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US Army Corps of Engineers

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CO-13

LABORATORY TECHNIQUES FOR EVALUATING EFFECTIVENESS OF SEALING VOIDS IN RUBBLE-MOUND BREAKWATERS AND JETTIES WITH GROUTS AND CONCRETES

by

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

COVER PHOTOS:

TOP — Drilling sealant holes at Buhne Point, Humboldt Harbor, CA.

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

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Asphaltic cements	Chemical sealants	Rubble-mound
Breakwaters	Grout	Sand-asphalt
Cementitious sealants	Jetties	Void sealing

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Many US Army Corps of Engineers (USACE) breakwaters and jetties have become permeable to sand transport and wave transmission, a condition which results in increased operation and maintenance dredging costs and increased risks and delays to navigation. 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. 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.

This report is the second milestone in a multiyear project to better understand cementitious, chemical, and bituminous materials, and injection techniques applicable to USACE projects that are experiencing detrimental levels of sediment infiltration or wave energy transmission. Other products of this research investigation will include results of field

(Continued)

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19. ABSTRACT (Continued).

monitoring of recommendations and tests arising from these laboratory evaluations, and development of guidance for field use of cementitious, chemical, and bituminous sealants specifically directed toward coastal projects. Laboratory investigations consisted of tests for injecting sealant materials in a model structure to describe their flow behavior and sealing ability inside a scaled, submerged, rubble-mound structure. Other tasks reported herein include (a) casting specimens of sealant materials, (b) measuring their initial properties, (c) placing those specimens in the prototype environment for a series of long-term time-dependent durability tests, (d) determining the effects of the environment on the materials, and (e) conversely, determining the effects of the materials on the environment.

The purposes 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, (b) perform bio-assay tests on materials with potential for adverse environmental effects, and (c) initiate a series of long-term exposure tests to estimate the durability of various sealants under real prototype environmental conditions.

Specific objectives of the laboratory investigations include (a) construction of a rubble-mound physical model at a scale sufficiently large so 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-asphalt mixture), recording for each the quantities, locations of injection, pumping rates, and gel times of the materials; (c) providing specific description of materials by precise recording of components and proportions, and obtaining determinations of standard parameters for the respective materials; (d) recording spread, shape, competency, and continuity of the hardened sealants upon disassembly of the structure; (e) abbreviated bio-assay tests to bracket toxicity effects on the laboratory animal *Daphnia* by levels of concentrations of the sealant materials; (f) casting specimens of each sealant type, performing baseline measurements of parameters that will provide an indication of strength variance with time, including pulse velocity and dynamic modulus of elasticity for the cementitious and chemical sealants, and the Marshall stability test for the asphaltic concrete; and (g) 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. The durability test specimens were placed at Treat Island, MA; Duck, NC; and Miami, FL.

It was determined that 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. Results indicated aggregate containing cementitious mixtures 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. The sodium silicate-diacetin used to fill the voids in the sand layer did not completely solidify the sand to a hard bulbous mass. The dissembled sections showed concrete mixtures can form such a bulbous mass in a rubble-mound structure when injected under water. Precise monitoring and control of conditions are required when chemical sealants and cementitious sealants containing hardening accelerators are used. Sand-asphalt sealants set hard and bond well, although no means for emplacing this material in production quantities has been developed at this time. Long-term time-dependent evaluations of the durability of these materials under prototype conditions are continuing by periodic reevaluations at the field locations.

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 (CEWES-CR-P) and Ms. Joan Pope (CEWES-CD-S) were the Principal Investigators. Mr. John H. Lockhart (CECW-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), US Army Waterways Experiment Station (WES) is the REMR Program Manager. Mr. D. Donald Davidson (CEWES-CW-R) is the Problem Area Leader.

The work was performed at US Army Engineer Waterways Experiment Station and this report was prepared by Messrs. David P. Simpson and Jeffrey L. Thomas of the Coastal Engineering Research Center (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, CERC; and Mr. Thomas W. Richardson, Chief, Engineering Development Division, CERC; and the direct supervision of Dr. Stephen H. Hughes and Mr. Bruce A. Ebersole, former Chief and Chief, respectively, Coastal Processes Branch, CERC; and Ms. Joan Pope, Chief, Coastal Structures and Evaluation Branch, CERC.

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 Applications 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); Mr. Henry T. Thornton, Jr., Evaluation and Monitoring Unit, CTD, SL; and Dr. Henry E. Tatem, Contaminant Mobility and Regulatory Criteria Group, Ecosystem

Research and Simulation Division, Environmental Laboratory.

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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CONTENTS

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

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

Multiply	By	To Obtain
cubic feet	0.028317	cubic metres
cubic yards	0.7645549	cubic metres
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)	0.51444444	metres per second
miles (US statute)	1.609347	kilometres
ounces (US fluid)	0.28349525	kilograms
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6,894.757	pascals
square feet	0.09290304	square metres
square inches		
tons (2,000 lb, mass)	907.1847	kilograms
tons (2,000 lb, mass) per cubic yard	1,186.552725	kilograms per cubic metre

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

LABORATORY TECHNIQUES FOR EVALUATING EFFECTIVENESS OF SEALING VOIDS IN RUBBLE-MOUND BREAKWATERS AND JETTIES WITH GROUTS AND CONCRETES

PART I: INTRODUCTION

Background

1. Many US Army Corps of Engineers (USACE) breakwaters and jetties have become permeable to sand transport and wave transmission, a condition which results in increased Operation and Maintenance dredging costs and increased risks and delays to navigation. 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. Void dimensions which emphasize the problem are shown in Figure 1. Evidence of sand transport through a permeable structure is shown in Figure 2. 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.

Figure 1. Representative void size in many rubble-mound coastal breakwaters and jetties

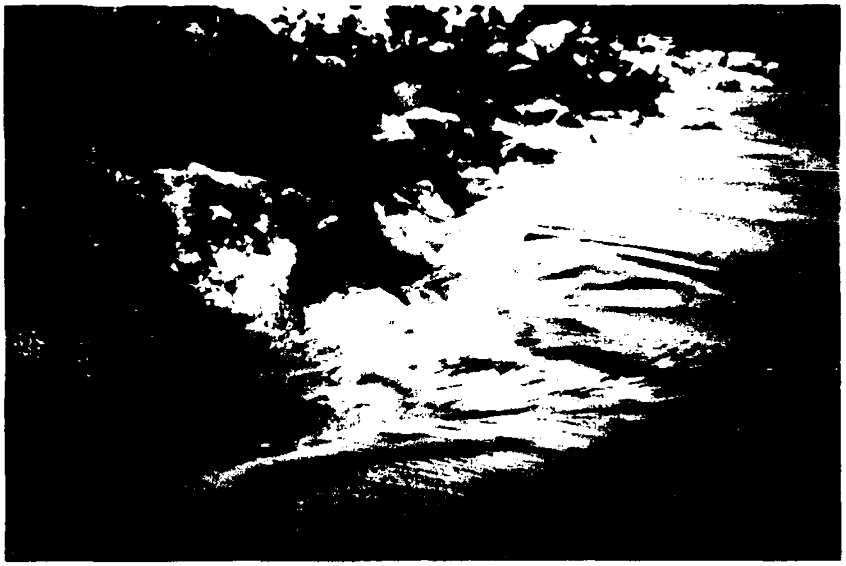

Figure 2. Prototype field evidence of sand transport through rubble-mound breakwaters or jetties

2. 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. A schematic of a jetty sealing operation is shown in Figure 3.

3. Engineers in some coastal Districts have applied grouting techniques to the problem of sealing jetty voids by using cementitious sealants and chemical grouts. To refine the methods and materials and provide field guidance in this promising type of rehabilitation, the present Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program work unit was initiated in FY 86 by the US Army Engineer Waterways Experiment Station (WES). That year's effort was summarized in REMR technical report "State-of-the-Art Procedures for Sealing Coastal Structures with Grouts and Concretes" (Simpson 1989), which reviews pertinent grouting literature and field experiences with sealing coastal structures. Grouting is only one of several methods of making

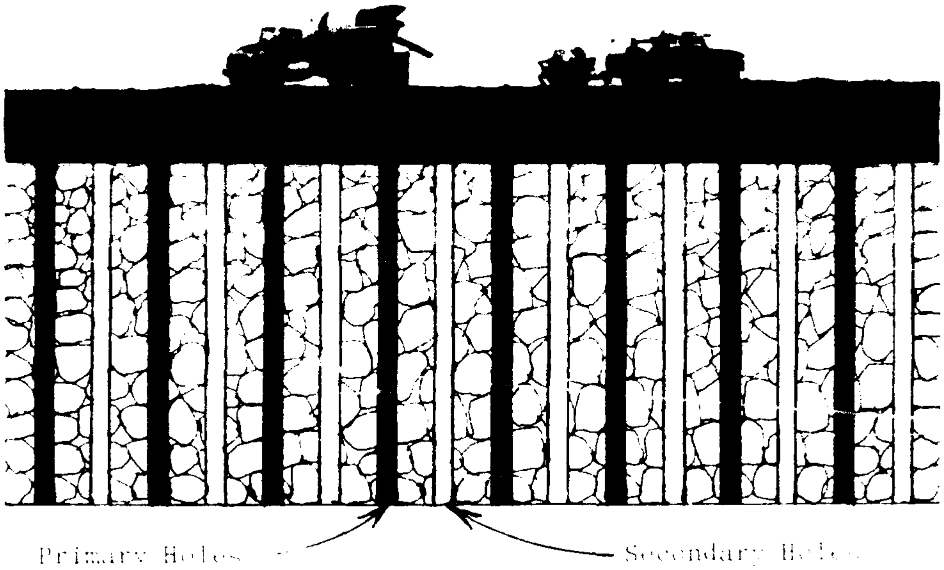

Figure 3. Schematic of jetty sealing operation. Sealant holes are drilled, and equipment delivers sealant to field operation. Below the jetty crest, primary holes are sealed first; then secondary holes are sealed to complete closure of all interconnecting structure voids

a jetty less permeable to sand movement, as discussed in a separate WES Coastal Engineering Research Center (CERC) technical report, "Sand Sealing of Coastal Structures" (Thomas, in preparation).

4. This report is the second milestone in a multiyear project to better understand cementitious, chemical, and bituminous materials and injection techniques applicable to USACE projects that are experiencing detrimental levels of sediment infiltration or wave energy transmission. Other products of this research investigation will include the results of field monitoring of recommended materials and techniques arising from these laboratory evaluations and the development of guidance for field use of cementitious, chemical, and bituminous sealants specifically directed toward coastal projects.

5. Grout is defined by EM 1110-2-3506 (Headquarters, Department of the Army 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 it 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 problem would have difficulty trying to apply typical grouting materials and techniques to highly porous coastal rubble-mound breakwaters and jetties.

Statement of the Problem

6. The overall problem under investigation can be logically separated into two distinct parts. One part requires the evaluation of materials already being used and the development of new materials that can be emplaced to seal voids and be durable in the environment. The second part entails 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.

7. Tasks reported herein included (a) casting specimens of sealant materials, (b) measuring their initial properties, (c) placing those specimens in the prototype environment for a series of long-term time-dependent durability tests, (d) determining the effects of the environment on the materials, and (e) conversely, determining the effects of the materials on the environment. Additional laboratory investigations consisted of tests for injecting those same materials in a model structure to describe their flow behavior and sealing ability inside a scaled, submerged, rubble-mound structure.

Laboratory Investigations

8. The purposes 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.

b. Perform bio-assay tests on materials with potential for adverse environmental effects.

c. Initiate a series of long-term exposure tests to estimate the durability of various sealants under prototype environmental conditions.

9. Specific objectives of the laboratory investigations included:

- a. Construction of a rubble-mound physical model at a scale sufficiently large so that deviations from similitude would be negligible.
- b. Preparation and injection 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. Providing specific descriptions of materials by precise recording of components and proportions, and obtaining determinations of standard parameters for the respective materials.
- d. Recording spread, shape, competency, and continuity of the hardened sealants upon disassembly of the structure.
- e. Abbreviated bio-assay tests to bracket toxicity effects on the laboratory animal *Daphnia* by levels of concentrations of the sealant materials.
- f. Casting specimens of each sealant type, performing baseline measurements of parameters that will provide an indication of strength variance with time, including pulse velocity and dynamic modulus of elasticity for the cementitious and chemical sealants, and the Marshall stability test for the asphaltic concrete.
- g. 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.

PART II: DESIGN OF SEALANT INJECTION TESTS

Sealants Selected for Injection Tests

10. 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 which 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-asphalt mixture being injected into jetty voids. Rheological properties of sand asphalt, however, made the sand-asphalt mixture an attractive test material. A concrete mixture with specific admixtures that give the material high cohesiveness and relatively high fluidity (WES mixture) was developed by the Structures Laboratory, WES. These five materials (WES mixture, Buhne Point mixture, sodium silicate-cement mixture, sodium silicate-diacetin mixture, and sand-asphalt mixture) were chosen for evaluation, both for injection into the physical model and for long-term time-dependent durability testing under prototype environmental conditions.

WES mixture

11. A sanded cement sealant mixture, with additives which 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 which produce 1-cu-yd* volume of sealant and yield a 10-in. slump.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 5.

Table 1

Mixture Proportions of Cementitious Sealants

Injected in Model Jetty

Material	Quantity, lb/cu yd WES Mixture	Quantity, lb/cu yd Buhne Point Mixture
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

12. 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.

13. 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 which 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.

Sodium silicate-cement mixture

14. 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 to 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 in this investigation are listed in Table 2.

Table 2

Mixture Proportions of Chemical Sealants Injected in Model Jetty

Constituents	gal/cu ft	percent by volume
Sodium Silicate-Cement Sealant Prepared at WES by Structures Laboratory Personnel		
Type I portland cement	0.512	6.7
Sodium silicate	1.496	20.0
Water	5.472	73.3
Total	7.480	100.0
Sodium Silicate-Cement Sealant Prepared at WES by Grouting Contractor		
Type I portland cement	0.500	7.0
Sodium silicate	1.480	20.0
Water	5.500	73.0
Total	7.480	100.0
Sodium Silicate-Diacetin Mixture for Stabilizing Sand Layer Prepared at WES by Structures Laboratory Personnel		
Sodium silicate	2.618	35.0
Diacetin	0.449	6.0
Water	4.413	59.0
Total	7.480	100.0
Sodium Silicate-Diacetin Mixture for Stabilizing Sand Layer Prepared at WES by Grouting Contractor		
Sodium silicate	3.000	40.0
Diacetin	0.300	4.0
Water	4.180	56.0
Total	7.480	100.0

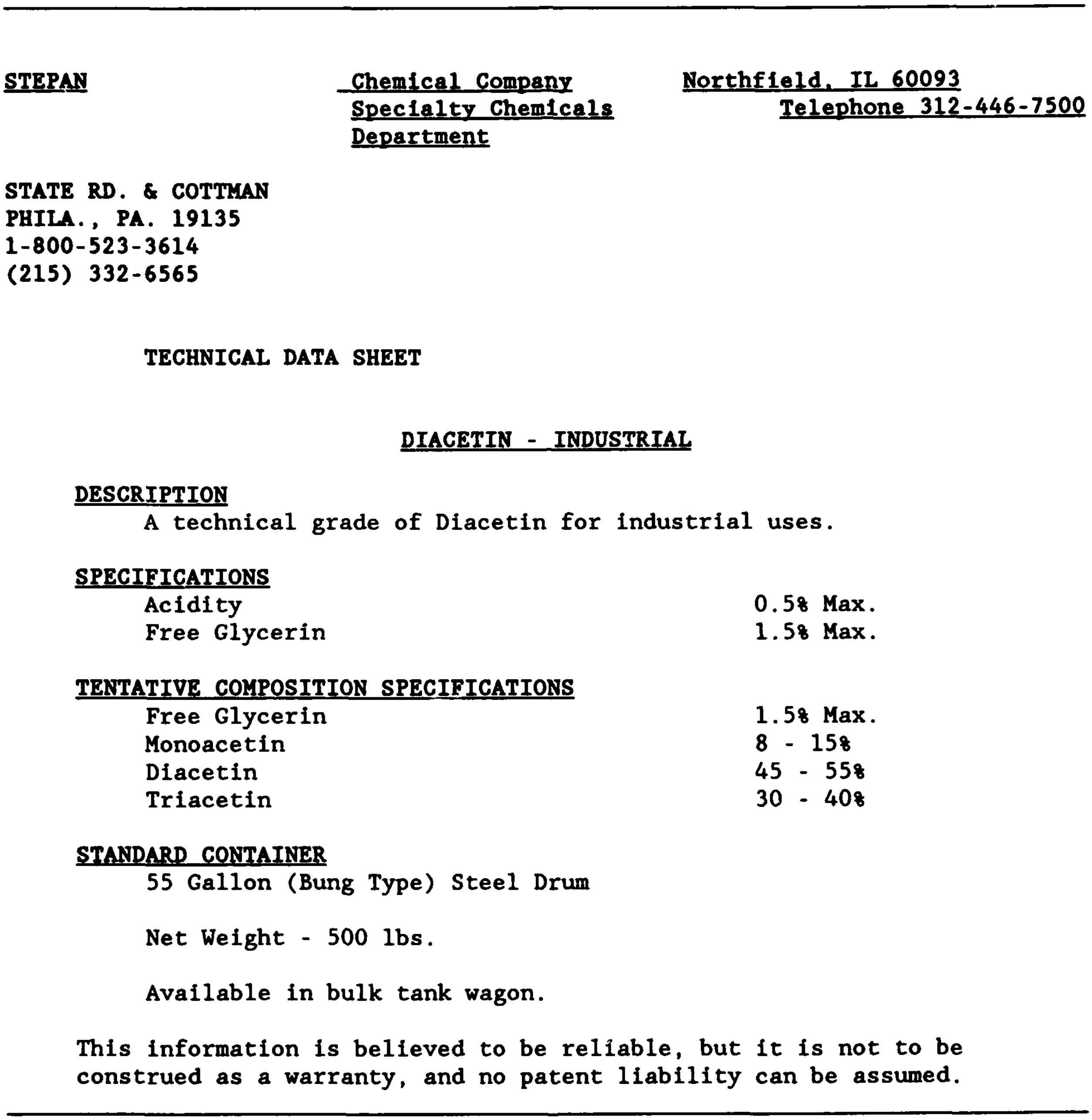
Sodium silicate-diacetin mixture

15. Sodium silicate in solution with a chemical reactant was used for permeation sealing of sand which 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, 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 which cause gelation of the sodium silicate. Since there are no solid constituents to pack together, paths of permeation cannot be blocked.

