to ASTM Type I specifications in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 150. Fly ash comprised a minimum of 15 percent and a maximum of 40 percent of the total cementitious (cement and fly ash) content by weight in the quick-set sealant mix. The sealant was considered to have set when it had attained a compressive strength of 200 psi as determined by ASTM specifications in the Handbook for Concrete and Cement (WES 1949), Method CRD-C 403, and should have attained a minimum compressive strength of 1,500 psi after 28 days. A minimum of three distinct design mixes were required to be submitted by the contractor for set times of 10, 15, and 20 sec, respectively. These designs were tested and submitted to the contracting officer to allow the contractor to change from one design mix to another as site conditions required to completely fill the voids within the limits desired.

209. Cementitious sealant. The cementitious sealant was placed from the top of the crib stone fill to the bottom of the concrete cap, thus filling all remaining voids in the cribs between the quick-set sealant walls. This sealant was composed of portland cement, fine aggregates, fly ash, and water.

The fly ash could vary from a minimum of 10 percent to a maximum of 30 percent of the total cementitious (cement and fly ash) material, by weight, in the cement sealant mix. Fine aggregates conformed to the requirements of ASTM specifications in the Handbook for Concrete and Cement (WES 1943), Method CRD-C 33. The cementitious sealant was required to have a minimum compressive strength of 3,000 psi after 28 days.

Sealant injection procedures

210. Sodium silicate-cement quick-set sealant. Holes for the quick-set sealing could be drilled by either rotary or percussion drills. The holes were drilled in a split-space manner, in which the structure was drilled and sealed at 8-ft intervals and then drilled and sealed at the intermediate 8-ft intervals. All drill holes had a diameter of 8 in. The onsite spacing could be modified due to site conditions, tie rods, wood timbers, cross ties, monolith joints, and other undrillable obstructions. The sodium silicate-cement sealant was injected into the voids in and above the stone fill at a rate of placement such that the material was extruded in a slow, pastelike flow. The maximum flow rate per nozzle was 40 gal/min and could be varied based on site conditions to assure the complete filling of the voids. A two-stream method was utilized with the cement, fly ash, and water slurry being agitated in a separate vessel from the sodium silicate solution. When the materials from both vessels were thoroughly agitated, they were then blended using the two-stream procedure. Injection was initiated at zero pressure (gravity); then pressure was increased gradually until all voids between the concrete cap and the stone fill were filled. Injection continued until the contractor could not inject 1 cu ft of sealant in 10 min. The contractor could also inject no more than two times the estimated volume. If this limit was achieved, sealing was stopped in that hole for a minimum of 1 hr and then resumed with no more than one additional estimated volume of sealant being injected. This limitation of injecting no more than a total of three times the estimated volume always applied.

211. Cementitious sealant. Holes 3 in. in diameter were drilled through the concrete cap to the top of the stone fill for applying the cementitious sealant. Upon reaching final depth, the drilling apparatus was withdrawn from the drill hole, and straight casing was inserted to the bottom. Hole locations could be shifted as much as 6 in. to avoid encountering structure members other than rubble-mound stone. The cementitious sealant was injected into the voids in and above the stone fill under pressure through an

open-end pipe. The maximum flow rate per nozzle was 50 gal/min, but was variable based on the site conditions to ensure complete filling of the voids with the cementitious sealant material. Inspection holes were drilled along the lines of sealant holes midway between the sealant holes for alternate holes. Each inspection hole was used to monitor the flow of cementitious sealant injected into the two adjacent drill holes.

Prototype test section

212. The initial contract associated with rehabilitating the north detached breakwater consisted of sealing 742 lin ft of the structure with both sodium silicate-cement sealant and cementitious sealant as a prototype field test to determine whether sealing of the structure was a viable alternative for rehabilitation. Regarding the sodium silicate-cement quick-set sealant, the information obtained indicated the requirements for a variable mix design, for the ability to change the sequencing and pumping rate, and for casings that are snug with the holes. It was also determined to be desirable to have a sealant that sets quickly, stays where it is placed, is thoroughly mixed, and can be extruded in a pastelike consistency. Regarding the cementitious sealant, it was concluded that there exists the requirement for a variable mix design, for the ability to change the sealant sequencing and injection rate, for packers or casings that are snug with the holes, and for a thick sealant that stays where it is placed, is thoroughly mixed, and can be injected into the stone fill under pressure. It was determined from these tests that sealing is a viable alternative for rehabilitating this structure. Conclusions and knowledge gained from the prototype field test were incorporated into subsequent contract features pertaining to completion of sealing of the north detached breakwater at Milwaukee, WI.

Contractor capability demonstration

213. Prior to the beginning of production drilling and sealing of the entire structure length, the successful contract bidder was required to conduct an in-place demonstration to the satisfaction of the contracting officer of sealing methods in a 100-ft section from Sta 44+50 to Sta 45+50. Regarding the sodium silicate-cement quick-set sealant, the capability demonstration consisted of drilling the holes as shown on the plans; quick-set sealing using the equipment, mix designs, and methods proposed; coring; and furnishing field core logs and records to the contracting officer within 5 calendar days after coring. The demonstration was considered successfully completed when the voids between the concrete cap and the top of the stone fill were completely

filled within the limits shown on the contract drawings. Regarding the cementitious sealant, the capability demonstration consisted of drilling the holes as shown on the plans; cement-sealing using the equipment, mix designs, and methods proposed; coring; and furnishing field core logs and records to the contracting officer within 1 calendar day after coring. The demonstration was considered successfully completed when the voids between the concrete cap and the top of the stone fill (vertically) and between the quick-set sealant walls (horizontally) were completely filled.

Production sealing of the breakwater

214. Based on successful demonstration of the contractor's capability to drill and seal a 100-ft section of the north detached breakwater, a contract was awarded for production sealing 3,788 lin ft of this structure with both sodium silicate-cement and cementitious sealants. This contract was successfully completed during the summer of 1988.

Mission Bay, California, Jetty Sealing

215. Mission Bay lies on the coast of southern California, adjacent to the San Diego River at its mouth. A common jetty separates river discharges from tidal flows of the bay. The project has a second jetty that forms the north jetty of the bay, as well as a third jetty comprising the south jetty of the river. Shoaling of the Mission Bay channel was attributed to sand passing through both the north and the middle jetties (Herron 1972).

216. A cement-sand material with admixtures was chosen to seal the Mission Bay jetties, with pressure injection through holes drilled through the jetty crests. This was accomplished in 1959, and sealants were tested specifically for this job to evaluate their ability to resist erosion and dilution by flowing water. Discussion of test results by Loudon (1959) include:

The following admixtures were tested as stabilizing agents for beach sand-cement sealant:

- Airox pozzolan (processed volcanic tuff)
- Alfesil (fly ash)
- Zeogel (barite clay)
- Aquagel (bentonite)
- Rotary drilling clay P-95 (Macco Corporation)
- Natural sandy loam and cement

The only tests made were comparative in nature. Sealant specimens were molded in a conic frustum 1-1/2 in. across the top, 3-1/2 in. across the bottom, and 3 in.

high. The specimens were anchored to a steel plate with three small prongs and placed in a hydraulic flume running 12 in. deep at a velocity of 4.5 ft/sec. Time of immersion and loss of material were as follows:

<u>Test No.</u>	<u>Mixture</u>	<u>Immersion Time</u>	<u>Loss, %</u>
1	0.95 lb beach sand 0.47 lb cement 0.10 lb airox pozzolan 0.52 lb water	52 sec	100
2	0.95 lb beach sand 0.30 lb cement 0.20 lb airox pozzolan 0.35 lb water	1 min	75
3	1.00 lb beach sand 0.30 lb cement 0.30 lb alfesil 0.22 lb water	1 min	92
4	1.00 lb sandy loam 0.22 lb cement 0.27 lb water	1 min	55
5	1.00 lb beach sand 0.30 lb cement 0.30 lb aquagel 0.51 lb water	1 min	1.8
6	1.00 lb beach sand 0.30 lb cement 0.30 lb P-95 rotary clay 0.31 lb water	1 min	1.7
7	1.00 lb beach sand 0.30 lb cement 0.30 lb zeogel 0.59 lb water	1 min	14.5
8	1.00 lb beach sand 0.30 lb cement 0.30 lb P-95 rotary clay 0.31 lb water	24 min	78.8

The results of tests 1-8 indicate that only the aquagel, rotary clay, and zeogel contributed materially toward making the sealant cohesive and resistant to erosion during the presetting period. Sealant with the clays added exhibited characteristics similar to those of pure clay. These properties were attributed in part to the smallness of the beach sand particles because the small particles cause less interruption of the micellar bonding forces of the clay. Thus, the attraction between water films toughened by valence bond created a sealant of high plasticity

217. The P-95 drilling clay, said by the refiner to be the micaceous fraction of illite, mined at Muroc Dry Lake, CA, was selected as the stabilizing admixture to be used in the sealant. Proportions of the sealant mix that yield 1 cu yd are shown below.

Sand	2,000 lb
Cement	752 lb
Clay (4 sacks)	400 lb
Calcium chloride	16 lb
Water	64.3 gal

218. An experimental contract was awarded for sealing a short reach of the middle jetty in December 1958. The contract provided for placement of 400 cu yd of sealant in that portion of the jetty passing through the surf zone. A wagon drill was used to drill 2-in.-diam holes through the crest of the jetty spaced approximately 8 ft apart on the jetty center line. Sealant was injected through a 1-1/2-in.-diam hose at an average rate of 18 cu yd/working day.

219. In some voids that extended to the surface, it was possible to observe sealant as it became stiff and set up in interior openings as large as 1 ft or more across. Some exploratory holes were drilled between filled sealant holes. The voids were filled satisfactorily. Dye tests also showed that the sealant barrier curtain was effective.

220. Final construction was accomplished in the spring of 1959. Sealant holes were roughly 6.5 ft apart, and between 6 and 9 cu yd of sealant was injected into each hole. Final cost, including experimental contract, was \$41/lin ft (1959 dollars). Surveys made through November 1959 indicated the sand accumulations on the channel sides of the jetties had disappeared, suggesting the sealing job was successful. However, since that time, the structures have been battered by a series of intense winter storms which have resulted in extensive armor stone displacement, and probably internal core and sealant damage. Repair and rehabilitation have been performed by placing additional armor stone on the cover layer without regard for reinforcing the barrier curtain created by the sealing process. Recent observations of these structures indicate that most of the 1959 sealing material probably has disappeared, as longshore sediments are again passing through the north and middle jetties into the navigation channel.

221. Jetty sealing, using materials and techniques similar to those at Buhne Point and Mission Bay, was also accomplished in California at Oceanside

north and south jetties, San Luis Rey River jetties, groins in the vicinity of Newport Beach, Marina Del Rey jetties, and the Santa Cruz west breakwater. Of all these rehabilitated structures, only the Santa Cruz effort was thought to have obtained slightly less than expected effectiveness, even though the overall performance has been satisfactory with only minimal passage of sediments through the breakwater. Insufficient sealant spread is thought to be the reason for the slightly less than desired results.

Port of Haina, Dominican Republic, Slope Sealing

222. Asphalt application to rubble slopes for the purpose of slope stabilization was successfully accomplished at the Port of Haina, Dominican Republic, in 1983 (Schmeltz, McCarthy, and Lopez 1984). Because of the lack of suitable stone and the requirement for quickly providing wave protection for dock structural elements, the selected method of armoring the slope was to apply a designed asphalt binder. A continuous asphalt coating was applied over the relatively lightweight rubble from the top of the slope down to a distance of 1.5 times the design wave height below the datum. Below that level, asphalt was applied by the "pattern sealing" method, achieving a 50-percent coverage. By placing patches of sealant in a predetermined pattern, the armor stone was partially connected and formed "clusters." Through "pattern sealing," the apparent weight of the armor stone in computations of resistance to wave forces can be increased at least 5 times (van Garderen and Mulders 1983). The purpose of the pattern sealing was to permit relief of pore pressures in the rock fill. Penetration of the asphalt to a depth of 1 ft was judged to be adequate to bind the primary armor.

223. The slope was intended to withstand wave heights up to 8.5 ft. Although different from routine pavement asphalt, mixes used in this type of construction could be manufactured in any asphalt plant that was in satisfactory operating condition. A structure so produced could withstand wave heights up to approximately 13 ft. Selection of the proper mix was an iterative process, and the trial mix proportions were:

<u>Trial</u>	<u>Asphalt, lb</u>	<u>Sand, lb</u>	<u>Filler, lb</u>	<u>Gravel, lb</u>	<u>Result</u>
1	15	70	15	--	Too fluid; penetration too great (60-70%)
2	12	52	11	25	Too viscous; rock voids not filled enough
Final	12	58	15	15	Good flow and filling

224. Most of the material was placed at approximately 330° F, with lower or higher temperatures causing trouble in placement. The material was placed on the rock slope with a 4-cu yd clamshell dragline bucket. When placed above water, the material was moved as needed by workmen with shovels and rakes. For below-water placement, the clamshell was opened near the water surface, and material was dropped in mass to the rock surface. To obtain a good pattern, a system of locating the bucket must be established at each site.

Asbury Park, New Jersey, Groin Sealing

225. Groins were rehabilitated with asphaltic sealant near the Asbury Park Convention Hall, New Jersey, in the 1960's (Avakian 1969). The first to be rehabilitated was the Deal Lake groin in 1963. The outer 75-ft section was rebuilt by incorporating an asphaltic hot-mix and has been entirely successful in terms of its service record. The method of rehabilitation was to lay down a foundation of rock, advancing seaward from the existing groin tip. Next, a hot asphalt-aggregate mixture was delivered by insulated trucks to a crane-rigged core box. The filled core box was swung into position over the placed stone and tripped. An approximately flat layer of hot mix was thus created for a length of about 20 ft and for the width of the groin. Next, 5-ton stones were specially placed on and in the asphalt. The next layer of asphalt was made to cover those stones on all sides, and the process was repeated until the design crest elevation had been achieved. In this way, the asphalt replaced the core of the "typical" groin section and acted as a binder to hold the structure together as a monolithic mass.

226. In the 24 years since this work was completed, no repair work has been necessary. Today, two stones appear to be dislodged from the end of the Deal Lake groin. This is a noteworthy record of service and shows the

possible benefits to be realized from using a properly designed and emplaced asphaltic mixture.

PART VII: LARGE-SCALE LABORATORY TESTS

Sealants Evaluated

227. Evaluations of parameters in the interior of prototype structures are difficult because of the inaccessibility to the regions of interest. Conversely, a physical model such as that constructed for this study can be disassembled for close inspection and analysis. Specific objectives of the large-scale laboratory investigation included (a) construction of a rubble-mound physical model at a scale sufficiently large that deviations from similitude would be negligible; (b) preparation and injection into the model two types of cementitious sealants (WES Mixture and Buhne Point Mixture), two types of chemical sealants (Sodium Silicate-Cement Mixture, and Sodium Silicate-Diacetin Mixture for sand layer stabilization), and one asphaltic concrete (Sand-Asphaltic Mixture), recording for each the quantities, location of injection, pumping rates, and gel times of the materials; (c) providing specific descriptions of material by precise recording of components and proportions, and obtaining determinations of standard parameters for the respective materials; and (d) recording spread, shape, competency, and continuity of the hardened sealants upon disassembly of the structure.

228. Sealants to be evaluated were selected based on their (a) potential to be easily pumped, (b) having a short controllable set time, (c) ability to resist dilution and dispersion, and (d) chemical stability and structural integrity, once set. Materials that previously showed potential for success in field applications by Corps Districts included a stiff concrete mixture with bentonite as an additive (Buhne Point Mixture), a sodium silicate-portland cement mixture (Sodium Silicate-Cement Mixture), and a sodium silicate-formamide mixture. Diacetin also causes gellation of sodium silicate, and this reactant was chosen for use in an experimental mixture (Sodium Silicate-Diacetin Mixture) evaluation because it presents a lower health risk than formamide. There is abundant literature on marine applications of asphalt, but there are no known cases of a sand-asphaltic mixture being injected into jetty voids. Rheological properties of some asphalt, however, made the Sand-Asphaltic Mixture an attractive test material. A concrete mixture (WES Mixture) with certain specific admixtures that give the material high cohesiveness and relatively high fluidity was developed by WES's Structures Laboratory. These five materials (WES Mixture, Buhne Point

Mixture, Sodium Silicate-Cement Mixture, Sodium Silicate-Diacetin Mixture, and Sand-Asphaltic Mixture) were chosen for evaluation.

WES Mixture

229. A sanded cement sealant mixture, with additives that give it a resistance to "washout" or erosion by flowing water, was developed for this investigation. The ingredients of this mixture, termed the WES Mixture, are listed in Table 1, in pounds that produce 1-cu yd volume of sealant and yield a 10-in. slump.

Table 1
Mixture Proportions of Cementitious Sealants
Injected in Model Jetty

<u>Material</u>	<u>Quantity, lb/cu yd</u>	
	<u>WES Mixture</u>	<u>Buhne Point Mixture</u>
Type I portland cement	643	700
Fly ash	32	--
Silica fume	65	--
Bentonite	--	27
Masonry sand	2,430	2,311
Water	378	435
Antiwashout admixture	1.8	--
Air-detraining agent	0.4	--
Sodium citrate	0.4	--
Water-reducing admixture (lignosulfonate)	218 oz	--
Water-cement ratio, wt.	0.51	0.62

Buhne Point Mixture

230. Concretes have been used for a few limited jetty-sealing applications along the California coastline, with varying results. The latest application was at the Buhne Point Shoreline Demonstration Project, in Humboldt Bay, California.

231. Ingredients of the concrete used at Buhne Point included about 30 percent by weight coarse aggregate. The coarse aggregate prevented it from being used in the physical model, however, because of the risk of the larger particles sealing off the voids in the scaled rubble-mound structure. Therefore, a sanded mixture that had essentially the same strength properties was formulated for use in the model. Test cylinders of that mixture were also

cast for durability testing. Ingredients, in pounds, which produce 1-cu yd volume of that mixture and yield a 5-in. slump are listed in Table 1 as the Buhne Point Mixture.

Sodium Silicate-Cement Mixture

232. The sodium silicate-cement mixture used in the investigation is composed of two solutions mixed in a 1-to-1 ratio. One solution is sodium silicate and water mixed in the proportions of 16 gal of silicate (the silicate itself being a 42-percent solution) and 64 gal of fresh water, making a total volume of 80 gal. The second solution is the reactant, which is enough water added to three sacks of ordinary portland cement to also make a total volume of 80 gal. In the combined state, the sealant is composed of 4.2-percent sodium silicate and 7.0-percent portland cement. The set time for a sealant of these proportions is less than 1 min and is accelerated by high temperature and increased cement concentrations. The sealant is intended to seal large voids by displacing water in the submerged portion of the structure, and set at a time after injection so that there is minimal sealant loss to the exterior of the structure. Proportions of the Sodium Silicate-Cement Mixture injected into the test sections of this investigation are listed in Table 2.

Sodium Silicate-Diacetin Mixture

233. Sodium silicate in solution with a chemical reactant was used for permeation sealing of sand that had filled voids in a section of the model jetty. The objective of sealing a sand-filled section was to simulate the operation of arresting sand movement by stabilizing the sand in the interior of the jetty. In field practice, an alternative to stabilizing the sand is flushing the sand from the void region and then backfilling with a cementitious or chemical sealant mixture. This test was conducted as part of an evaluation of the technique of stabilizing the sand layer prior to filling voids between the sand layer and the upper elevation to which sealing will be performed. Formamide and diacetin are two of several reactants that cause gelation of the sodium silicate. Since there are no solid constituents to pack together, paths of permeation cannot be blocked. Proportions of the Sodium Silicate-Diacetin Mixture used in this investigation also are listed in Table 2.

234. Formamide was used in a previous jetty sealing project, but diacetin was chosen for this experimental investigation because, in the future, that reactant may be preferred in production sealing. The reason is

Table 2
Mixture Proportions of Chemical Sealants
Injected in Model Jetty

<u>Constituents</u>	<u>gal/cu ft</u>	<u>percent by volume</u>
<u>Sodium Silicate-Cement Sealant Prepared at WES</u> <u>by Structures Laboratory Personnel</u>		
Type I portland cement	0.512	6.7
Sodium silicate	1.496	20.0
Water	<u>5.472</u>	<u>73.3</u>
Total	7.480	100.0
<u>Sodium Silicate-Cement Sealant Prepared at WES</u> <u>by Grouting Contractor</u>		
Type I portland cement	0.500	7.0
Sodium silicate	1.480	20.0
Water	<u>5.500</u>	<u>73.0</u>
Total	7.480	100.0
<u>Sodium Silicate-Diacetin Mixture for Stabilizing Sand Layer</u> <u>Prepared at WES by Structures Laboratory Personnel</u>		
Sodium silicate	2.618	35.0
Diacetin	0.449	6.0
Water	<u>4.413</u>	<u>59.0</u>
Total	7.480	100.0
<u>Sodium Silicate-Diacetin Mixture for Stabilizing Sand Layer</u> <u>Prepared at WES by Grouting Contractor</u>		
Sodium silicate	3.060	40.0
Diacetin	0.300	4.0
Water	<u>4.180</u>	<u>56.0</u>
Total	7.480	100.0

that handling diacetin presents a lower risk to health than handling formamide. In the combined state, the sealant used in the injection testing was 40-percent sodium silicate, 4-percent diacetin, and 56-percent water. The set time was about 14 min.

Sand-Asphaltic Mixture

235. Vast experience has been gained in constructing coastal works in The Netherlands with asphaltic materials (Mulders et al. 1981). However, asphalt has been used relatively little in rehabilitating coastal structures in the United States. The known applications in the United States have been with mass-placed sand asphalt mixtures (The Asphalt Institute 1969). The favorable rheological properties of sand asphalt (yielding under slow deformation, yet mobilizing high shear resistance under impact loading) made it worthy of evaluation as a material that could be emplaced using a grouting technique for sealant placement. Mixtures containing 10-, 12-, and 15-percent asphalt were evaluated. Of the solid constituents, 85 percent were sand and 15 percent were portland cement. Specimens cast for long-term time-dependent durability testing in the prototype environment were composed of 12-percent asphalt. The injectability of straight asphalt also was investigated.

Physical Model Scale

236. Scale effects were recognized as being important in interpreting the results obtained from injecting prototype sealants in smaller-than-prototype voids. The scaling laws applicable to this process, however, had not been determined. Model void sizes as close as possible to prototype void sizes were desired, but were constrained by the limiting size of the facility in which such a rubble-mound structure could be built. Additional limitations included the necessity that the scale model structure be submerged, sealed, disassembled, and analyzed under controlled conditions. The stone weight that could be handled practically in the facility also imposed a further restraint.

237. The facility available to carry out the injection tests was a sump for a tidal hydraulic model and was located in the open air. The facility was 80 ft long, 30 ft wide, and 10 ft deep and could be easily filled and emptied with water. The model stones were classified as "225-lb riprap" by the supplier, which meant the largest stones in that class weighed about 225 lb. An approximate axial dimension of these stones was 1 ft, and nearly all the stones could be handled by one person. This was an important consideration

because model construction involved hand placement of individual stones. Disassembly of the model structure also required removing individual stones manually to expose the sealant effectiveness.

238. The jetty dimensions were scaled to the representative stone size. The jetty crest width was chosen to be the sum of five stone diameters, consistent with many prototype designs. A 5-ft crest width was thereby selected for the model. The sealing process would entail injecting the sealants successively in lifts of one stone diameter (1 ft). Four lifts were necessary to meet testing requirements. The water depth was therefore fixed at 5 ft, and the structure height was determined to be 6 ft. As in many prototype structures, the side slopes were designed to be 1.5-to-1 horizontal-to-vertical dimensions. This rubble-mound model structure was constructed at prototype scale for some groins. However, for the majority of coastal rubble-mound breakwaters and jetties, the model crest width was 1-to-6 model-to-prototype, and the stone weight was about 1-to-1,000 model-to-prototype.

Parameters Tested

239. The particular aspect of void sealing that seems to remain within the realm of art instead of pure science is the knowledge (intuition) of how far the sealant spreads in a rubble-mound structure if a specific amount of material is injected. The final shape of the sealant mass cannot be precisely calculated, nor can the amount of sealant loss that may be expected to occur during emplacement. These parameters must be approximated from precision laboratory experiments and the best prototype experiences available.

240. Parameters of the cementitious mixtures that must be measured to describe the sealants include (a) slump, (b) workability in tremie placement, (c) air content, (d) unit weight, (e) water-to-cement ratio, (f) cohesiveness, and (g) some measure of its resistance to "washing out," or being diluted and dispersed in flowing water. During injection, the pumping rate and volume pumped at each level of the injector nozzle were recorded. Each lift, or volume of sealant emplaced at a certain elevation in the structure, was stained with dye to distinguish it from the sealant placed during other lifts and to make it possible to trace the sealant's flow and measure its shape upon disassembling the structure. Bonding of the material to the model stones and continuity of the material injected from adjacent holes spaced at varying distances were evaluated qualitatively. Concurrent with the sealing

operation, specimens of the mixture were cast for long-term time-dependent durability and strength testing.

241. Sodium silicate sealant parameters that were documented included (a) constituent proportions, (b) set time, (c) pumping rate, and (d) volume injected per lift. Salinity of the water into which the sodium silicate-cement sealant was to be injected also was measured. The extent of sealant travel, shape, continuity, and competence of the resultant mass were then evaluated. For the sodium silicate-diacetin injected into the sand-filled voids of the model stones, competence of the sealed mass and effect of discharge pressure on the sand structure were also evaluated.

242. Sand asphalt injection was evaluated by (a) observing the reaction of the hot-mix to immersion in water, (b) spread, (c) bonding, (d) ability to retain its emplaced shape, and (e) continuity. A determination of the effect of cooling as the sand asphalt spread was made from the appearance of the material at different distances from the injection nozzle.

243. In the initial planning of the laboratory investigation, it was desired to analyze the rate of sealant spread and shape of the sealant mass being emplaced as functions of (a) injection pressure, (b) injection rate, (c) material viscosity, and (d) cohesion. This analysis was intended to be accomplished by using a material for which the viscosity and cohesion could be varied and by placing sensors in the model at known distances from the injection pipe that would detect the arrival of the sealant formation. REVERT is a commercial powder that, when mixed with water, produces a viscous solution. The viscosity of a sealant mixture can be designed by specifying a desired amount of REVERT. Addition of cellulose ether introduced cohesion to the mixture.

Physical Model Design and Construction

244. The model was partitioned into six sections that were labeled Sections A through F, respectively, for injecting and evaluating the mixtures. Plywood partitions were installed (a) to preclude the possibility of a mixture in one section from influencing the mixture in another section, (b) to form templates for placing the rock, and (c) to serve as supports for a crest-level work platform to be built after the rock was in place. Section C was enclosed with watertight walls to confine the saltwater test to that one specific section. Not all of the susp water was salt water because of the difficulties

created by salt action on the sump equipment and because of the environmental limitations imposed on the disposal of such a large quantity of salt water. The model sections were constructed around preplaced vertical injection pipes and instrument conduits. When construction was completed, the pipes and conduits formed a single line along the jetty center line. Various stages during the construction of the rubble-mound physical model are shown in Figures 9 through 13.

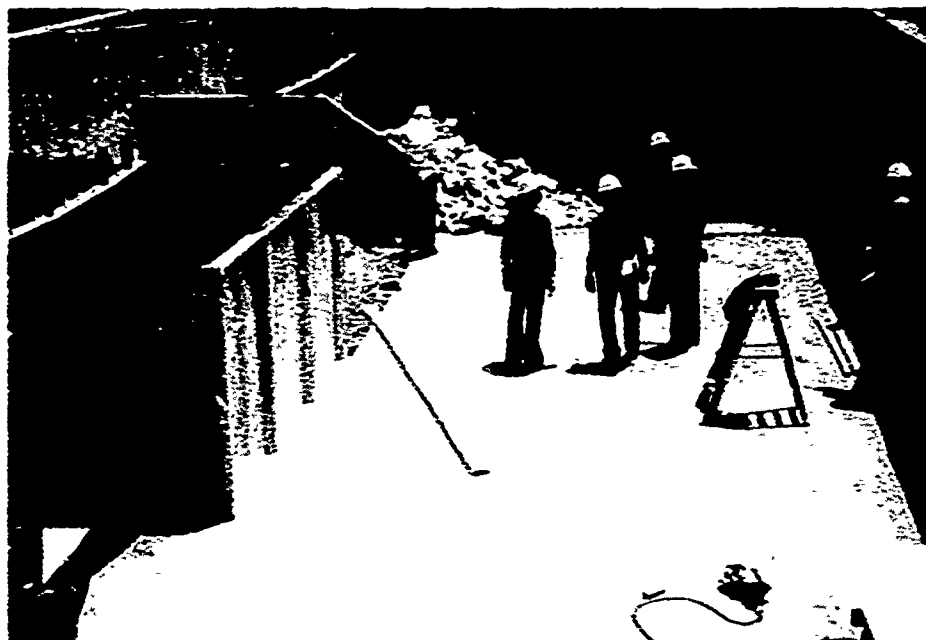


Figure 9. Initial stages of construction of rubble-mound physical model of breakwater or jetty

245. The jetty center line was offset from the sump center line as a means of conserving both rock construction material and labor (Figure 14). The jetty center line was positioned 6 ft away from the east wall of the sump, a distance calculated as sufficient to cause no "wall effect" on the sealant placement.

246. The cross-sectional area of a typical section through the jetty was approximately 75 sq ft. The 80-ft-long rubble-mound structure required 245 cu yd of stone for construction, which included additional rock necessary to be placed in lowered portions of the ends of the sump. Approximately 153 tons of stone were utilized in constructing the rubble-mound physical model of a breakwater or jetty.

247. Wooden partitions were fabricated from 3/8-in. plywood attached to framing that was fastened to the sump floor and wall. Plastic sheeting was



Figure 10. Construction of rubble-mound physical model around saltwater test section to determine salinity effects

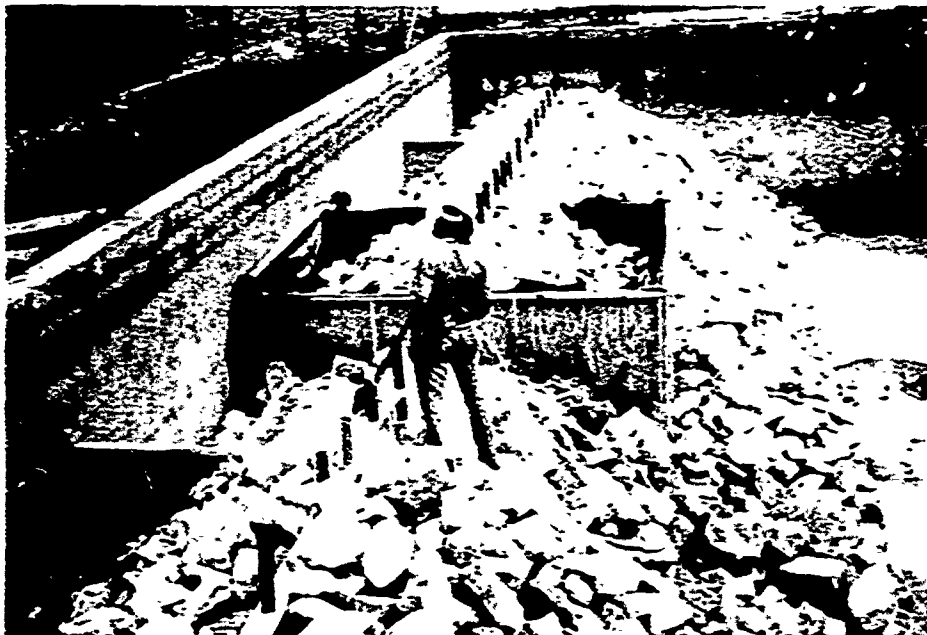


Figure 11. Construction of rubble-mound physical model section to investigate ability to stabilize sand layers



Figure 12. Completed physical model of rubble-mound breakwater or jetty for sealing evaluations

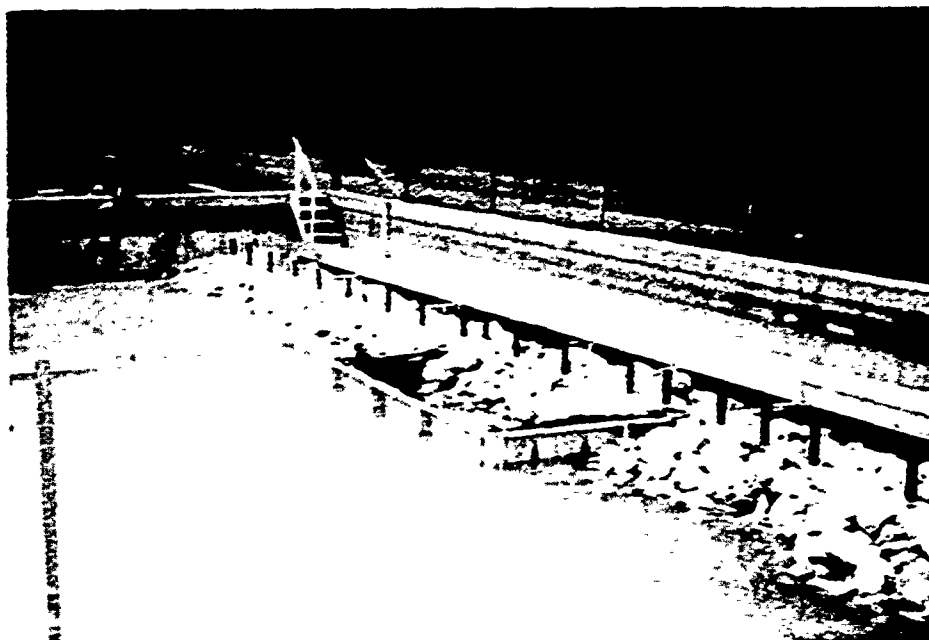


Figure 13. Physical model of rubble-mound breakwater or jetty flooded for sealant injection

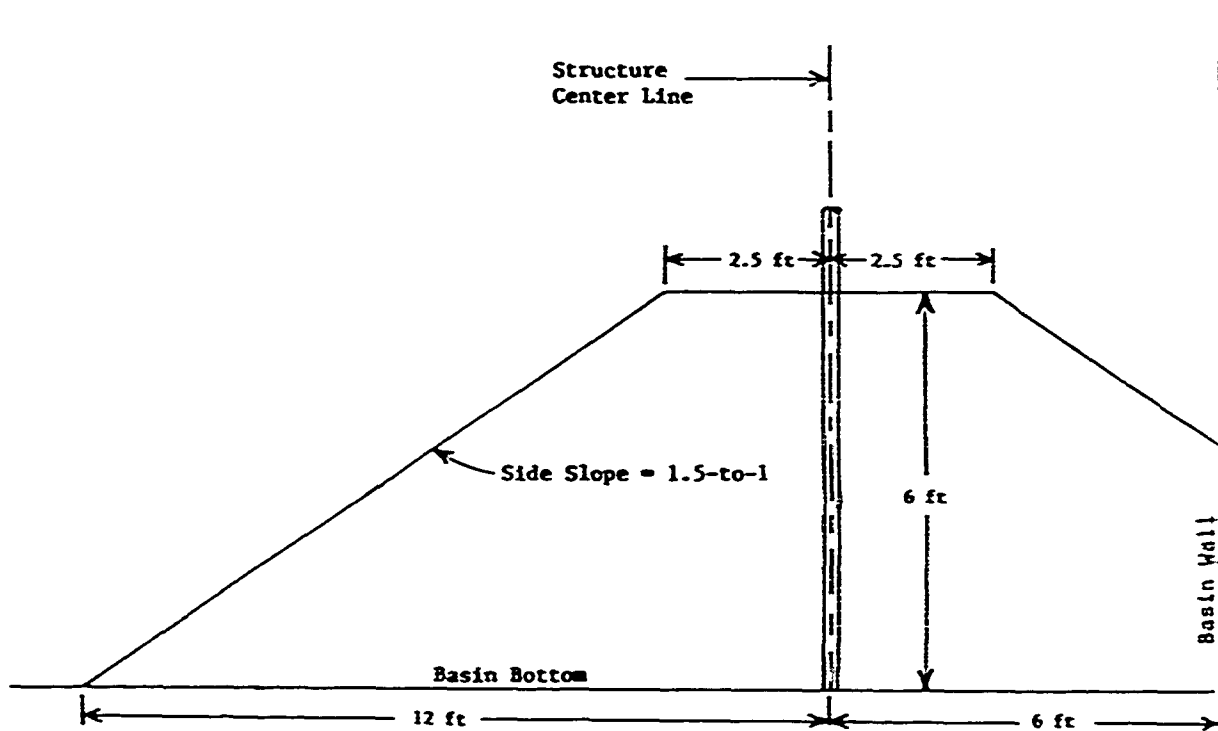


Figure 14. Physical model of rubble-mound breakwater or jetty, showing center-line location with respect to basin wall

placed on the sump floor and wall to act as a bond-breaker and to aid in cleaning the sealants from the sump after the testing was completed. Sealant injection pipes were 2-in.-diam, 7-ft-long steel pipes threaded to accept the contractor's sealant equipment header attachment. Lifting lugs were welded to the pipes so they could be raised for injecting the sealant in lifts. Instrument conduits were 1.5-in.-diam, 6-ft-2-in.-long polyvinyl chloride (pvc) pipes with 1/2-in.-diam holes drilled through the pipes at 1-ft intervals measured from the bottom of the sump. The sealant injection pipes and instrument conduits were also designed to act as rock retainers, so that a nearly vertical section of the interior of the model could be viewed when the outer layers of stone were removed.

248. Prior to injecting sealants into a section, wire-resistance gages were positioned at the 1/2-in.-diam openings in the conduits. The conductivity of the injected materials upon reaching the gages would cause a deflection of the metering instrumentation. All the pipes were held in place by wooden attachments at both top and bottom as the section was constructed around them (Figure 15). Details of the section for evaluating the ability to stabilize a sand layer under a structure are shown in Figure 16. Sand was dumped onto the



Figure 15. Sealant pipes and instrumentation conduits in physical model of rubble-mound breakwater or jetty

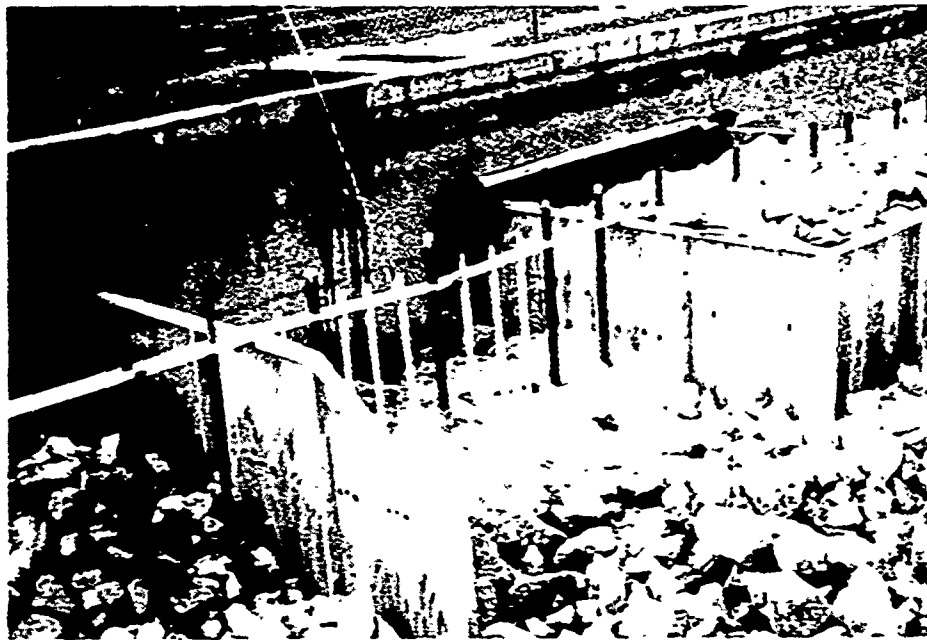


Figure 16. Details of section for evaluation of ability to stabilize a sand layer under a structure

first layer of stones and washed into the voids; then another layer of stones was placed. Sand and stones were alternately placed up to within 1 ft of the jetty crest. Plan views of Sections A through F, showing spacings and dimensions, are shown in Figures 17 through 22, respectively.

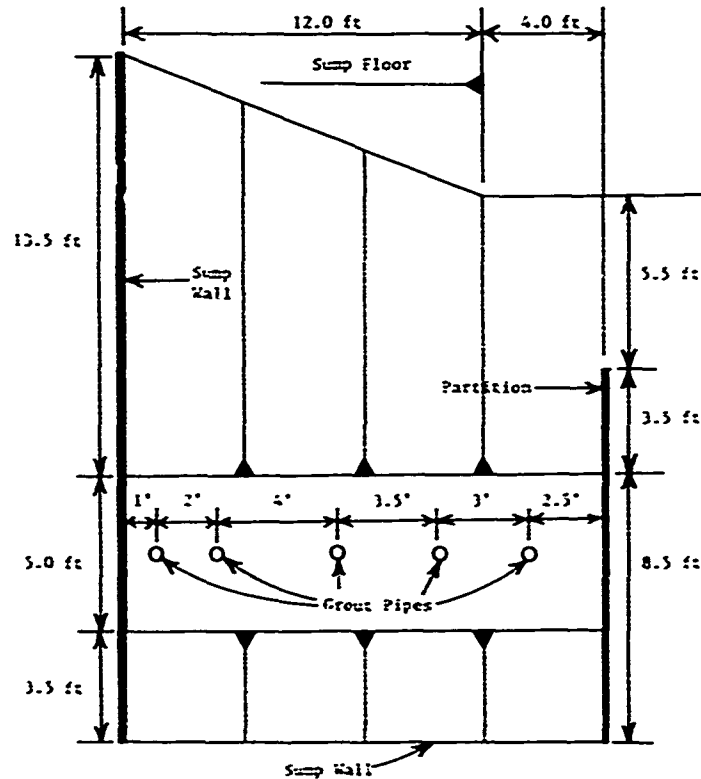


Figure 17. Section A of physical model utilized to evaluate WES Mixture of cementitious sealant with additives to provide resistance to erosion by flowing water. Sealant placed by commercial bulk concrete plant personnel

249. The sump was filled with fresh water from a fire hydrant, except for Section C, which was simultaneously filled with fresh water and with salt-water brine piped from a nearby lixator. Each phase of the model construction was videotaped, and the tapes are available for future reference.

Rubble-Mound Structure Properties

250. The average unit weight of the stones from which the model was constructed was 164.7 lb/cu ft, with the unit weights of individual stones varying from 162.2 to 169.7 lb/cu ft. Darker stones were denser than lighter colored stones. The stones were made of limestone with small amounts of

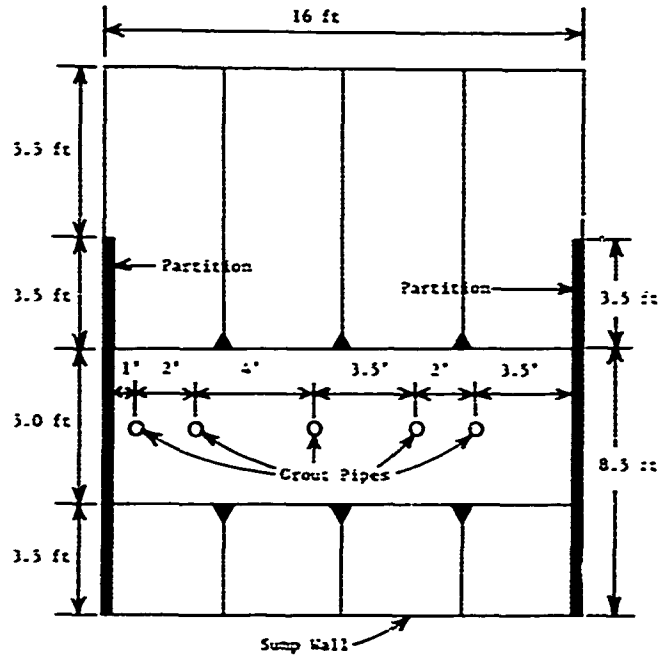


Figure 18. Section B of physical model utilized to evaluate WES Mixture of cementitious sealant with additives to provide resistance to erosion by flowing water. Sealant placed by WES Structures Laboratory personnel

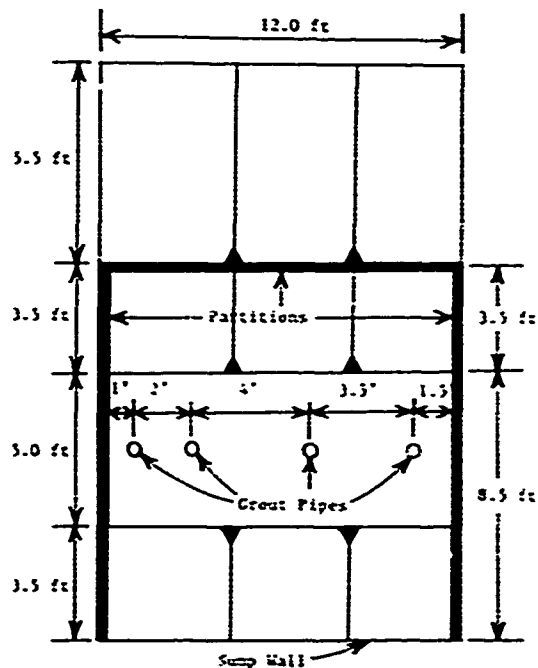


Figure 19. Section C of physical model utilized to evaluate Sodium Silicate-Cement Mixture of sealant placed in the saltwater section to investigate salinity effects

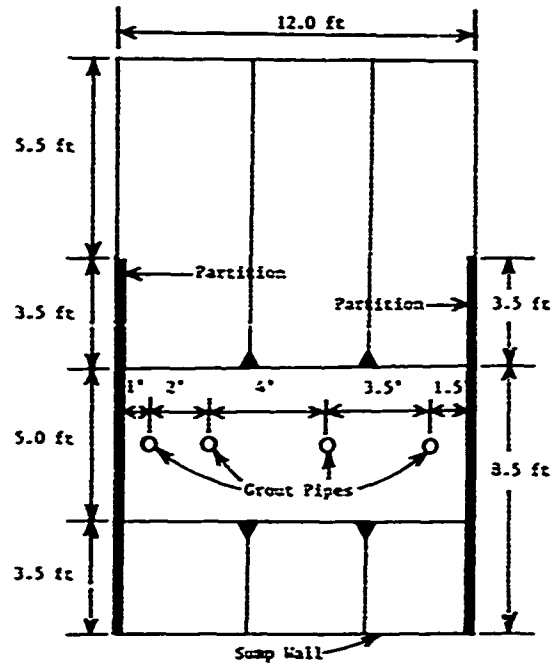


Figure 20. Section D of physical model utilized to evaluate Sodium Silicate-Biacetic Mixture of sealant to investigate stabilization of sand layer along bottom of structure

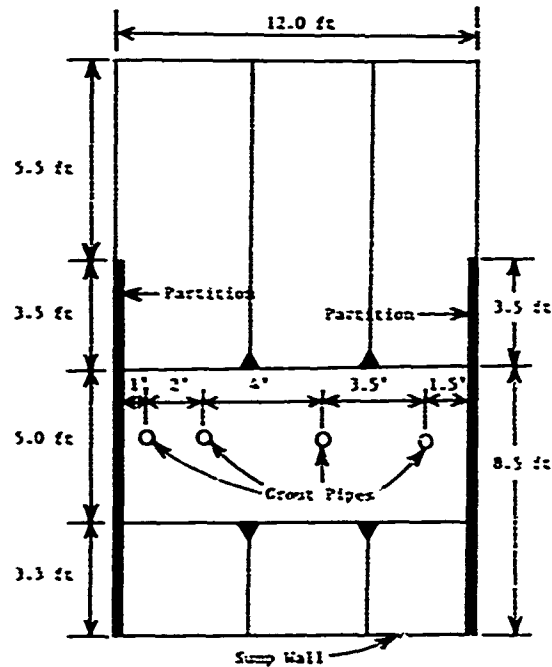


Figure 21. Section E of physical model utilized to evaluate Sand-Asphaltic Mixtures as potential sealant materials for sealing voids in rubble-mound breakwaters or jetties

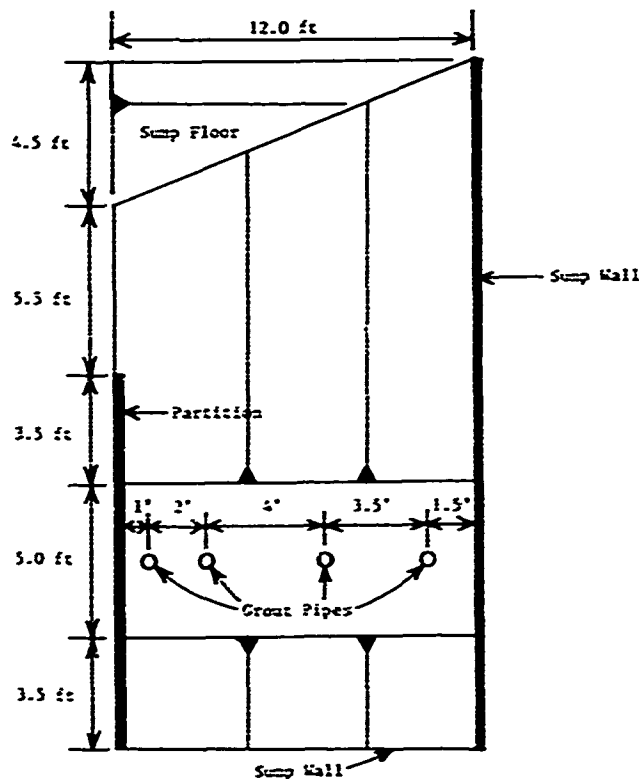


Figure 22. Section F of physical model utilized to evaluate Buhne Point Mixture of cementitious sealant with additives of clay to form stiff sealant to resist erosion by flowing water through a rubble-mound structure

crystallization and incipient metamorphism. The average specific gravity, calculated by using stones taken from the structure and referenced to fresh water, was 2.64. Average porosity of the structure is defined as the ratio of the volume of voids to the total volume. Porosity, computed from the average unit weight of the stones and the specific gravity, was 35 percent. Hence, the average unit weight of the total volume of the structure (voids plus stones) was 1.45 tons/cu yd. The average void size in the structure was determined to be 0.19 cu ft.

Sealant Properties

251. Sealants utilized in this study and their properties are described in detail for correlating material behavior with injection results. Rheological characteristics of the thicker mixtures (cementitious sealants) are important for interpretation of void sealing results in the model and for

determining how these results relate to field conditions. The chemical sealants were very fluid, and tests in the ungelled state were not performed. Asphaltic compounds were not tested for rheological properties in the heated state in this study.

Cementitious sealants

252. Research on formulations of concrete that could be effectively emplaced under flowing water has previously been conducted at WES (Neeley 1988), and the present investigation benefitted from that work. A special sanded sealant, designated the WES Mixture, was developed. It has the beneficial characteristics of being relatively fluid for ease of pumping, yet is very cohesive, which gives it a good ability to resist dispersion and dilution when emplaced in the coastal environment. Mixture proportions for the WES Mixture and the Buhne Point Mixture are shown in Table 1. Specific parameters tested and their values for the WES Mixture and Buhne Point Mixture are presented in Table 3. The values shown in "Plate Cohesion" are the weights in pounds of material adhering to both sides of a 1- by 1-ft square plate having uniformly roughened sides (nonskid surface) after being dipped into the wet mixture (Figures 23 and 24). Significantly more of the WES Mixture adhered to the plate cohesion meter than did the Buhne Point Mixture, which is a more typical concrete, although the WES Mixture had almost twice the slump (10 in.) as did the Buhne Point Mixture (6 in.). That apparatus was similar to a plate cohesion meter described by Deere (1982).

253. Yield point and viscosity are terms that describe properties of a Bingham fluid, but cannot strictly be applied to concrete because it is a granular mixture. However, Tattersall and Banfill (1983) contend that the workability of concrete can be measured by these two parameters. Test data consist of pairs of torque and speed of rotation values for an impeller rotating in a vessel containing the mixture and are represented by the equation:

$$T = g + hN \quad (8)$$

where g is the intercept on the torque axis, h is the reciprocal of the slope of the line, and N is the speed of rotation. Since this is the form of the equation for a Bingham model, it can be inferred that g is a measure of the yield value and that h is a measure of the plastic viscosity. The test procedure is described by Neeley (1988).

Table 3
Test Results for Fresh and Hardened Cementitious Sealants

Mixture	Slump in.	Air Content Percent	Unit Weight lb/cv ft	Washout Percent	Plate Cohesion lb	Two-Point Test*		Setting Time, hr	Dynamic Modulus E psi x 10 ⁶	Pulse Velocity ft/sec	Compressive Strength psi
						$\frac{g^2}{h}$	$\frac{r}{h}$				
WES	10.50	6.3	128.0	28.0	4.0	2.12	0.19	0.99	2.60	11,492	4,360
WES	10.50	5.2	127.2	..	0.6	18 Initial 22 final	3.50	12,039	4,360
Buhne Point	6.00	3.7	129.6	26.2	0.4	2.97	0.33	0.97	2.80	10,960	2,490

* See paragraph 253.

** g = intercept on the torque axis

h = reciprocal of the slope of the line

r = correlation coefficient



Figure 23. Dipping plate cohesion meter into wet cementitious sealant for void sealing tests

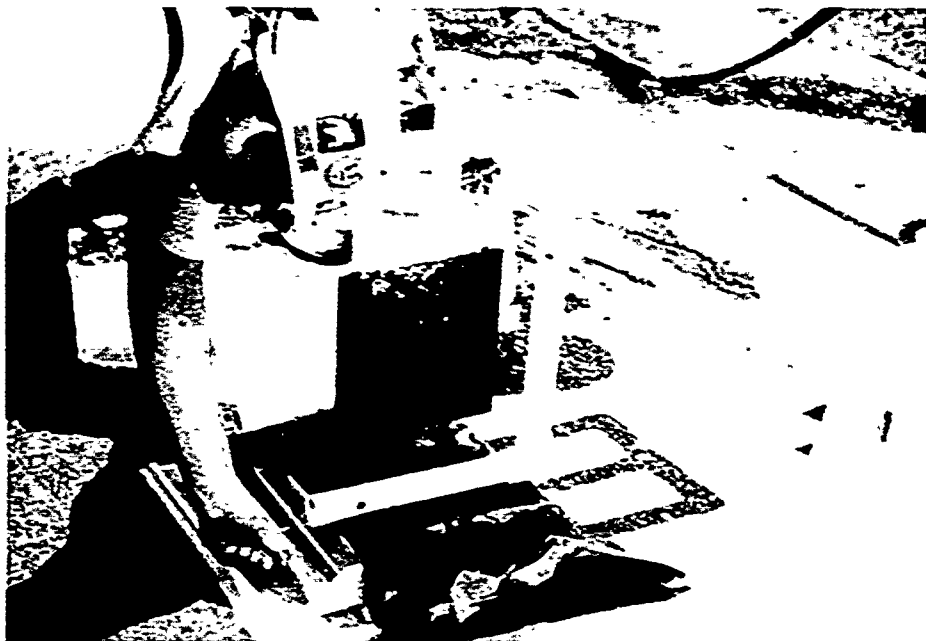


Figure 24. Weighing cohesion meter plate with cementitious sealant adhering to sides of plate

254. The WES Mixture was a flowable, self-leveling grout as indicated by the 10-1/2-in. slump, while the Buhne Point Mixture was not (slump = 6 in.). Even though the WES Mixture was more mobile, it had cohesive properties equal or superior to those of the Buhne Point Mixture, as indicated by the Two-Point Test, the Washout Test, and the Plate Cohesion Test. The g-value of the Buhne Point Mixture was slightly higher than that of the WES Mixture, indicating a small cohesive advantage for the Buhne Point Mixture. The results of the Washout Test were virtually identical for the two mixtures, while the Plate Cohesion Test indicated a distinct cohesive advantage for the WES Mixture.

255. The WES Mixture should be more durable if placed in an environment where it would be subjected to freezing and thawing cycles, due to its higher air content and lower water-cement ratio. It is likely that the Buhne Point Mixture would lose some of its cohesiveness if its air content were increased to equal that of the WES Mixture. A possible disadvantage of the WES Mixture is the length of time required for the grout to harden (18 hr for an initial set and 22 hr for final set). The time of set was not determined for the Buhne Point Mixture, but it is likely that the setting time is less than half that of the WES Mixture. The retardation of the WES Mixture is primarily the result of the large amount of water-reducing admixture.

256. Although the time required for the WES Mixture to attain its final set was longer, it gained strength rapidly after hardening and had almost twice the compressive strength of the Buhne Point Mixture at 28-days age (4,360 and 2,490 psi respectively). The mean pulse velocity of the WES Mixture was 12,039 ft/sec, and the mean dynamic modulus of elasticity, E , was 3,490,000 psi. The latter two tests are standard nondestructive evaluations performed in the WES Structures Laboratory. Values are obtained from the transmission of translatory waves that pass through the specimen. By comparison, the hardened Buhne Point Mixture had a pulse velocity of approximately 10,904 ft/sec and a dynamic modulus of elasticity, E , of 2,779,000 psi.

Chemical sealants

257. Measurements of the properties of chemical sealant specimens tested at WES are summarized in Table 4. The sodium silicate-portland cement sealant was discharged from a contractor's (W. G. Jaques Company, Des Moines, IA) pump into 6-in.-diam, 12-in.-long cylinders and developed 260 psi unconfined compressive strength. The pulse velocity was 5,202 ft/sec, and the dynamic modulus of elasticity, E , was 94,000 psi. The set time for this

Table 4
Test Results for Hardened Chemical Sealants

<u>Sealant Materials</u>	<u>Average Pulse Velocity ft/sec</u>	<u>Average Young's Dynamic Modulus, E psi x 1,000,000</u>
Sodium Silicate-Cement Mixture, prepared at WES by Structures Laboratory personnel	5,587	0.111
Sodium Silicate-Cement Mixture, prepared at WES by W. G. Jaques Company, Des Moines, IA	5,202	0.094
Sodium Silicate-Diacetin Mixture for stabilizing sand layer, prepared at WES by Structures Laboratory personnel	3,651	0.099
Sodium Silicate-Diacetin Mixture for stabilizing sand layer, prepared at WES by W. G. Jaques Company, Des Moines, IA	3,156	0.058

material was about 1 min. Specimens of sodium silicate-cement cast at WES's Structures Laboratory had 285 psi unconfined compressive strength, mean pulse velocity of 5,587 ft/sec, and a modulus of elasticity, E, of 111,600 psi. The set time for this material was about 30 sec.

258. A sodium silicate-diacetin mixture pumped by the contractor was combined with masonry sand in 6-in.-diam by 12-in.-long cylinders. After setting, it had an unconfined compressive strength of 40 psi, mean pulse velocity of 3,156 ft/sec, and a mean dynamic modulus of elasticity, E, of 58,000 psi. The sodium silicate-diacetin mixed with masonry sand at the WES Structures Laboratory had 65 psi unconfined compressive strength, a mean pulse velocity of 3,651 ft/sec, and a dynamic modulus of elasticity, E, of 73,500 psi. One test sample of neat sodium silicate-diacetin sealant (no sand) mixed by the contractor had nearly zero compressive strength.

Injection Procedure

WES Mixture

259. Ingredients of the WES Mixture of cementitious sealant were added at the batch plant to best attain a uniform concentration of the admixtures. Samples of the material were obtained for determining slump, unit weight, air content, and unconfined compressive strength and for performing the tremie and two-point workability tests. Equipment for the tremie and two-point workability tests are shown in Figures 25 and 26. The mixture was delivered by



Figure 25. Equipment for performing tremie test

ready-mix truck to the hopper of the contractor's grout pump (Figure 27). The pump was an air-driven Wagener Simplex pump. Inside diameters of the hoses were 1.25 in. Pumping was begun in Hole A3 with the end of the injector pipe raised 1 ft above the sump floor. Problems with pumping the mixture were quickly encountered. It was determined that the mixture contained some



Figure 26. Equipment for performing two-point workability test

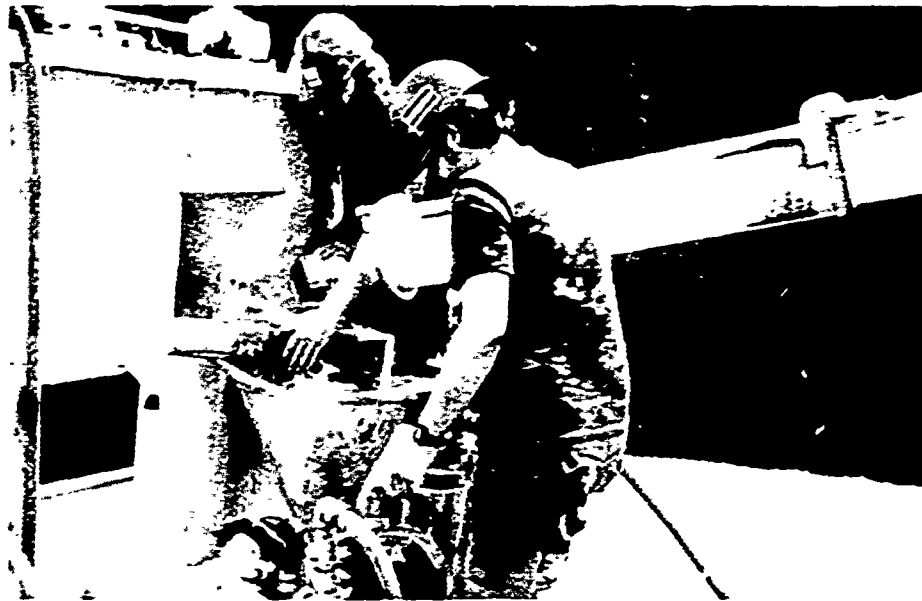


Figure 27. WES Mixture of cementitious sealant being delivered to contractor's grout pump

aggregate much larger than that specified, and blockage of the pump occurred. Less than 1 cu yd of sealant was actually pumped into Hole A3 at that time.

260. Another batch of sealant was ordered, and it was ensured the aggregate was the masonry sand specified. After repeating the tests, the header pipe was reconnected to Hole A3, and slightly more than 1 cu yd of sealant was pumped with the end of the injection pipe again being located 1 ft above the datum. Datum for the model was the level portion of the sump floor. A pressure of 10 psi was maintained at the header pipe. There was difficulty in pumping this mixture also, which necessitated occasional starting and stopping of the pump.

261. Connections were next made to Hole A4. Slightly more than 1 cu yd of sealant was pumped in 11.5 min at el 1.2 ft. Hole A2 was injected with less than 1 cu yd in two lifts, at 0.8 and 1.8 ft above the sump floor, in 6.7 min. It was then realized the contractor operator had added more water at the hopper of the pump to keep the mixture pumpable. The reason for doing this was to prevent the line from becoming blocked. In that event, the contractor would risk having the sealant harden in the pump and lines. The water content of the diluted mixture pumped into the hole was unknown.

262. The WES Structures Laboratory staff then undertook to inject the WES Mixture of cementitious sealant. The material was prepared in the WES Structures Laboratory's 16-cu ft mixer, and the specified tests were again performed. The mixture was then transported to the test site in a concrete bucket and pumped with an auger-type progressive cavity pump (Moyno Pump) (Figure 28). A new section, Section B, was used to ensure that results of emplacement by the two techniques could be distinguished. Approximately 20 cu ft of material was pumped into Hole B3.

263. The first lift was injected at el 0.5 ft. The volume of mixture for that lift was 5 cu ft and was dyed black. The next lift, 4 cu ft in volume, was dyed red and injected at el 1.8 ft. The third lift was a gold-dyed 5-cu ft volume injected at el 3.5 ft. The last lift was injected at el 4.5 ft. It contained no dye and was 4 cu ft in volume.