16. Diacetin was the chosen reactant for this experimental investigation, although formamide was used in a previous jetty sealing project. The reason for this choice is that handling diacetin presents a lower risk to health than handling formamide and therefore diacetin may be preferred in production sealing. The material safety data sheet for diacetin (glycerol diacetate) is reproduced in Figure 4. 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. Proportions of the silicate-diacetin mixture injected into the test sections in this investigation are listed in Table 2. For each sealant type, sealants were prepared by the contractor for pumping into the test sections and by WES personnel for casting specimens to test sealant properties. The proportions listed in Table 2 show that for each sealant type the two batches were nearly identical.

Sand-asphalt mixture

17. 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 which could be emplaced using a grouting technique for sealant placement. Mixtures containing 10-, 12-, and 15-percent



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PHILA., PA. 19135
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(215) 332-6565

TECHNICAL DATA SHEET

DIACETIN - INDUSTRIAL

DESCRIPTION

A technical grade of Diacetin for industrial uses.

SPECIFICATIONS

Acidity	0.5% Max.
Free Glycerin	1.5% Max.

TENTATIVE COMPOSITION SPECIFICATIONS

Free Glycerin	1.5% Max.
Monoacetin	8 - 15%
Diacetin	45 - 55%
Triacetin	30 - 40%

STANDARD CONTAINER

55 Gallon (Bung Type) Steel Drum

Net Weight - 500 lbs.

Available in bulk tank wagon.

This information is believed to be reliable, but it is not to be construed as a warranty, and no patent liability can be assumed.

Figure 4. Stephan Chemical Company material safety data sheet for diacetin (glycerol diacetate) (Sheet 1 of 3)

Stepan S

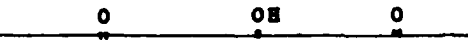
MATERIAL SAFETY DATA SHEET

CHEMICAL NAME: DIACETIN MD

SYNONYMS:

CHEMICAL FAMILY: Acetate Esters

FORMULA:



$CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2-\overset{OH}{\overset{|}{CH_2}}-CH_2-O\overset{O}{\overset{\|}{C}}CH_3$

MOLECULAR WEIGHT: 176.2

TRADE NAME AND SYNONYMS: Glycerol Diacetate - Glyceryl Diacetate

[redacted]

BOILING POINT, 760 mm. Hg	220-285°C	FREEZING POINT	~ -35°C.
SPECIFIC GRAVITY (H_2O=1)	1.178 (25°C.)	VAPOR PRESSURE at 20° C.	∠1 mm Hg
VAPOR DENSITY (air = 1)		SOLUBILITY IN WATER, % by wt. at 20° C.	Soluble
PER CENT VOLATILES BY VOLUME		EVAPORATION RATE (Butyl Acetate = 1)	∠ 1
APPEARANCE AND ODOR	Amber liquid - Slight odor		

[redacted]

MATERIAL	%	TLV (Units)
Diacetin MD is non-hazardous material as		
defined by Part 1501.2 Safety and Health		
Regulations for Ship Repairs, U. S. Dept.		
of Labor		

[redacted]

FLASH POINT (test method)	295°F. C.O.C.	AUTOIGNITION TEMPERATURE			
FLAMMABLE LIMITS IN AIR, % by volume		LOWER		UPPER	
EXTINGUISHING MEDIA	Foam, dry chemical, carbon dioxide, water				
UNUSUAL FIRE AND EXPLOSION HAZARDS					
SPECIAL FIRE FIGHTING PROCEDURES					

Figure 4. (Sheet 2 of 3)

[redacted]

NATURAL TOXICITY LD_{50}	10.8 ml/Kg	This data for Diacetin Distill Grade - See note below for Diacet ND
DERMAL IRRITATION	Not a Primary Skin Irritant or corrosive material Draize Primary Skin Irritation Index 0.25	
EYE IRRITATION	Not an eye irritant Draize Eye Irritation Index - 0	
THRESHOLD LIMIT VALUE		
EFFECTS OF OVEREXPOSURE		
EMERGENCY AND FIRST AID PROCEDURES	Diacetin ND is an industrial grade non-distilled diacetin. Residual acidity may cause skin and eye irritation. Wash with copious amounts of water if exposed.	

[redacted]

STABILITY		CONDITIONS TO AVOID	
UNSTABLE	STABLE		
	X		
INCOMPATIBILTY (materials to avoid)		Strong inorganic oxidants	
HAZARDOUS POLYMERIZATION		CONDITIONS TO AVOID	
May Occur	Will not Occur		
	X		
HAZARDOUS DECOMPOSITION PRODUCTS			

[redacted]

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED	Flush down with water if possible, or absorb on floor sweeping compound
WASTE DISPOSAL METHOD	Spilled material may be flushed with water into sewer system.

[redacted]

RESPIRATORY PROTECTION (specify type)				
VENTILATION	LOCAL EXHAUST		SPECIAL	
	MECHANICAL (general)		OTHER	
PROTECTIVE GLOVES		Yes	EYE PROTECTION	Yes
OTHER PROTECTIVE EQUIPMENT				

[redacted]

PRECAUTIONARY LABELING	
OTHER HANDLING AND STORAGE CONDITIONS	

[redacted]

Figure 4. (Sheet 3 of 3)

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.

Model Scale

18. 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.

19. The facility available to carry out the injection tests was a sump for a tidal hydraulic model and was located in the open air. This facility was 80 ft long, 30 ft wide, and 10 ft deep; it 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.

20. 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 1.5H-to-1V. 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

21. 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.

22. Parameters of the cementitious mixtures which are necessary to measure for describing the sealants included (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.

23. Sodium silicate sealant parameters which 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, and continuity and the 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.

24. Sand-asphalt injection was evaluated by observing (a) the reaction of the hot-mix to immersion in water, (b) spread, (c) bonding, (d) ability to

retain its emplaced shaped, 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.

25. 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 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 which would detect the arrival of the sealant formation. The commercial powder REVERT, when mixed with water, produces a viscous solution. The viscosity of a test sealant mixture could be designed by specifying the amount of REVERT. Addition of cellulose ether introduced cohesion to the mixture.

Model Design and Construction

26. The model was partitioned into six sections labeled Sections A through F, respectively, for injecting and evaluating the mixtures. Plywood partitions were installed to (a) 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 specific section. Not all of the sump 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. Construction details are shown in Figures 5 through 7.

27. The jetty centerline was offset from the sump center line as a means of conserving both rock construction material and labor (Figure 8). 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 emplacement.

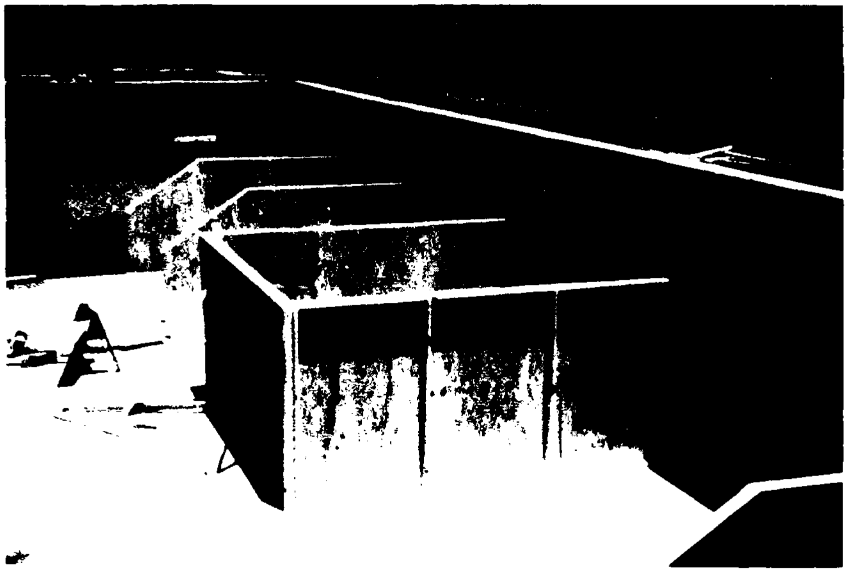


Figure 5. Partitions for dividing rubble-mound physical model

Figure 6. Details of partition in rubble-mound physical model

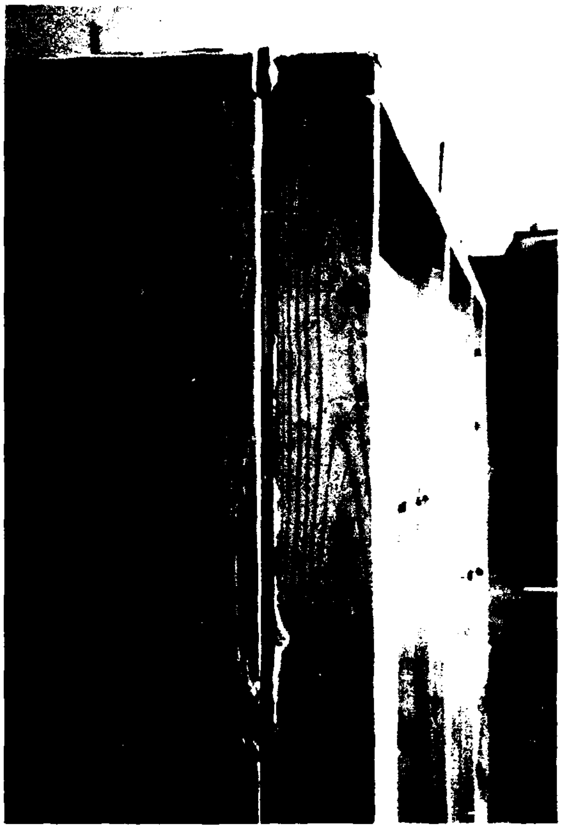


Figure 7. Method for sealing salt-water containment section in physical model of rubble-mound breakwater or jetty

28. 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 353 tons of stone were used in constructing the rubble-mound physical model of a breakwater or jetty.

29. Wooden partitions were fabricated from 3/8-in. plywood attached to framing which was fastened to the sump floor and wall. Plastic sheeting was 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 that they could be raised for injecting the sealant in lifts. Instrument conduits were 1.5-in.-diam, 6-ft-2-in.-long polyvinyl chloride

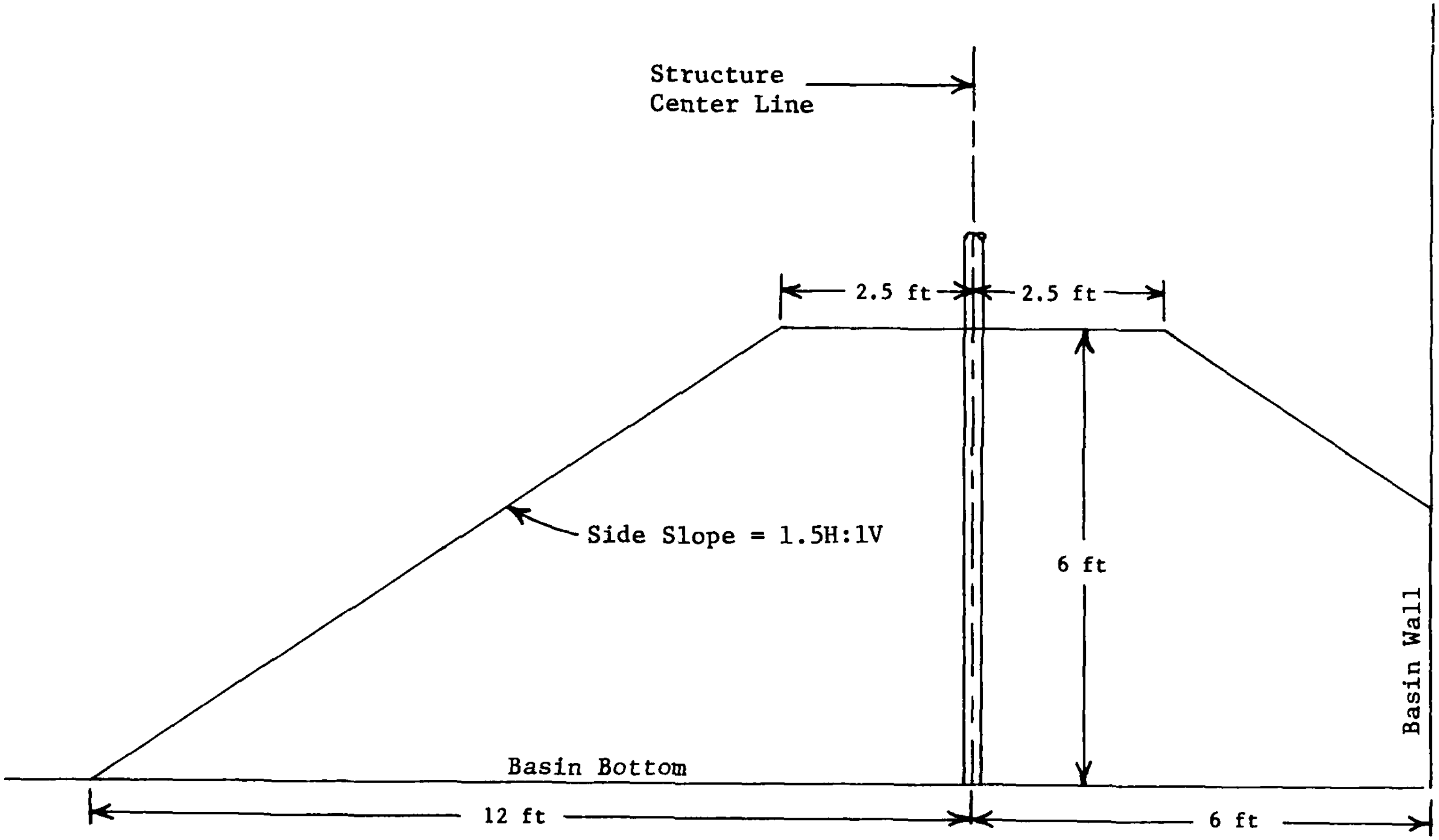


Figure 8. Dimensions of typical cross section of rubble-mound physical model

(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.

30. Prior to injecting sealants into a section, wire-resistance gages were positioned at the 1/2-in.-diam openings in the conduits. When it reached the gages, the conductivity of the injected materials 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 9). Construction of the sand layer stabilization test section is shown in Figure 10. Layouts of Sections A through F, showing hole spacing and section dimensions, are shown in Figures 11 through 16, respectively.

31. Rock placement was performed by a crane equipped with an orange-peel bucket (Figure 17) and by hand labor. To simulate a sand layer at the bottom of a rubble-mound structure in Section D, sand was dumped onto the 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. The completed model, as seen before the sump was flooded, is shown in Figure 18.

Figure 9. Placing stone around sealant pipes and instrumentation conduits in physical model of rubble-mound breakwater or jetty

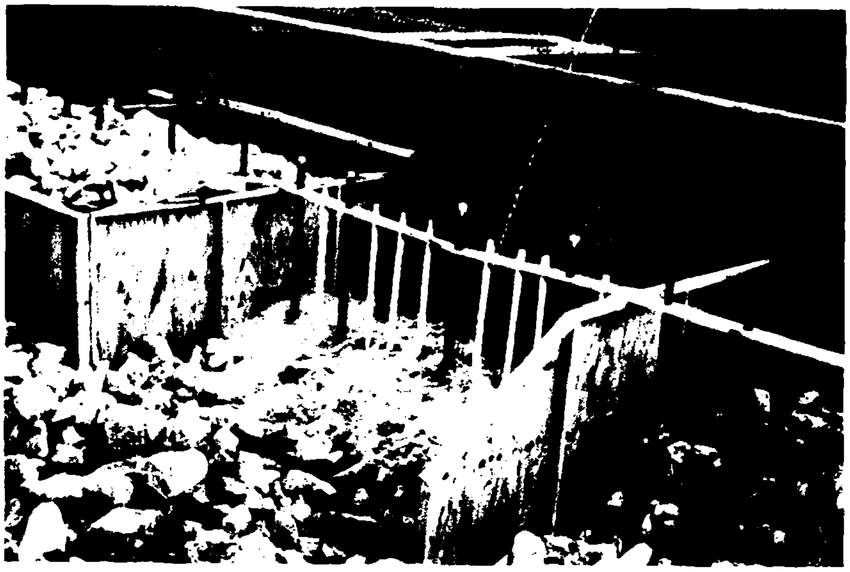


Figure 10. Construction of physical model Section D used to evaluate sodium silicate-diacetin sealant for stabilizing sand in a jetty interior

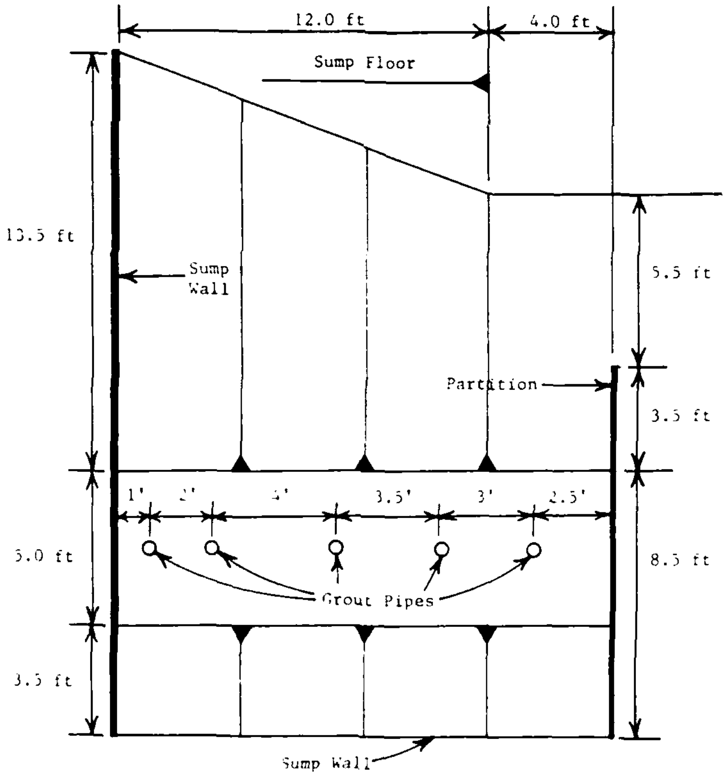


Figure 11. Section A of physical model used to evaluate WES mixture of cementitious sealant with additives to provide resistance to erosion by flowing water. Sealant placed by commercial bulk concrete plant personnel

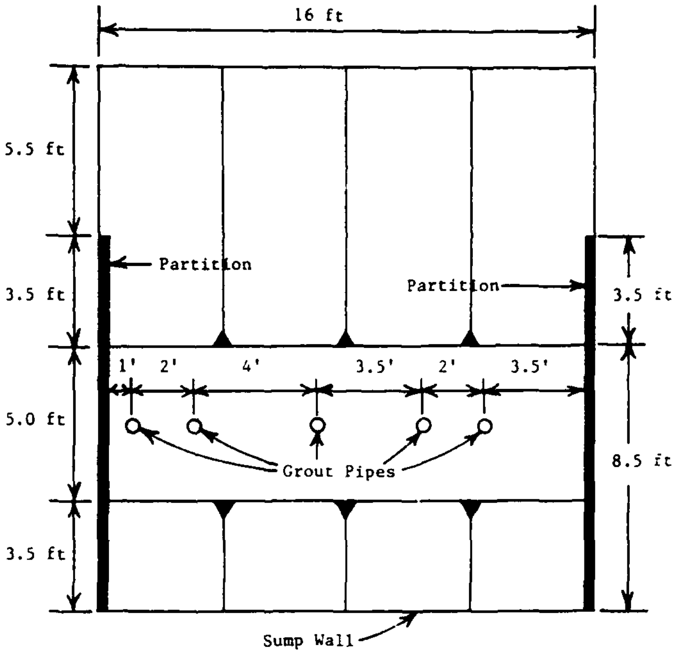


Figure 12. Section B of physical model used to evaluate WES mixture of cementitious sealant with additives to provide resistance to erosion by flowing water. Sealant placed by WES Structures Laboratory personnel

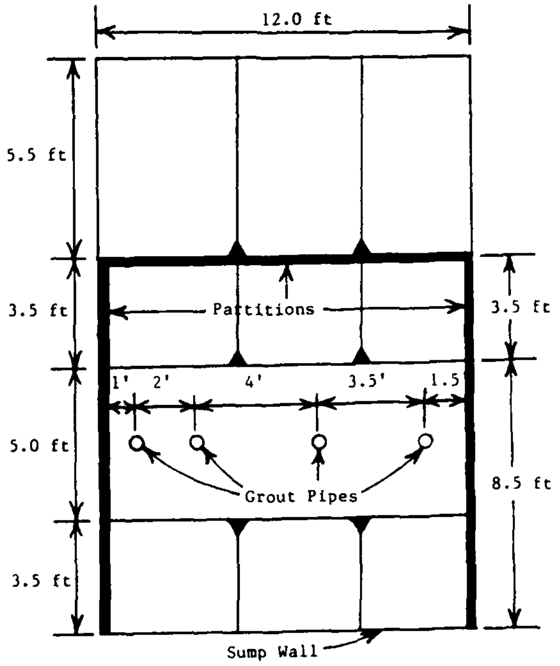


Figure 13. Section C of physical model used to evaluate sodium silicate-cement mixture of sealant placed in the saltwater section to investigate salinity effects

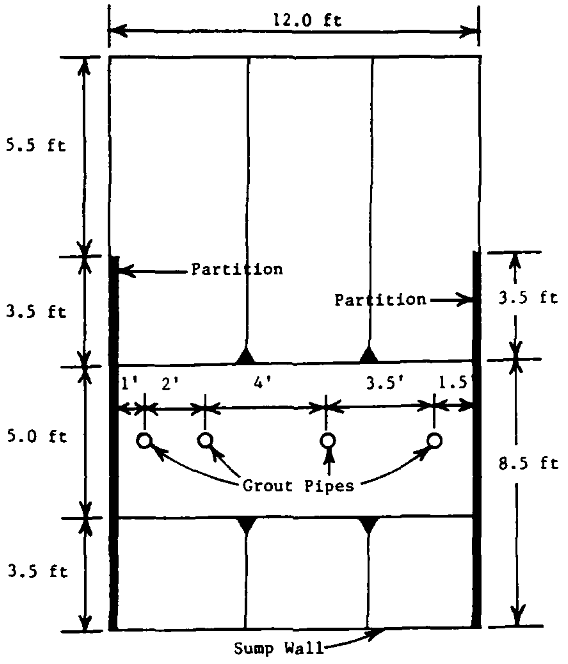


Figure 14. Section D of physical model used to evaluate sodium silicate-diacetin mixture of sealant to investigate stabilization of sand layer along bottom of structure

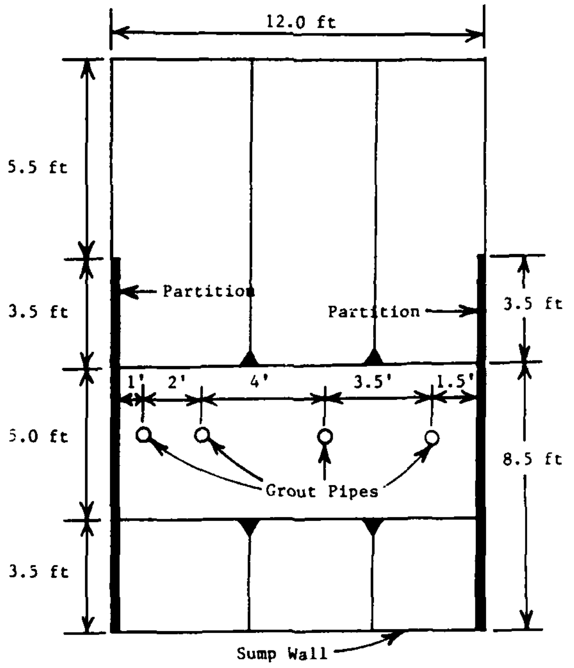


Figure 15. Section E of physical model used to evaluate sand-asphalt mixtures as potential sealant materials for for sealing voids in rubble-mound breakwaters or jetties

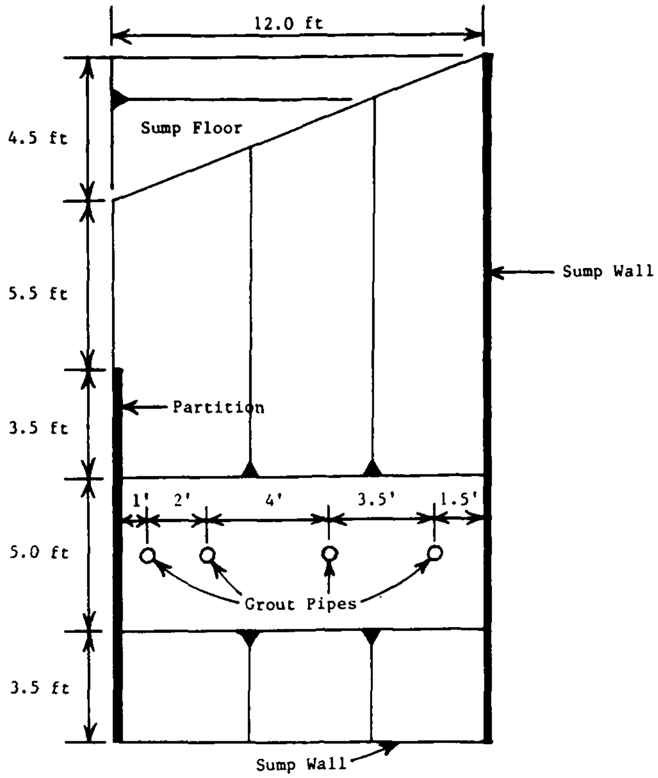


Figure 16. Section F of physical model used to evaluate Buhne Point mixture of cementitious sealant with additives of clay to form stiff sealant to resist erosion by flowing water through a rubble-mound structure

Figure 17. Crane and orange-peel bucket used to place stone in physical model of rubble-mound structure

Figure 18. Completed physical model of rubble-mound breakwater or jetty prior to flooding for sealant injection testing

32. 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.

PART III: VOID SEALING IN THE PHYSICAL MODEL

Rubble-Mound Structure Properties

33. 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 crystallization and incipient metamorphism. The average specific gravity, calculated 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.

34. A precise description of the medium into which the sealants were injected is provided for the purpose of aiding in relating model results to prototype behavior. For cases of stiff or cohesive sealants, important structural parameters are void size and cross-sectional area of the interconnection between voids. Void size is determined by particle sizes making up the medium and the size distribution, as well as the particle shape and the shape distribution. Those factors, in turn, are dependent on the structural geology, lithology, and mineralogy of the source area. Conclusions drawn from a multitude of studies of particle size distributions in other fields are that randomness of sizes and shapes can be assumed here and that central tendencies exist in the population. A Gaussian distribution of certain stone parameters was assumed in determining a representative void size. Area of interconnections between voids was not quantified in this study.

35. The development of relationships between measurable particle parameters and void size was initiated in the present study. It was recognized that the void size in a jetty is directly related to some characteristic stone size and a shape parameter and that the void size is inversely related to parameters which account for the distribution of sizes and shapes.

36. The characteristic stone dimension chosen for correlation purposes was the intermediate axis, a convention taken from material transport analyses, although no obvious reason exists for the intermediate axis being more

appropriate than another for the case of void sealing. It was not determined whether porosity of a rubble mass is affected to a greater or lesser extent by varying the dimensions of only the intermediate axis or those of another axis. The three-dimensional aspect of a stone is important in consideration of filling a space, and an appropriate shape factor was required. Well-known factors relate shape of a particle to its hydrodynamic properties, but they describe the shape in only two dimensions.

37. Most theoretical studies of particle packing deal with uniform size spheres (Allen 1985). Such is not the case with a rubble-mound breakwater or jetty, and results of analyzing those structures should depart significantly from results of packing of spheres. Analyses based on assumed ellipsoidal shapes were developed to make advancement in the simulation of packing and to provide a manageable way of dealing numerically with large numbers of those particles.

38. It is recognized that a particle cannot be uniquely described in three dimensions by specifying the intermediate axis length and a number combining the ratios of the axes' lengths. As an alternative, a factor was computed which compares the volume of the rock with the volume of an ellipsoid having the same axial dimensions. Representative values were obtained for the factors relating to particle size and shape discussed above by sampling the stones used to build the model. One hundred stones were weighed individually, and their long, intermediate, and short axes (A-, B-, and C-axes) were measured. The volume of each piece was computed based on the specific weight of 164.7 lb/cu ft. The volume of an ellipsoid having the same axial dimensions of each stone was also computed. Results are listed in Table 3.