Buhne Point Mixture

264. The Structures Laboratory staff similarly mixed and pumped the Buhne Point Mixture cementitious sealant, as it was a stiffer mixture than the WES Mixture and hence was less pumpable. The location for the placement of this mixture was Section F, Hole F3. The first lift was placed at 1 ft elevation above the datum. The volume of this lift was 5 cu ft and was dyed

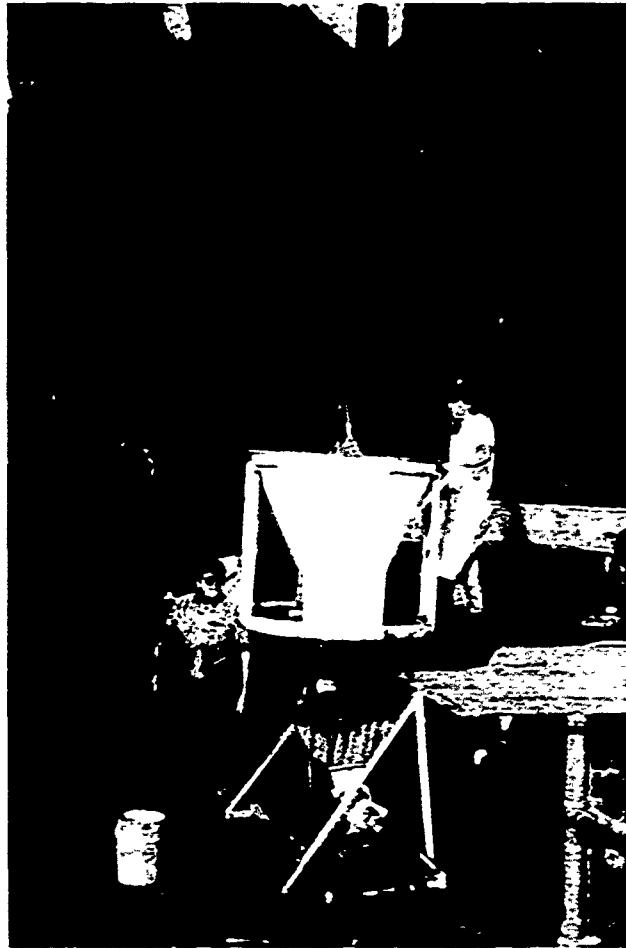


Figure 28. WES Mixture of cementitious sealant being placed into Moyno pump by WES Structures Laboratory personnel

black. The second lift, a red-dyed 5-cu ft volume, was injected at 2.2 ft elevation above the datum. The third lift was injected at 3.2 ft elevation above the datum, contained 5 cu ft of mixture, and was dyed gold. The last lift was placed at 4-ft elevation above the datum and consisted of 4 cu ft of undyed mixture.

Sodium Silicate-Cement Mixture

265. The chemical sealant components were prepared in two tubs and pumped with a Wagener Simplex pump, with all equipment being mounted as a portable grout plant (Figure 29). Four holes were sealed with the sodium silicate-cement sealant in the saltwater section of the model, Section C. Before sealing commenced, water in the enclosure was mixed thoroughly by withdrawing from the surface and pumping down a sealant pipe. Salinity readings



Figure 29. Sodium Silicate-Cement Mixture of chemical sealant being placed into Wagener Simplex pump by grouting contractor

varied between 19 and 21 parts per thousand (ppt), as determined by a refractometer.

266. Hole C3 was sealed first, and pumping was continuous as the sealant pipe was raised through the lifts. The pumping rate was 40 gal of sealant in 4.8 min, or 8.3 gal/min. Approximately 10 gal of sealant was injected in lifts at elevations of 1, 2, 3.5, and 4.5 ft. Pressure remained at zero until midway through the third lift, when pressure at the pump increased to the range of 25 to 30 psi. As the pipe was withdrawn for the next lift, pressure returned to near zero. Midway through pumping the fourth lift, pressure increased to the range of 10 to 15 psi.

267. Hole C2 was sealed with 40 gal of sealant in four lifts, each separated vertically by 1 ft of elevation. Pumping was continuous for 5.1 min, yielding an average flow rate of 7.87 gal/min. Black dye was added to the sealant at the pump to distinguish sealant injected in this specific hole from the sealant of adjacent holes. Pressure was near zero at the pump during the sealing of Hole C2, except for a pressure rise to the range of 25 to 30 psi midway through the third lift.

268. Hole C1 was then injected with 40 gal of red-dyed sealant. Sealing was performed in four lifts separated by 1 ft of elevation, beginning at

1 ft above the datum, and required 4.4 min, an average pumping rate of 9.12 gal/min. Zero pressure was registered at the pump.

269. Hole C4 was sealed in four lifts at 1-ft increments in 5.3 min. Forty gallons of yellow-dyed sealant was pumped at a rate of 7.5 gal/min. Pump pressure did not rise above zero during that time.

Sodium Silicate-Diacetin Mixture

270. Sodium silicate-diacetin sealant was injected in Section D to simulate the stabilizing of a sand layer that might be present in a porous jetty. The material used to simulate the sand-filled voids was typical masonry sand. Hole D3 was sealed first, beginning with the sealant pipe located 0.5 ft above the datum. In this lift, 33 gal of sealant was injected in 2.4 min, for an average rate of 13.75 gal/min. Sand placement during construction of the section may have initially plugged this pipe and could have been responsible for an initial pressure increase to the range of 80 to 90 psi at the top of the sealant pipe. After pumping for 1 min, the pipe was raised 0.5 ft higher and the pressure dropped to zero. The sensor located at a 1-ft radial distance from Hole D3 and located 1 ft above the datum (Sensor 4) indicated the presence of sealant 2.4 min after the initiation of the sealing operation. Pumping was stopped at the end of this lift.

271. The second lift in Hole D3 was an injection of 33 gal, with the end of the sealant pipe being located 1.5 ft above the datum. The duration of pumping was 6.5 min, yielding a placement rate of 5.1 gal/min. Two minutes after start of pumping at this lift, the arrival of sealant was detected at Sensor 1 (5 ft horizontally from Hole D3 and 1 ft above the datum) and at Sensor 6 (1.5 ft from Hole D3 in the opposite direction and 1 ft above the datum). After 6 min, Sensor 3 showed sealant had reached that location, between Hole D3 and Sensor 1. Meter deflections for Sensors 1 and 4 showed increases at 6 min, also. These deflections were inconsistent with a reasonable path of sealant flow and cast doubt on the accuracy of the timing recorded at this point. Further data acquired from these sensors were regarded as useless.

272. The third lift in Hole D3 was injected at a height of 2.5 ft above the datum at a placement rate of 4.3 gal/min. In 7.7 min, 33 gal of sealant was pumped into the hole.

273. The final lift in Hole D3 was placed at a height of 3.5 ft from the bottom of the structure. Thirty-three gallons of sealant was placed in 9.8 min, a placement rate of 3.4 gal/min.

274. hole D2 was sealed next, using a new batch of sealant. The diacetin concentration was lower, which gave a slightly longer set time. The first lift was injected 1 ft above the datum at a placement rate of 8.7 gal/min. Violet dye was mixed with 33 gal of sealant, which was placed in 3.8 min. Some of this material escaped to the surface along the side of the pipe and was visible after pumping for 2.5 min.

275. The second lift in Hole D2 was placed 2 ft above the datum. Thirty-three gallons of sealant was placed in 7.6 min, at a placement rate of 4.35 gal/min.

276. The third lift in Hole D2 was injected 3 ft above the datum and was dyed red. Thirty-three gallons of sealant was placed in 7.1 min, producing a flow rate of 4.6 gal/min.

277. The last lift in Hole D2 was undyed and was injected at a placement rate of 3.7 gal/min. Thirty-three gallons of sealant was injected 4 ft above the datum in 8.8 min.

278. Hole D1, being located only 1 ft away from a partition, was then sealed with small quantities of material in each lift. Two gallons of sealant was pumped at el 1 ft above the datum at a sealant flow rate of 4 gal/min.

279. The second lift in Hole D1, emplaced 2 ft above the datum, required 2 gal of sealant in 51 sec, producing a sealant flow rate of 2.4 gal/min.

280. The third lift in Hole D1 was placed at an el 3 ft above the datum. The volume placed was 2 gal of sealant in a pumping time of 53 sec, indicating a sealant flow rate of 2.3 gal/min.

281. The fourth lift in Hole D1 required 2 gal of sealant placed at a rate of 1.1 gal/min. Total pumping time was 1.9 min at this elevation of 4 ft above the datum.

Sand-Asphaltic Mixture

282. Section E was constructed for the purpose of evaluating asphaltic concrete as a void sealant. During the planning phase of the investigation, effort was made to locate equipment for pumping an aggregate containing asphaltic mixture, but none had been located by the time injection of cementitious and chemical sealants were completed. As a means of injecting for experimental purposes, a funnel with a capacity of 2 cu ft was fabricated and attached to the top of the 2-in.-diam steel pipe in Hole E2. The funnel was fitted with a closure device that could be removed when the funnel was filled.

283. The Sand-Asphaltic Mixture was prepared in small batches in the WES Geotechnical Laboratory at 400° F and stored in an oven at 425° F until a total of about 2 cu ft had been prepared. Asphalt (AC-30 grade) comprised 12 percent of the mixture, masonry sand constituted 75 percent of the volume, and mineral filler (portland cement) accounted for the remaining 13 percent. After being transported to the test site, the material remained at about 380° F. The end of the injection pipe was raised 2 ft above the sump floor. When all the mixture had been poured into the funnel, the closure device was removed; unfortunately, the funnel did not empty (Figure 30). A steel rod was inserted down the pipe to clear any possible blockage. The rod could be pushed only to within a short distance from the bottom of the pipe.



Figure 30. Funnel filled with Sand-Asphaltic Mixture of sealant for injection into physical model of rubble-mound structure

284. It was not known if cooling of the mixture as it was deposited in the pipe through the water column, frictional resistance of the sandy mixture, or combinations of both prevented the placement. Therefore, injecting mastic with no solids was next attempted. Five gallons of AC-30 asphalt was heated to 400° F and poured into the closed funnel (Figure 31). For this test, the



Figure 31. Heated Mastic Asphalt being poured into funnel for injection into physical model of rubble-mound structure

funnel was connected to the pipe in Hole E3. The bottom of the pipe was located 2.8 ft above the sump floor. At the time of placement, the asphalt temperature was 325° F. When the bottom closure device was removed, there was considerable bubbling of asphalt in the funnel, with minor loss out of the funnel, but all the asphalt in the funnel drained down the hole in about 10 sec. Only a small amount of steam was visible during this operation.

285. Sealing operations involving cementitious, chemical, and asphaltic materials were documented on videotape and archived for future reference and supplemental analyses.

Variable-viscosity driller's mud

286. The constituents of the commercial product REVERT were combined in the mixing tubs of the sealant equipment. The objective was to determine its rate of spread and shape of the resulting mass as it was being injected into the model rubble-mound structure. Detection after failure of the electronic apparatus was performed by lowering 1/2-in.-diam pvc pipe into the preplaced conduits and sensing the surface of the thick REVERT solution.

287. Eight pounds of REVERT was mixed with 40 gal of water; then 4 lb of Culminal M25 was added to give the solution a cohesive property. One pound and 1 oz of the material adhered to the plate cohesion meter when it was dipped in the mixing tub. During placement, the pressure was maintained at

25 psi at the pump, and a pressure range of 8 to 12 psi was achieved in the header. No REVERT was detected in the conduits in the structure with this mixture. Insufficient size of perforations in the conduits was believed to be the reason for not being able to detect the REVERT, and the conduits were removed from the model. The 1/2-in.-diam pvc pipes could not be reinserted to full depth where the conduits had previously been emplaced, and the REVERT experiment was terminated.

Sealant Injection Analyses

288. Results and conclusion of the experimental laboratory investigation pertaining to the injection of sealants into the physical model of a rubble-mound breakwater or jetty model were derived from both qualitative and quantitative evidence. The structure was disassembled in two phases and was photographed and videotaped in precise detail during each phase of disassembly. Various stages of the structure disassembly are shown in Figures 32 through 35. The WES Structures Laboratory, Concrete and Grouting Group, provided videotaped analyses of sealant injection results after the second phase of disassembly. This laboratory also discussed and analyzed results of specimen casting for long-term durability evaluations. These data tapes are archived for future reference and supplemental analysis.

WES Mixture

289. The WES Mixture of cementitious sealant pumped into Section A with excessive amounts of water created the hardened mass shown in Figures 36 (Phase 1) and 37 (Phase 2). Continuity of the sealant between Holes A3 and A4 was good, a distance of 3.5 ft. The sealant was sufficiently cohesive to build a mass 1 ft higher than the injection point elevation in Hole A3. Because of the spread from that hole, the material injected in the adjacent Hole A4 built up about 2 ft higher than the injection level. Spread of the mixture was about 3 ft laterally from the injection pipe and created an oblate spheroidal shape. Completeness of sealing the individual voids was very good. In the set condition, the material was very hard. Bond strength was very good. In attempting to dislodge a stone with a sledge hammer, the stone split before it would be loosened, creating a dramatically impressive scene on the videotape. No mixture injected in Hole A2 could be found in the structure. The material was probably washed out by the increasing amounts of water added at the pump as the last amount of the batch was being placed.



Figure 32. Initial disassembly of physical model



Figure 33. Disassembly of physical model section for evaluation of effectiveness of Sodium Silicate-Diacetin Mixture to stabilize sand layer



Figure 34. Disassembly of physical model section for evaluation of Sand-Asphaltic Mixture as potential material for void sealing



Figure 35. Disassembly of physical model section for evaluation of Buhne Point Mixture of cementitious material for sealing voids



Figure 36. Section A, Phase 1 disassembly. (WES Mixture of cementitious sealant placed by W. G. Jaques Company, Des Moines, IA)

290. A columnar structure resulted in Section B from placing the WES Mixture, which was proportioned exactly as specified. The hardened mass was about 3 ft in diameter and extended to elevation 5 ft, which was 0.5 ft higher than the injection level, as shown in Figures 38 (Phase 1) and 39 (Phase 2). The lateral penetration was good, with the sealant entering nearly all the voids in the injected structure region. Using the above dimensions and an estimated void ratio of 35 percent, the WES Mixture of cementitious sealant filled one-half of the void space of the cemented mass. It was an extremely competent sealant, and its bonding to the rocks was very good.

Buhne Point Mixture

291. Injecting the Buhne Point Mixture of cementitious sealant into Section F resulted in a cemented mass of stones to a height of approximately 5 ft above the datum. The material assumed a nearly conical shape with a base diameter of about 6 ft, shown in Figures 40 (Phase 1) and 41 (Phase 2). There was less continuity of the sealant from void to void than with the WES Mixture, but porosity of the mass was reduced to such an extent that it would effectively block sand movement. Bonding of the concrete to the stones was variable within the injected area. Bonding was good in the upper 2 ft of the sealed rubber, but the concrete was of such consistency in the lower part that



Figure 37. Section A, Phase 2 disassembly.
(WES Mixture of cementitious sealant placed
by W. G. Jaques Company, Des Moines, IA)



Figure 38. Section B, Phase 1 disassembly.
(WES Mixture of cementitious sealant placed
by WES Structures Laboratory)



Figure 39. Section B, Phase 2 disassembly. (WES Mixture of
cementitious sealant placed by WES Structures Laboratory)



Figure 40. Section F, Phase 1 disassembly.
(Buhne Point Mixture of cementitious sealant
placed by WES Structures Laboratory)



Figure 41. Section F, Phase 2 disassembly. (Buhne Point Mixture of cementitious sealant placed by WES Structures Laboratory)

it could be easily scraped from the stones. The material in the upper 2 ft had an unconfined compressive strength of up to 3,000 psi.

Sodium Silicate-Cement Mixture

292. The Sodium Silicate-Cement Mixture of chemical sealant injected into Section C did not form the continuously sealed mass with high integrity as anticipated, shown in Figures 42 (Phase 1) and 43 (Phase 2). At higher elevations within the structure, sealant could be found only on horizontal surfaces and in isolated voids. Pockets of sealant were not firmly set; it could be easily squeezed through the researcher's fingers. This was an indication that penetration was good, but that interference had occurred with the mixing of the components of the sealant or with its gelation in the section. Water in this enclosed section had been circulated in order to create a uniform salinity, and the mixing action suspended a high concentration of fine material and may have affected the reaction of the components. The set time of the sodium silicate-cement sealant placed into the structure was 50 to 60 sec. This section was found to be completely porous.



Figure 42. Section C, Phase 1 disassembly.
(Sodium Silicate-Cement Mixture of chemical
sealant placed by W. G. Jaques Company,
Des Moines, IA)



Figure 43. Section C, Phase 2 disassembly. (Sodium Silicate-Cement Mixture of chemical sealant placed by W. G. Jaques Company, Des Moines, IA)

Sodium Silicate-Diacetin Mixture

293. The Sodium Silicate-Diacetin Mixture of chemical sealant injected in Section D did not solidify the sand into which it had been injected, as shown in Figures 44 (Phase 1) and 45 (Phase 2). While dismantling the section, traces of the dye could be found in the sand, sometimes at distances of 3 ft from the injection pipe, but the sand had no characteristics of actually being sealed. Farther than 6 in. from the injection pipe, sodium silicate was present in only trace amounts in the sand. The set time of this sealant was about 15 min. Results indicate that the set time should have been about half that duration. Bond strength was essentially zero, except in localized areas around Hole D3. A pocket of neat sealant was found at the upper level of the sand layer of the section, and it may have resulted from a flow channel being created adjacent to the outside of the injection pipe during sealing of the first lift (Figure 45). A thin layer of sodium silicate covered the sump floor beyond the structure (Figure 46).

Sand-Asphaltic Mixture

294. No trace of the Sand-Asphaltic Mixture of sealant was found in the structure. It was concluded that the material traveled no farther than the lower end of the pipe and did not actually penetrate any voids. AC-30 mastic,



Figure 44. Section D, Phase 1 disassembly.
(Sodium Silicate-Diacetin Mixture for sand
stabilization placed by W. G. Jaques Company,
Des Moines, IA)



Figure 45. Section D, Phase 2 disassembly. (Sodium Silicate-Diacetin Mixture for sand stabilization placed by W. G. Jaques Company, Des Moines, IA)



Figure 46. Layer of Sodium Silicate-Diacetin Mixture on sump floor which was not retained within the sand layer

when poured through the injection pipe, covered stones at a distance of one stone diameter from the pipe. Effects of the temperature difference between the mastic asphalt and the water caused irregular "splashing" of the mastic asphalt within the water-filled voids, shown in Figures 47 (Phase 1) and 48 (Phase 2). After draining the water from the model, most of the mastic asphalt was found at the bottom of the rubble directly below the pipe. That was attributed to the viscosity of the AC-30 at the ambient temperature (approximately 100° F) during the time of the model disassembly.

Sealant Injection Test Conclusions

295. Sealing of rubble-mound coastal structures requires that both the construction grouter and the sponsor field inspector be fully experienced with the materials being used for the sealing work and with the characteristics of the medium being sealed. Problems may still be encountered at the site, but sand-cement mixtures with additives will almost always harden. However, certain types of mixing or environmental conditions may sometimes prevent sodium silicate sealants from gelling adequately. One objective of the present laboratory experimental investigation was to evaluate methods of permeation sealing of sand layers that fill voids in rubble-mound breakwaters or jetties and of alternatively flushing sand from such regions for sealing the resulting voids with a sealant mixture. Results indicated cementitious mixtures containing aggregate achieved a more satisfactory final product for sealing a section than did a sodium silicate-cement sealant, provided the aggregate was not so large as to impede pumping or did not seal off the void interconnections. Dye staining indicated the sodium silicate-cement sealant permeated as far as 5 ft from the injection pipe, but it formed only a weak gel on the floor of the test basin. The sodium silicate-diacetin that was used to fill the voids in the sand layer did not completely solidify (harden) the sand.

296. The disassembled sections showed that concrete can form a bulbous mass in a rubble structure when injected underwater. It spread to a radius of at least 3 ft in a rock mass where the stones averaged 50 lb in weight. The average size of the voids was computed to be 0.19 cu ft. The two sealants (WES Mixture and Buhne Point Mixture of cementitious sealants) had slumps of 10 and 5 in., respectively. The void volume in the coherent mass was approximately half-filled with sealant. Such a condition was judged to be sufficient for sealing the structure against sand transport.



Figure 47. Section E, Phase 1 disassembly.
(Mastic asphalt placed by WES Geotechnical
Laboratory.)

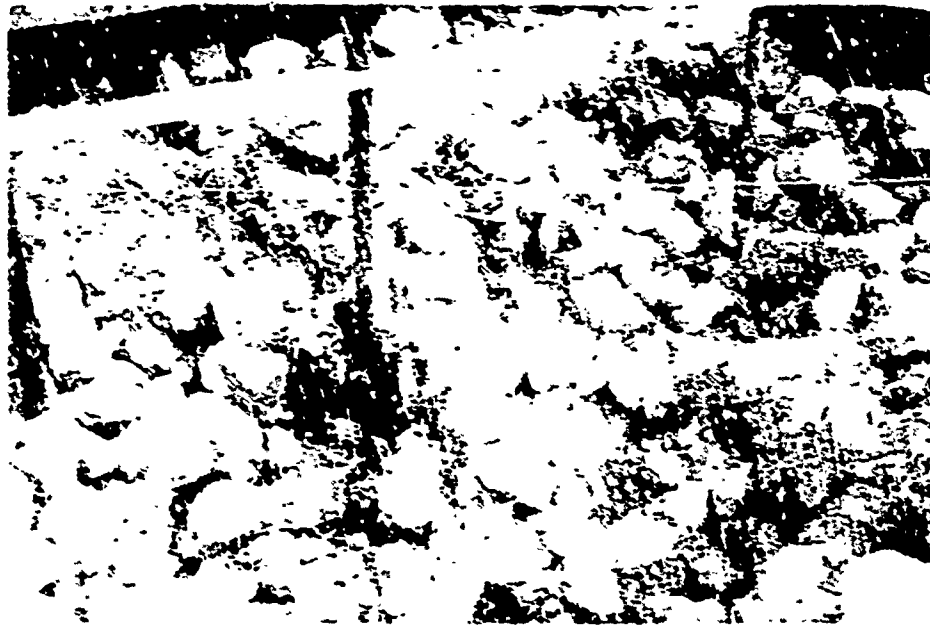


Figure 48. Section E, Phase 2 disassembly. (Mastic
asphalt placed by WES Geotechnical Laboratory.)

297. Precise monitoring and control of conditions are required in chemical sealant placement. A set time of 5 to 10 min for chemical sealing of sand-filled voids was found to be appropriate. For filling open voids with a sodium silicate-cement sealant, a fast injection rate (10 gal/min or greater) and a fast set time (about 30 sec) appeared to be required.

298. Sand asphaltic sealant composed of 12-percent AC-30 asphalt seems from initial observations to set hard and bond well, although no means for emplacing it in production quantities has been developed at this time. Pressure injection is necessary, and either 4- or 6-in.-diam pipes are required. Sand asphaltic concrete heated to 390° F did not react violently when placed in water during this experimental investigation. Mastic asphalt heated to 390° F and emplaced in the structure caused bubbling of asphalt, and steam was generated. That operation was deemed not satisfactory because of potentially dangerous working conditions and poor void filling results.

PART VIII: ENVIRONMENTAL EFFECTS OF SEALANTS

Aquatic Toxicity Assessment

299. The materials under consideration as sealants must be easily pumped or injected, resistant to dilution and erosion when placed in flowing water, and absolutely safe in the aquatic environment. Sealants can be shown to be safe in the aquatic environment by using standard laboratory bioassay tests where sensitive aquatic animals are exposed to different concentrations of sealant materials in water. Since these materials (different cements, gel-forming chemicals, and asphalts) are unlikely to be highly toxic, the optimum means for evaluating the potential danger to the environment or aquatic organisms would be to conduct static, short-term bioassays using standard test animals such as the water flea *Daphnia*, a freshwater animal, and the small estuarine shrimp *Mysidopsis*. These animals are sensitive to aquatic contaminants that might be harmful to fish or other larger animals, yet are easily held and cultured under laboratory conditions. During 10-day tests, the animals can be observed for acute toxicity, as well as effects on growth and reproduction.

300. A typical test involves the utilization of five replicate beakers, each containing 10 animals, for each material or concentration of material to be tested. A sediment toxicity test involves preparation of a standard sediment suspended particulate mixture (spm) where sediment and water are shaken in a 1-to-4 ratio of sediment-to-water for 40 min and then allowed to settle overnight. Animals are then exposed to the spm in beakers with a layer of the sediment at the bottom (Tatem 1988). These tests can be modified to test sealants, since the sealants will be likely to solidify shortly after being placed in the water.

301. There are at least two areas of concern of possible toxicity. One concern involves the immediate effects as the sealants are placed in the water. The second concern relates to the long-term effects when the sealant has hardened or gelled, but may slowly leach some toxic substance into the ambient waters. An initial evaluation of these materials should include the following:

- a. A description of the compounds used to make the sealants.
- b. An initial literature search for studies related to the potential environmental effects of sealants.

- c. An initial laboratory assessment of the acute toxicity of sealants using *Daphnia magna*.

The *Daphnia* should be exposed to a range of sealant concentrations added to standard *Daphnia* water, using standardized test conditions. No chemical analyses of the sealants or sealant-water mixtures are necessary unless toxicity is observed.

Toxicity Bioassay Analyses

302. The WES Environmental Laboratory performed preliminary toxicity bioassay analyses of three sealant mixtures, including (a) WES Mixture of cementitious sealant containing the variety of admixtures, (b) Sodium Silicate-Diacetin Mixture of chemical sealant, and (c) a Sand-Asphaltic Mixture. The Sand-Asphaltic Mixture was delivered to WES Environmental Laboratory in the form of solid blocks, being approximately 3.5-in.-diam by 2.0-in.-high specimens. The WES Mixture was conveyed in a plastic container as a cementlike slurry rather than a solid. The Sodium Silicate-Diacetin Mixture was transported in separate bottles, both being in liquid form. Prior to conducting the bioassay testing, both the sodium silicate and diacetin were mixed with water (1 gal water to 0.67 gal sodium silicate, and 1 gal water to 0.087 gal diacetin). The resulting solutions were then combined in equal volumes, with the material produced being a white solid that was not as hardened as the WES Mixture (after it had set) or the Sand-Asphaltic Mixture. All of these materials were received by the bioassay laboratory in a fresh condition (within 1 or 2 days of their preparation) and were tested within the following 1 or 2 days. The WES Mixture was tested within 2 hr after being delivered to Environmental Laboratory because the mixture hardens quickly. The Sodium Silicate-Diacetin Mixture was prepared immediately prior to being used in the *Daphnia* bioassays. The *Daphnia* were exposed for 96 hr to a range of sealant concentrations.

303. These initial bioassays were designed to be range-finding tests. Since these materials were intuitively believed to be of only limited toxicity, the animals were exposed to a wide range of concentrations, from 100 parts per million (ppm) (100 µg/l of test water) to 100,000 ppm. The animals were exposed to different concentrations of the sealant materials placed on the bottom of glass exposure beakers. The Sand-Asphaltic Mixture was broken into 1-cm pieces before being weighed and added to the beakers.

The WES Mixture and the Sodium Silicate-Diacetin Mixture were tested in their thick liquid form. There were 40 test organisms, divided among four replicate beakers, for each sealant concentration. Each experiment had four control beakers, containing 10 animals/beaker. Tests were conducted at a temperature of 72° F. Dissolved oxygen (DO) and pH were monitored in the beakers during the 4-day tests. Survival of the test animals is shown in Table 5, and statistical analyses of these means are presented in Table 6.

304. These data are an initial indication that two of the sealant mixtures (the WES Mixture and the Sodium Silicate-Diacetin Mixture) can be harmful to sensitive, freshwater, aquatic animals under laboratory exposure conditions where exposure concentrations are high and the pH of the exposure water is increased by the sealant mixtures. The WES Mixture exhibits high pH values compared with the Sand-Asphaltic Mixture. This caustic condition may contribute to low survival of *Daphnia*. A neutralizing agent may reduce the toxicity to freshwater aquatic animals. It is interesting that pH changed the least for the Sand-Asphaltic Mixture and more *Daphnia* survived at the two higher concentrations of asphalt compared with the other two sealant mixtures. The data indicate that the Sand-Asphaltic Mixture was more toxic at the 1,000-ppm concentration than at the 10,000-ppm concentration. Variation of the physical parameters of DO and pH with time is presented in Tables 7 through 9 for the WES Mixture, the Sand-Asphaltic Mixture, and the Sodium Silicate-Diacetin Mixture, respectively.

305. As part of the long-term time-dependent exposure tests to estimate the durability of various sealants under real prototype environmental conditions, samples of attaching organisms will be obtained and analyzed for toxicity effects. Also, representative samples of attaching organisms from both the sealed and nonsealed portions of the Buhne Point, California, groin structure will be obtained and similarly analyzed.

Table 5
Survival of *Daphnia* Exposed to Coastal Rubble-Mound
Structure Void Sealants

<u>Treatment</u>	<u>Initial</u>	<u>WES Mixture, hr</u>			<u>Sand-Asphaltic Mixture, hr</u>			<u>Sodium Silicate-Diacetin Mixture, hr</u>		
		<u>24</u>	<u>48</u>	<u>96</u>	<u>24</u>	<u>48</u>	<u>96</u>	<u>24</u>	<u>48</u>	<u>96</u>
Control	10	10	10	10	10	10	10	10	10	10
Sample 1	10	10	10	10	10	10	10	9	9	9
Sample 2	10	10	10	10	10	10	10	10	10	10
Sample 3	10	10	10	9	10	10	9	10	10	10
Mean			9.75			9.75			9.75	
100 ppm	10	10	10	10	8	8	8	10	10	10
Sample 1	10	10	10	10	10	10	9	10	10	10
Sample 2	10	9	9	9	10	10	9	9	9	9
Sample 3	10	10	10	10	10	9	6	10	10	10
Mean			9.75			8.00			9.75	
1,000 ppm	10	4	4	4	9	9	8	10	10	9
Sample 1	10	7	7	7	9	9	6	10	10	10
Sample 2	10	4	3	3	10	10	9	10	10	10
Sample 3	10	5	5	2	10	10	8	9	9	9
Mean			4.00			7.75			9.50	
10,000 ppm	10	0	0	0	10	9	9	10	8	0
Sample 1	10	0	0	0	10	10	10	10	8	0
Sample 2	10	0	0	0	10	10	10	9	7	0
Sample 3	10	0	0	0	10	10	10	10	9	0
Mean			0.00			9.75			0.00	
100,000 ppm	10	0	0	0	10	10	10	0	0	0
Sample 1	10	0	0	0	10	9	7	0	0	0
Sample 2	10	0	0	0	9	8	8	0	0	0
Sample 3	10	0	0	0	10	10	10	0	0	0
Mean			0.00			8.75			0.00	

Table 6
Survival of Daphnia After 96-hr Exposure to Coastal
 Rubble-Mound Structure Void Sealants

<u>Treatment</u>	<u>Mean Number of Survivors*</u>		
	<u>WES Mixture</u>	<u>Sand- Asphaltic Mixture</u>	<u>Sodium-Silicate Diacetin Mixture</u>
Control	97.5 A	97.5 A	97.5 A
100 ppm	97.5 A	80.0 AB	97.5 A
1,000 ppm	40.0 B	77.5 B	95.0 A
10,000 ppm	0.0 C	97.5 A	0.0 B
100,000 ppm	0.0 C	87.5 AB	0.0 B

* Numbers with same letter are not significantly different at the 0.05 level. Letters show differences between treatment for each material.

Table 7
Variation of DO and pH WES Mixture of Cementitious
Sealant Bioassay with *Daphnia*

Treatment	Test Date							
	29 June 87		30 June 87		1 July 87		2 July 87	
	DO	pH	DO	pH	DO	pH	DO	pH
Control	8.10	8.60			12.20	8.74	11.20	8.55
Sample 1	8.40	8.62			12.20	8.75	11.40	8.65
Sample 2			8.70	8.83	12.20	8.71	11.60	8.67
Sample 3			8.70	8.86	12.20	8.77	11.60	8.65
100 ppm	8.40	9.13			12.20	9.09	12.20	8.92
Sample 1	8.50	9.22			11.80	9.08	12.00	8.94
Sample 2			8.60	9.35	12.00	9.11	12.20	8.98
Sample 3			8.80	9.36	12.20	9.09	12.40	8.96
1,000 ppm	8.40	10.28			12.20	10.46	11.20	9.96
Sample 1	8.40	10.22			12.20	10.30	11.20	9.82
Sample 2			8.50	10.84	12.20	10.43	11.40	9.95
Sample 3			8.60	10.91	12.20	10.44	11.40	9.98
10,000 ppm	8.40	12.00						
Sample 1	8.40	11.96						
Sample 2			8.40	12.80				
Sample 3			8.40	12.85				
100,000 ppm	8.30	12.52	7.80	13.37				
Sample 1	8.40	12.55						
Sample 2			7.50	13.28				
Sample 3			7.80	13.31				

Table 8
Variation of DO and pH Sand-Asphaltic Mixture of Sand
Stabilization Sealant Bicassay with *Daphnia*

<u>Treatment</u>	<u>Test Date</u>							
	<u>6 July 87</u>		<u>7 July 87</u>		<u>8 July 87</u>		<u>9 July 87</u>	
	<u>DO</u>	<u>pH</u>	<u>DO</u>	<u>pH</u>	<u>DO</u>	<u>pH</u>	<u>DO</u>	<u>pH</u>
Control	10.60	8.59	5.00	7.98	5.40	7.23	5.80	7.30
Sample 1	10.60	8.60	5.40	7.98	5.80	7.21	8.20	7.53
Sample 2	10.60	8.61	7.00	8.14	4.40	7.21	5.60	7.39
Sample 3	10.60	8.61	7.20	8.20	5.40	7.30	6.00	7.40
100 ppm	10.80	8.60	6.20	7.85	5.60	7.35	7.80	7.52
Sample 1	10.80	8.61	6.60	8.03	6.20	7.45	8.60	7.68
Sample 2	10.80	8.60	6.80	8.06	6.20	7.50	8.80	7.74
Sample 3	10.80	8.50	8.80	8.42	4.80	7.39	9.60	7.71
1,000 ppm	10.80	8.62	6.40	8.15	5.80	7.48	9.60	7.76
Sample 1	10.80	8.63	6.20	8.16	5.20	7.46	7.60	7.64
Sample 2	10.80	8.62	5.80	8.07	4.80	7.45	7.60	7.60
Sample 3	10.80	8.57	5.80	8.04	4.20	7.37	6.40	7.52
10,000 ppm	10.80	8.62	6.60	8.78	5.60	7.84	9.40	8.06
Sample 1	10.80	8.60	5.60	8.40	5.20	7.71	7.20	7.84
Sample 2	10.80	8.62	5.60	8.64	5.60	7.88	7.40	8.04
Sample 3	10.80	8.62	6.20	8.55	5.60	7.80	9.60	8.03
100,000 ppm	10.80	8.96	7.60	10.09	4.40	9.64	7.80	9.80
Sample 1	10.80	8.89	7.60	10.11	4.60	9.82	5.40	9.99
Sample 2	10.60	8.89	7.60	10.13	4.80	9.73	4.60	9.97
Sample 3	10.60	8.89	7.80	10.08	3.60	9.71	7.20	9.84

Table 9
Variation of DO and pH Sodium Silicate-Diacetin Mixture
of Chemical Sealant Bioassay with *Daphnia*

<u>Treatment</u>	<u>Test Date</u>							
	<u>7 July 87</u>		<u>8 July 87</u>		<u>9 July 87</u>		<u>10 July 87</u>	
	<u>DO</u>	<u>pH</u>	<u>DO</u>	<u>pH</u>	<u>DO</u>	<u>pH</u>	<u>DO</u>	<u>pH</u>
Control	11.20	8.35	9.80	8.40	14.20	8.31	16.20	8.57
Sample 1	10.80	8.43	10.00	8.49	15.20	8.37	16.40	8.63
Sample 2	10.80	8.46	10.20	8.51	14.80	8.56	16.00	8.81
Sample 3	10.80	8.80	10.20	8.74	14.60	8.57	16.20	8.86
100 ppm	10.80	8.74	10.20	8.74	14.20	8.56	15.20	8.79
Sample 1	10.60	8.75	10.20	8.76	14.60	8.59	16.00	8.90
Sample 2	10.60	8.66	10.20	8.79	14.20	8.52	16.00	8.87
Sample 3	10.60	8.80	10.00	8.79	14.00	8.61	15.80	8.89
1,000 ppm	10.60	9.56	9.80	9.49	13.60	9.19	15.80	9.37
Sample 1	10.60	9.55	9.80	9.54	13.60	9.25	13.20	9.41
Sample 2	10.60	9.67	9.80	9.52	13.80	9.22	13.80	9.39
Sample 3	10.60	9.38	10.00	9.51	13.60	9.23	14.80	9.37
10,000 ppm	10.80	10.06	10.40	10.08	8.40	10.27	8.60	10.38
Sample 1	10.80	10.18	10.20	10.05	13.80	10.32	5.80	10.48
Sample 2	10.80	9.99	10.40	10.07	13.60	10.25	5.80	10.30
Sample 3	11.00	10.15	10.40	10.22	14.00	10.27	8.40	10.43
100,000 ppm	11.20	11.42	10.60	11.62				
Sample 1	11.00	11.47	10.60	11.69				
Sample 2	11.00	11.50	10.60	11.74				
Sample 3	11.00	11.57	10.60	11.80				

PART IX: LONG-TERM SEALANT DURABILITY TESTS

Purpose of the Tests

306. The sealant durability time-dependent tests were formulated to determine how the sealant materials would endure under actual field conditions. Effects of environmental exposure to waves, currents, freezing and thawing cycles, wetting and drying cycles, abrasion, biological influences, and chemical reactions are being evaluated. A monitoring effort of indefinitely long duration was established to determine the performance with time of sealant materials in the field environment.

307. In order to monitor material performance, representative samples of each sealant material evaluated in the physical model rubble-mound structure laboratory experimental investigation were cast as specimens and placed in locations with varied climatic conditions. Since the specimen exposure is direct and unconfined, the test is actually more severe and extreme than if the material were placed inside a structure.

308. Three sites were selected as typical climatic environments to which the sealants would be exposed, those locations being (a) Treat Island, ME; (b) Duck, NC; and (c) Miami, FL. These locations represent conditions of cold, moderate, and warmwater environments. Each climatic condition entails varying chemical effects on the sealant specimens. Other environmental factors such as freezing and thawing cycles in the cold regions and biological influences in the moderate to semitropical regions affect the specimens.

309. At each test site, the specimens were placed at the two water levels of (a) mean water line and (b) below mean lower low water. These placement locations will allow comparisons between materials which have been continuously submerged with those undergoing wetting and drying cycles due to tidal variations. A reference standard specimen for each material is maintained at the WES Structures Laboratory for comparison with exposed specimens. A complete series of tests will be used as indicators of material performance. Testing methods are uniform for all three site locations. Although testing techniques vary for different materials, qualitative comparisons can be achieved between all sealant specimens. All specimens were tested immediately prior to placement in the water; hence, subsequent testing will indicate the degree of erosion or deterioration induced by the environmental factors at the three field sites.

Selection of Test Methods

310. Many different types of tests are available, and the tests chosen optimized the number of specimens required, test equipment required, and knowledge gained from test results. The majority of the tests are nondestructive, which reduces the number of specimens required to conduct the investigation. Destructive testing is performed only on the asphaltic specimens.

311. Nondestructive and destructive tests were designed for the purpose of documenting aspects of material strength. The change in properties with length of exposure to the environment provides a measure of environmental effects on the sealant. Material specimens were formed to accommodate test procedures as well as handling at field sites. Nonasphaltic mixtures were formed into cylinders having the minimum length-to-diameter ratio of 2-to-1 for pulse velocity measurements. Cylinder dimensions were selected to be 12 in. long and 6 in. in diameter. Because the asphaltic materials required different testing methods, the sizes for the asphaltic specimens were selected to be 2 in. long and 4 in. in diameter. A minimum of four specimens of each sealant type was installed at each water level at each test site to provide the proper number of sampling results.

Cementitious and chemical sealant specimens

312. Compressive strength. Compressive strength tests were performed to determine the strength values of the WES Mixture and the Buhne Point Mixture of the cementitious sealants. An indication of the ultimate strength of the material is obtained by loading the specimens to failure. These tests were performed 7, 14, and 28 days after casting to determine the strength of the materials placed at the three field test sites.

313. Ultrasonic pulse velocity. This test measures the travel time of a sound pulse through the specimen and is performed according to the criteria and standards established by ASTM Specification No. D-C597-71. Sound velocity is determined from the path length and sound travel time. The square of the pulse velocity is related to Young's dynamic modulus of elasticity, E . Changes in E provided an indication of deterioration.

314. Resonant frequency. Specimens are tested to determine their fundamental transverse frequency according to ASTM Specification No. D-C215-60. The specimens are supported at the nodes in a horizontal position and vibrated in the fundamental flexural mode. The resonant frequency is obtained by

varying the vibration frequency. Young's dynamic modulus of elasticity, E , is calculated using the fundamental transverse frequency and specimen dimensions and weight. Changes in the modulus provide an indication of deterioration.

315. Failure criteria. The criteria for failure were established as follows. Subsequent calculated value of Young's dynamic modulus of elasticity, E , for each specimen will be expressed as a percentage of the value at installation. When the calculated value becomes less than half the initial value during the exposure periods, the specimen will be considered to have failed (Thornton 1977). If specimen deterioration occurs to an extent such that measurements cannot be made or if the specimen separates, failure is considered to have occurred.

Sand-asphaltic specimens

316. Marshall stability test. This test, conducted according to ASTM Specification No. D-1559, measures strength and plastic flow resistance and provides an indication of stability of the material. Density and void properties also are determined during this test.

317. Indirect tensile strength. This test allows the computation of the tensile strength of asphaltic material by indirect methods according to procedures in ASTM Specification No. D-4123. The tensile strength of a specimen is calculated for use in determining the resilient modulus. The tensile strength, ST , of the specimen is calculated as:

$$ST = \frac{2P_{ult}}{PI \ t D} \quad (9)$$

where

P_{ult} = applied load, lb

PI = plasticity index (range of moisture contents), percent

t = specimen thickness, in.

D = specimen diameter, in.

318. Resilient modulus. This test is conducted to evaluate material quality as well as conditioning related to temperature and moisture. The test was developed within the guidelines of ASTM Specification No. D-4123. Although these specifications recommend that 25 percent of the tensile strength be used as a basis for applying a vertical load to the specimen,

10 percent of the tensile strength is actually used in these evaluations. A simplified form of the expression recommended by ASTM Specification No. D-4123 is used to calculate the instantaneous resilient modulus, RM .

$$RM = \frac{3.59 P}{tv} \quad (10)$$

where

P = applied load, lb

v = vertical deformation, in.

Mixing and Casting of Specimens

319. To provide an adequate supply of samples for the long-term exposure test evaluations, 40 specimens of each cementitious and chemical sealant and 350 specimens of the sand-asphaltic mixture were cast for the durability testing program. Details of the specimen mixing and casting procedures for each sealant follow.

Microfine cement

320. The injection of microfine cement into a sand layer was performed in the laboratory to evaluate the potential of such materials in future experimental and field applications. No specimens for long-term field exposure performance were cast. The initial attempt at injecting the particulate solution into the voids of the fine-grain material was only partially successful. The microfine cement solution was designed according to the following weight:

Microfine cement	38.60 lb
Silica fume	4.29 lb
Water	47.20 lb

321. It was necessary to apply such high pressure in order to inject the cement particles between the sand grains that the plastic cylinders containing the mass failed. The second attempt involved the application of additional water and a high-range water reducer. The mix was formulated according to the microfine cement manufacturer's specifications utilizing a 2-to-1 water-to-cement volumetric ratio. The 2-to-1 ratio was selected over other possibilities to provide a more viscous mix, thus rendering a more critical

examination. The second mix design proved successful, and the sand was sealed throughout the column. The ingredients of the mixture are:

Water	200 l
NS-200 (high-range water reducer)	1 l
MC-500 (microfine cement)	100 kg

WES Mixture

322. The WES Mixture uses concrete as a dominant sealing material. The mixture was prepared in a batch mixer according to the following specifications.

Type I portland cement	23.8 lb
Masonry sand	90.0 lb
Monier fly ash	1.2 lb
Silica fume	2.4 lb
D-air	6.2 g
Sodium citrate	6.2 g
Anti-washout additive	31.0 g
HPSR* (proprietary)	239.3 ml
Water	14.0 lb

After the batch was mixed, the percentage of entrained air was determined to be low. An increase of entrained air was accomplished by adding air entraining admixtures while the batch was in the mixer. Difficulty was encountered in accomplishing this process, probably because adding air to an already prepared mix is formidable. The use of so many additional additives may have also contributed to the difficulty. Because of the high number of ingredients involved and the proportions required, this may not be the optimum mix design for field use. Forty specimens of the WES Mixture of cementitious sealant were cast, each with an average weight of 27 lb.

Buhne Point Mixture

323. The Buhne Point Mixture of cementitious sealant was fashioned to conform to the mixture used in the Buhne Point Shoreline Demonstration Project, Humboldt Bay, California. When the mix was initially prepared in the WES Structures Laboratory, it appeared to be too stiff with no measurable slump. Modifications to the mix design were conducted to provide for a 5-in. slump. The cement content was held constant, and the water-to-cement ratio was increased from 0.49 to 0.62. Although this alteration would apparently result in a decrease in material strength, the actual compressive strength of the cement was not deemed a critical parameter since the primary function of the

* HPSR = High Performance Stabilizing Reagent.

sealant was to create a sediment barrier, and not to sustain direct loading.

The following mix proportions were utilized:

Coarse aggregate (pea gravel)	1,115.00 lb
Fine aggregate (concrete sand)	1,655.00 lb
Cement	705.00 lb
Clay (bentonite)	37.00 lb
Water (modified from 283 lb)	371.00 lb
Calcium chloride	15.00 lb
Air entrainment additive	0.41 lb

Forty specimens of the Buhne Point Mixture of cementitious sealant were cast, each with an average weight of 23 lb.

Sodium Silicate-Cement Mixture

324. The Sodium Silicate-Cement Mixture of chemical sealant was mixed by using the following specifications:

Sodium silicate	1.50 gal = 20% by volume
Portland cement	0.50 gal = 7% by volume
Water	5.47 gal = 73% by volume

A vertical tub-type sealant mixer was used to combine these ingredients. A mixture of portland cement and water was placed in one tub while the sodium silicate with water mixture was placed in another tub. The mixtures were pumped at equal rates into a hopper, then through a hose into an in-line mixer. The mixture was then pumped into plastic 6-in.-diam by 12-in.-long cylinders. The mixture set time was 30 to 35 sec, with air temperature being 79° F. Forty specimens of the Sodium Silicate-Cement Mixture of chemical sealant were cast, each with an average weight of 23 lb.

Sodium Silicate-Diacetin Mixture

325. The Sodium Silicate-Diacetin Mixture of chemical sealant, which was pumped into sand, was designed according to the following mix:

Sodium silicate	2.62 gal = 35% by volume
Diacetin	0.45 gal = 6% by volume
Water	4.44 gal = 59% by volume

Polyvinyl chloride pipe (6 in. diameter, 5 ft long) was used as a mold in casting the specimens. Pea gravel was placed in the bottom portion of the pipe. Masonry sand was then placed over the gravel, filling the pipe to the top. The mass was then saturated with water, requiring approximately 3 gal. The sodium silicate sealant (approximately 5 gal) was then pumped through the bottom of the column. Set time was approximately 10 min. Forty specimens of the Sodium Silicate-Diacetin Mixture were cast, each weighing around 23 lb.

Sand-Asphaltic Mixture

326. Design of the Sand-Asphaltic Mixture was based upon designs previously utilized at Asbury Park, NJ, and Galveston, TX. These sites were chosen because of the sustained performance of the material that had previously been applied at these locations, although those applications were significantly different from that being proposed in the present investigation. Ten-pound samples of asphaltic material were obtained from both locations. An extraction and recovery procedure was accomplished on the samples to determine the material content and mix design. The following were determined: (a) grain size distribution of the sand component, (b) percent bitumen, (c) percent voids, (d) density, (e) specific gravity, and (f) percent water absorption. Table 10 is a summary of those analyses. Also included is the WES Sand-Asphaltic Mixture that was ultimately developed. Table 10 can be used as a guide for future mix designs. Based upon the analyses of the Asbury Park and Galveston mixtures, the WES Sand-Asphaltic Mixture shown in Table 10 was developed for the long-term time-dependent exposure field tests. Sand and cement contents were 79 and 21 percent, respectively.

327. The performance of sand-asphaltic mixtures in the environment appears to be temperature dependent. Prior to determining the percentage of asphalt to blend into the specimens, a few sample specimens were made with varying asphalt content to determine deformation characteristics at room temperature. If deformation was experienced by the specimens at room temperature, it would be easier for the material to be washed from the interior of a rubble-mound structure. Sagging and loss of stiffness would also result, causing settlement or creep.

328. The mixtures used in this preliminary evaluation were 10-, 12.5-, and 15-percent asphalt by weight. The 15-percent asphalt content mixture slumped at room temperature. Since these sealant samples could not retain their cast shape, they could not be used for reliable testing. The 12.5-percent samples exhibited only minor slumping at room temperature and could be used for tests. The 10-percent specimens completely retained their shape and could definitely be used for testing purposes. Based upon these initial observations, a 12-percent asphalt content was selected for use in the test specimens, since it was desired to use as large an asphalt content as possible to be more durable for aging and weathering. Mixing procedures involved heating the aggregate to 400° F while heating the asphalt cement to

Table 10
Sand-Asphaltic Mixture Analyses

<u>Percent Passing Sieve Size</u>	<u>Asbury Park, NJ</u>	<u>Galveston, TX</u>	<u>WES Sand-Asphaltic Mixture</u>
1 in.			
3/4 in.			
1/2 in.	100.0		
3/8 in.	99.3		100.0
No. 4	68.4		99.9
No. 8	55.8	100.0	99.6
No. 16	51.2	99.8	97.8
No. 30	42.4	98.7	88.4
No. 50	24.3	97.7	36.0
No. 100	11.7	90.8	3.2
No. 200	3.0	13.5	0.1
Percent bitumen	9.0	12.6	12.0
Pen grade of removed bitumen	20		30
Percent voids of total mixture	6.2		
Percent voids filled	76.2		
Density, lb/cu ft	142.5	118.4	
Aggregate specific gravity	2.80	2.63	
Aggregate percent water absorption	0.8		

350° F. Mixing temperatures were documented at 350° F. Heating asphalt to higher temperature may cause material hardening.

Initial Testing of Specimens

Cementitious and chemical sealant specimens

329. Initial tests were conducted to provide reference standard values for each sealant material. Subsequent tests will be conducted periodically at each field test site. Tests repeated at least yearly for a time period

sufficiently long enough to ascertain the ultimate long-term disposition of cementitious, chemical, and asphaltic materials are desirable. This will provide adequate data to determine the amount, if any, of deterioration of the materials due to environmental factors. Table 11 shows the characteristics obtained during initial tests conducted on the cementitious and chemical sealant specimens.

Table 11
Initial Performance Values of Cementitious and Chemical Sealant
Specimens Cast for Long-Term Durability Evaluation

<u>Material</u>	<u>Pulse Velocity ft/sec</u>	<u>Young's Dynamic Modulus of Elasticity, E psi</u>	<u>Compressive Strength psi</u>
WES Mixture	12,000	3,500,000	4,360
Buhne Point Mixture	13,000	2,830,000	2,485
Sodium Silicate-Cement Mixture	5,600	100,000	285
Sodium Silicate-Diacetin Mixture	2,600 to 6,600	37,000 to 94,000	65

330. The values presented in Table 11 are averages of a large number of test results. No problems were encountered while testing the WES Mixture and the Buhne Point Mixture of the cementitious sealants. However, some difficulty arose in testing the Sodium Silicate-Cement and Sodium Silicate-Diacetin Mixture specimens of chemical sealants. Specimens of these materials had low strength, as shown by both the compressive strength and Young's dynamic modulus of elasticity, E. The sand and sealant materials did not appear to be fully consolidated into a monolithic mass, as did the WES Mixture and the Buhne Point Mixture of cementitious sealants. When undergoing testing, the low-strength material did not vibrate crisply. Testing under field evaluation conditions did provide adequate results for all samples, although the data obtained from the Sodium Silicate-Diacetin Mixture were of lower quality than those of the other sealants. Long-term exposure testing will ascertain the acceptability of the Sodium Silicate-Cement Mixture and Sodium Silicate-Diacetin Mixture for sealing voids in rubble-mound structures.

Sand-asphaltic sealant specimens

331. The Sand-Asphaltic Mixture specimens underwent a different set of tests than did the other materials. Indirect tensile strength, resilient modulus, and the Marshall stability tests were performed to determine characteristics of the Sand-Asphaltic Mixture. Temperature and moisture were considered critical parameters for asphalt performance. Tests were performed at 40°-, 55°-, and 65°-F temperatures. The retained strength of the material was to be compared in a wet versus a dry condition. Specimens for the wet condition were soaked in a saltwater solution with a salinity of 32 ppt. Table 12 outlines the curing conditions of wetting and drying cycles for determining retained strength characteristics of the Sand-Asphaltic Mixture. The initial tests were conducted to determine baseline parameters. Future tests would be conducted during the field investigation periods. While the compressive strength of the Sand-Asphaltic Mixture is less than other sealants, its flexibility may allow it to satisfactorily serve as a void sealing material for rubble-mound structures.

Placement at Field Sites

332. The specimens for long-term time-dependent durability testing were placed in locations where a range of environmental conditions would be experienced, from freezing and thawing cycles at a northern location to biologically active regions in a warmer water locality, through some intermediate situation along the mid-Atlantic region. Wetting and drying cycles would also be experienced at each test facility. Site selection was also based on the existence of nearby established research facilities, thereby necessitating minimal test site preparation and, thus, increasing monitoring opportunities. Environmental factors, such as temperature of the air and water, wave height, and salinity, were measured during initial installation to define placement conditions and will be repeated periodically throughout the exposure period.

333. Although the specimens were given identification codes when cast, a simple labeling scheme was developed for easily identifying the specimens while in the field. The labeling system is as follows;

- 1-10 WES Mixture of cementitious sealant
- 11-20 Buhne Point Mixture of cementitious sealant
- 21-30 Sodium Silicate-Diacetin Sand Stabilizer Mixture
- 31-40 Sodium Silicate-Cement Mixture of chemical sealant

Table 12
Curing Conditions and Initial Performance Values for Sand-Asphaltic
Mixture Specimens Cast for Long-Term Durability Evaluation

<u>Curing Conditions</u>				
<u>Soaking in Salt Water</u> Salinity = 32 ppt				<u>Drying</u>
24 hr				24 hr
48 hr				96 hr
96 hr				1 week
1 week				2 weeks
2 weeks				4 weeks
4 weeks				Test
<u>Initial Performance Values</u>				
<u>Tensile Strength, psi</u>				
<u>When Tested</u>	<u>T = 40° F</u>	<u>T = 55° F</u>	<u>T = 65° F</u>	
In air after 24 hr	233.7	200.6	169.8	
In air after 96 hr	286.4	304.8	313.0	
In air after 168 hr	391.6	253.1	265.4	
In air after 336 hr	344.7	149.9	293.0	
In air after 672 hr	320.8	344.0	253.5	
After soaking for 24 hr	237.5	186.2	181.5	
After soaking for 48 hr	290.0	248.8	280.1	
After soaking for 96 hr	273.6	255.9	303.2	
After soaking for 168 hr	326.4	233.8	276.3	
After soaking for 336 hr	380.9	136.1	313.7	
After soaking for 672 hr	334.6	367.3	224.2	

All mean tide level elevation specimens are the first five in each series. All specimens at the elevation below mean lower low water are the last five of each series. A letter designation also was associated with the number for site identification as follows:

T = Treat Island, ME
D = Duck, NC
M = Miami, FL

334. The cementitious and chemical sealant test specimens were placed in vinyl-coated wire mesh baskets similar to gabions. This ensured that specimens could be installed securely and easily at the site. Four specimens each of sealant types WES Mixture of cementitious sealant, Buhne Point Mixture of cementitious sealant, Sodium Silicate-Diacetin Mixture of chemical sealant with stabilized sand, and Sodium Silicate-Cement Mixture of chemical sealant were placed in each of four baskets, which would correspond to one sealant type per water level. The Sand-Asphaltic Mixture samples were housed in a pvc pipe apparatus to ensure that deformation would not occur either during shipping or in the field. Shape retention of the asphaltic specimens was crucial for accurate testing. Each housing contained four sand asphalt specimens. Eight housings were placed at each of the two water levels at each field station.

Treat Island, ME

335. Treat Island is located in Cobscook Bay, approximately 3/4 mile from Eastport, ME (Figure 49). The USACE has utilized this site as an exposure station for monitoring the effects of natural weathering of concrete materials since 1936. At present, the Corps has over 1,700 specimens of various compositions undergoing test exposure at this site for many different purposes. This location was selected as an exposure station to monitor specimens in extreme cold weathering conditions.

336. Specimens were placed in July 1987 on a 120-ft-long by 40-ft-wide platform located at mean tide level (Figures 50 and 51). This placement allows the specimens to experience wetting and drying as the tide level varies. Other specimens were placed at lower elevations to maintain continued submergence. Average water temperatures range from 37° F in the winter to 48° F in the summer. Salinity in the region is approximately 35.27 ppt. During the winter when the specimens undergo freezing and thawing, the specimens thaw when submerged in the 37° F water and then refreeze when exposed to air that sometimes has a temperature of -10° F. The specimens are exposed to over 100 cycles of freezing and thawing during a winter season (Thornton 1980).

337. Figures 52 through 56 show the condition of some of these specimens when they were retrieved and retested in September 1989, after having been exposed to the environment for 26 months. The storage arrangement and all specimens were completely covered by sediment and marine plant growth, which, in turn, provided habitat for coldwater marine animals. All cementitious specimens were in good condition. The sodium silicate chemical

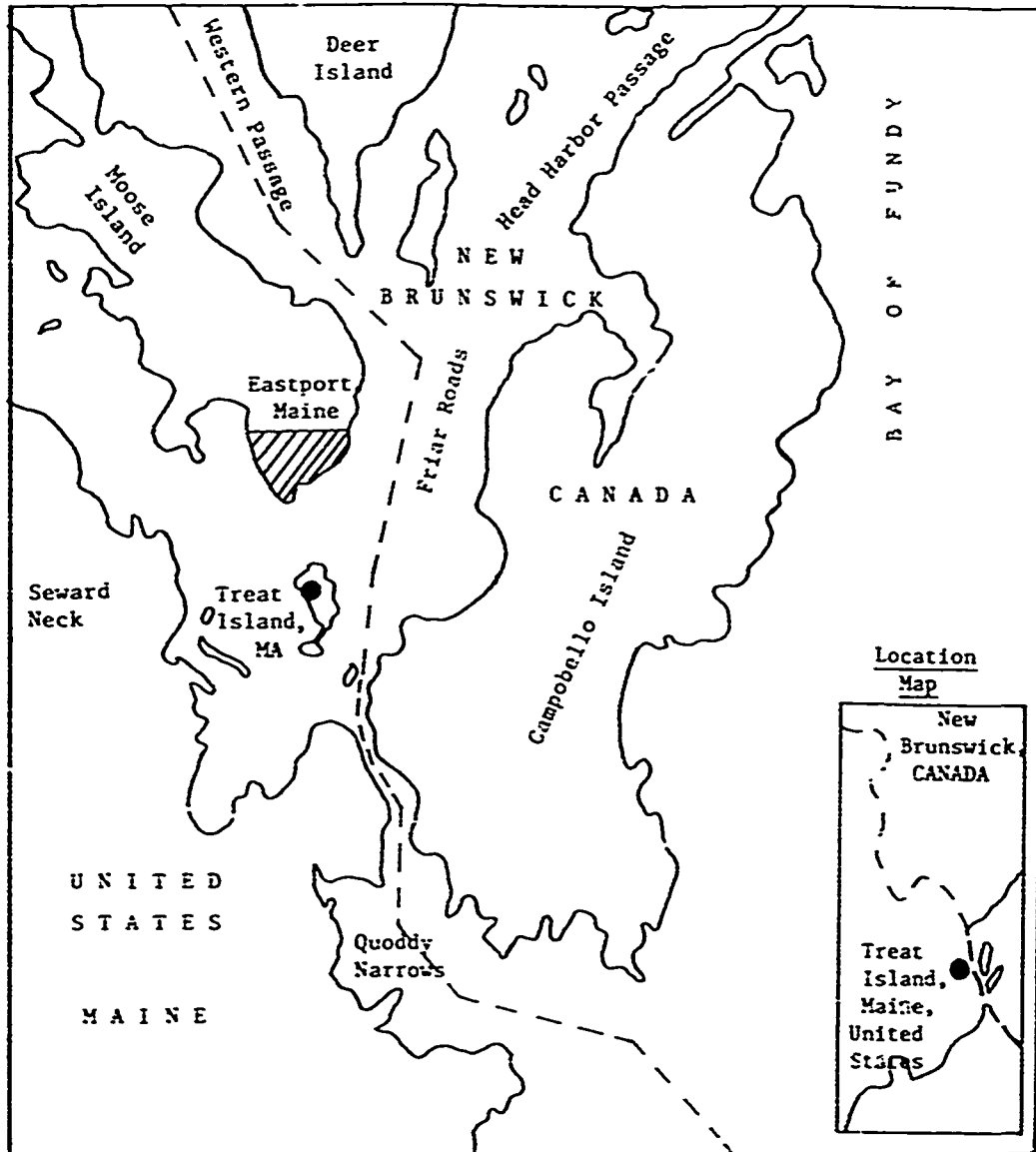


Figure 49. WES natural weathering station for concrete and long-term durability field station, Treat Island, ME

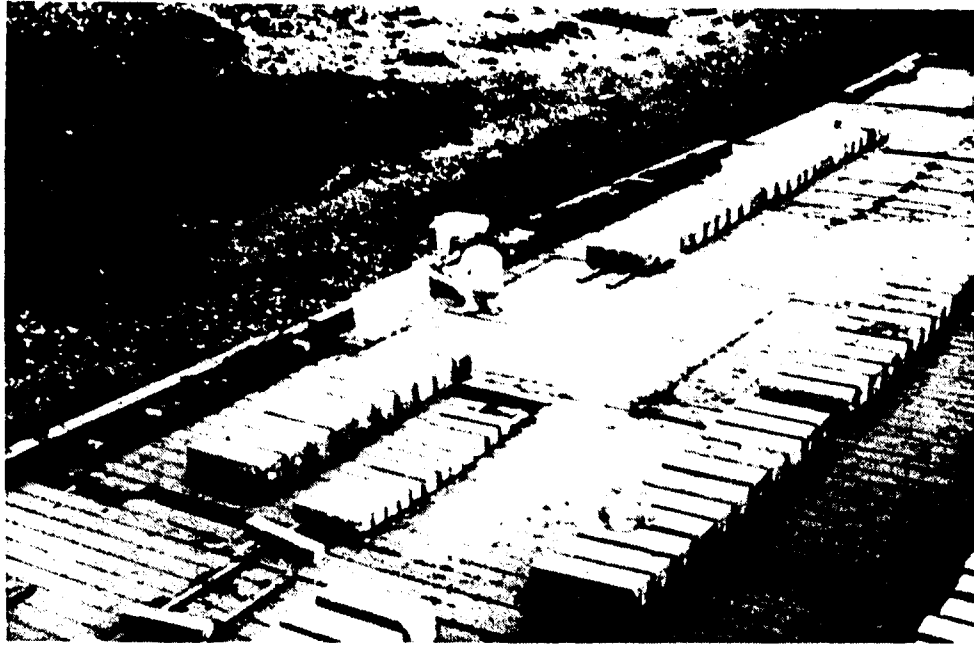


Figure 50. Mean water level platform for repeatedly submerging and exposing specimens, for freezing and thawing, and wetting and drying cycles, Treat Island, ME, field exposure station

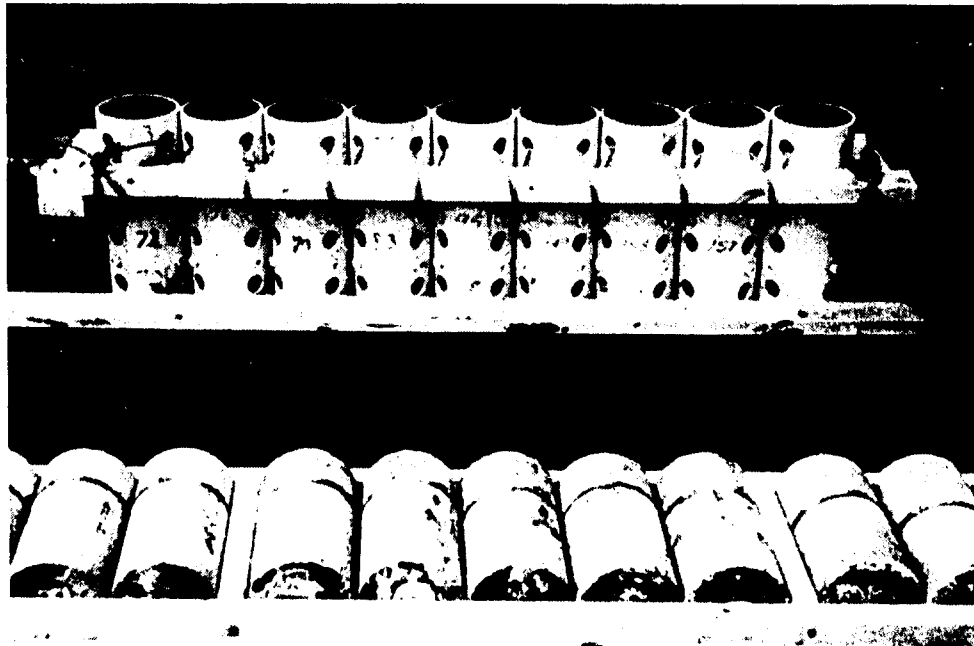


Figure 51. Arrangement for storing specimens at mean water level, Treat Island, ME, field exposure station



Figure 52. Cementitious and asphaltic sealant specimens at mean water line after 26 months exposure, Treat Island, ME



Figure 53. Marine growth covering sealant specimens at mean water line after 26 months exposure, Treat Island, ME



Figure 54. Cementitious sealant specimens at mean waterline being prepared for retesting, Treat Island, ME



Figure 55. WES Structures Laboratory employee retesting cementitious sealant specimens at mean waterline, Treat Island, ME



Figure 56. Sodium Silicate-Cement Mixture of chemical sealant specimens after 26 months exposure on bottom of field test site, Treat Island, ME

specimens (Sodium Silicate-Cement Mixture and Sodium Silicate-Diacetin Mixture) placed on the bottom at the exposure station were extensively deteriorated to a degree that re-investigation by instrumentation was precluded, and such specimens on the platform at mean waterline had completely disappeared. Freezing and thawing, wetting and drying, and storm wave activity had induced total disintegration of the sample specimens. The asphaltic samples (Figure 57) in the pvc pipe arrangement were intact, although heavily covered with marine growth.