39. The ratio of volume of rock to volume of ellipsoid having the same axial dimensions is termed the volume shape factor, VSF . For comparative purposes, the Corey shape factor, familiar to researchers of material transport studies, was also computed. Intermediate and other axes length distributions are shown graphically in Figure 19. Mean and standard deviation of the intermediate axis were calculated from that distribution using the Folk and Ward (1957) convention, but linear measurements were used instead of logarithmic measurements of particle dimensions. That appeared justifiable in light of research results by Wolman (1954). The mean length of the intermediate axis, BL , was 0.82 ft, and the standard deviation, σ_{BL} , was 0.19. Standard deviation of the axis and volume shape factor is expressed as:

Table 3

Characteristics of Stones Sampled in the Physical Model

No.	Rock Weight lb	Volume of Rock cu ft	A-Axis ft	B-Axis ft	C-Axis ft	Volume of Ellipsoid Same Axes cu ft	Volume Ratio: Rock/ Ellipsoid	Corey Shape Factor
1	29	0.18	1.17	0.88	0.58	0.31	0.57	0.57
2	30	0.18	1.08	0.58	0.58	0.19	0.94	0.73
3	39	0.24	0.92	0.79	0.58	0.22	1.07	0.68
4	25	0.15	0.83	0.79	0.54	0.19	0.81	0.67
5	65	0.39	1.33	1.00	0.71	0.49	0.80	0.61
6	15	0.09	0.88	0.58	0.50	0.13	0.68	0.70
7	26	0.16	1.08	0.58	0.58	0.19	0.82	0.73
8	87	0.53	1.04	1.00	0.75	0.41	1.29	0.73
9	80	0.49	1.50	0.92	0.75	0.54	0.90	0.64
10	48	0.29	1.00	0.92	0.63	0.30	0.97	0.65
11	50	0.30	1.00	0.96	0.58	0.29	1.04	0.60
12	19	0.12	1.12	0.63	0.42	0.16	0.73	0.49
13	57	0.35	1.75	0.83	0.62	0.48	0.73	0.52
14	37	0.22	1.29	0.92	0.46	0.28	0.79	0.42
15	65	0.39	1.58	0.83	0.71	0.49	0.81	0.62
16	42	0.26	1.33	0.83	0.75	0.44	0.58	0.71
17	50	0.30	1.25	0.92	0.75	0.45	0.67	0.70
18	18	0.11	0.71	0.67	0.50	0.12	0.88	0.73
19	30	0.18	1.12	0.75	0.50	0.23	0.80	0.53
20	49	0.30	1.33	1.00	0.75	0.52	0.57	0.65
21	76	0.46	1.21	1.00	0.62	0.40	1.17	0.57
22	58	0.35	1.46	1.08	0.58	0.46	0.73	0.46
23	78	0.47	1.92	0.75	0.71	0.53	0.89	0.59
24	79	0.48	1.83	0.92	0.50	0.44	1.09	0.39
25	38	0.23	0.88	0.88	0.62	0.25	0.92	0.71
26	54	0.33	1.08	0.92	0.83	0.43	0.76	0.84
27	38	0.23	1.67	0.50	0.42	0.18	1.27	0.46
28	24	0.15	0.83	0.75	0.58	0.19	0.76	0.74
29	24	0.15	1.04	0.71	0.42	0.16	0.91	0.49
30	13	0.08	0.75	0.46	0.42	0.08	1.05	0.71
31	20	0.12	0.83	0.62	0.46	0.12	0.97	0.64
32	50	0.30	1.12	0.88	0.62	0.33	0.91	0.62
33	19	0.12	0.79	0.62	0.38	0.10	1.19	0.53
34	11	0.07	0.75	0.46	0.38	0.07	0.99	0.64
35	33	0.20	0.75	0.75	0.54	0.16	1.26	0.72

(Continued)

(Sheet 1 of 3)

Table 3 (Continued)

No.	Rock Weight lb	Volume of Rock cu ft	A-Axis ft	B-Axis ft	C-Axis ft	Volume of Ellipsoid Same Axes cu ft	Volume Ratio: Rock/ Ellipsoid	Corey Shape Factor
36	82	0.50	1.33	1.08	0.79	0.60	0.83	0.66
37	29	0.18	1.00	0.79	0.67	0.28	0.64	0.75
38	19	0.12	0.88	0.54	0.46	0.11	1.01	0.67
39	20	0.12	0.88	0.58	0.54	0.14	0.84	0.76
40	26	0.16	1.00	0.79	0.54	0.22	0.70	0.61
41	39	0.24	1.25	0.75	0.50	0.25	0.97	0.52
42	10	0.06	0.58	0.54	0.38	0.06	0.98	0.67
43	37	0.22	1.12	0.67	0.62	0.25	0.88	0.71
44	15	0.09	0.83	0.62	0.38	0.10	0.89	0.52
45	25	0.15	1.04	0.58	0.54	0.17	0.88	0.69
46	38	0.23	1.17	0.83	0.54	0.28	0.84	0.55
47	54	0.33	1.50	1.00	0.83	0.65	0.50	0.68
48	43	0.26	0.96	0.92	0.67	0.31	0.85	0.71
49	42	0.26	1.38	0.67	0.50	0.24	1.06	0.52
50	39	0.24	1.00	0.67	0.62	0.22	1.09	0.77
51	212	1.29	1.83	1.67	0.92	1.47	0.88	0.52
52	163	0.99	1.67	1.67	0.92	1.33	0.74	0.55
53	35	0.21	1.12	0.83	0.42	0.21	1.00	0.42
54	113	0.69	1.50	1.12	0.83	0.74	0.93	0.64
55	39	0.24	1.12	0.71	0.54	0.23	1.05	0.61
56	28	0.17	1.08	0.92	0.29	0.15	1.12	0.29
57	64	0.39	1.08	0.92	0.71	0.37	1.06	0.71
58	76	0.46	1.75	1.00	0.50	0.46	1.01	0.38
59	52	0.32	1.21	0.83	0.58	0.31	1.03	0.58
60	61	0.37	1.12	0.83	0.71	0.36	1.03	0.72
61	35	0.21	1.17	0.75	0.50	0.23	0.93	0.53
62	39	0.24	1.08	0.75	0.67	0.28	0.84	0.74
63	28	0.17	1.00	0.67	0.50	0.17	0.97	0.61
64	33	0.20	1.25	0.75	0.58	0.29	0.70	0.60
65	54	0.33	1.42	1.00	0.83	0.62	0.53	0.70
66	11	0.07	0.58	0.50	0.42	0.06	1.05	0.77
67	35	0.21	1.00	0.67	0.67	0.23	0.91	0.82
68	32	0.19	1.25	0.79	0.71	0.37	0.53	0.71
69	70	0.42	1.42	1.08	0.71	0.57	0.75	0.57
70	78	0.47	1.42	0.83	0.71	0.44	1.08	0.65

(Continued)

(Sheet 2 of 3)

Table 3 (Concluded)

No.	Rock Weight lb	Volume of Rock cu ft	A-Axis ft	B-Axis ft	C-Axis ft	Volume of Ellipsoid Same Axes cu ft	Volume Ratio: Rock/ Ellipsoid	Corey Shape Factor
71	79	0.48	1.83	0.83	0.75	0.60	0.80	0.61
72	42	0.26	1.08	0.83	0.67	0.32	0.81	0.70
73	179	1.09	1.75	1.75	0.67	1.07	1.02	0.38
74	22	0.13	0.92	0.67	0.46	0.15	0.91	0.59
75	48	0.29	1.12	0.96	0.54	0.31	0.95	0.52
76	27	0.16	0.92	0.75	0.54	0.19	0.84	0.65
77	100	0.61	1.42	0.92	0.83	0.57	1.07	0.73
78	51	0.31	1.42	0.83	0.54	0.33	0.93	0.50
79	47	0.29	1.17	0.83	0.67	0.34	0.84	0.68
80	25	0.15	0.92	0.83	0.54	0.22	0.70	0.62
81	43	0.26	1.08	0.75	0.58	0.25	1.05	0.65
82	37	0.22	1.00	0.83	0.62	0.27	0.82	0.68
83	30	0.18	0.92	0.75	0.50	0.18	1.01	0.60
84	97	0.59	1.75	1.17	0.62	0.67	0.88	0.44
85	77	0.47	1.50	1.08	0.83	0.71	0.66	0.65
86	8	0.05	0.71	0.50	0.38	0.07	0.70	0.63
87	29	0.18	1.25	0.54	0.46	0.16	1.08	0.56
88	70	0.42	1.67	0.92	0.67	0.53	0.80	0.54
89	36	0.22	1.08	0.75	0.58	0.25	0.88	0.65
90	50	0.30	1.58	0.75	0.50	0.31	0.98	0.46
91	17	0.10	0.83	0.58	0.58	0.15	0.70	0.84
92	31	0.19	1.17	0.71	0.67	0.29	0.65	0.73
93	14	0.08	0.92	0.67	0.42	0.13	0.64	0.53
94	37	0.22	1.33	0.75	0.62	0.33	0.69	0.62
95	40	0.24	0.92	0.83	0.58	0.23	1.04	0.67
96	92	0.56	1.54	1.17	0.67	0.63	0.89	0.50
97	68	0.41	1.58	1.00	0.58	0.48	0.85	0.46
98	10	0.05	0.67	0.58	0.42	0.08	0.57	0.67
99	25	0.15	1.25	0.58	0.46	0.17	0.87	0.54
100	117	0.71	1.62	1.00	0.88	0.74	0.95	0.69

(Sheet 3 of 3)

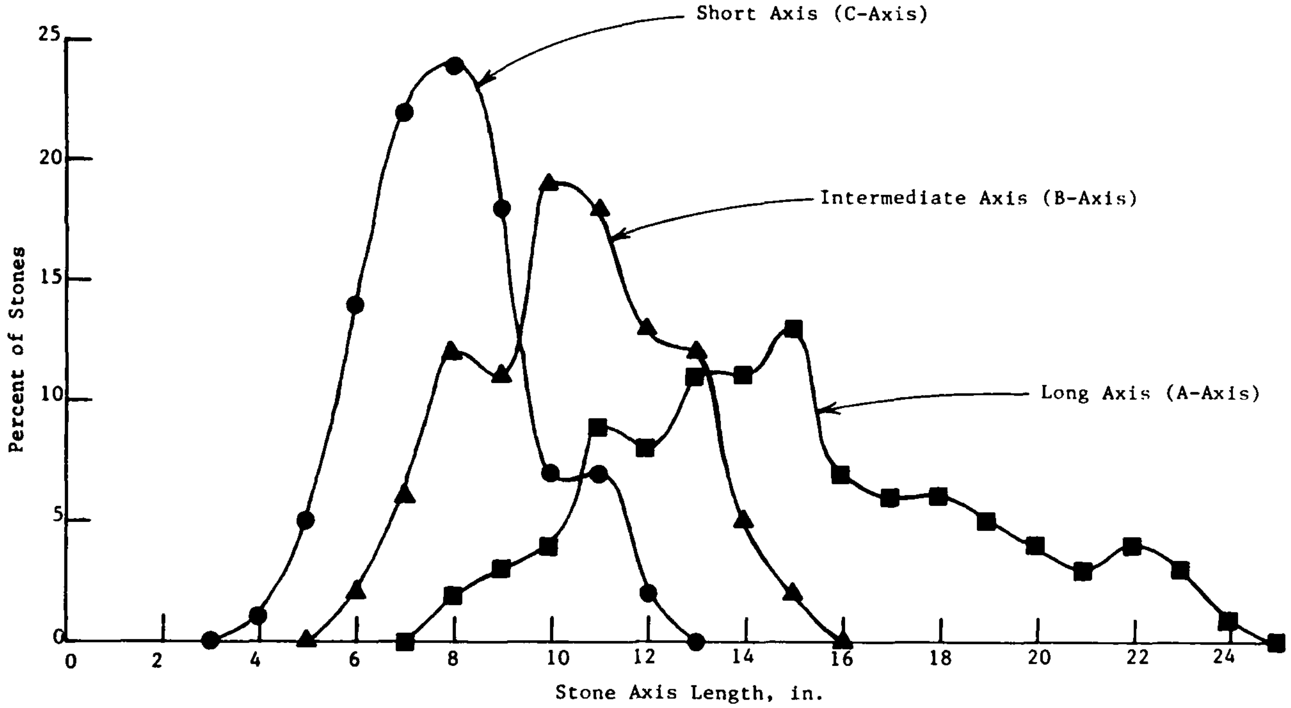


Figure 19. Axes length distribution of sample of stones comprising physical model of rubble-mound breakwater or jetty used in void sealing laboratory investigation

$$\sigma = \left[\frac{N \sum X_i^2 - \left(\sum X_i\right)^2}{N\ (N - 1)} \right]^{1/2} \qquad (1)$$

where

N = number of individuals in the sample, dimensionless

X_i = individual sample values

The mean of VSF was determined to be 0.88, and σ_{VSF} was computed to be 0.17. There was a -0.18 correlation coefficient between volume shape factor and Corey shape factor.

40. The factor relating average void size to stone parameters was calculated based on the estimated average void size. Void size was obtained from the void volume and number of voids produced by 100 stones. Number of voids was obtained by counting the voids and stones in numerous photographs of the model interior after one side of the model had been disassembled for analysis. Six repetitions yielded an average number-of-voids to number-of-stones ratio

of 0.83 and a standard deviation of 0.062. (The number of voids in the sample was only 83 percent of the number of stones in the sample.) It was considered that the void-to-stone ratio measured in two dimensions is proportional to an analogous measurement if taken in three dimensions. The 100 stones of the sample had a total weight of 4,790 lb, a bulk volume of 44.9 cu ft, and a total void volume of 15.8 cu ft. The average void size, AVS , was therefore 15.8/(0.83 × 100) = 0.19 cu ft.

Sealant Properties

41. Sealants and their properties are described in detail to provide a means of 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

42. 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 benefited 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 and the Buhne Point mixtures are presented in Table 4. The values shown under "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 (non-skid surface) after being dipped into the wet mixture (Figures 20 and 21). 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).

Table 4

Test Results for Fresh and Hardened Cementitious Sealants

Mixture	Slump in.	Air Content percent	Unit Weight lb/cu ft	Washout percent	Plate Cohesion lb	Two-Point Test*			Setting Time, hr	Dynamic Modulus E psi × 10^6	Pulse Velocity ft/sec	Compressive Strength psi
						g	h	r				
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

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* See paragraph 43. g = intercept on the torque axis; h = reciprocal of the slope of the line; r = correlation coefficient.

Figure 20. Dipping plate cohesion meter into wet cementitious sealant for void-sealing tests

Figure 21. Weighing cohesion meter plate with cementitious sealant adhering to sides of plate

43. Yield point and viscosity are terms which 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:

$$T = g + hN \tag{2}$$

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).

44. 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 test 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.

45. 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 rate. 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.

46. 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

47. Measurements of the properties of chemical sealant specimens tested at WES are summarized in Table 5. 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

Table 5

Test Results for Hardened Chemical Sealants

Sealant Materials	Average Pulse Velocity ft/sec	Average Dynamic Modulus E psi x 1,000,000
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

modulus of elasticity, E , was 94,000 psi. The set time for this material was about 1 min. Specimens of sodium silicate-cement mixed and cast at WES Structures Laboratory had 285 psi unconfined compressive strength, mean pulse velocity of 5,587 ft/sec, and a mean dynamic modulus of elasticity, E , of 111,000 psi. The set time for this material was about 30 sec.

48. 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.

Injection Procedure

49. Figures 22 through 27 summarize the locations and amounts of sealants injected into the model. Details of the procedure follow.

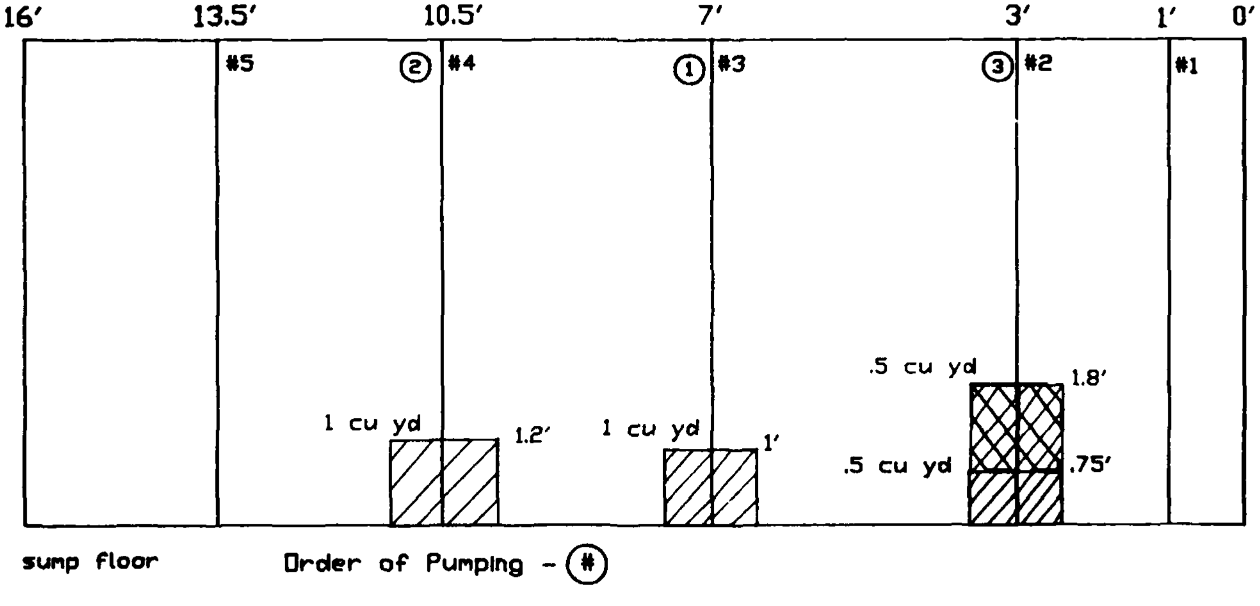


Figure 22. Section A of physical model of rubble-mound breakwater or jetty where WES mixture of cementitious sealant was evaluated. (Sealant placed by W. G. Jaques Company, Des Moines, IA)

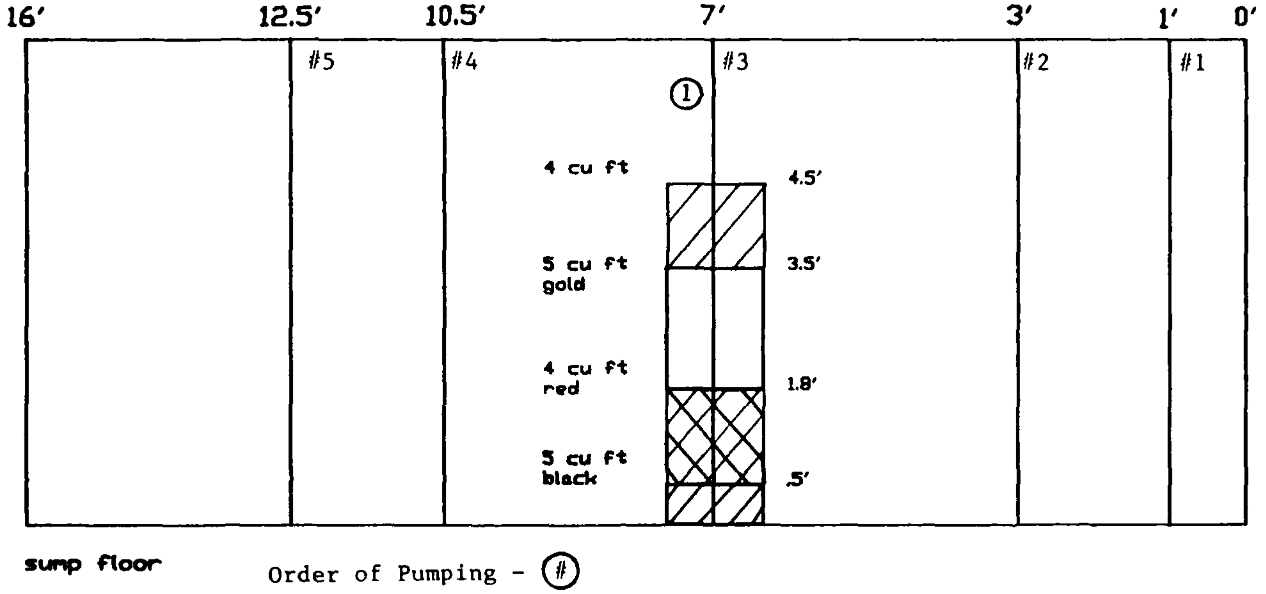


Figure 23. Section B of physical model of rubble-mound breakwater or jetty where WES mixture of cementitious sealant was evaluated. (Schematic of sealant placed by WES Structures Laboratory personnel)

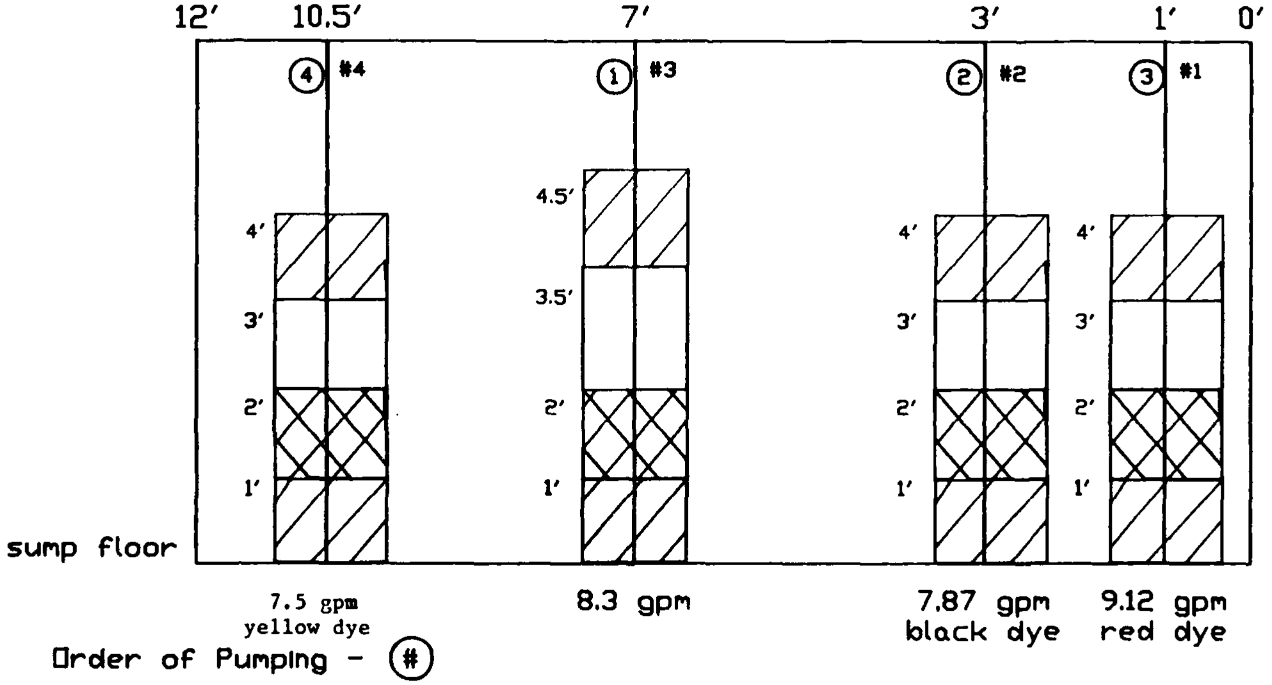


Figure 24. Section C of physical model of rubble-mound breakwater or jetty where sodium silicate-cement mixture of chemical sealant was evaluated. (Schematic of sealant placed by WES Structures Laboratory personnel)

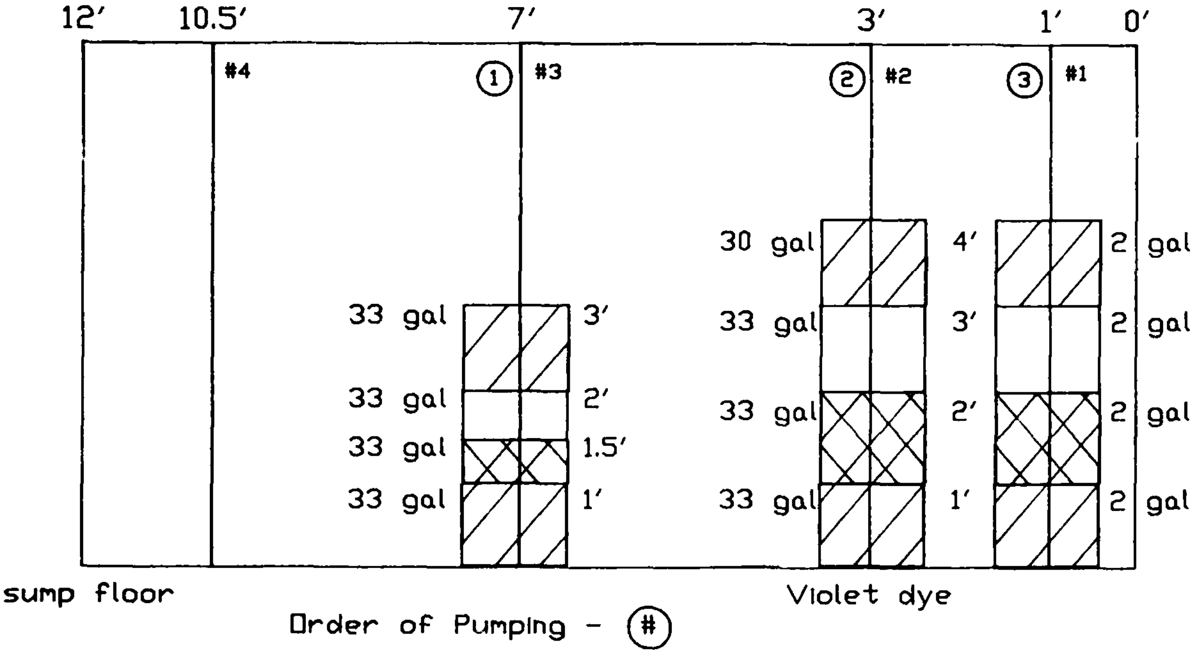


Figure 25. Section D of physical model of rubble-mound breakwater or jetty where sodium silicate-diacetin mixture for sand layer stabilization was evaluated. (Schematic of sealant placed by WES Structures Laboratory personnel)

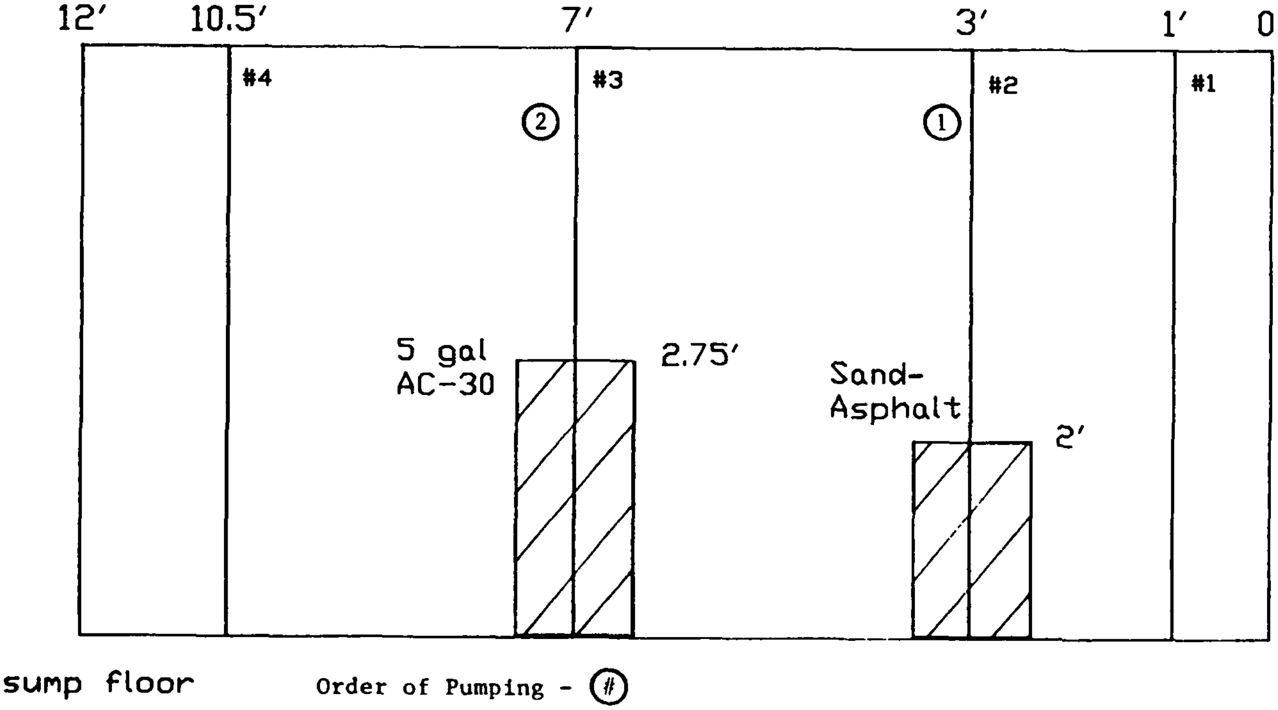


Figure 26. Section E of physical model of rubble-mound breakwater or jetty where sand-asphalt mixture of sealant was evaluated. (Schematic of sealant placed by WES Structures Laboratory personnel)

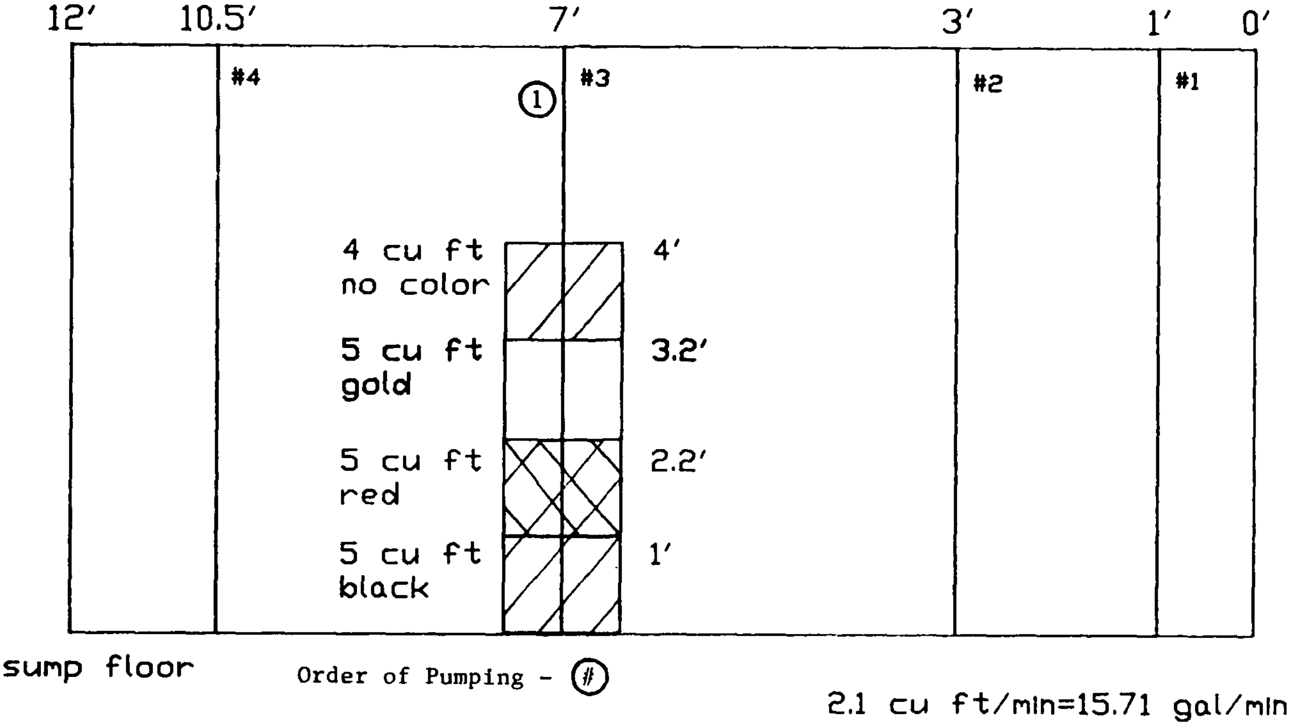


Figure 27. Section F of physical model of rubble-mound breakwater or jetty where Buhne Point mixture of cementitious sealant was evaluated. (Schematic of sealant placed by WES Structures Laboratory personnel)

<u>WES mixture</u>

50. 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 28 and 29. The mixture was delivered by readymix truck to the hopper of the contractor's grout pump (Figure 30). The pump was an air-driven Wagener Simplex pump. Inside diameter of the hoses was 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 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.