Duck, NC

338. The Field Research Facility (FRF) of the Coastal Engineering Research Center (CERC), WES, is located along the Atlantic coast barrier islands at Duck, NC. The FRF is situated near the middle of Currituck Spit, along a 100-km stretch of unbroken shoreline extending south from Rudee Inlet, Virginia, to Oregon Inlet, North Carolina (Figure 58). It is bordered by the Atlantic Ocean on the east and by Currituck Sound on the west. The region has a moderate climate with the average summer temperature being 86° F for air and 68° F for water. The average winter temperatures are 45° F for air and 41° F for water. The sealant specimens are situated in the relatively protected bay region that borders the FRF facility on the west. Because the tide range in



Figure 57. Sand-Asphaltic Mixture of sealant specimen as placed in pvc pipe arrangements at long-term field exposure stations

Currituck Sound at the FRF is insufficient to provide wetting and drying cycles for the specimens positioned at mean tide elevation, the sealant specimens are actually located in Roanoke Sound about 20 miles south of Duck, NC, closer to Oregon Inlet where the tide range is sufficient for wetting and drying these specimens. Here tides have a mean range of about 1 m. The actual site is located within a wildlife management area of the Cape Hatteras National Seashore; hence, security concerns are minimal.

339. The sealant specimens were placed in the waters of Roanoke Sound in May 1988. Mean water depth at this location is about 6 ft. A frame and rack system with 4-in.-diam pipe driven into the bottom was fabricated to retain the gabion baskets that contained the specimens. Figure 59 shows the initial placement of the specimens, under low tide condition, at the mean tide elevation. The specimens were visually inspected in September 1988 to ascertain their integrity after 4 months exposure. Figures 60 and 61 show the condition of the specimens placed at mean tide elevation and those placed on the bottom, respectively. A minimal amount of marine plant growth had become established on the system. Because of the mild weather conditions during the intervening time period, no noticeable evidence of deterioration to the sodium silicate specimens was detectable. The specimens were again visually

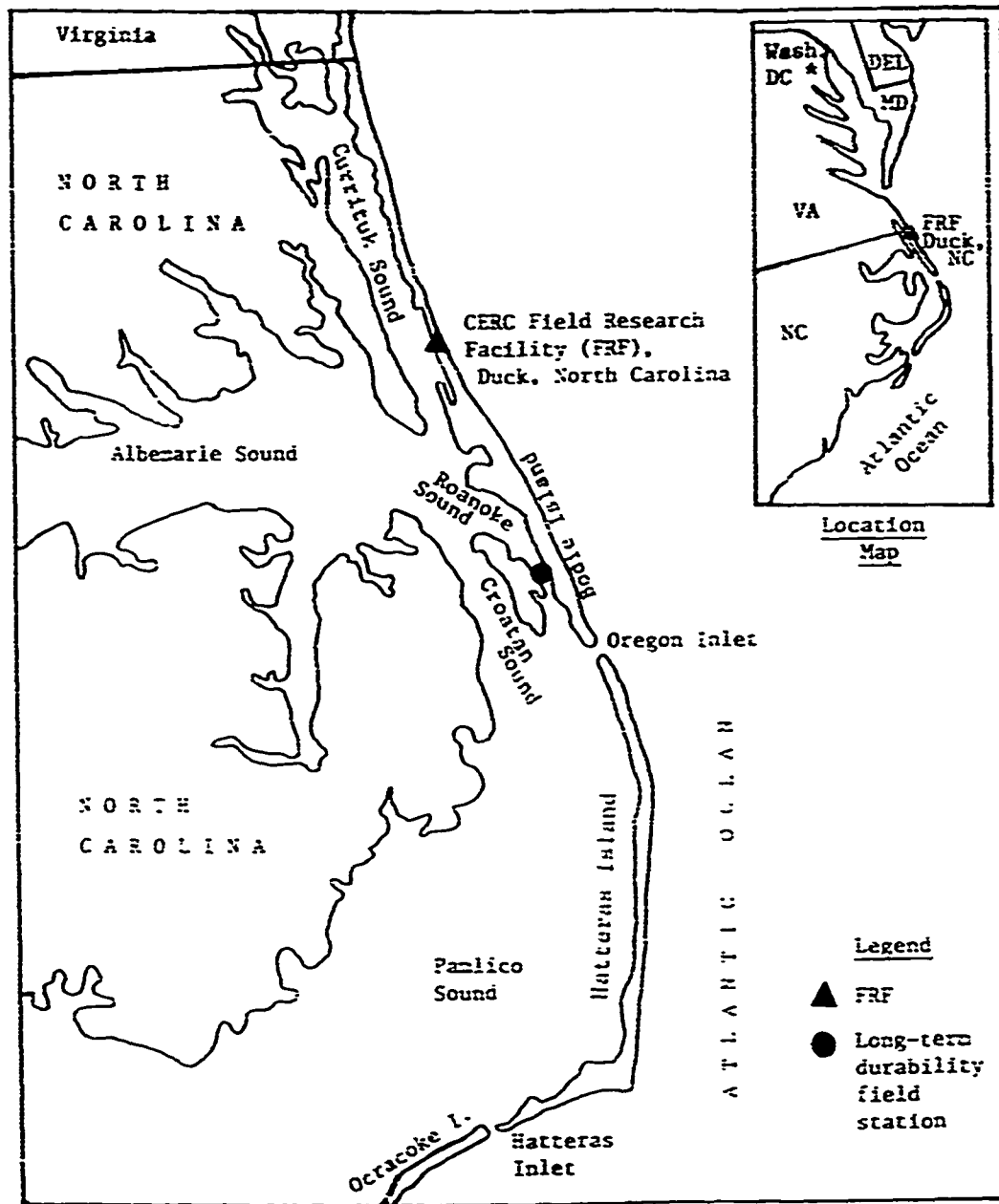


Figure 58. The FRF and long-term durability field station, Duck, NC



Figure 59. Initial placement of sealant specimens in Roakoke Sound, near the FRF, Duck, NC

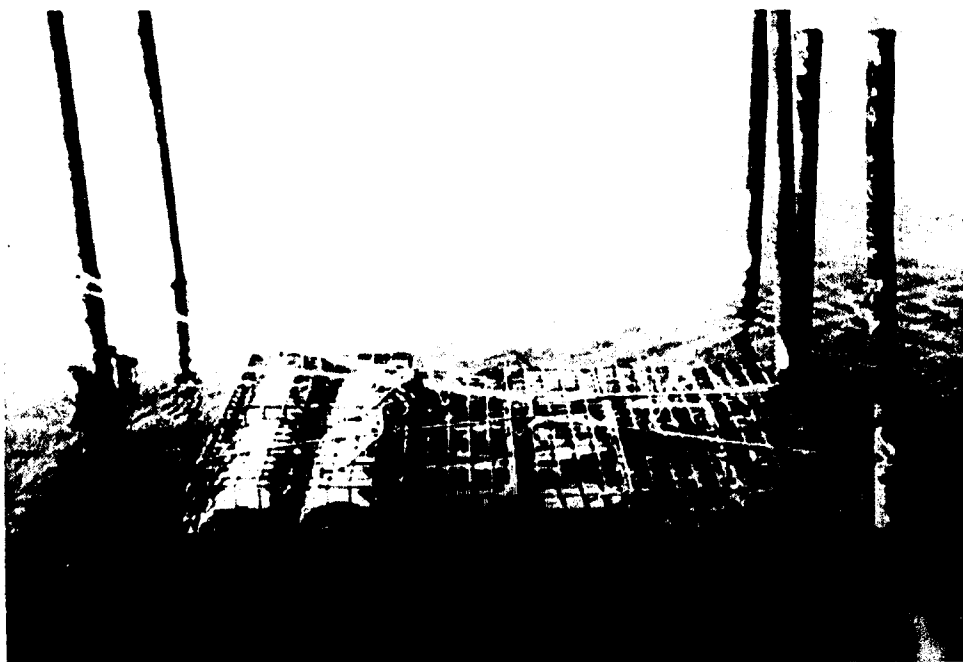


Figure 60. Sealant Specimens after 4 months exposure at mean waterline in Roanoke Sound, near the FRF, Duck, NC

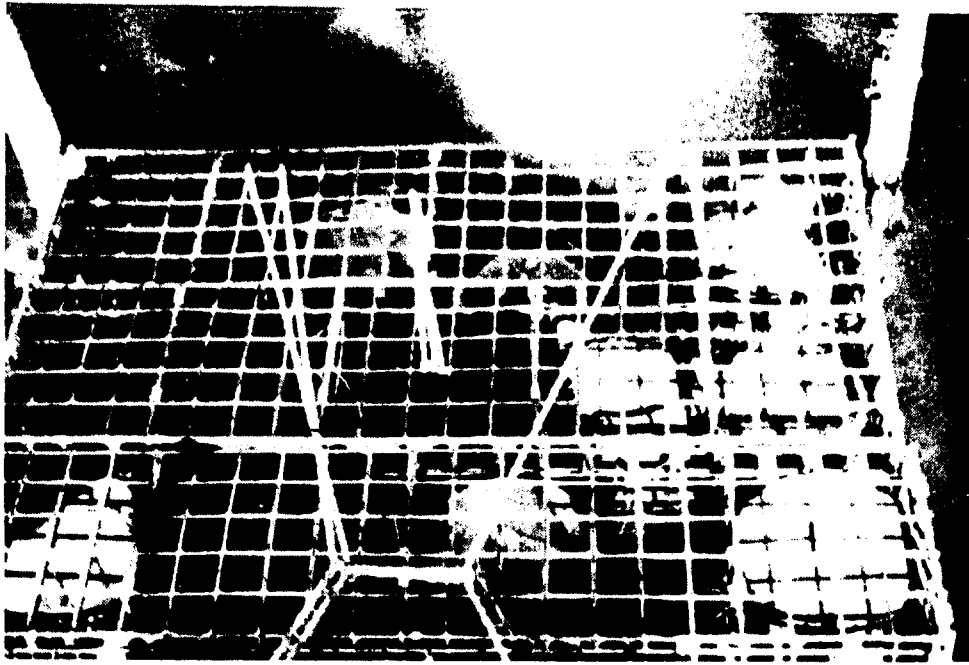


Figure 61. Sealant specimens after 4 months exposure on the bottom in Roanoke Sound, near the FRF, Duck, NC

inspected in May 1989. By this time (12 months after placement), extensive marine growth was evident (Figure 62), and the sodium silicate specimens had experienced a noticeable amount of erosion by current and wave activity.

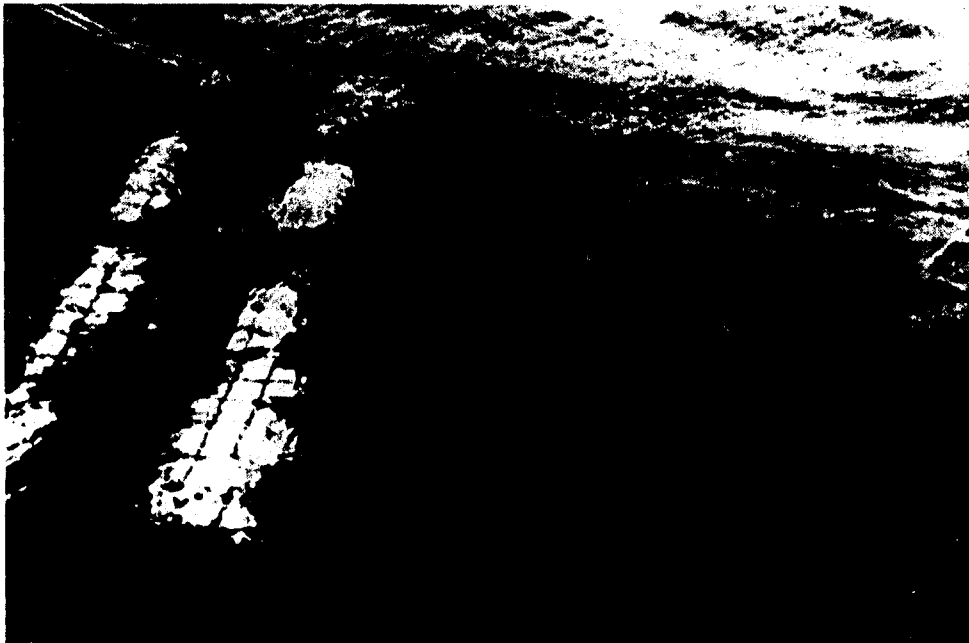


Figure 62. Sealant specimens after 12 months exposure at mean waterline in Roanoke Sound, near the FRF, Duck, NC

Miami, FL

340. Specimen placement, and some of the evaluations of the Miami, FL, exposure specimens, will be conducted by the University of Miami, Rosenstiel School of Marine and Atmospheric Science (RSMAS). The site for placing the specimens is located in Bear Cut, a small passage between Virginia Key and Key Biscayne, adjacent to Biscayne Bay and the Atlantic Ocean (Figure 63). Near-tropical environmental conditions exist for this region. Temperature averages in the summer are 89° F for air and 82° F for the surf zone. During the winter, surf temperatures average 72° F, and air temperatures average 68° F. The site is relatively sheltered from wave activity. However, tidal currents can average around 3 knots. Tide range in this region is approximately 2.6 ft. This area of the US Atlantic coastline is vulnerable to tropical storms and relatively frequent hurricanes that may impact sample durability.

341. The RSMAS maintains a permanent concrete pier erected on concrete piling that extends from RSMAS property into Biscayne Bay. The cementitious and asphaltic sealant specimens were attached to the piling of this pier in April 1988, and the sodium silicate chemical specimens were attached to the piling in August 1988. Figures 64 through 67 show the cementitious specimens, the sodium silicate-cement specimens, the sodium silicate-diacetin stabilized sand specimens, and the asphaltic specimens, respectively, being placed in the gabion cages for initial placement at the Miami, FL, RSMAS field exposure site. A WES Structures Laboratory employee is shown in Figure 68 performing evaluations of the strength of the specimens prior to their placement in the water. An RSMAS graduate student diver is shown in Figure 69 preparing to place the sealant specimens in the water. Figure 70 shows the asphaltic specimen pvc arrangement attached to the RSMAS concrete pier at mean waterline, while Figure 71 shows the attachment of all specimen gabion cages attached underneath the pier.

342. During placement of the sodium silicate specimens in the water in August 1988, one cage of the cementitious specimens that had been placed on the bottom 4 months previously was retrieved for visual inspection (Figure 72). Tropical marine plant growth had essentially covered the entire cage, and small marine animals had colonized both the cage and the plant growth. It will be necessary to remove all such marine growth during retesting efforts.

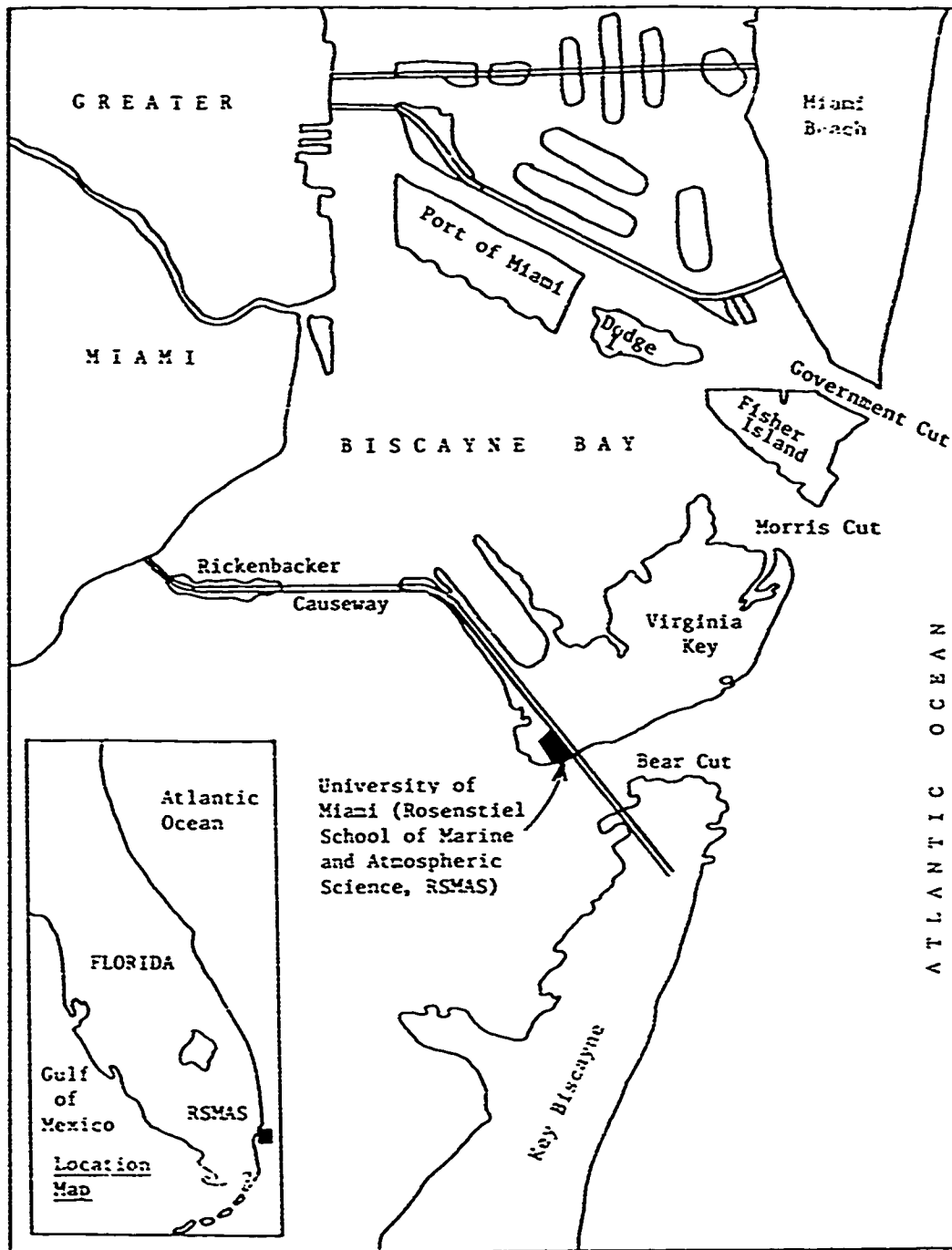


Figure 63. University of Miami, RSMAS, long-term durability field station, Miami, FL



Figure 64. Initial attachment of cementitious sealant specimens in cages for placement at long-term exposure site, Miami, FL

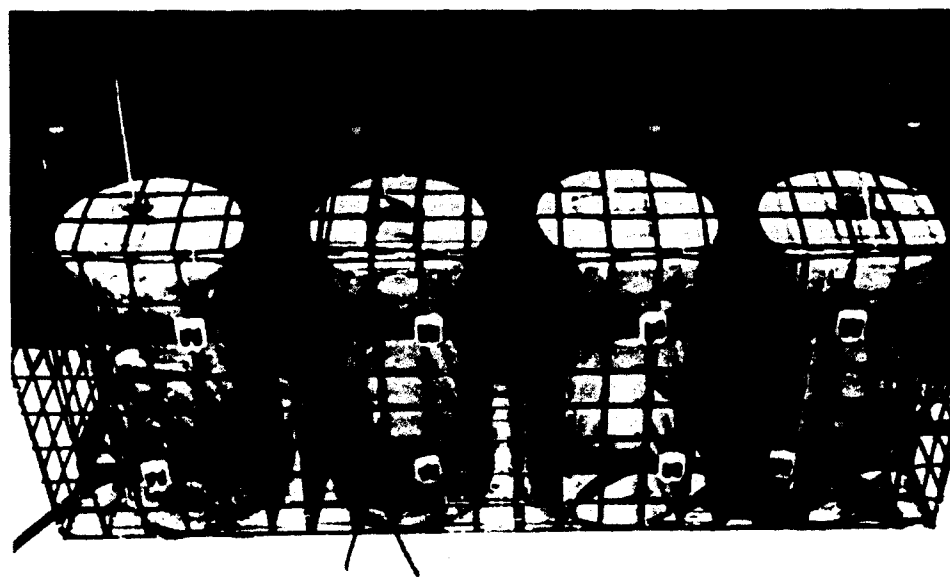


Figure 65. Initial attachment of sodium silicate-cement specimens in cages for placement at long-term exposure site, Miami, FL

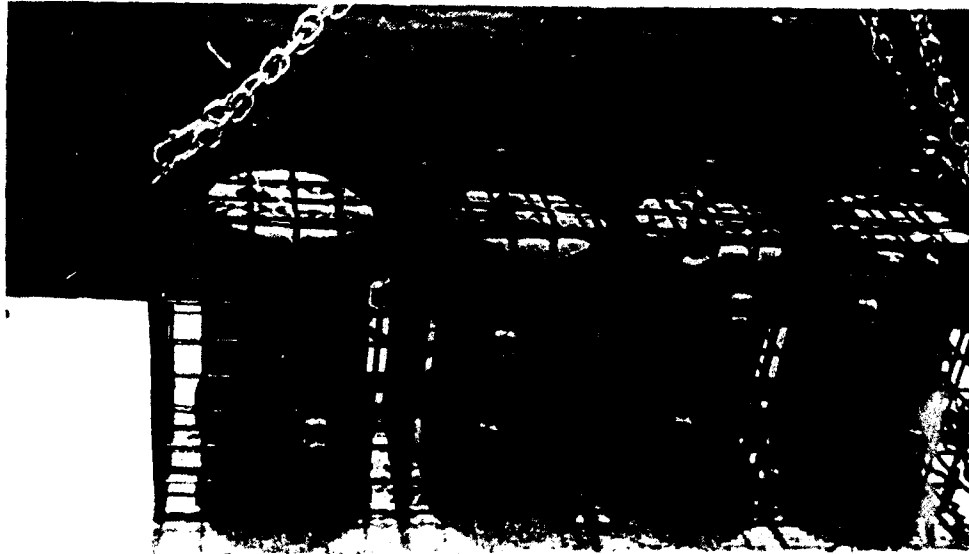


Figure 66. Initial attachment of sodium silicate-diacetin and stabilized sand specimens in cages for placement at long-term exposure site, Miami, FL



Figure 67. Initial attachment of asphaltic specimens in pcv and cages for placement at long-term exposure site, Miami, FL



Figure 68. A WES Structures Laboratory employee performing initial assessment of specimens prior to placement at long-term exposure site, Miami, FL

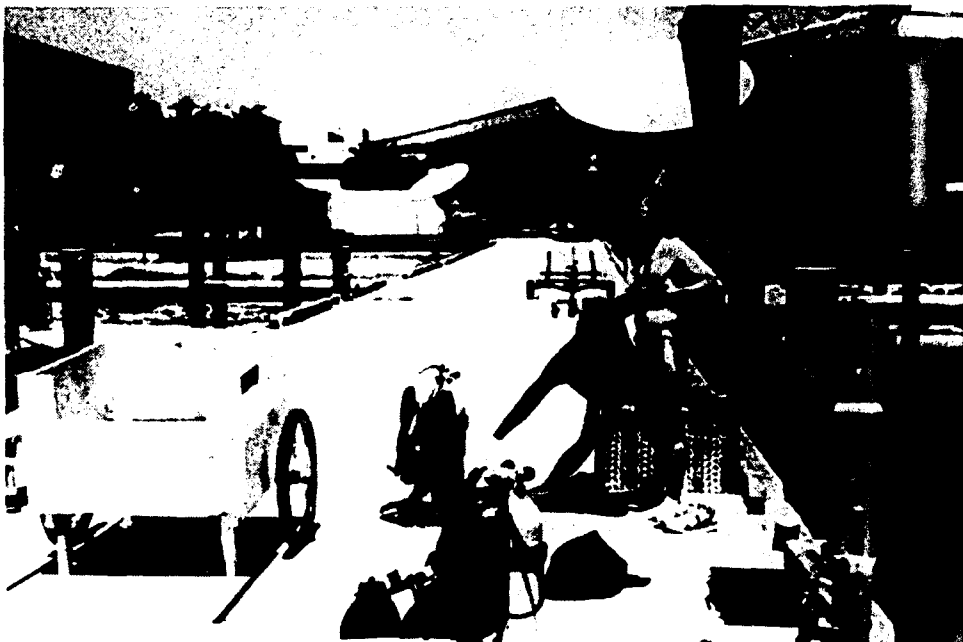


Figure 69. An RSMAS graduate student diver preparing for initial placement of sealant specimens at long-term exposure site, Miami, FL

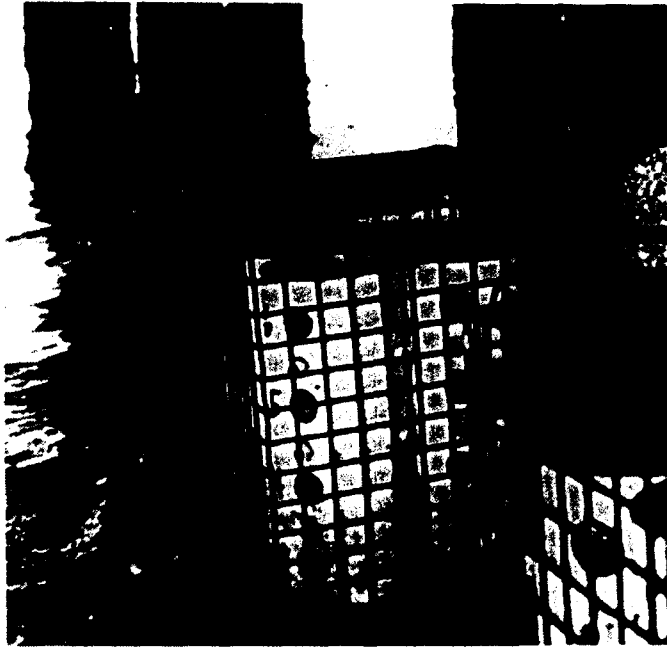


Figure 70. Asphaltic specimens in pvc pipe and cages attached at mean waterline to concrete piling beneath pier at long-term exposure site, Miami, FL

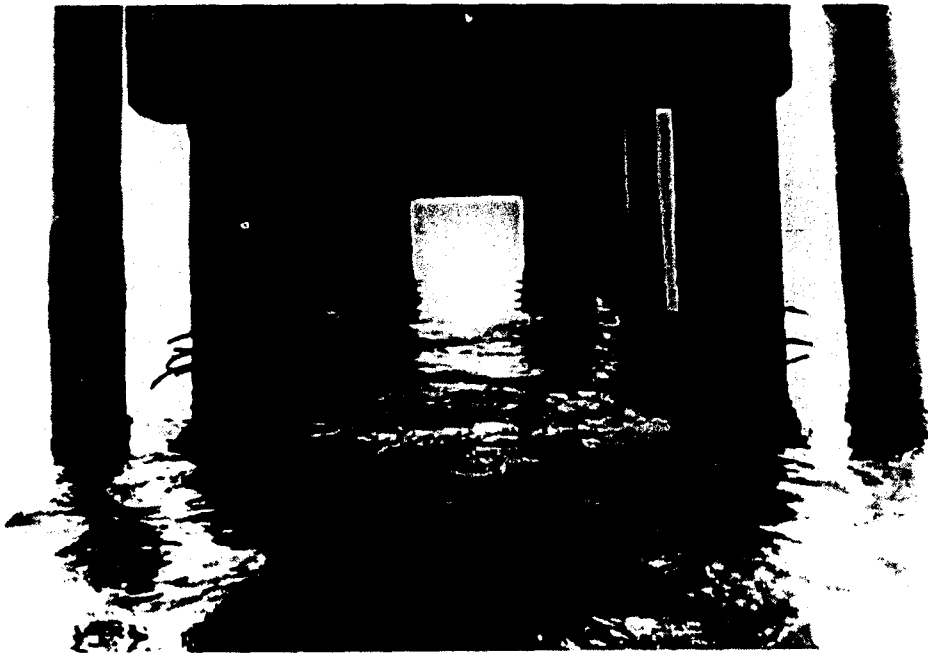


Figure 71. Attachment of all specimens at mean waterline to concrete piling beneath pier at long-term exposure site, Miami, FL



Figure 72. Cage containing cementitious sealant after 4 months placement on bottom at long-term exposure site, Miami, FL, covered with tropical marine plant and animal
— growth

PART X: FIELD EVALUATION OF PROTOTYPE JETTY SEALING

343. Sodium silicate-cement and sodium silicate-diacetin chemical sealants were utilized to seal voids in the Port Everglades, FL, south jetty, and eliminate the transmission of sand through the structure into the navigation channel. Prior to sealing, "man-sized" voids existed in the structure, impairing its function as a terminal groin for beach fills placed south of the structure. Continual erosion of the beach located immediately downcoast of the south jetty to Port Everglades entrance, owned by the State of Florida, prompted Broward County and the State to fund a jetty rehabilitation project and subsequent beach fill of the adjacent beach south of the structure. A monitoring plan to ascertain the effectiveness of the Port Everglades sealing project through a field evaluation was conducted by CERC with the cooperation of Broward County, the State, and the sealing contractor.

Port Everglades, FL. Jetty Sealing

Navigation Project

344. Port Everglades is a Federal navigation project located in Broward County approximately 48 miles south of Palm Beach Harbor and 23 miles north of Miami Harbor. The navigation project was authorized by the Rivers and Harbors Act of 3 July 1953 (House Document 346, 85th Congress, Second Session) and was modified based on a resolution adopted 30 September 1964 by the Committee of Public Works of the House of Representatives (Broward County Environmental Quality Control Board (BCEQCB) 1986). The initial project was for a channel 40 ft deep and 500 ft wide through the ocean bar, tapering to 300 ft wide and 37 ft deep between the rubblestone entrance jetties through to the turning basin of a similar depth. In 1984, new improvements pertinent to the present study included (a) increasing the channel depth to 42 ft in the entrance channel and main turning basin, with an additional 3-ft wave allowance in the ocean entrance; (b) widening the 300-ft width section of the entrance channel to 450 ft; and (c) removing part of the north jetty to accommodate channel widening. In addition, an asphalt fishing walkway on the south jetty was completed in April 1986 by Broward County (BCEQCB 1986).

Coastal processes

345. The net sediment transport rate at Port Everglades has been estimated to be approximately 50,000 cu yd/year to the south, with the net

sediment transport rate "between 2.4 and 5 percent of the gross transport in the project area" (BCEQCB 1986). The mean and spring tide ranges at Port Everglades are 2.6 and 3.2 ft, respectively. Average maximum tidal currents at Port Everglades are about 5.0 ft/sec and about 6.8 ft/sec on the flood and ebb tides, respectively (BCEQCB 1986).