51. Another batch of sealant was ordered, and it was ensured the aggregate was the masonry sand specified. After repeating the tests, the header

Figure 28. Equipment for performing tremie test

Figure 29. Equipment for performing two-point workability test

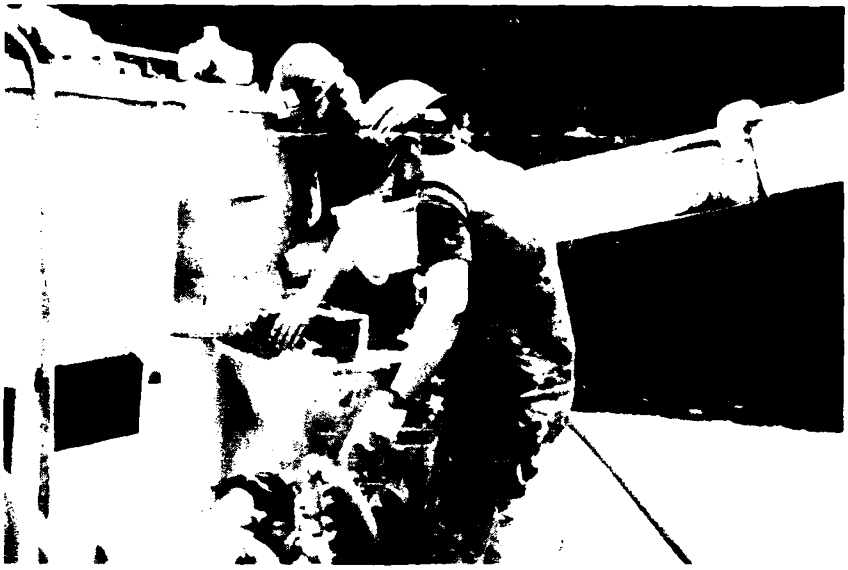


Figure 30. WES mixture of cementitious sealant being delivered to contractor's grout pump

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.

52. Connections were next made to Hole A4. Slightly more than 1 cu yd of sealant was pumped in 11.5 min at elevation 1.2 ft. Hole A2 was injected with less than 1 cu yd in two lifts, at 0.8 ft 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.

53. The WES Structures Laboratory staff then undertook to inject the WES mixture of cementitious sealant. The material was prepared in the 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 31). 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.

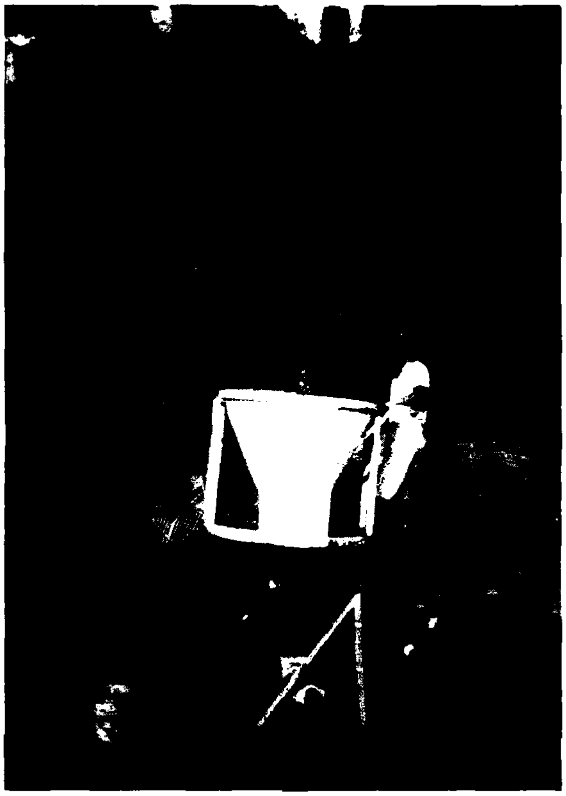


Figure 31. WES mixture of cementitious sealant being placed into Moyno pump by WES Structures Laboratory personnel

54. The first lift was injected at elevation 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 elevation 1.8 ft. The third lift was a gold-dyed 5-cu ft volume injected at elevation 3.5 ft. The last lift was injected at elevation 4.5 ft. It contained no dye and was 4 cu ft in volume.

<u>Buhne Point mixture</u>

55. 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 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

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

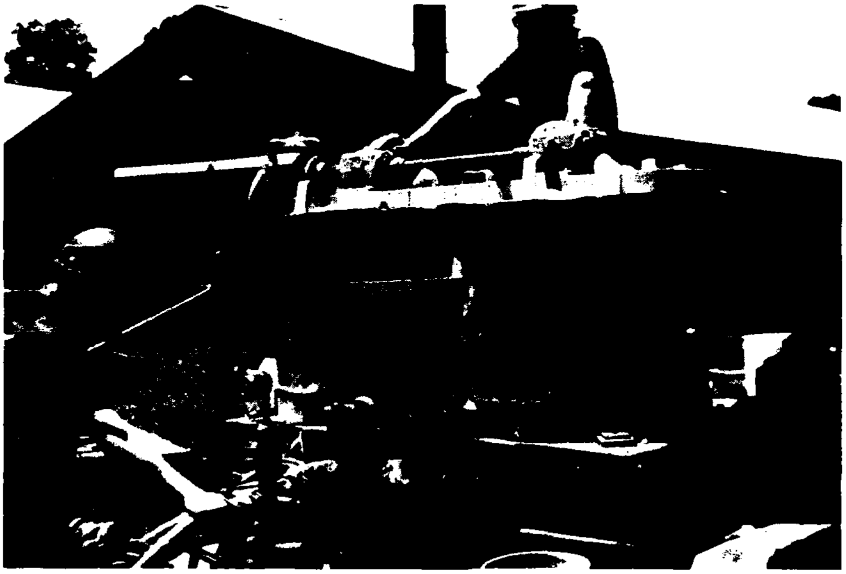


Figure 32. Sodium silicate-cement mixture of chemical sealant being placed into Wagener Simplex pump by grouting contractor

57. 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.

58. 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 7.9 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.

59. 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 9.1 gal/min. Zero pressure was registered at the pump.

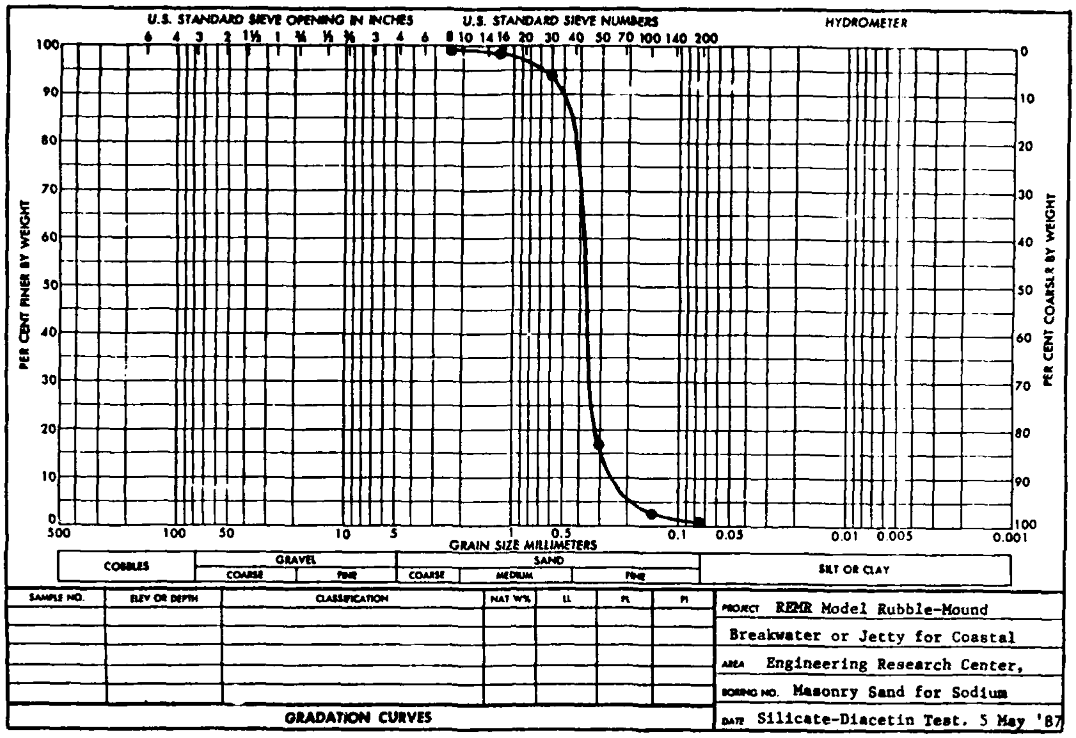
60. Hole C4 was sealed in four lifts at 1-ft increments in 5.3 min. Forty gallons of yellow-dyed sealant was pumped at a rate of 7.5 gal/min. Pump pressure did not rise above zero during that time.

Sodium silicate-diacetin mixture

61. 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. Its grain size distribution is presented graphically in Figure 33.

62. 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 13.7 gal/min. Sand placement during construction of the section might 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 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.

63. The second lift in Hole D3 was a 33-gal injection, 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



PROJECT REMR Model Rubble-Mound Breakwater or Jetty for Coastal
AREA Engineering Research Center,
BORING NO. Masonry Sand for Sodium
DATE Silicate-Diacetin Test. 5 May '87

Figure 33. Grain size distribution of material used to simulate layer for stabilization with sodium silicate-diacetin mixture

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 that 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.

64. 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.

65. 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.

66. 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.

67. 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 4.3 gal/min.

68. 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.

69. 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.

70. Hole D1, 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 elevation 1 ft above the datum at a sealant flow rate of 4 gal/min.

71. 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.

72. The third lift in Hole D1 was placed at an elevation 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.

73. 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-asphalt mixture

74. 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 was 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.

75. The sand-asphalt 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 34). 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 34. Funnel filled with sand-asphalt mixture of sealant for injection into physical model of rubble-mound structure

76. 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 35). For this test, the 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 395° 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.

Figure 35. Heated mastic asphalt being poured into funnel for injection into physical model of rubble-mound structure

77. 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

78. 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.

79. 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 one ounce 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.

PART IV: RESULTS OF SEALANT INJECTION TESTS

80. 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. The WES Structures Laboratory, Concrete and Grouting Group, provided videotaped analyses of sealant injection results after the second phase of disassembly. The staff also explained and analyzed results of specimen casting for long-term durability evaluations. These data tapes are archived for future reference and supplemental analyses.

The WES Mixture

81. The WES mixture of cementitious sealant pumped into Section A with additional water created the hardened mass shown in Figure 36 (Phase 1) and Figures 37 and 38 (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.

82. 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 (Figure 39 (Phase 1) and Figures 40 and 41 (Phase 2)). The lateral penetration was good, with the sealant entering nearly all the voids in the injected structure region. Using the above

Figure 36. Section A, Phase 1 disassembly of physical model of rubble-mound structure. (WES mixture of cementitious sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 37. Section A, Phase 2 disassembly of rubble-mound structure physical model. (WES mixture of cementitious sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 38. Section A, Phase 2 disassembly of physical model of rubble-mound structure. (WES mixture of cementitious sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 39. Section B, Phase 1 disassembly of physical model of rubble-mound structure. (WES mixture of cementitious sealant placed by WES Structures Laboratory personnel)

Figure 40. Section B, Phase 2 disassembly of physical model of rubble-mound structure. (WES mixture of cementitious sealant placed by WES Structures Laboratory personnel)

Figure 41. Section B, Phase 2 disassembly of rubble-mound structure physical model. (WES mixture of cementitious sealant placed by WES Structures Laboratory personnel)

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

83. 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 42 and 43 (Phase 1) and Figures 44 and 45 (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

Figure 42. Section F, Phase 1 disassembly of physical model of rubble-mound structure (Buhne Point mixture of cementitious sealant placed by WES Structures Laboratory personnel)

Figure 43. Section F, Phase 1 disassembly of rubble-mound structure physical model. (Buhne Point mixture of cementitious sealant placed by WES Structures Laboratory personnel)

Figure 44. Section F, Phase 2 disassembly of physical model of rubble-mound structure. (Buhne Point mixture of cementitious sealant by WES Structures Laboratory personnel)

Figure 45. Section F, Phase 2 disassembly of rubble-mound structure physical model. (Buhne Point mixture of cementitious sealant placed by WES Structures Laboratory personnel)

upper 2 ft of the sealed rubble, but the concrete was of such consistency in the lower part that 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

84. 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 46 through 48 (Phase 1) and Figures 49 and 50 (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 between 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 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 left completely porous.

Sodium Silicate-Diacetin Mixture

85. 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 51 through 53 (Phase 1) and Figures 54 and 55 (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 long. Bond strength was essentially zero, except in localized areas around Hole D3. A pocket of neat sealant found at the upper level of the sand layer of the section may have resulted from a flow channel being created adjacent to the outside of the injection pipe during sealing of the first lift (Figure 56). A thin layer of sodium silicate covered the sump floor beyond the structure.

Figure 46. Section C, Phase 1 disassembly of physical model of rubble-mound structure. (Sodium silicate-cement mixture of chemical sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 47. Disassembly of physical model of rubble-mound structure, Section C, Phase 1. (Sodium silicate-cement mixture of chemical sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 48. Section C, Phase 1 disassembly of rubble-mound structure physical model. (Sodium silicate-cement mixture of chemical sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 49. Section C, Phase 2 disassembly of rubble-mound structure physical model. (Sodium silicate-cement mixture of chemical sealant piaced by W. G. Jaques Company, Des Moines, IA)

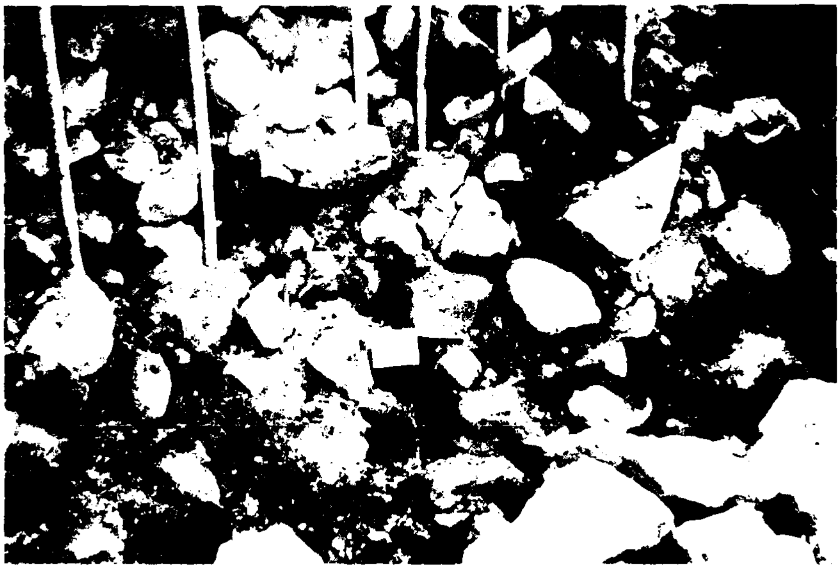


Figure 50. Section C, Phase 2 disassembly of physical model of rubble-mound structure. (Sodium silicate-cement mixture of chemical sealant placed by W. G. Jaques Company, Des Moines, IA)

Figure 51. Section D, Phase 1 disassembly of physical model of rubble-mound structure. (Sodium silicate-diacetin mixture for sand stabilization placed by W. G. Jaques Company, Des Moines, IA)

Figure 52. Section D, Phase 1 disassembly of rubble-mound structure physical model. (Sodium silicate-diacetin mixture for sand stabilization placed by W. G. Jaques Company, Des Moines, IA)

Figure 53. Disassembly of physical model of rubble-mound structure, Section D, Phase 1. (Sodium silicate-diacetin mixture for sand stabilization placed by W. G. Jaques Company, Des Moines, IA)

Figure 54. Section D, Phase 2 disassembly of rubble-mound structure physical model. (Sodium silicate-diacetin mixture for sand stabilization placed by W. G. Jaques Company, Des Moines, IA)

Figure 55. Section D, Phase 2 disassembly of physical model of rubble-mound structure. (Sodium silicate-diacetin mixture for sand stabilization placed by W. G. Jaques Company, Des Moines, IA)

Figure 56. Flow channel of neat sealant in sand layer of Section D where sodium silicate-diacetin mixture was used to stabilize sand in voids of rubble-mound structure

86. It is significant to note the effect of variability in proportioning of the components. Sealant was pumped from the hose into 6-in.-diam by 12-in.-long cylinders for testing. In the gelled state, the sealant occupied about one-third of the cylinder with the rest being water and ungelled constituents (Figure 57). An additional effect that must be prevented in field operations is the separation of sand into lenses by the pressure of the injected sealant. Examples of that kind of separation are displayed in the photograph of a laboratory specimen, shown in Figure 58.