Beach south of Port Everglades

346. Shoreline recession for the 2-mile reach immediately south of the entrance channel (Figure 73) averaged about 5 ft/year for the period 1929 to

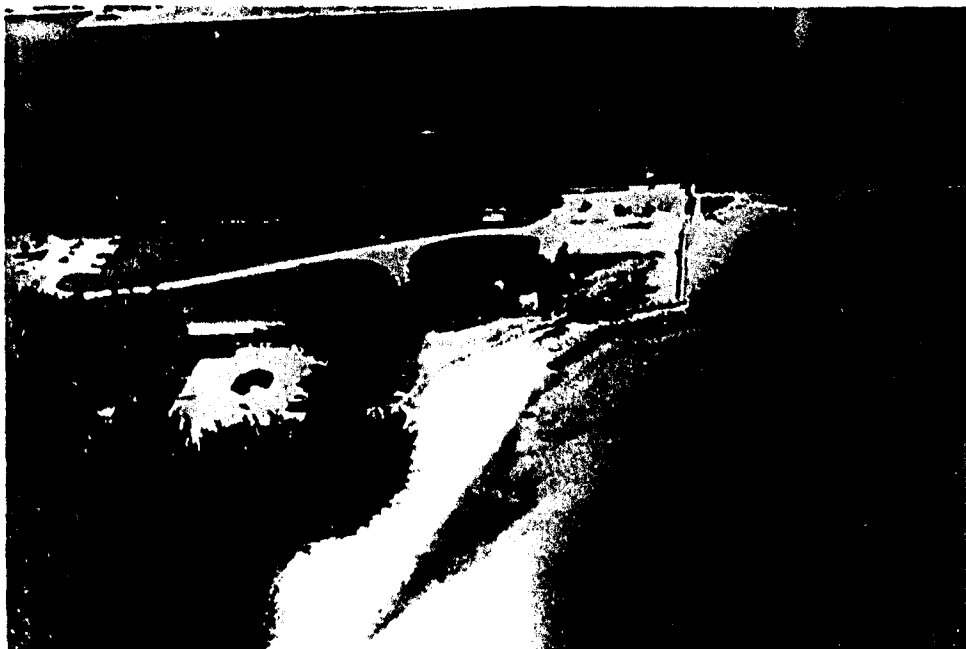


Figure 73. John U. Lloyd State Park immediately south of entrance channel to Port Everglades, FL, site of continual beach erosion

1961 (BCEQCB 1986). From 1961 to 1965, compatible dredged material from the entrance channel was placed on the south beach (county-owned at that time), totaling approximately 729,000 cu yd. In late 1976 and early 1977, a beach fill consisting of 1,090,000 cu yd of material dredged from borrow sites located 2 miles offshore of the south beach was placed along the 1.5-mile section of John U. Lloyd State Park (BCEQCB 1986). The beach-fill shoreline retreated at an average rate of 13 ft/year from 1978 through 1985 with the greatest losses occurring along the 4,000-ft section south of the south jetty. No material from the 1984 channel deepening was placed on the south beach. During site visits conducted in the present study, the south beach was observed to have a scarp approximately 6 ft in height. The high erosion rate

of the artificial beach at John U. Lloyd State Park and the lack of a large fillet immediately south of the structure (Figure 74) indicated to Broward County personnel that the south jetty was permeable, thus allowing northerly moving material to pass through the structure to the channel.



Figure 74. Absence of sand fillet formation adjacent to south jetty at entrance to Port Everglades, FL, indicating transport through structure

South jetty

347. The Port Everglades south jetty is a 1,000-ft-long rubble-mound structure constructed of 5- to 7-ton stone, approximately 30 ft wide at the base and 11 ft wide at the crest (Figure 75). The asphalt-paved fishing walkway on top of the structure (Figure 76) is approximately 10 to 12 ft wide and 4 to 12 in. thick, with a chinking stone subgrade base varying in thickness (Figure 77). The structure was constructed during 1926-1927 of native coquina rock, with an original bend towards the channel at Sta 8+00. The jetty was rebuilt in 1940 with granite placed over the coquina base, straightening the structure to its present east-west orientation.* A diver reconnaissance conducted by Broward County personnel during February 1985 indicated that the jetty was ". . . ill-maintained and in disrepair, evidenced by the numerous

* Personal Communication, 17 November 1989, Stephen H. Higgins, Hydrologic Engineer/Diver, Erosion Control District of the Environmental Quality Control Board of Broward County, Fort Lauderdale, FL.

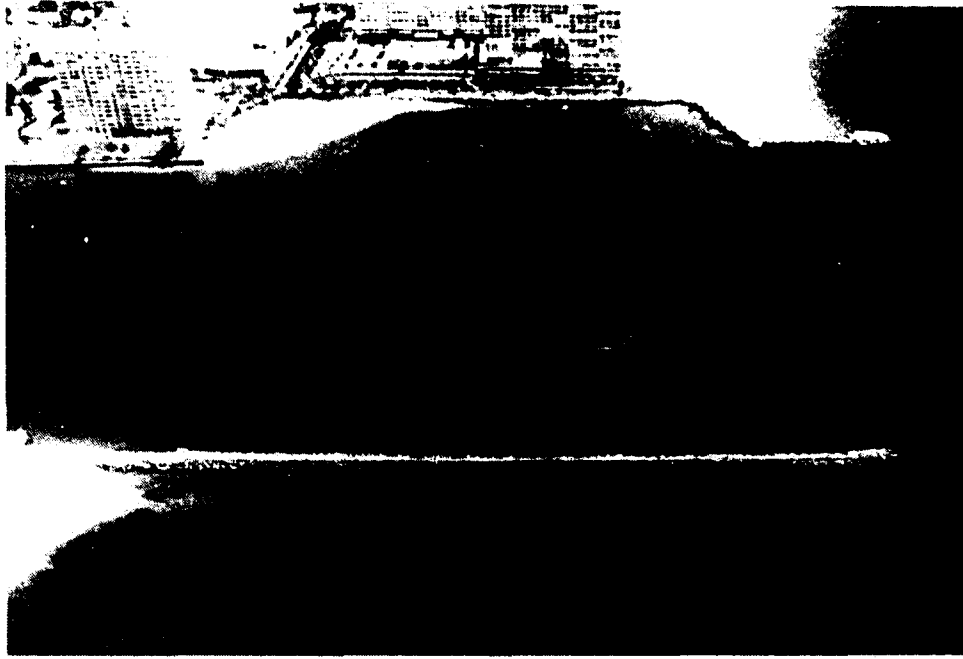


Figure 75. South jetty at entrance to
Port Everglades, FL, June 1988

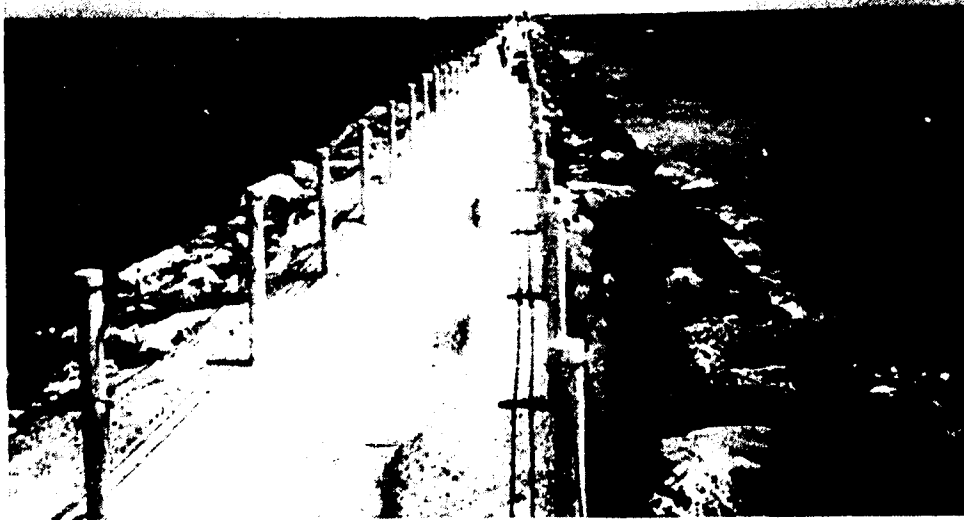


Figure 76. Asphalt-paved fishing walkway
on top of south jetty at entrance to Port
Everglades, FL

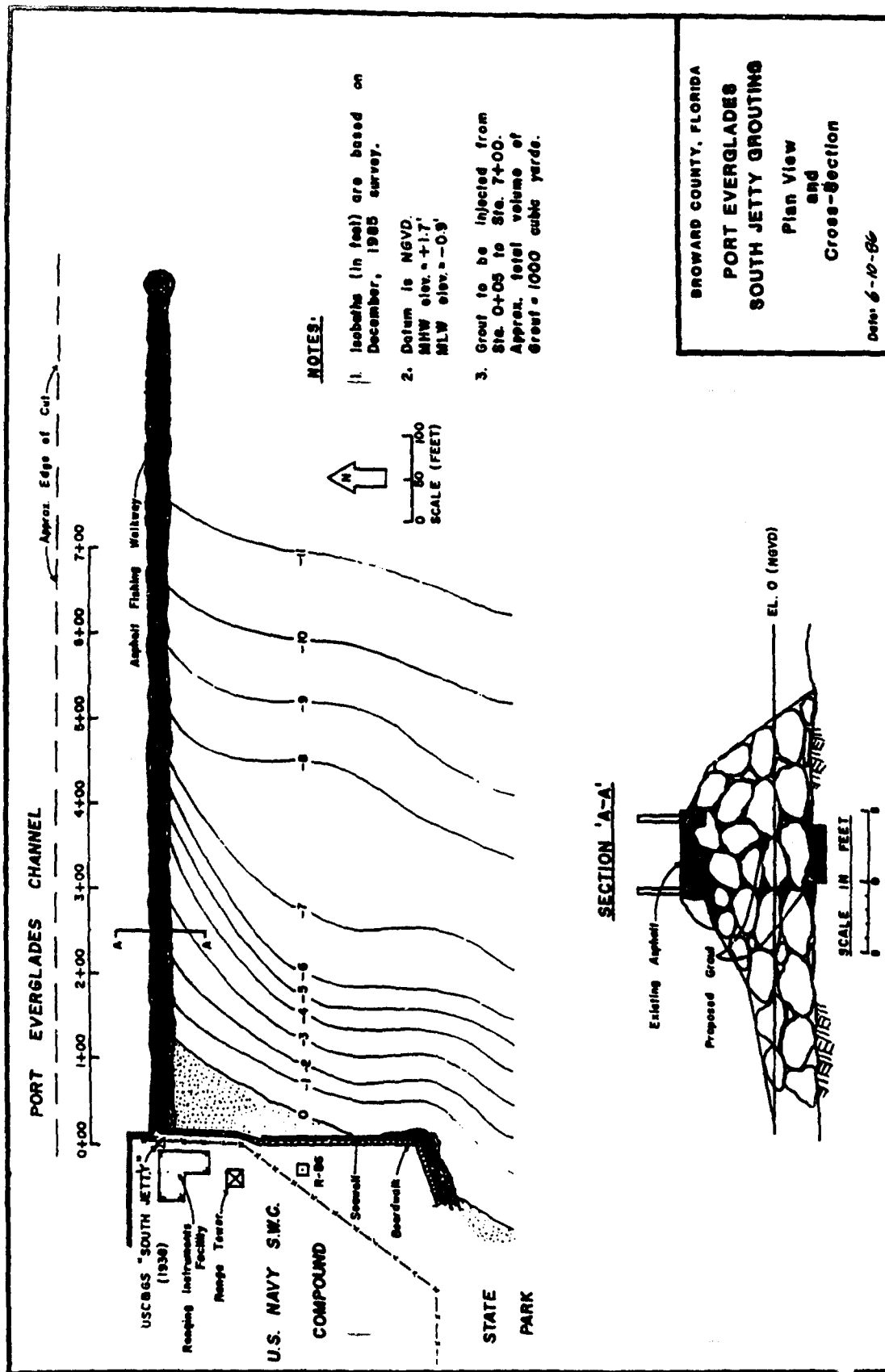


Figure 77. Plan view and cross section, Port Everglades, FL, south jetty sealing project (after BCEQCB 1986)

large gaps and voids near the base . . ." (BCEQCB 1986). County personnel discussed the lack of sand accumulation on either side of the structure and concluded that ". . . if sand is passing through the structure, it happens during periods of high waves from the southeast, and is spread out by the ebb current along and into the Port Everglades channel . . ." (BCEQCB 1986).

348. Based on entrance channel dredging quantities from 1934 to 1962 totaling 5,078,000 cu yd and survey records showing growth of the north fillet to be approximately 24,000 cu yd/year, Broward County personnel concluded that the inlet channel is nearly a complete barrier to the southward movement of littoral sediments (BCEQCB 1986). The 26,000 cu yd/year that presumably bypasses the north jetty apparently never reaches the beach south of the inlet (BCEQCB 1986).

349. During periods of northerly sediment transport, a buildup of a fillet at the south jetty would be expected. However, only a small accumulation has been apparent, possibly due to loss of material through the porous south jetty. A dye study also conducted by Broward County personnel in February 1985 confirmed that the structure was very permeable, and it was estimated that at least 5,000 cu yd/year passed through the structure and accumulated in the navigation channel, primarily on ebb tides. However, the methodology used to estimate this quantity passing through the structure was not discussed. Nourishment of the 7,920-ft section south of the south jetty with 500,000 cu yd of material was planned to restore the beach (Figure 78), and the proposed sealing of the south jetty was determined to be a cost-effective alternative to losing the estimated 5,000 cu yd/year of beach material through the structure. Sealing the portion of the jetty that would be adjacent to the beach fill, the shoreward 700 ft, was estimated to save approximately \$159,000/year as opposed to replacing the estimated quantity of littoral material lost through the structure (BCEQCB 1986).

Jetty Drilling and Sealing

350. The voids in the Port Everglades south jetty were sealed with sodium silicate-cement sealant such that it would function as a terminal groin to the John U. Lloyd State Park beach fill. The sand layer beneath the jetty and the voids within the structure that were filled with sand were stabilized with sodium silicate-diacetin sealant. The rehabilitation effort began in September 1988 and was completed in November 1988. The contractor,

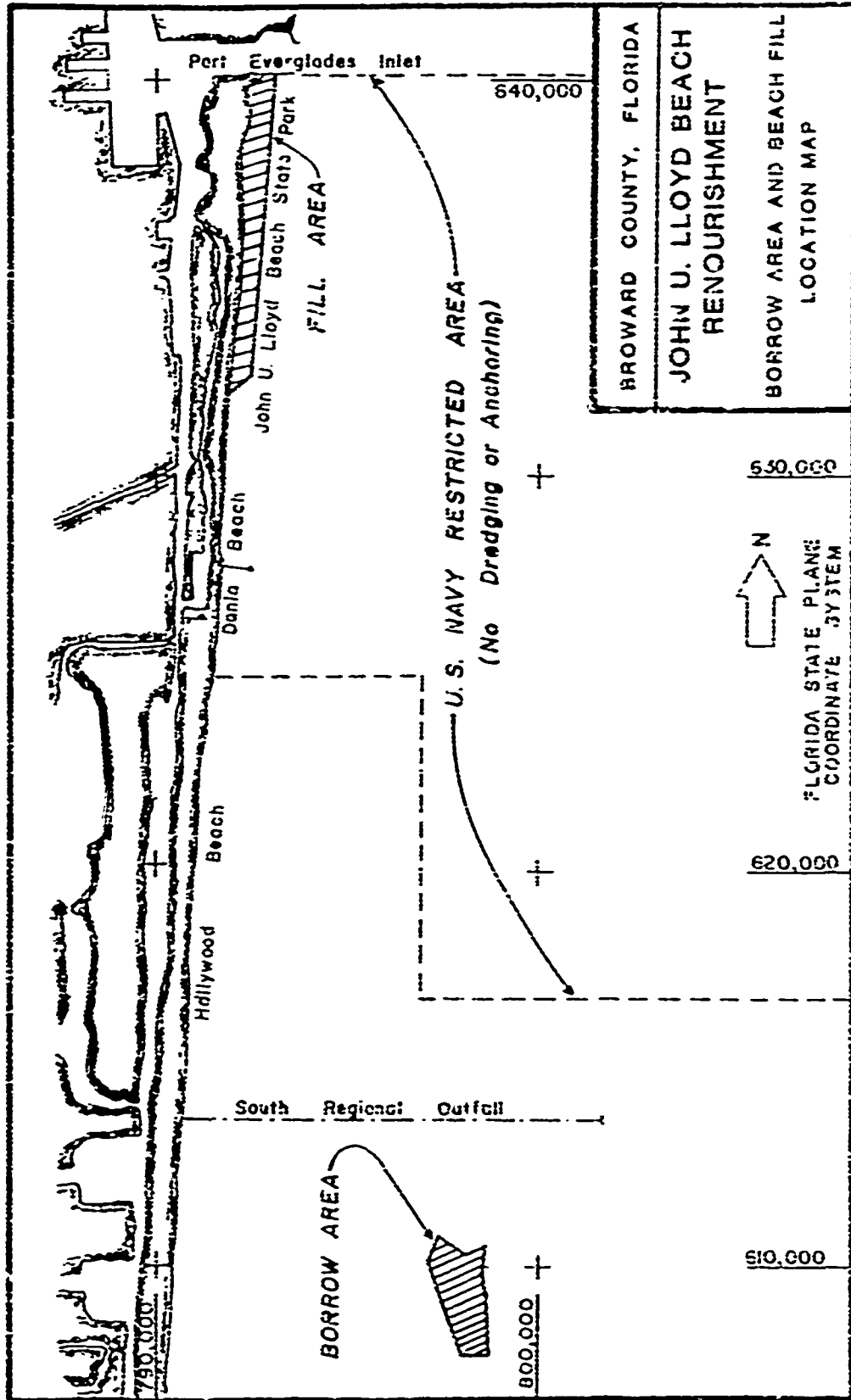


Figure 78. Location of beach fill along John U. Lloyd Beach State Park, adjacent to south jetties, Port Everglades, F. (modified after BCEQCB 1986)

W. G. Jaques Company, Des Moines, IA, was required to complete sealing the landward half of the structure prior to the placement of beach fill; in actuality, all rehabilitation sealing was completed before placement of the beach fill in May 1989.

351. The 3-1/2-in.-diam sealant holes at 3-ft spacings along the center line of the structure were drilled to previously specified elevations beneath the structure bed. The asphalt fishing walkway provided an ideal foundation from which to operate the drilling and sealing operation. Initially, every alternate hole (primary) located 6 ft apart was sealed with sodium silicate-cement sealant, which began to "set up" in 70 to 80 sec. After the primary holes were sufficiently strengthened (approximately 24 hr), the secondary holes (also located 6 ft apart) existing between the primary holes were sealed with the sodium silicate-cement sealant. Usually the quantity of sealant required for the secondary holes was on the order of only 10 percent of the adjacent primary hole quantity. It was expected that this procedure would result in a 4-ft-wide sealant curtain longitudinally within the structure.

352. After the secondary holes had strengthened, the primary holes were redrilled, and a quick-set sodium silicate-diacetin sealant designed to permeate any sand-filled areas beneath the structure and in structure voids that had become filled with sand was pumped into the holes. The pumping requirements for the sealant were at least 30 gal/min of sealant slurry and at least 100 psi of pressure. The holes were capped with a nonviscous cement designed to flow into any small voids left open and provide a durable surface on the asphalt walkway. The drilling and sealing procedures are shown in Figures 79 through 84. Quantities of sodium silicate-cement sealant and sodium silicate-diacetin pumped into each hole along the length of the jetty are displayed in Figure 85. The corresponding elevation of the jetty crest, average sand elevation at the jetty base, and depth of drilling as a function of jetty length are shown in Figure 86.

353. An effort was made to obtain post-project cores of selected structure sections by Broward County to evaluate the effectiveness of the sealing operation. However, the alternating degrees of hardness between jetty stone and sealant material caused the cores to crumble during the drilling, and an evaluation could not be accomplished.

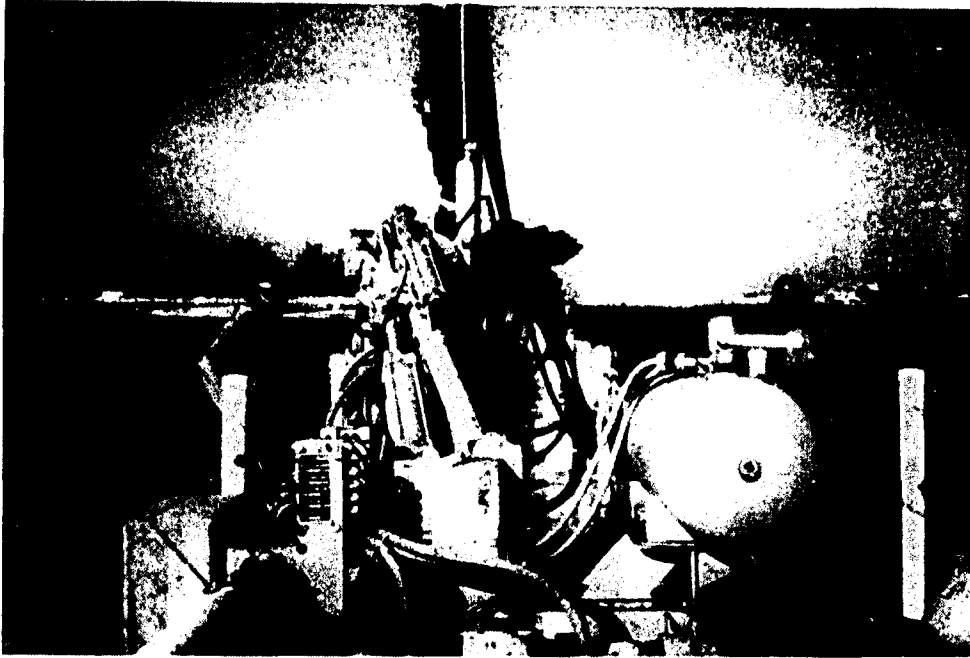


Figure 79. Drilling operations on south jetty
at entrance to Port Everglades, FL



Figure 80. Drilling south jetty at entrance
to Port Everglades, FL



Figure 81. Sealing south jetty at entrance to Port Everglades, FL



Figure 82. Regulating volume flow rate of sodium silicate-cement sealant during sealing south jetty at entrance to Port Everglades, FL



Figure 83. Injecting sodium silicate-cement sealant during sealing south jetty at entrance to Port Everglades, FL



Figure 84. Determining drill hole location for sealing south jetty to Port Everglades, FL

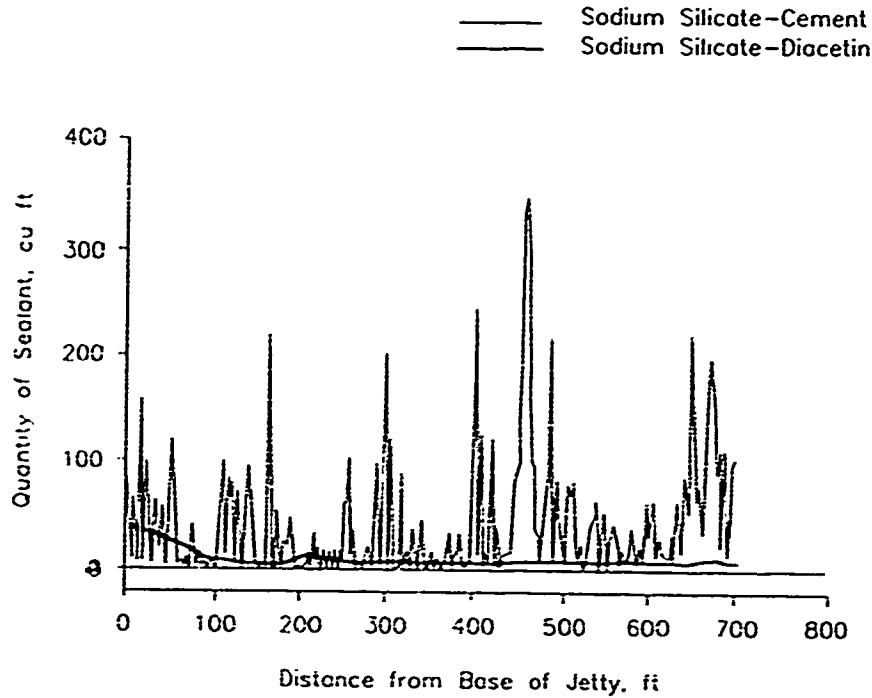


Figure 85. Quantities of sodium silicate-cement and sodium silicate-diacetin sealants placed into south jetty at entrance to Port Everglades, FL

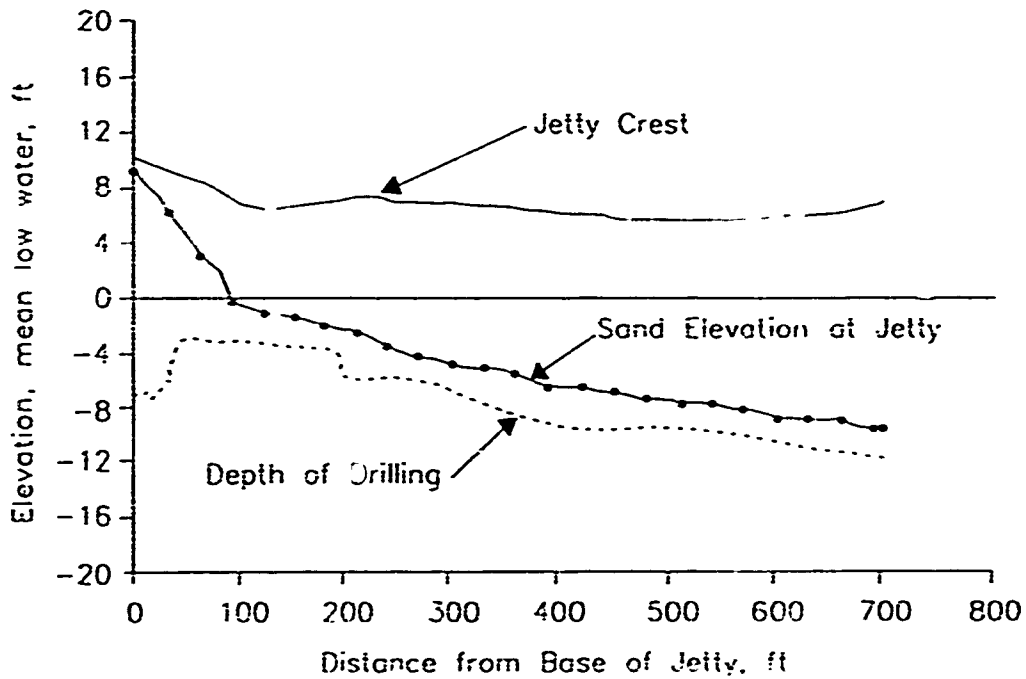


Figure 86. Depth of drilled holes for placing sodium silicate-cement and sodium silicate-diacetin sealants into south jetty at entrance to Port Everglades, FL

Field Monitoring Program at Port Everglades, FL

354. The purpose of the monitoring program was to evaluate the degree of structure permeability both before and after grouting. Qualitative information such as the condition of the structure determined from underwater inspection and the presence or absence of bed forms and shoals were used as indicators of structure permeability. The amount of water exchange from one side of the structure to the other, as indicated by the movement of dye, was used as the primary quantitative indicator of structure permeability. Current velocities in structure voids before and after grouting were also measured in an attempt to quantify the rate of net fluid movement through the structure. Attempts to quantify sand transport through the structure using suspended load sand traps and bed-load pan samplers were unsuccessful, primarily due to the lack of littoral transport during the experiment intervals. Large quantities of material may move through the structure only during storm events.

355. The monitoring program consisted of four phases: (a) reconnaissance evaluation designed to obtain preliminary information so that later phases of the monitoring program could be better planned, (b) preconstruction experiment to qualitatively and quantitatively evaluate the presealing condition of the structure, (c) during-construction observations of the drilling and sealing techniques, and (d) postconstruction experiment that repeated tests conducted during the preconstruction phase so that the degree to which structure sealing occurred could be assessed.

Reconnaissance evaluation

356. The purpose of the reconnaissance trip, conducted during the period 27-29 June 1988, was to obtain detailed information about the south jetty infrastructure, current patterns, and surrounding beach and bathymetry conditions so that later phases of the monitoring program could be better planned. In particular, the following information was collected: (a) locations, dimensions, and photographs of structure voids for possible future mounting of current meters and sediment traps, (b) characteristics and photographs of the seabed north and south of the jetty, (c) current velocities and patterns through the structure during peak flood and ebb flows, and (d) sketches and photographs of dye dispersion through the structure during peak flood and ebb flows.

357. Structure voids. On the morning and early afternoon of 27 June 1988, a snorkeling inspection of the north and south sides of the south jetty

was conducted. Larger structure voids that extended far into the structure were located and measured (Figures 87 through 89), and three voids on the

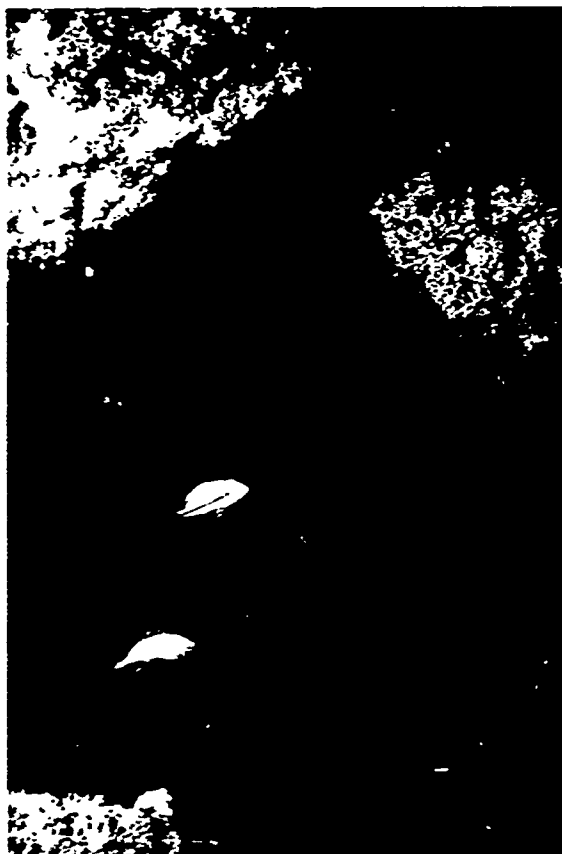


Figure 87. Large structure voids on south side of jetty at entrance to Port Everglades, FL

south side of the jetty were identified for possible placement of current meters and sediment traps during future experiments. The three voids chosen extended deep into the structure, were at least partially filled with water at all tide levels, and were located approximately at the toe of the proposed beach fill (Sta 6+40), at the crest of the proposed beach fill (Sta 4+70), and near the existing storm breaker line (Sta 3+76, 6-ft mean water depth).

358. Characteristics of the seabed. During the structure void inspection, characteristics of the seabed north and south of the structure were also noted. Except for an area on the shoreward end of the north side of the jetty, the seabed extending from 5 to 15 ft out from the sides of the structure consisted of small pieces of coral. The region extending farther than

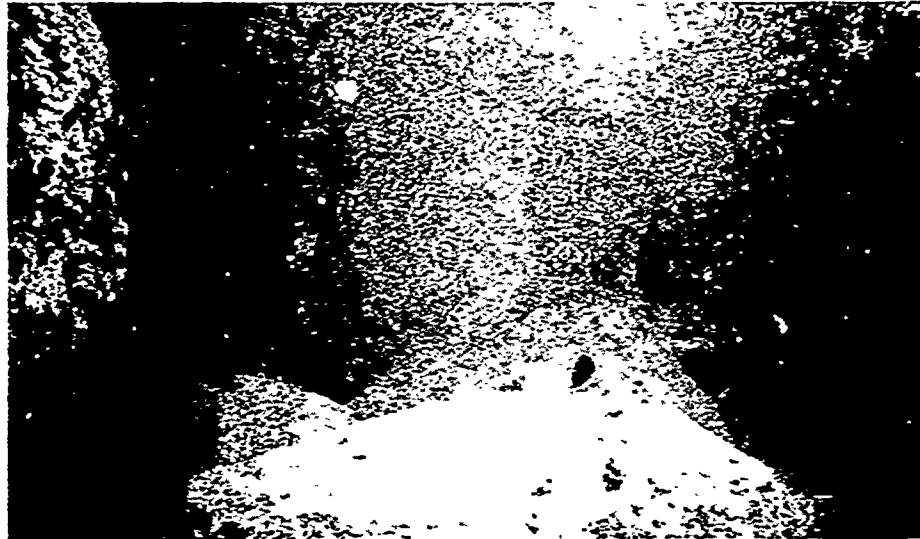


Figure 28. Large structure voids on south side of jetty at entrance to Port Everglades, FL, where current meter was placed

15 ft from the structure was sandy, with wave-induced ripples in shallower water. The seabed extending for approximately 100 ft along the shoreward portion of the north side of the jetty was mostly sandy, although some coral fragments were visible. No shoals or large sediment deposits along the length of the structure were noted, indicating that, if sediment passed through the structure, it was carried away from the sides of the jetty. The small area of the seabed visible inside structure voids was composed of fine sand.