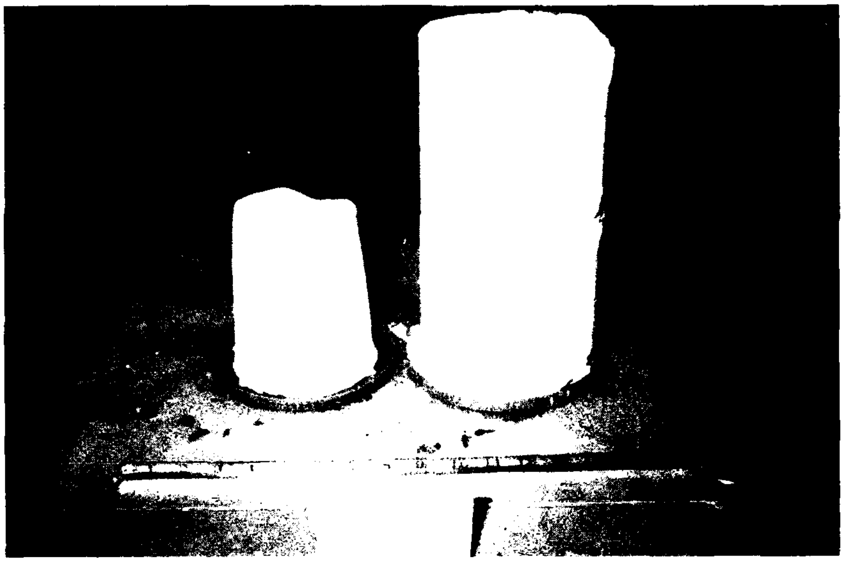


Figure 57. Neat sodium silicate-diacetin mixture is sensitive to proportioning of constituents. After setting in an unplaced condition, the mixture with a low percentage of diacetin tends to separate from the water and lose volume

Figure 58. Sodium silicate-diacetin sealant injected under pressure into sand specimens occasionally caused separation of the sand into lenses or stratified layers

Sand-Asphalt Mixture

87. No trace of the sand-asphalt 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. When poured through the injection pipe, AC-30 mastic 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 Figure 59 (Phase 1) and Figure 60 (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 during the time of the model disassembly, being approximately 100° F.

Figure 59. Section E, Phase 1 disassembly of physical model of rubble-mound structure. (Mastic asphalt subjected to irregular splashing caused by temperature differences between mastic and water-filled voids, placed by WES Geotchnical Laboratory personnel)

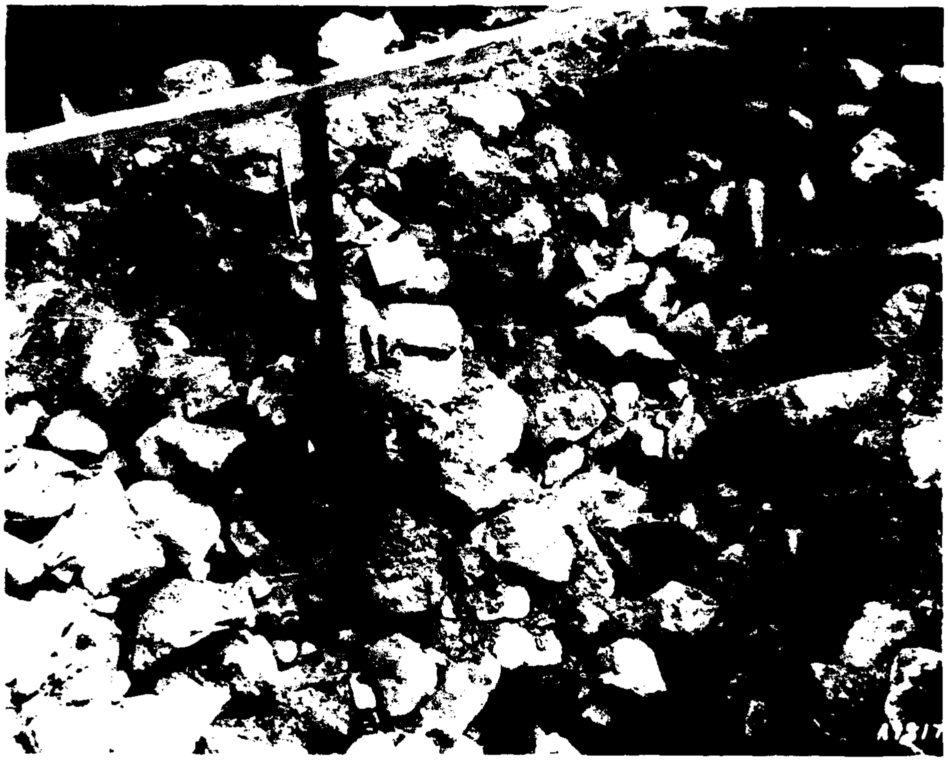


Figure 60. Section E, Phase 2 disassembly of physical model of rubble-mound structure. (Mastic asphalt subjected to irregular splashing caused by temperature differences between mastic and water-filled voids, placed by WES Geotechnical Laboratory personnel)

PART V: DESIGN OF SEALANT DURABILITY TESTS

Purpose of the Tests

88. The sealant durability time-dependent tests were formulated to determine how the sealant materials would endure under actual field conditions. Effects of 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 of sealant materials in the field environment with time.

89. To monitor material performance, representative samples of each sealant material evaluated in the physical model rubble-mound structure 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.

90. Three sites were selected as typical climatic environments to which the sealants would be exposed: Treat Island, Maine; Duck, North Carolina; and Miami, Florida. These locations represent conditions of cold, moderate, and warmwater environments. This range in climatic conditions imposes 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, also affect the specimens.

91. At each test site, the specimens were placed at the two water levels of (a) mean water line (mwl) and (b) below mean lower low water (-mllw). These placement locations allow comparisons between materials which have been continuously submerged with those undergoing wetting and drying cycles resulting from 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

92. 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. Tests are still ongoing. 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.

93. 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

94. Compressive strength. Compressive strength tests were performed to determine the strength values of the WES and the Buhne Point mixtures of the cementitious sealants. An indication of the ultimate strength of the material was 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.

95. Ultrasonic pulse velocity. The ultrasonic pulse velocity test measures the travel time of a sound pulse through the specimen and is performed according to the criteria and standards established by the American Society for Testing and Materials (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 velocity of sound in the specimen provided an indication of deterioration.

96. Resonant frequency. Specimens were tested to determine their fundamental transverse frequency according to ASTM Specification No. D-C215-60. The specimens were supported at the nodes in a horizontal position and vibrated in the fundamental flexural mode. The resonant frequency was obtained by varying the vibration frequency and observing the specimen's maximum response. Young's dynamic modulus of elasticity, E, was calculated using the fundamental transverse frequency and specimen dimensions and weight. Changes in the modulus provided an indication of deterioration.

97. Failure criteria. The criteria for failure were established as follows. Subsequent calculations of Young's dynamic modulus of elasticity, E, for each specimen were expressed as a percentage of the values at installation. When the calculated value became less than half the initial value during the exposure periods, the specimen was considered to have failed (Thornton 1980). If specimen deterioration occurred to an extent such that measurements could not be made or if the specimen separated, failure was considered to have occurred.

Sand asphaltic specimens

98. Marshall stability test. The Marshall stability test, conducted according to ASTM Specification No. D-1559, measured strength and plastic flow resistance and provided an indication of stability of the material. Density and void properties were also determined during this test.

99. Indirect tensile strength. This test allowed 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 was calculated for use in determining the resilient modulus. The tensile strength, ST, of the specimen is calculated as follows:

$$ST = \frac{2\,P_{ult}}{PI\ tD} \tag{3}$$

where

P_{ult} = applied load, lb

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

t = specimen thickness, in.

D = specimen diameter, in.

The test method is illustrated in Figure 61.

100. Resilient modulus. The resilient modulus test was 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 was actually used in these evaluations. A simplified form of the expression recommended by ASTM Specification No. D-4123 was used to calculate the instantaneous resilient modulus, RM .

$$RM = \frac{3.59\ P}{tv} \tag{4}$$

where

P = applied load, lb
t = specimen thickness, in.
v = vertical deformation, in.

An illustration of the testing system and arrangement is shown in Figure 62.

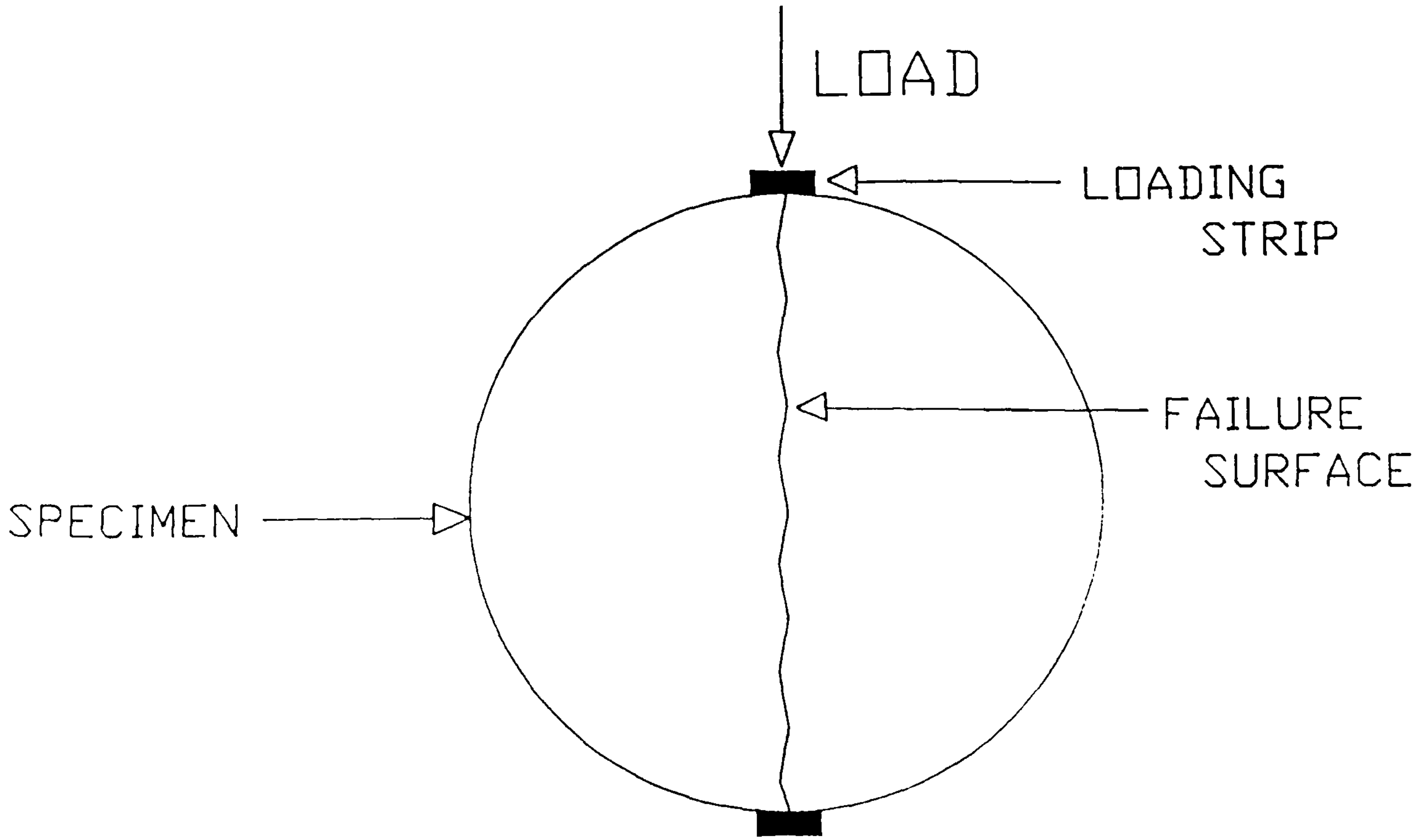


Figure 61. Schematic for indirect tensile strength determination

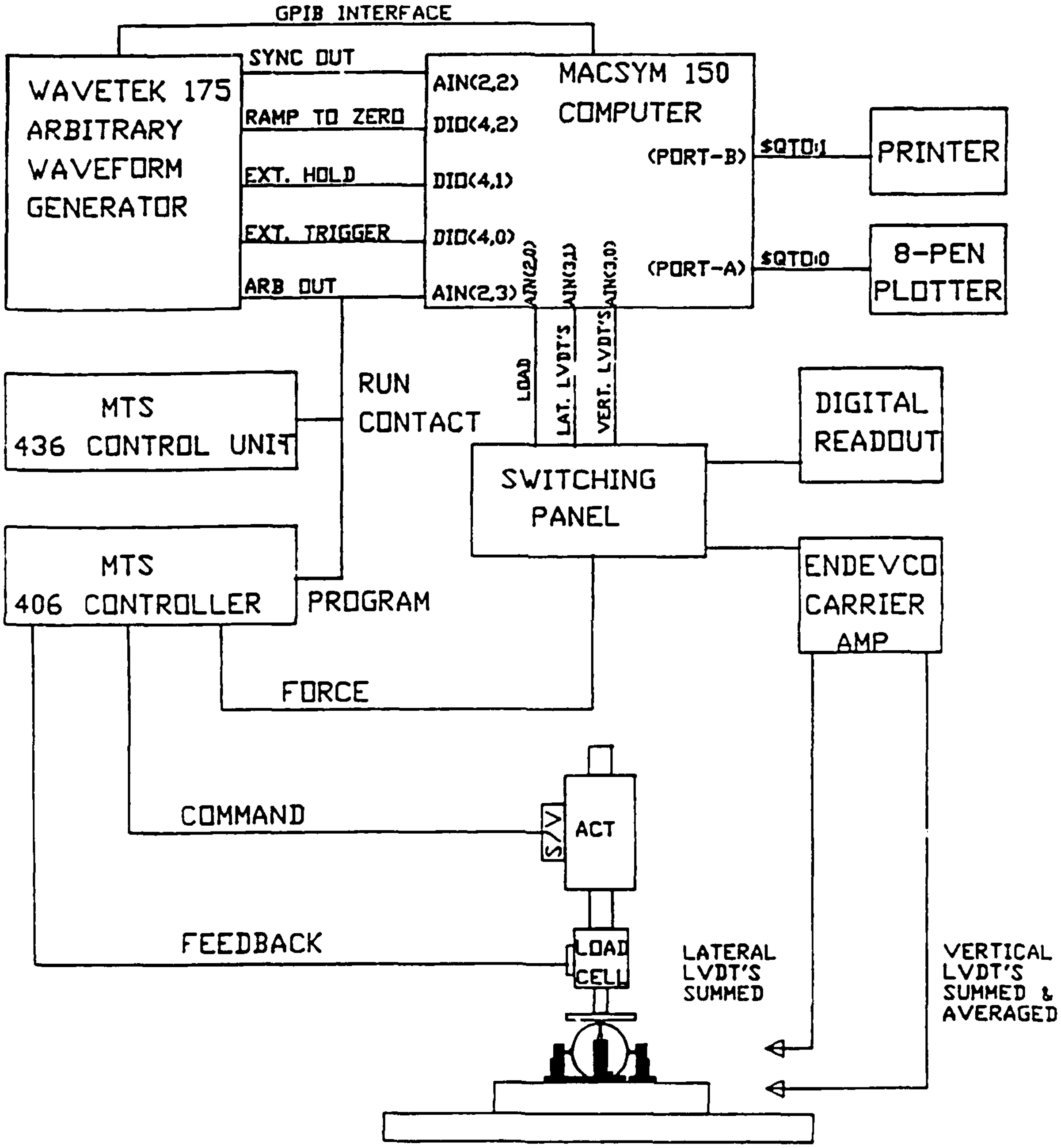


Figure 62. Schematic for resilient modulus determination

PART VI: CASTING AND LABORATORY EVALUATION OF SEALANT SPECIMENS FOR LONG-TERM EXPOSURE TESTING

Mixing and Casting of Specimens

101. 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-asphalt mixture were cast for the durability testing program. Details of the specimen mixing and casting procedures for each sealant follow.