359. Currents through the structure. Current velocity through the structure were not measured during the reconnaissance phase due to an equipment failure and logistical problems in obtaining a replacement current meter.

360. Dye dispersion through the structure. Three dye dispersal tests were conducted, during two peak flood flows and an ebb flow. Sand sample bags weighted with rocks and filled with approximately 1/4 to 1/3 cup of powdered fluorescein dye proved to provide the continuous dye source necessary for dye visibility and longevity. Injecting voids with liquid dye from a pressure sprayer did not provide the continuous, concentrated quantity of dye required. On the afternoon of 27 June 1988, a large quantity of powdered dye in a weighted sand sample bag was placed in a void (Sta 4+10) on the south side of the jetty just prior to peak flood flow (0.9 ft/sec). The dye was placed as close to the center of the structure as possible, and the dispersion of dye through time was mapped in planform (Figure 90). During the test, the wind

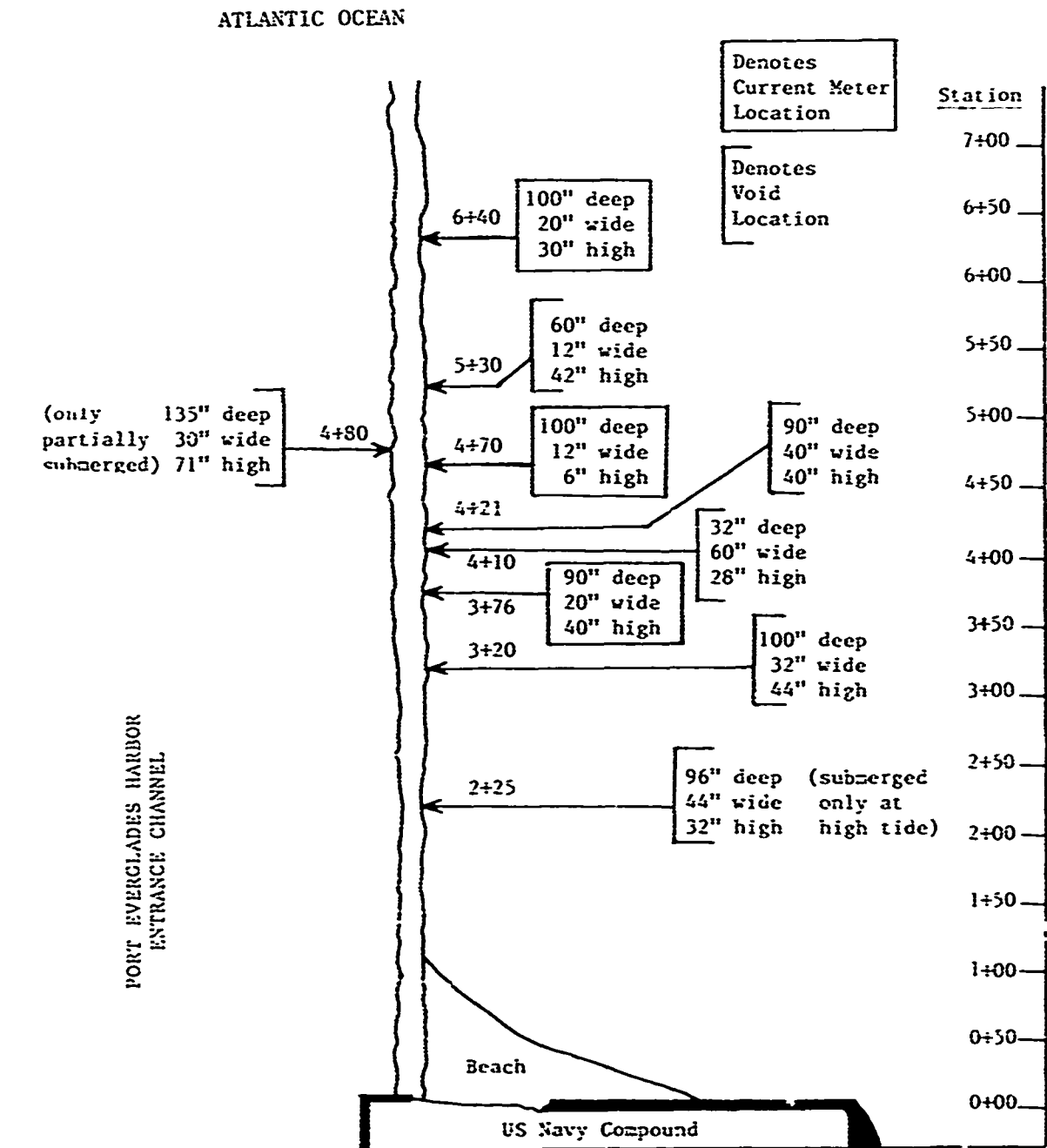


Figure 89. Locations and dimensions of larger structure voids along south jetty at entrance to Port Everglades, FL

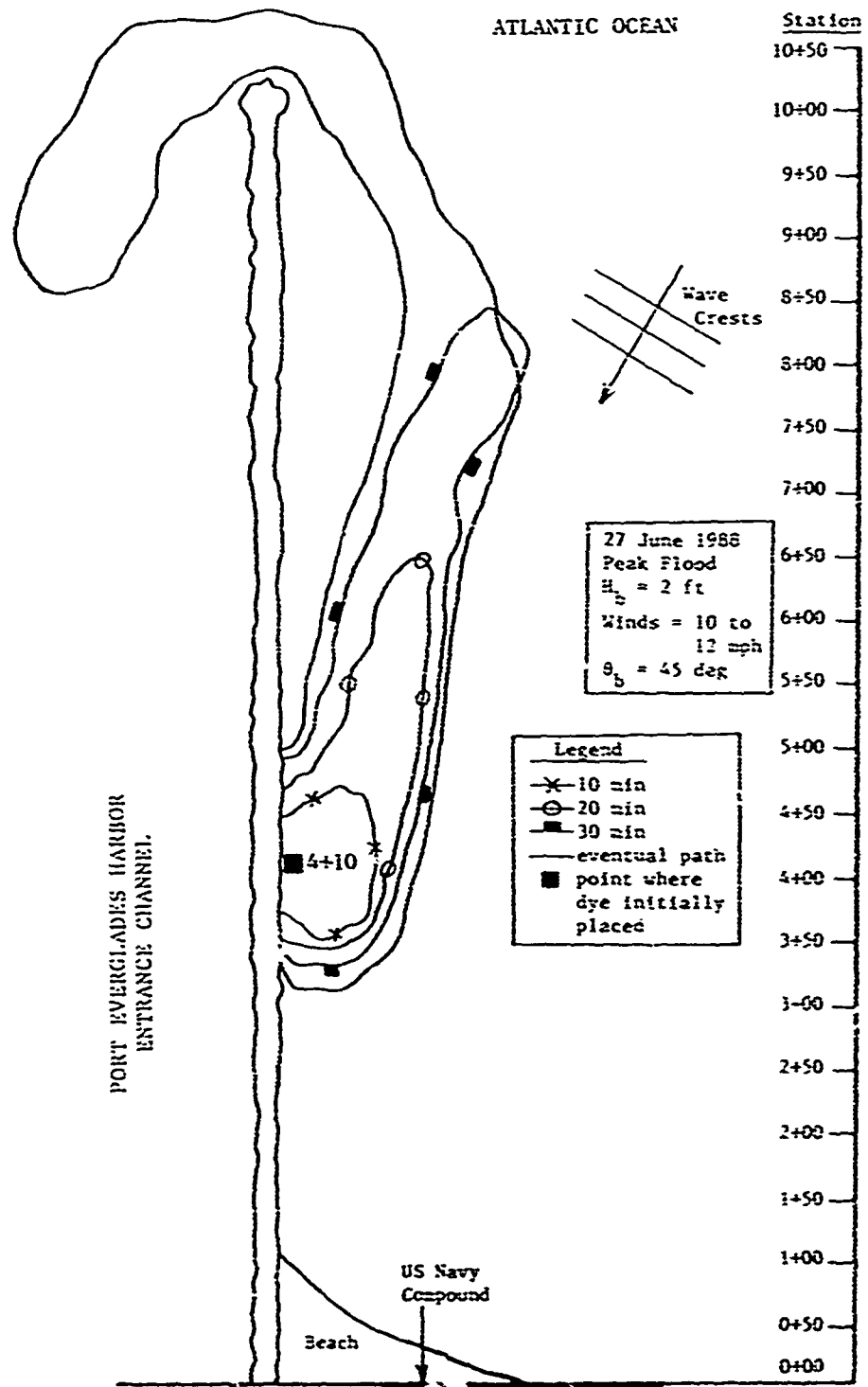


Figure 90. Visually observed dispersion of dye through south jetty at entrance to Port Everglades, FL. peak flood flow. 27 June 1988

speed was from 10 to 12 mph from the southeast, and 2-ft-high waves from the southeast were breaking at an angle of 45 deg to the shoreline. The test indicated that a portion of the dye passed through the structure in approximately 10 min; however, a large portion of the dye was carried offshore, along the length of the structure and into the channel by the flood flow approximately 1 hr after dye release.

361. The dispersion of dye placed at two voids on the north side of the south jetty (Sta 4+10 and Sta 4+80) 10 min prior to peak ebb flow (1.1 ft/sec) on the morning of 28 June 1988 was documented with oblique aerial photography for an hour after peak ebb flow. The dispersion of dye through time is mapped in Figure 91. The dye passed through the structure to the south side at two locations within 10 min. Winds were calm, with a breaking wave height of about 0.5 ft at approximately 10 deg to the shoreline from the southeast.

362. The third dye dispersal test was conducted on the afternoon of 28 June 1988 at peak flood velocity (1.1 ft/sec). Winds were approximately 8.5 to 9.5 mph, and 2-ft-high waves from the southeast were breaking at a 45-deg angle to the shoreline. The dispersal of dye was documented with oblique aerial photography for approximately an hour after dye release. Weighted sand sample bags partially filled with powdered dye were placed as close to the structure as possible in voids at Sta 3+76, Sta 4+70, and Sta 6+40 on the south side of the structure. A weighted dye packet was also thrown into the surf zone from the south end of the Navy Compound to indicate the direction and relative magnitude of any longshore current. The dispersion of dye from the structure voids was similar to that observed on the afternoon of 27 June 1988, with the same tendency for offshore movement of dye along the length of structure (Figure 92). Dye passed through the structure voids at Sta 4+70 in approximately 10 min and at Sta 6+40 in approximately 20 min, respectively. The dye thrown into the surf zone at the south end of the Navy Compound dissipated, only indicating a slight longshore current.

363. Sediment transport indication. Several qualitative measurements of sediment transport through the structure were made, using suspended bottle sediment samplers, a streamer trap nozzle, and a pan bed-load sampler. Three suspended sediment samples were collected at the bed, middepth, and surface elevations using an 8-oz bottle on the south side of the south jetty on the afternoon of 27 June 1988. Approximate weights of sediment in the bottom, middepth, and surface samples were 2.1 and 0.5 g, respectively.

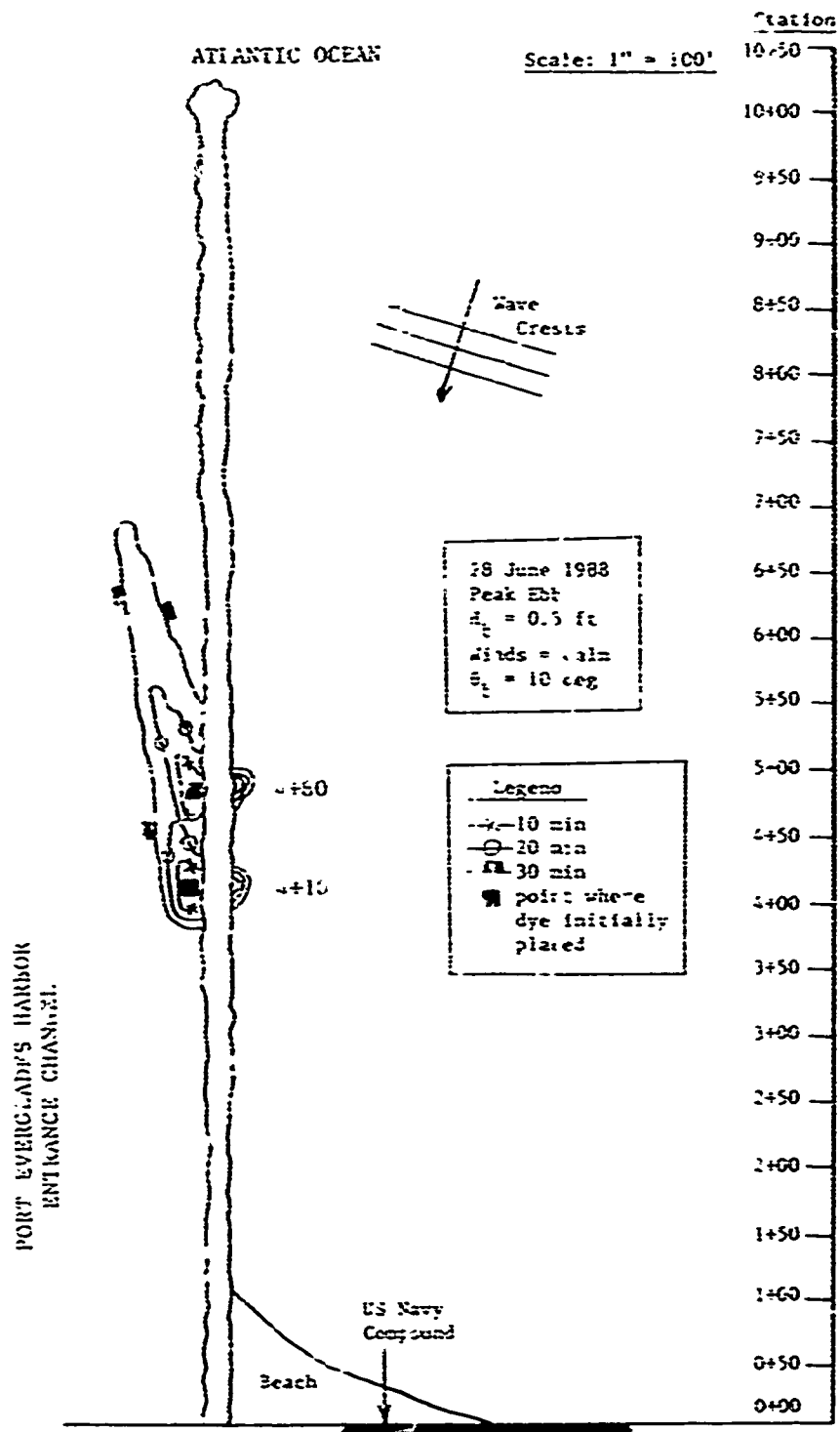


Figure 91. Visually observed dispersion of dye through south jetty at entrance to Port Everglades, FL, peak ebb flow, 28 June 1988

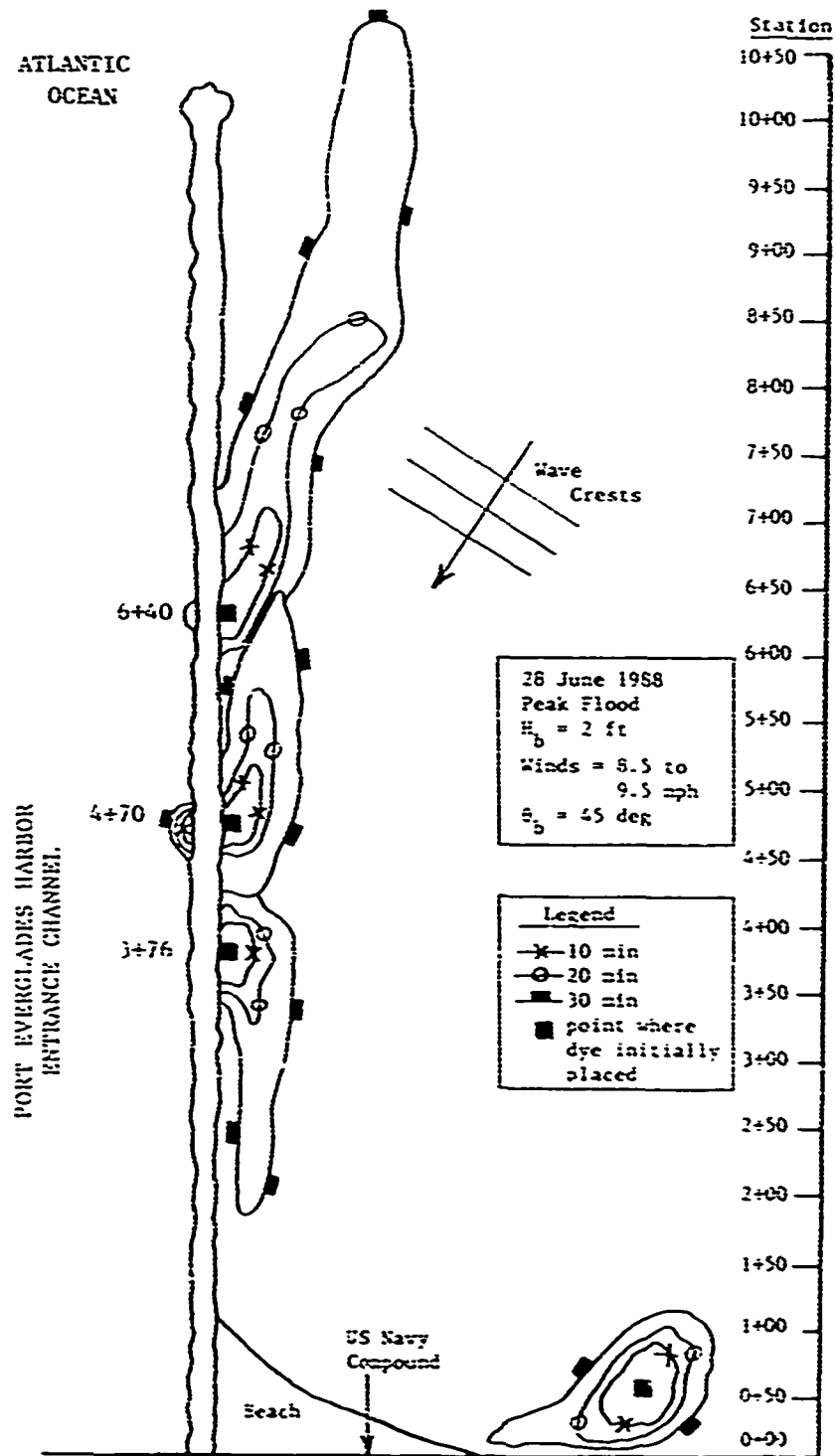


Figure 92. Visually observed dispersion of dye through south jetty at entrance to Port Everglades, FL. peak flood flow, 28 June 1988

364. A streamer trap nozzle was placed in the void at Sta 3+76 near the bed on the morning of 28 June 1988. The mouth of the nozzle was oriented such that sediment entering the structure at that location would be collected in the streamer. The streamer bag extended deep into the void. The nozzle was removed on the afternoon of 28 June 1988, and it was observed that the streamer bag extended out of the void, such that the streamer mouth was effectively closed by the streamer bag. Very little sediment had been collected in the streamer.

365. An attempt was made to bury a pan bed-load sampler to the depth of the bed; however, it was difficult to dig a trough in the coral bed near the structure during higher wave action. Instead, two pan bed-load samplers were weighted with pieces of coral and placed in two voids at Sta 4+21 and Sta 5+30 on the afternoon of 27 June 1988. The pan in void Sta 4+21 was retrieved on the morning of 28 June and had not collected any sediment; the pan in void Sta 5+30 was lost. It was decided that the sediment traps and bed-load pan samplers would not be used to measure sediment transport through the structure in later phases of the monitoring program.

Preconstruction experiment

366. The preconstruction experiment, conducted during the period 22-26 August 1988, consisted of collecting current magnitude and direction data in three structure voids and measuring the time rate of dye dispersal through the structure with a fluorometer. Data were collected for an hour, beginning 1/2 hr prior to either peak flood, peak ebb, or slack flow.

367. Dye study. One-fourth of a rhodamine dye "donut" (3-in. diameter) was placed in sediment sample bags weighted with coral, and the packets were placed as far into structure voids as possible at the start of each data collection (Figure 93). Because of the extreme sensitivity of the fluorometer to rhodamine dye, this type of dye rather than fluorescein was used during all experiments after the reconnaissance trip. During peak flood conditions, the packets were placed on the south side of the structure, in voids at Sta 3+76, Sta 4+70, and Sta 6+40. During peak ebb, the packets were placed in crevices on the north side corresponding to these voids. Dye packets were placed on the side of the structure with the most wave action during slack flow conditions. Surface water samples were taken every 10 min for an hour at all three stations, both on the south and north sides of the structure. Water samples were also taken at the seabed for several tests to determine if dye transmission was uniform with depth. Samples were retained and analyzed at the site



Figure 93. Preconstruction dye transmission test at south jetty to entrance at Port Everglades, FL

after each test was completed using a portable field fluorometer. Seven dye transmission tests were conducted during the preconstruction experiment, one at high-water slack and two each at low-water slack, peak ebb flow, and peak flood flow.

368. Current meters. One-inch diameter Marsh-McBirney electromagnetic current meters (Figure 94) were mounted in voids at Sta 3+76, Sta 4+70, and Sta 6+40 using a turnbolt bracing system. The current meter mounting system was stabilized as the braces were tightened against the armor stone, so that the current meter was positioned in the center of the void. The current meters were cabled to shore and data were stored in a portable computer.

During-construction observations

369. Details of the drilling and sealing procedure were observed during the period 9-11 October 1988. In addition, a dye test designed to evaluate the degree to which the sealant permeated the structure voids in a representative section was conducted. At the time of the site visit, both sodium silicate-cement and sodium silicate-diacetin sealing had been completed in the shoreward 350 ft of the structure, and primary hole sodium silicate-cement sealing was continuing in the seaward portion of the structure.

370. Underwater inspection. An inspection of the underwater portion of the jetty was conducted using snorkeling gear. Small portions of sealant



Figure 94. Marsh-McBirney electromagnetic current meter for velocity measurements through south jetty at entrance to Port Everglades, FL

could be occasionally observed in smaller voids located farther in the structure, indicating that the material had indeed filled the voids in that area. A 50-ft-wide area of sealant extending south from Sta 3+15 (section already completed) was observed on the seabed. A thin crust had formed on the top of the material, which was primarily cement. Extending out 150 ft from Sta 3+15, 0.5- to 1-ft-diam "sealant stones" were lying on the seabed. These stones were composed primarily of sodium silicate. The sealant stones became brittle when left out of the water overnight, and outside layers of sealant easily crumbled off. This region of sealant south of Sta 3+15 was discussed and observed by the contractor and county personnel. Both the county and contractor believed the most likely reason for the sealant in the area was due to the contractor's practice of flushing the sealant pipe over the side of the jetty

when it occasionally became clogged with a stiff sealant mixture, rather than extensive loss of sealant through large structure voids.

371. Dye dispersal test. The dispersal of dye from an unsealed secondary hole adjacent to two unsealed primary holes (representative unsealed section) was compared with the dispersal of dye from an unsealed secondary hole adjacent to two sealed primary holes (representative sealed section). The time history of dye dispersal was measured during a peak ebb flow. On 10 October 1988, one-fourth of a rhodamine dye "donut" was placed in an unsealed secondary hole at Sta 4+68 approximately 30 min prior to peak ebb flow (Figure 95). Water samples were taken at 10-min intervals on the north

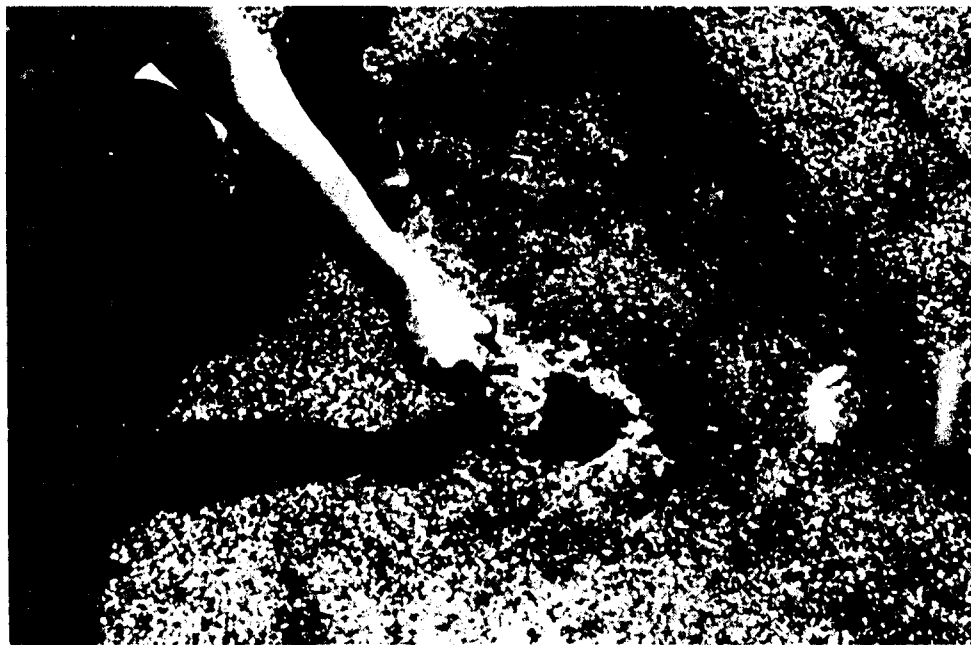


Figure 95. Portion of dye "donut" being placed in sealant drill hole during sealing of south jetty at entrance to Port Everglades, FL

and south sides of the structure for 1 hr. Dye was visually observed to pass through the structure within 1 min. A similar procedure was followed for a test of an unsealed secondary hole bordered by two sealed primary holes at Sta 3+75 on 11 October 1988. Dye was never visually observed to pass through the structure, although the fluorescence of the water did increase slightly during the 1-hr measurement period.

Postconstruction experiment

372. The postconstruction experiment was conducted from 29 January through 1 February 1989 and consisted of collecting data similar to those

measured in the preconstruction experiment phase. Dye transmission and current meter data were measured at one peak ebb, two high-water slack, and two peak flood conditions, with tidal currents similar to those that occurred in the previous tests. The dye tests were conducted with the same techniques utilized in the preconstruction tests, with packets released in voids at Sta 3+76, Sta 4+70, and Sta 6+40. Occasionally, dye packets released from a previous test were visually observed to be emitting dye prior to the start of a later test conducted on the same day. For these situations, additional dye was not released for the later test. One-inch Marsh-McBirney current meters were positioned in the three voids, with an additional 3-in. Marsh-McBirney current meter deployed approximately 50 ft south of the void at Sta 4+70 for all but one test, in which it was positioned approximately 50 ft north of the same void.

Field Monitoring Conclusions

Reconnaissance observations

373. Information gathered during the reconnaissance evaluation indicated that a current might be diverted offshore at the Port Everglades south jetty during certain wave and tidal conditions, surmised from both the absence of sediment near the structure and the offshore movement of dye along the length of the structure during peak flood flows with onshore winds. A streamer trap that had been placed in a structure void was displaced, with the orientation of the streamer bag extending out from the void. The bag orientation indicated that there might be some reflection of wave energy away from the structure that might contribute to the offshore current. The offshore current could be a contributing factor in the persistent erosion of the south beach; however, a strong current would be necessary to entrain sediment through the 12- to 15-ft water depths at the head of the structure. In addition, the absence of sediment along the major length of the structure might only indicate that the source for sediment movement through the structure had been depleted.

During-construction dye transmission

374. The rates of dye transmission through unsealed and sealed sections of the structure were evaluated during the site visit to observe the sealing operation. Dye was placed in hollow sealant holes during two peak ebb conditions. The first test measured dye transmission from a hollow sealant hole

adjacent to two hollow sealant holes (unsealed test). During the second test, dye was placed in a hollow sealant hole adjacent to two sealed holes (sealed test). Results of these tests are presented in Table 13.

Table 13
During-Construction Dye Transmission South Jetty Sealing,
Port Everglades, FL

<u>Location</u>	<u>Date of Test</u>	<u>Peak Ebb Current knot</u>	<u>Concentration, ppm</u>	
			<u>South</u>	<u>North</u>
"Unsealed" Sta 4+68	10/10/88	0.6	92.3	17.0
"Sealed" Sta 3+76	10/11/88	0.6	0.1	0.0

375. Assuming that the same concentration of dye existed in each drill hole (similar quantity of dye released, same water level in voids, etc.), then transmission of the sealed section decreased 99.9 percent on the south side and 100.0 percent on the north side of the structure. If it is assumed that the cross sections of the structure at these stations were originally similar with similar permeabilities and that these two sections were representative "unsealed" and "sealed" sections, this test suggests that sealing of the structure was extremely successful in filling structure voids.

Pre- and postconstruction dye transmission comparison

376. Table 14 presents the concentration of dye for the source (location dye was placed) voids and sink (location dye transmitted) voids, averaged over the data collection interval (usually 60 min) for both the pre- and postconstruction experiments. The average percent transmission was computed by dividing the sink concentration by the source concentration and multiplying by 100. The percent transmission (also referred to as transmission coefficient) is tabulated in the last column for each void during each test. The average percent transmission prior to the sealing was 5.6 and 1.9 percent after the sealing (t-statistic = -1.35). This t statistic indicates that there is an 80-percent probability that a statistically significant difference exists between the two construction conditions. The low-water slack flow condition occurs only during the presealing phase. It is reasonable to remove these measurements from the data set to increase uniformity in flow conditions

Table 14

Average Concentration and Percent Transmission for South Jetty
Pre- and Postconstruction Sealing Tests, Port Everglades, FL

<u>Flow Condition</u>	<u>Date</u>	<u>Location Station</u>	<u>Average*</u>		<u>Percent Transmission</u>
			<u>Concentration, ppm Source</u>	<u>Sink</u>	
High water slack	8/23/88	3+76	44.8	0.0	0.0
High water slack	8/23/88	4+70	21.0	1.8	8.6
Peak ebb	8/24/88	3+76	22.8	0.7	3.1
Peak ebb	8/24/88	4+70	11.5	0.9	7.8
Low water slack	8/24/88	3+76	13.4	0.1	0.7
Low water slack	8/24/88	4+70	70.8	0.1	0.1
Low water slack	8/24/88	6+40	13.2	0.0	0.0
Peak flood	8/24/88	3+76	3.7	0.0	0.0
Peak flood	8/24/88	4+70	1.2	0.1	8.3
Peak ebb	8/25/88	3+76	3.5	1.7	48.6
Peak ebb	8/25/88	4+70	8.3	0.9	10.8
Low water slack	8/25/88	3+76	7.0	0.0	0.0
Low water slack	8/25/88	4+70	3.2	0.0	0.0
Peak flood	8/25/88	3+76	20.4	0.0	0.0
Peak flood	8/25/88	4+70	11.1	0.1	0.9
Peak flood	8/25/88	6+40	0.6	0.0	0.0
Presealing Average Transmission Coefficient:					5.6
Peak ebb	1/30/89	3+76	123.9	0.5	0.4
Peak ebb	1/30/89	4+70	164.1	13.2	8.0
Peak ebb	1/30/89	6+40	84.1	0.3	0.4
Peak flood	1/31/89	3+76	120.0	2.0	1.7
Peak flood	1/31/89	4+70	346.5	1.9	0.5
Peak flood	1/31/89	6+40	397.1	1.7	0.4
High water slack	1/31/89	3+76	35.2	0.2	0.6
High water slack	1/31/89	4+70	79.3	0.4	0.5
High water slack	1/31/89	6+40	20.9	0.4	1.9
Peak flood	2/01/89	3+76	125.1	0.3	0.2
Peak flood	2/01/89	4+70	278.9	0.5	0.2
Peak flood	2/01/89	6+40	210.4	0.6	0.3
Peak flood	2/01/89	7+00	74.7	0.8	1.1
High water slack	2/01/89	3+76	8.6	0.2	2.3
High water slack	2/01/89	4+70	5.4	0.2	3.7
High water slack	2/01/89	6+40	9.9	0.3	3.0
High water slack	2/01/89	7+00	8.6	0.5	5.8
Peak ebb	2/02/89	3+76	176.1**	1.0**	0.6
Peak ebb	2/02/89	4+70	79.8**	6.0**	7.5
Peak ebb	2/02/89	6+40	102.0**	0.1**	0.1
Peak ebb	2/02/89	7+00	97.8	1.0	1.0
Postsealing Average Transmission Coefficient:					1.9

* Averaged over data collection period.

** Prior measurement subtracted from succeeding data to obtain average.

between the pre- and postsealing conditions. Removing these data reveals an average percent transmissibility prior to sealing of 8.0 and 1.9 percent after sealing (t-statistic = -1.96). There is a nearly 95-percent probability that the difference is statistically significant.

377. Because of the nonuniformity in flow conditions between the pre- and postsealing events, each flow condition should be examined separately. The largest difference between the pre- and postsealing situations occurred during peak ebb flow conditions. During peak ebb there is at least a 90-percent probability that a significant difference exists between the two construction conditions (t-statistic = -1.93). During peak flood events there is no significant difference between the two construction conditions (t-statistic = -0.88). A comparison of the high-water slack events also shows no significant difference (t-statistic = -0.76) between the pre- and post-sealing situations. A tabulation of the statistics is presented in Table 15.

Table 15
Statistics on Percent Transmission for Different Flow Conditions
Sealing South Jetty, Port Everglades, FL

<u>Flow Condition</u>	<u>Percent Transmission</u>		<u>t-Statistic</u>	<u>Percent Significant</u>
	<u>Presealing Mean</u>	<u>Postsealing Mean</u>		
Combined flow	5.6	1.9	-1.35	81.4
Combined flow w/o low-water slack	8.0	1.9	-1.96	94.0
Peak ebb flow	17.6	2.6	-1.93	91.4
Peak flood flow	1.8	0.6	-0.88	60.3
High-water slack	4.3	2.5	-0.76	53.0

378. These results must be interpreted with caution for the following three reasons. First, the transmission coefficients in the presealing condition are not normally distributed but are rather positively skewed. This is caused by the 48.6-percent transmission that occurred on 25 August 1989 during peak ebb flow. This outlier is very much larger than the other data points

and has a strong effect on raising the mean. If this outlier is removed from the data set, the statistical differences between the pre- and postsealing conditions weakens. For example, the probability of a statistically significant difference between the transmissibility coefficients during the pre- and postsealing conditions for the entire data set slips from just over 80 percent (t-statistic = -1.35) to no significance (t-statistic = -0.72). When considering the data set with the low-water slack data removed, the probability of a significant difference between the transmissibility coefficient in each data sets slips from nearly 95 percent (t-statistic = -1.96) to less than 90 percent (t-statistic = -1.67) when the outlier is removed. When isolating the peak ebb flow conditions, the probability of a significant difference between the pre- and posttransmissibility data is reduced from over 90 percent (t-statistic = -1.93) to less than 85 percent (t-statistic = -1.78). The revised statistics are presented in Table 16.

Table 16
Statistics on Percent Transmission with Outlier Removed
Sealing South Jetty, Port Everglades, FL

<u>Flow Condition</u>	<u>Percent Transmission</u>		<u>t-Statistic</u>	<u>Percent Significant</u>
	<u>Presealing Mean</u>	<u>Postsealing Mean</u>		
Combined flow	2.7	1.9	-0.72	52.6
Combined flow w/o low water slack	4.0	1.9	-1.67	89.5
Peak ebb flow	7.2	2.6	-1.78	84.0
Peak flood flow	1.8	0.6	-0.88	60.3
High water slack	4.3	2.5	-0.76	53.0

379. Second, a significant relationship between the source and sink data in either the pre- or postsealing conditions appears only during the peak ebb flow condition. One would expect that during the presealing condition, as more dye is added to the water, more dye should move through the structure. Such a relationship does not exist when all the flow data are analyzed

together. A regression of sink concentration as a function of source concentration shows a coefficient of determination, r^2 , of 0.008 in the pre-sealing condition and 0.029 during the postsealing phase. The coefficient of determination is used to ascertain the variability in the data that may be explained by the correlation between variables. In this case the sink concentrations are completely independent of the source concentrations. Table 17 shows the coefficients of determination for the different types of flow regimes investigated.

Table 17
Coefficient of Determination for Different Flow Conditions
Sealing South Jetty, Port Everglades, FL

<u>Flow Condition</u>	<u>Coefficient of Determination, r^2</u>		<u>F-Statistic</u>		<u>Percent Significant</u>	
	<u>Preseal</u>	<u>Postseal</u>	<u>Preseal</u>	<u>Postseal</u>	<u>Preseal</u>	<u>Postseal</u>
Combined flow	0.008	0.029	0.12	0.57	26.2	54.1
Combined flow w/o low-water slack	0.003	0.029	0.03	0.57	13.2	54.1
Peak ebb flow	0.632	0.129	3.43	0.74	79.5	57.1
Peak flood flow	0.019	0.148	0.06	0.87	17.3	60.7
High-water slack	--	0.052	--	0.28	--	37.8

380. The only flow condition that shows a statistical relationship between the source and sink concentrations is the peak ebb flow regime during the presealing condition. In this case the r^2 of 0.632 indicates that a regression line explains 63.2 percent of the variation seen. The F-statistic can be used to test the significance of the r^2 statistic. The F-statistic tests the hypothesis that the linear slope of the dependent variable (sink concentration) is zero. In this case the high F-statistic of 3.43 allows almost 80-percent confidence that the regression line explains at least 63.2 percent of the variation in the amounts of concentration on the source and sink sides of the jetty during the presealing phase of the peak ebb regime.

381. Third, although the same amount of dye was added to the source side of the jetty during each experiment, the resulting concentrations during the postsealing condition were an order of magnitude higher (121.4 ppm) than that during the presealing condition (16.0 ppm). This may bias the study results. These source-side concentrations are significantly different to greater than 99 percent (t -statistic = 3.78). However, the concentrations of dye measured on the sink side of the jetty do not as readily show a significant difference. They are only significantly different to 85 percent (t -statistic = 1.49). Again, the transmission coefficient is obtained by dividing the sink concentrations by the source concentrations and multiplying by 100. Because the postsealing sink concentrations are divided by numbers an order to magnitude larger than the presealing sink concentrations, they will yield a much smaller transmissibility coefficient.

382. It is important to understand why the concentrations of dye were so much higher during the postsealing phase. The most probable explanation is that the success of the sealing allowed less dye to seep into (and eventually through) the structure. The dye could only increase in concentration (as the pellet degraded) on the source side of the jetty. The data also indicate that the highest source-side concentrations were measured during the peak flow conditions. This indicates that the high flow conditions provided added agitation that helped disintegrate the dye pellets.

383. The sealing may be viewed as reducing the permeability of the jetty only during peak ebb flow conditions, and then only to nearly 85-percent statistical certainty.

Pre- and postconstruction current meter data

384. Evaluation of the current meter data was complicated by the fact that some or all of the current meters were above the water level during all or part of the low-water slack tests. Therefore, comparison of the pre- and postconstruction current meter data is limited to the peak flood, high-water slack, and peak ebb tests.

385. Averaging the x - and y -components of the flow for the three current meters deployed during a test results in average magnitude and direction vectors for the pre- and postconstruction experiments. These components are presented in Table 18, and the vectors are displayed in Figure 96 for the peak flood, high-water slack, and peak ebb tests. For the preconstruction tests, average currents move through the structure into the channel for all three flow test conditions. However, the vectors are directed away from the

Table 18
Average Current Data for Pre- and Postconstruction Conditions
Sealing South Jetty, Port Everglades, FL

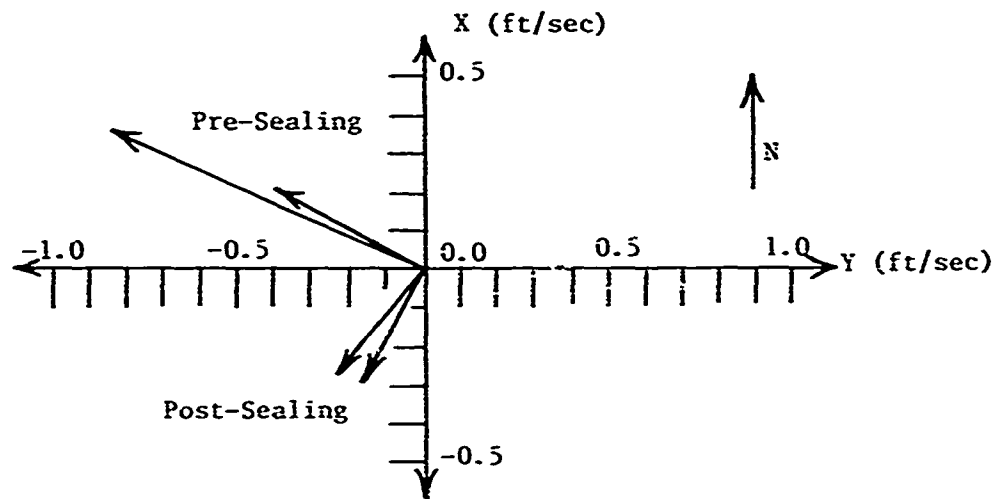
<u>Flow Condition</u>	<u>Preconstruction</u>		<u>Postconstruction</u>	
	<u>X_{AVG}</u> <u>ft/sec</u>	<u>Y_{AVG}</u> <u>ft/sec</u>	<u>X_{AVG}</u> <u>ft/sec</u>	<u>Y_{AVG}</u> <u>ft/sec</u>
Peak flood	0.32	-0.86	-0.30	-0.16
	0.19	-0.40	-0.29	-0.22
	0.03	-0.05	--	--
High slack	0.06	-0.34	-0.36	-0.19
Peak ebb	0.27	-0.55	-0.01*	0.17*
	0.09	-0.55	-0.23	-0.15

* Data available from only two current meters.

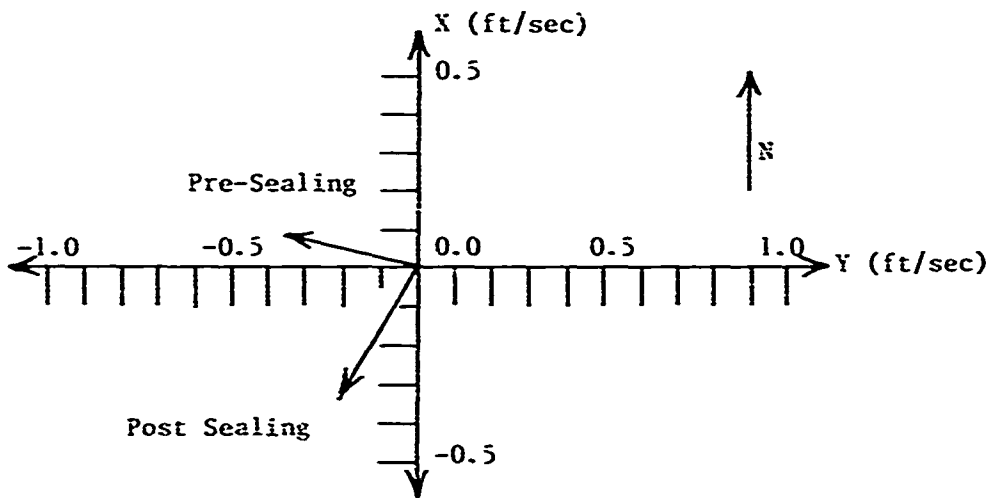
structure in the postconstruction tests, nearly perpendicular to the preconstruction vectors. This change in vector direction demonstrates a deflection in current flow and wave action, indicating a more reflective (hence, less transmissible) cross section.

Evaluation of Jetty Sealing Effectiveness.
Port Everglades, FL

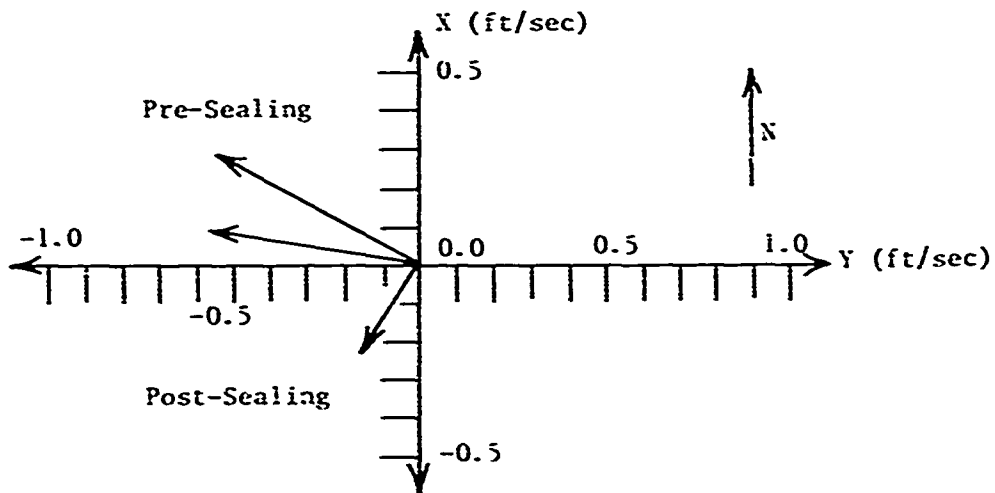
386. The evaluations conducted during the monitoring of the Port Everglades, FL, south jetty sealing project indicate that the transmissibility of the structure has been reduced. Comparison of the concentration of dye transmitted from an unsealed and a sealed section of the structure indicated that the sealing operation decreased structure transmission by almost 100 percent. Dye transmission data obtained before and after structure sealing for the entire structure under all flow conditions indicated that average structure transmissibility had been reduced from 2.7 percent (outlier removed) to 1.9 percent, significant to only a 53-percent level. If the low-water slack test cases are eliminated from the preconstruction test data (to obtain uniformity between the pre- and postconstruction data sets), the unsealed structure was approximately 4.0 percent transmissible (outlier removed), which reduced to 1.9-percent transmissibility after sealing of the structure was completed (nearly 90-percent certainty). A larger decrease in structure transmissibility was observed when the pre- and postconstruction peak ebb flow



a. Peak flood



b. High-water slack



c. Peak ebb

Figure 96. Average currents measured in structure voids for pre- and postsealing conditions at south jetty, Port Everglades, FL

data were compared; however, this decrease is significant only to a low statistical level (not quite 85 percent). A change in average current vector direction, measured during peak flood, high-water slack, and peak ebb conditions, indicated that the structure was more reflective in the postsealing condition and, therefore, less transmissible.

PART XI: SUMMARY AND CONCLUSIONS

Summary

387. Many Corps breakwaters and jetties have become permeable to sand transport and wave transmission, a condition that results in increased Operation and Maintenance dredging costs and increased risks and delays to navigation. The engineering problem facing a coastal planner or engineer is to economically rehabilitate such coastal rubble-mound structure by permanently closing the large voids in a specified zone of its interior, where the void size may be on the order of a metre in diameter. It is apparent that significant first-cost savings could be realized by applying to coastal projects those grouting techniques and sealing procedures developed in civil and mining engineering for closing voids and fractures, instead of the more expensive method of applying layers of chinking and armor stone to the existing structure. However, the longevity of such grouts and sealants placed in voids in the interior of rubble-mound structures exposed to wave and current conditions is not well known. The term "sealant" is used in this report to describe any material that closes voids in rubble-mound structures and includes grouts as well as very stiff, aggregate-containing cementitious and asphaltic materials.

388. The overall problem under investigation was logically separated into two distinct parts. One part required an evaluation of the effectiveness of materials already being used. The second part entailed the development of guidance on sealant hole drilling, quantities to inject, techniques of injection, and knowledge of material properties to effectively create the needed barrier with the optimum combination of drilling effort and sealant quantities. This research investigated three different aspects pertaining to sealing voids in rubble-mound structures with grouts and concrete sealants:

- (a) large-scale laboratory investigations for evaluating the effectiveness of sealant injection into such structures and bioassay tests of materials with potential for adverse environmental effects;
- (b) long-term time-dependent durability exposure testing of sealant specimens in three different prototype environments (cold region: Treat Island, ME; moderate region: Duck, NC; near-tropical region: Miami, FL); and
- (c) precise monitoring of the sealing and resulting effectiveness of a prototype rubble-mound jetty.

Purposes of laboratory investigations

389. Specific objectives of the large-scale laboratory investigations included (a) construction of a rubble-mound physical model at a scale sufficiently large that deviations from similitude would be negligible; (b) preparation and injection into the model two types of cementitious sealants (WES Mixture and Buhne Point Mixture), two types of chemical sealants (Sodium Silicate-Cement Mixture and Sodium Silicate-Diacetin Mixture for sand layer stabilization), and one asphaltic concrete (Sand-Asphaltic Mixture), recording for each the quantities, location of injection, pumping rates, and gel times of the materials; (c) providing specific descriptions of material by precise recording of components and proportions and obtaining determinations of standard parameters for the respective materials; and (d) recording spread, shape, competency, and continuity of the hardened sealants upon disassembly of the structure.

390. Sealants to be evaluated were selected based on their (a) potential to be easily pumped, (b) having a short controllable set time, (c) ability to resist dilution and dispersion, and (d) chemical stability and structural integrity, once set. Materials that previously showed potential for success in field applications by Corps Districts included a stiff concrete mixture with bentonite as an additive (Buhne Point Mixture), a sodium silicate-portland cement mixture (Sodium Silicate-Cement Mixture), and a sodium silicate-formamide mixture. Diacetin also causes gelation of sodium silicate, and this reactant was chosen for use in an experimental mixture (Sodium Silicate-Diacetin Mixture) evaluation because it presents a lower health risk than formamide. There is abundant literature on marine applications of asphalt, but there are no known cases of a sand-asphaltic mixture being injected into jetty voids. Rheological properties of sand asphalt, however, made it (Sand-Asphaltic Mixture) an attractive test material. A concrete mixture (WES Mixture) with certain specific admixtures that gives the material high cohesiveness and relatively high fluidity was developed by WES's Structures Laboratory.

Purposes of long-term exposure testing

391. The sealant durability time-dependent tests were formulated to determine how the sealant materials would endure under actual field conditions. Effects of environmental exposure to waves, currents, freezing and thawing cycles, wetting and drying cycles, abrasion, biological influences, and chemical reactions are being evaluated. A monitoring effort of

indefinitely long duration was established to determine the performance with time of sealant materials in the field environment. Representative samples of each sealant material evaluated in the physical model rubble-mound structure laboratory experimental investigation were cast as specimens and placed in locations with varied climatic conditions. Since the specimen exposure is direct and unconfined, the test is actually more severe and extreme than if the material were placed inside a structure.

392. At each test site (Treat Island, ME; Duck, NC; Miami, FL), the specimens were placed at the two water levels of (a) mean water line and (b) below mean lower low water. These placement locations will allow comparisons between materials that have been continuously submerged with those undergoing wetting and drying cycles due to tidal variations. Although testing techniques vary for different materials, qualitative comparisons will be achieved between all sealant specimens. All specimens were tested immediately prior to placement in the water; hence, subsequent testing will indicate the degree of erosion or deterioration induced by the environmental factors at the sites.

393. Nondestructive and destructive tests were designed for the purpose of documenting aspects of material strength. The change in properties with length of exposure to the environment provides a measure of environmental effects on the sealant. A minimum of four specimens of each sealant type was installed at each water level at each test site to provide the proper number of sampling results.

Purposes of monitoring
prototype structure sealing

394. Sodium silicate-cement and sodium silicate-diacetin chemical sealants were utilized to seal voids in the Port Everglades, FL, south jetty and reduce the transmission of sand through the structure into the navigation channel. Prior to sealing, "man-sized" voids existed in the structure, impairing its function as a terminal groin for beach fills placed south of the structure. Continual erosion of the beach located immediately downcoast (south) of the south jetty to Port Everglades entrance, owned by the State of Florida, prompted Broward County and the State to fund a jetty rehabilitation project and subsequent beach fill of the adjacent beach south of the structure. A monitoring plan to ascertain the effectiveness of the Port Everglades sealing project through a field evaluation was conducted by CERC with the cooperation of Broward County, the State, and the sealing contractor.

395. The voids in the Port Everglades south jetty were sealed with sodium silicate-cement sealant such that it would function as a terminal groin to the John U. Lloyd State Park beach fill. The sand layer beneath the jetty and the voids within the structure that were filled with sand were stabilized with sodium silicate-diacetin sealant. The rehabilitation effort began in September 1988 and was completed in November 1988. The 3-1/2-in.-diam sealant holes at 3-ft spacings along the center line of the structure were drilled to previously specified elevations beneath the bed of the structure. The asphalt fishing walkway provided an ideal platform from which to operate the drilling and sealing operation.

396. Initially, every other hole (primary) was sealed with sodium silicate-cement sealant, which began to "set up" in 70 to 80 sec. After the primary holes were sufficiently strengthened (approximately 24 hr), secondary holes between the primary holes were sealed with the sodium silicate-cement sealant. Usually the quantity of sealant required for the secondary holes was on the order of only 10 percent of the adjacent primary hole quantity. It was expected that this procedure would result in a 4-ft-wide sealant curtain longitudinally within the structure.

397. After the secondary holes had strengthened, the primary holes were redrilled, and a quick-set sodium silicate-diacetin sealant designed to permeate any sand-filled areas beneath the structure and in structure voids that had become filled with sand was pumped into the holes. The pumping requirements for the sealant were at least 30 gal/min of sealant slurry and at least 100 psi of pressure. The holes were capped with a nonviscous cement designed to flow into any small voids left open and provide a durable surface on the asphalt walkway.

Conclusions

398. Sealing coastal structures with chemical gels and concretes shows promise of returning high economic benefits to the project. The technologies of sealant mixtures and injection methods are at an advanced state, due primarily to impetus from the areas of mining, tunneling, foundation engineering, and dam construction. Potentially, many Corps of Engineers projects could benefit from these technologies. Those coastal projects that are candidates for being economically improved by applying sealants in the voids of structures should be catalogued. Structures permitting excessive wave transmission

are easily identified by local citizens and property owners at harbors and mooring areas through personal knowledge and first-hand observations of wave effects during storm events.

Laboratory investigations

399. Sealing rubble-mound coastal structures requires that both the construction grouter and the sponsor field inspector be fully experienced with the materials being used for the sealing work and with the characteristics of the medium being sealed. Problems may still be encountered at the site, but sand-cement mixtures with additives will almost always harden. However, certain mixing or environmental conditions may sometimes prevent sodium silicate sealants from gelling adequately. Large-scale laboratory model results indicated cementitious mixtures containing aggregate achieved a more satisfactory final product for sealing a section than did a sodium silicate-cement sealant, provided the aggregate was not so large as to impede pumping or did not seal off the void interconnections. Dye staining indicated the sodium silicate-cement sealant permeated as far as 5 ft from the injection pipe, but it formed only a weak gel on the floor of the test basin. The sodium silicate-diacetin used to fill the voids in the sand layer did not completely solidify (harden) the sand layer.

400. The disassembled sections of the physical model showed that concrete can form a bulbous mass in a rubble structure when injected underwater. It spread to a radius of at least 3 ft in a rock mass where the stones averaged 50 lb in weight. The average size of the voids was computed to be 0.19 cu ft. The two cementitious sealants (WES Mixture and Buhne Point Mixture) had slumps of 10 and 5 in., respectively.

401. Precise monitoring and control of conditions are required in chemical sealant placement. A set time of 5 to 10 min for chemical sealing of sand-filled voids was found to be appropriate. For filling open voids with a sodium silicate-cement sealant, a fast injection rate (10 gal/min or greater) and a fast set time (about 30 sec) appear to be required.

402. Sand-asphaltic sealant composed of 12-percent AC-30 asphalt seems from initial observations to set hard and bond well, although no means for emplacing it in production quantities has been developed at this time. Pressure injection is necessary, and either 4- or 6-in.-diam pipes are required. Sand-asphaltic concrete heated to 390° F did not react violently when placed in water during this experimental investigation. Mastic asphalt heated to 390° F and emplaced in the structure caused bubbling of asphalt, and steam was

generated. That operation was deemed not satisfactory because of potentially dangerous working conditions and poor void filling results.

Long-term exposure tests

403. Long-term exposure tests to ascertain the durability and longevity of various cementitious and chemical sealants are continuing and will be reported in final form subsequently. Initial exposure results indicate both the WES Mixture and Buhne Point Mixture of cementitious sealants have strength characteristics of other typically representative concretes. The Sodium Silicate-Cement and Sodium Silicate-Diacetin specimens are experiencing significant erosion and deterioration, especially at mean water line where wave effects are greatest. However, this situation may be more extreme than that existing within a rubble-mound structure and, therefore, may not be truly representative of actual conditions to which placed sealants would be subjected.

Monitoring prototype structure sealing

404. The evaluations conducted during the monitoring of the Port Everglades, Florida, south jetty sealing project indicate that the transmissibility of the structure has been reduced. Comparison of the concentration of dye transmitted from an unsealed and a sealed section of the structure indicated that the sealing operation decreased structure transmission by almost 100 percent. Dye transmission data obtained before and after structure sealing for the entire structure under all flow conditions indicated that average structure transmissibility had been reduced from 2.7 percent (outlier removed) to 1.9 percent, significant to only a 53-percent level. If the low-water slack test cases are eliminated from the preconstruction test data (to obtain uniformity between the pre- and postconstruction data sets), the unsealed structure was approximately 4.0 percent transmissible (outlier removed), which reduced to 1.9-percent transmissibility after sealing of the structure was completed (nearly 90-percent certainty). A larger decrease in structure transmissibility was observed when the pre- and postconstruction peak ebb flow data were compared; however, this decrease is significant only to a low statistical level (not quite 85 percent). A change in average current vector direction, measured during peak flood, high-water slack, and peak ebb conditions, indicated that the structure was more reflective in the postsealing condition and, therefore, less transmissible.

Materials

405. Materials that are potentially effective in sealing permeable coastal structures to prevent sand movement and wave transmission include two cementitious sealants (WES Mixture and Buhne Point Mixture) and two sodium silicate sealants (Sodium Silicate-Cement Mixture and Sodium Silicate-Diacetin Mixture). The WES Mixture showed good flow characteristics, bonded well to the jetty rocks, and was competent. When the admixtures were measured and added to the cement mixture by experienced WES Concrete Technology Division staff, sealant quality was consistent. It is absolutely essential that trained and experienced personnel be used to consistently batch a good quality WES Mixture of cementitious sealant for production quantities in the field. Some admixtures are required in such low concentrations that extreme care must be exercised to add them correctly and at the right time during batching and mixing. If performed improperly or not in precisely the right proportions, the resulting mixture will behave quite unsatisfactorily. The Buhne Point Mixture was simpler to batch and, in some cases, showed flow and bonding characteristics quite similar to the WES Mixture.

406. The sodium silicate sealants have extensive records of successful applications in rock fissure grouting. Because of the controllable set time and high fluidity, these sealants are theoretically ideally suited for sealing permeable coastal rubble-mound structures. However, certain environmental factors or incomplete mixing can have serious consequences on the gelation of the sodium silicate sealants.

Methods of application

407. Equipment for injecting cementitious and sodium silicate sealants is already developed and well suited for coastal applications. If equipment for pressure-injecting hot sand-asphaltic concrete is developed, then that material should be thoroughly evaluated as part of a prototype field test program. For all sealant types, the equipment must be as portable as possible to shorten the line lengths from mixer or pump to drill hole.

408. Concrete pumps are ideal for emplacing both the WES Mixture and the Buhne Point Mixture of cementitious sealants. Progressive cavity-type pumps also work well with mixtures having a 5-in. slump, but if there is any risk of coarse aggregate being contained in the mixture, that type of pump should not be used.

409. Positive displacement pumps are a standard type of pump for injecting chemical sealants in large spaces. Comparison between laboratory

samples which were created by a static in-line mixer and samples of model injections which relied on mixing in the hopper of the pump documented that the in-line mixer achieved better sealant consistency. The pumping rate of between 5 and 10 gal/min for the Sodium Silicate-Diacetin Mixture was shown to be adequate for permeation of the sand and did not flush the sand from the jetty voids.

410. The field experience of USAED, North Central, using static in-line mixers for sodium silicate-cement sealants resulted in plugged lines because the solutions gelled too rapidly. Two Moyno pumps were used to pump the cementitious solution (27 gal/min) and the sodium silicate solution (9 gal/min). Once the solutions were joined at the header, completely mixed quick-set sealant resulted at the end of the 22-ft injection hose. Faster pumping rates by USAED, North Carolina, eliminated the need for the static mixers.

Specifications

411. Contract specifications for prototype rubble-mound structure sealing should be prepared to give the broadest possible decision-making powers to the Contracting Officer's Representative (COR). Many decisions and adjustments will be required as a test sealing program progresses. Such contract modifications should be facilitated by language requiring the least amount of formal correspondence. The COR should be knowledgeable about sealing coastal structures.

Environmental effects

412. The potential danger to the environment and aquatic organisms from sealant material placement in rubble-mound structures exposed to open water was evaluated by a series of static, short-term bioassays using the standard test animal *Daphnia*. Those results strongly suggested that additional in-depth investigations on the potential toxicity of sealant materials to *Daphnia* should be conducted. In addition, tests should be conducted using a marine organism such as the estuarine shrimp *Mysidopsis*. The tests should consider the initial effects as sealant materials are added to an area and longer term effects after the sealants have hardened. Some testing should be conducted for as long as 10 to 12 days, with effects on growth and reproduction potential evaluated using sealant concentrations representative of amounts that would be used in the field.

413. As part of the long-term time-dependent exposure tests to estimate the durability of various sealants under real prototype environmental

conditions, specimens of attaching marine organisms from these test samples will be obtained and subjected to bioassay analysis for toxicity effects. Also, representative samples of attaching marine organisms from both the sealed and nonsealed portions of the Buhne Point, CA, groin structure will be obtained and similarly analyzed, since breakwaters and jetties to which this research is directed are primarily located in marine environments.

414. Hazardous or toxic substances should not be used, and reasonable caution should guide the preparation, operation, and cleanup phases of repair activities involving potentially hazardous or toxic chemical substances. Manufacturers' directions and recommendations for the protection of occupational health and environmental quality should be carefully followed. Material safety data sheets should be obtained from the manufacturers of such materials. In cases where the effects of a chemical substance on occupational health and environmental quality are unknown, chemical substances should be considered hazardous or toxic until their health and environmental consequences are determined.

Summary Conclusions

415. The importance of having an experienced contractor cannot be over-emphasized. Having a good inspector is exceedingly important, but having a good contractor is the most important aspect of a coastal rubble-mound breakwater or jetty sealing effort. Proper spacing of the sealant holes is probably the second most important aspect of a sealing project, since drill hole spacing determines the drilling cost and radius of the sealant volume at each hole. The spacing, in turn, is determined by the injectibility, set time, and cost of the sealant mixture. Field conditions may vary from hole to hole, and proportions of the mixture may need to be quickly adjusted accordingly. Staging and sequencing the injection may become necessary or may need revising in a fast response time. Experienced evaluation of the sealing as it proceeds and revision of operations accordingly are necessary to avoid waste and to achieve a continuously injected barrier sealant curtain.

416. Considering the very low compressive strengths of the Sodium Silicate-Cement and Sodium Silicate-Diacetin test specimens and the observed rapid erosion and deterioration of such specimens at the long-term exposure field stations, it is essential that prototype monitoring of completed sealing projects be performed. It is highly recommended that periodic reevaluation of

the effectiveness of the Sodium Silicate-Cement and Sodium Silicate-Diacetin sealant placement at West Palm Beach, FL, south jetty, and Port Everglades, FL, south jetty be conducted to ascertain the actual useful life of these sealing efforts so that true economic benefits and cost comparisons of all alternatives are realistic.

417. The use of synthetic materials such as those used in these applications and investigations continues to draw scrutiny from various environmental advocacy groups. The USACE is in full agreement with such concerns and recognizes the health, safety, and water quality aspects associated with such materials. The USACE is committed to fully understanding all environmental consequences associated with their utilization and will adhere to all standards, specifications, and safeguards pertaining thereto.

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