Microfine cement

102. 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

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 (Figure 63). 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 using 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 of the injection process. The second mix design proved successful, and the sand was sealed throughout the column (Figure 64). The ingredients of the mixture are:

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

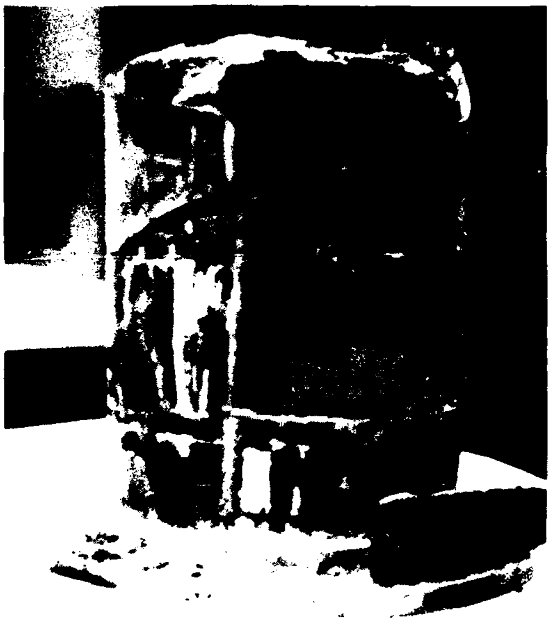


Figure 63. Injection of microfine cement into sand column caused failure of plastic cylinder because of high required pressure

Figure 64. Sand column sealed with microfine cement using 2-to-1 water-to-cement ratio

WES mixture

103. The WES mixture is a type of concrete. The mixture was prepared in a batch mixer according to the following proportions to produce 1 cu yd.

Ingredient	Quantity
Type I portland cement	23.8 lb
Masonry sand	90.0 lb
Monier fly ash	1.2 lb
Silica fume	2.4 lb
Air-detraining agent	6.2 g
Sodium citrate	6.2 g
Antiwashout additive	31.0 g
Water-reducing admixture	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 might 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

104. 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 sealant was to create a sediment barrier and not to sustain direct loading. Mixture ingredients were proportioned as shown below to produce 1 cu yd. The following mix proportions were used:

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

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

Sodium silicate-cement mixture

105. 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

106. 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 pipes of 6-in. diam and 5-ft lengths were used as a mold in casting the specimens (Figure 65). 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.

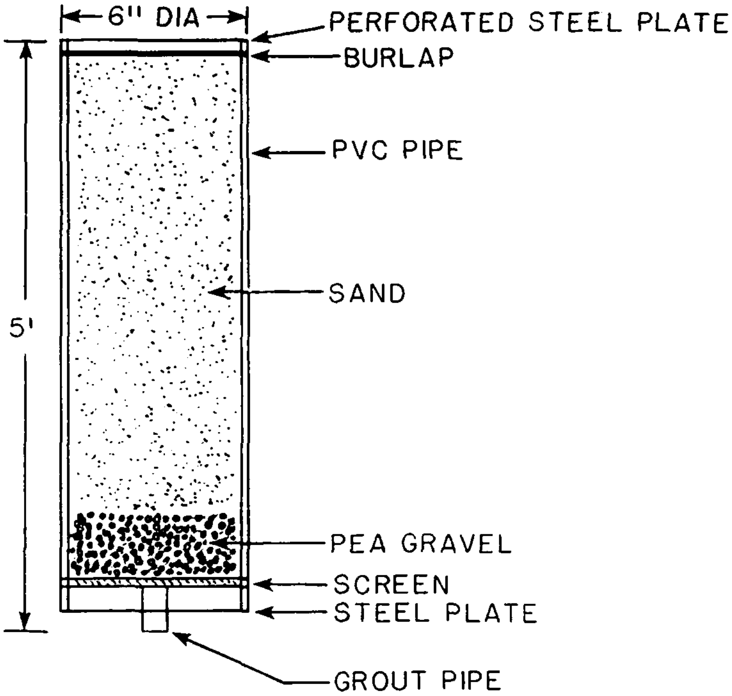


Figure 65. Schematic of sodium silicate-diacetin mixture *of sealant being injected into sand specimens*

Sand-asphalt mixture

107. Design of the sand-asphalt mixture was based upon designs previously used at Asbury Park, New Jersey, and Galveston, Texas. These sites were chosen because of the sustained performance of the material which 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 6 summarizes results of those analyses. Also included is the WES sand-asphalt mixture that was ultimately developed. Table 6 can be used as a guide for future mix designs. Based upon the analyses of the Asbury Park and Galveston mixtures, the WES sand-asphalt mixture shown in Table 6 was developed for the long-term time-dependent exposure field tests. Sand and cement contents were 79 percent and 21 percent, respectively.

Table 6

Sand-Asphalt Mixture Analyses

	Percent Passing		
Sieve Size	Asbury Park, New Jersey	Galveston, Texas	WES Sand-Asphalt Mixture
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		

108. The performance of sand-asphalt mixtures in the environment appears to be temperature dependent. Prior to determining the percentage of asphalt to blend into the specimens, a few 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 of the asphalt would result in

settlement or creep of the mixture within the structure.

109. 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 350° F. Heating asphalt to higher temperature may cause material hardening.

Testing of Specimens

Cementitious and chemical sealant specimens

110. Initial tests were conducted to provide reference standard values for each sealant material. Subsequent tests will be conducted at each field test site. Tests repeated at least yearly for the duration of the REMR program are desirable to provide adequate data to determine the amount, if any, of deterioration of the material because of environmental factors. Table 7 shows the characteristics obtained during initial tests conducted on the cementitious and chemical sealant specimens.

111. The values presented in Table 7 are averages of a large number of test results. No problems were encountered while testing the WES and the Buhne Point mixtures 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 and the Buhne Point mixtures 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

Table 7

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

Material	Pulse Velocity ft/sec	Young's Dynamic Modulus of Elasticity, E psi	Compressive Strength psi
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

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-asphalt sealant specimens

112. The sand-asphalt 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-asphalt 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 8 outlines the curing conditions of wetting and drying cycles for determining retained strength characteristics of the sand-asphalt mixture. The initial tests were conducted to determine baseline parameters. Future tests will be conducted during the field investigation periods. While the compressive strength of the sand-asphalt mixture is less than other sealants, its rheology may allow it to satisfactorily serve as a void-sealing material for rubble-mound structures.

Table 8

Curing Conditions and Initial Tensile Strength Values for Sand-Asphalt Mixture Specimens Cast for Long-Term Durability Evaluation

Curing Conditions	
Soaking in Saltwater Salinity = 32 ppt	Drying
24 hr	24 hr
48 hr	96 hr
96 hr	1 week
1 week	2 weeks
2 weeks	4 weeks
4 weeks	Test

	Tensile strength, psi		
When Tested	T = 40° F	T = 55° F	T = 65° F
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

PART VII: EMPLACEMENT OF DURABILITY TEST SPECIMENS

Site Selections

113. 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.

Site Descriptions

Treat Island, Maine

114. Treat Island, Maine, is located in Cobscook Bay, approximately 3/4 mile from Eastport (Figure 66). The USACE has used 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. This location was selected as an exposure station to monitor specimens in extreme cold weathering conditions.

115. Specimens are placed on a 120-ft-long by 40-ft-wide platform located at mean tide level. This allows the specimens to experience wetting and drying as the tide level varies. Average water temperature ranges 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, then freeze when exposed to air which sometimes has a temperature of -10° F. The specimens are exposed to over 100 freezing and thawing cycles during a winter season (Thornton 1980).

Duck, North Carolina

116. The WES CERC Field Research Facility (FRF) is located on an Atlantic coast barrier island at Duck, North Carolina. The FRF is situated near the middle of Currituck Spit, along a 100-km stretch of unbroken

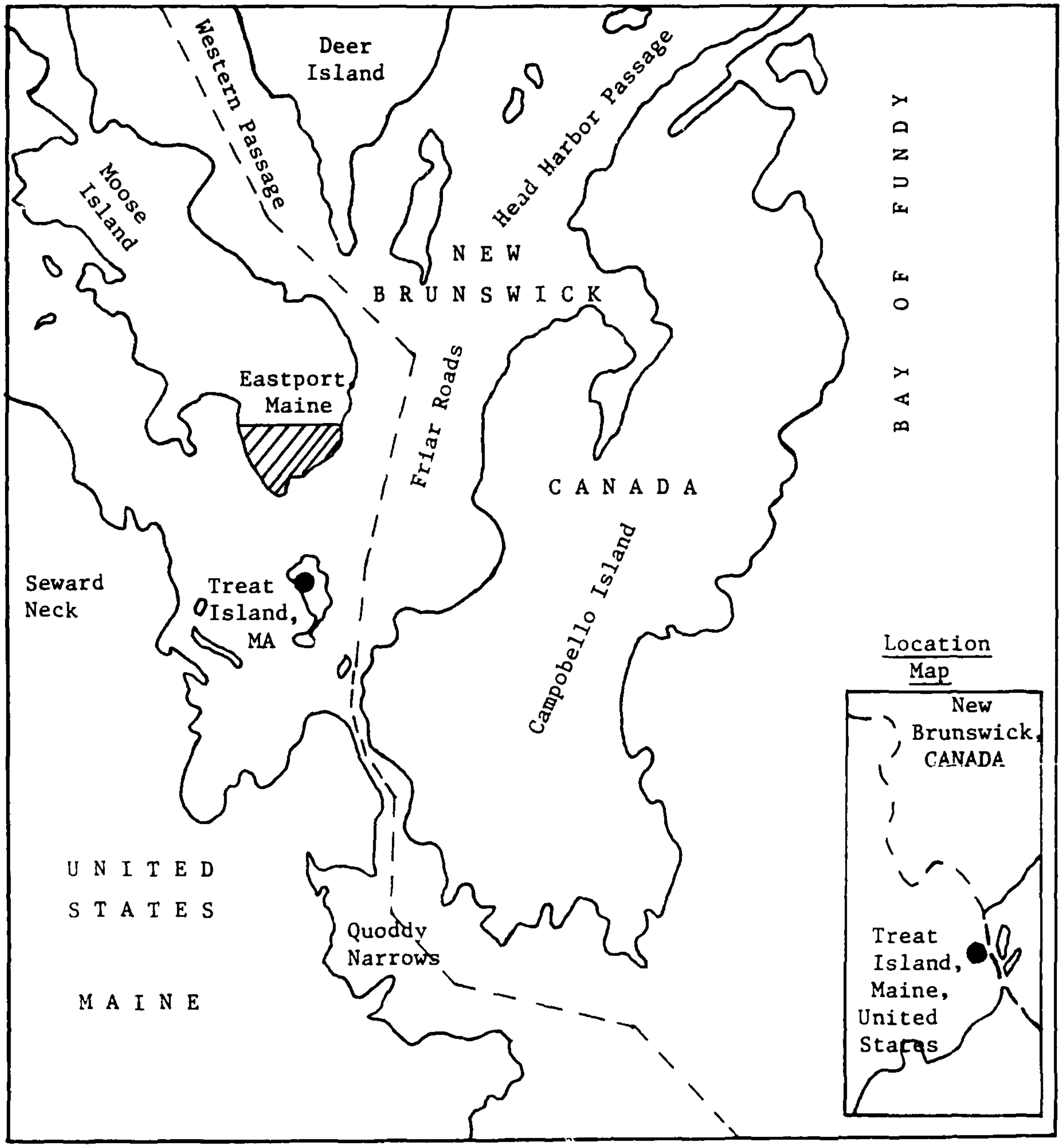


Figure 66. The WES concrete natural weathering station, Treat Island, Maine

shoreline extending south from Rudee Inlet, Virginia, to Oregon Inlet, North Carolina (Figure 67). 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 on the west side of the spit. Because the tide range in Currituck Sound due west of 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, North Carolina, 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.

Miami, Florida

117. Specimen placement and some of the evaluations at Miami, Florida, 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 68). 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, which may impact sample durability.

Specimen Placement Technique

118. Test specimens have been installed in each of the three locations previously discussed. Environmental factors, such as temperature of the air and water, wave height, and salinity, were measured during installation to define placement conditions, and measurements will be repeated periodically throughout the testing period. The specimens were given identification codes when cast, and a simple labeling scheme was developed for easily identifying the specimens while in the field. The labeling system is as follows:

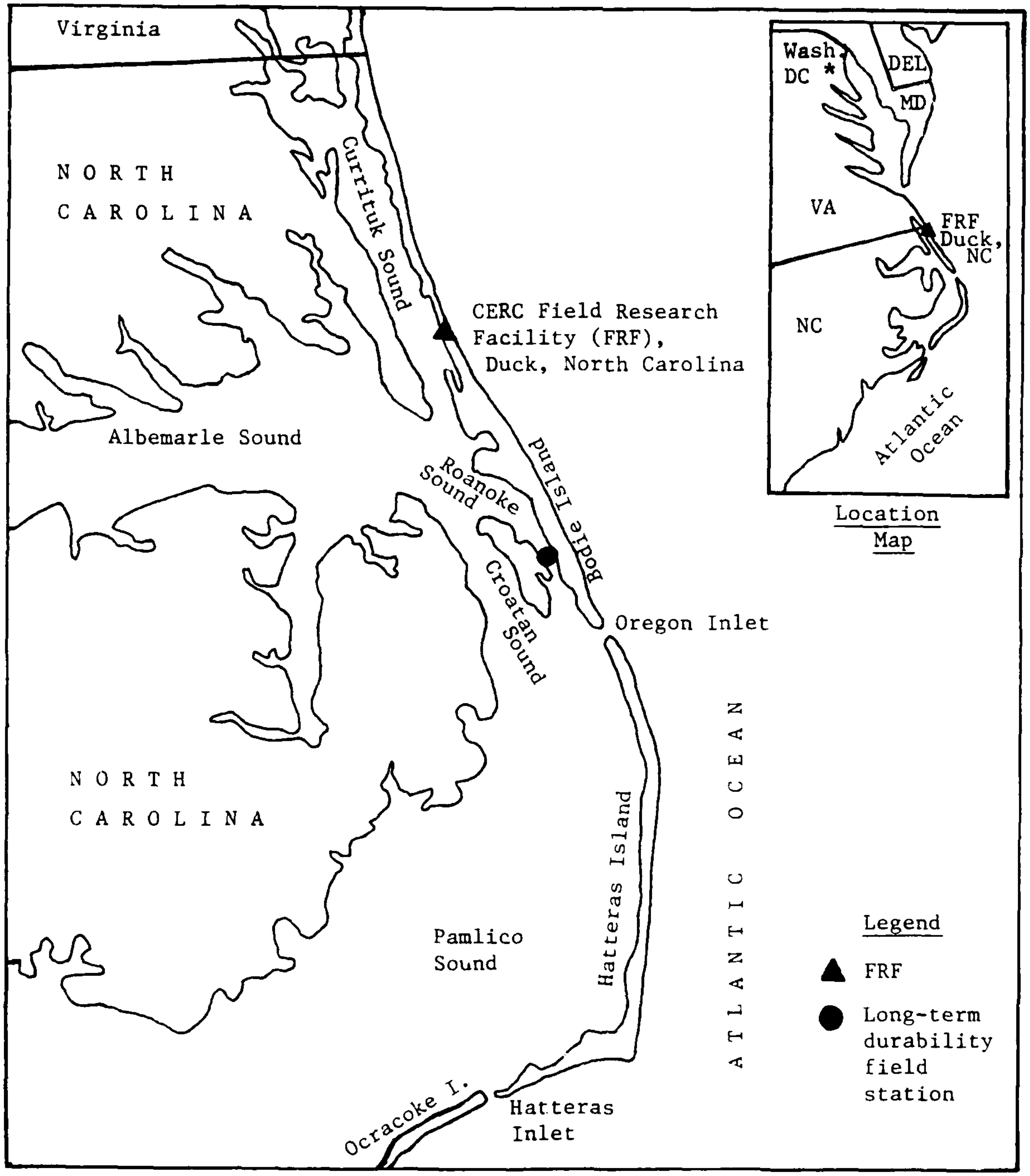


Figure 67. The WES CERC, FRF, Duck, North Carolina, and location of long-term durability field station

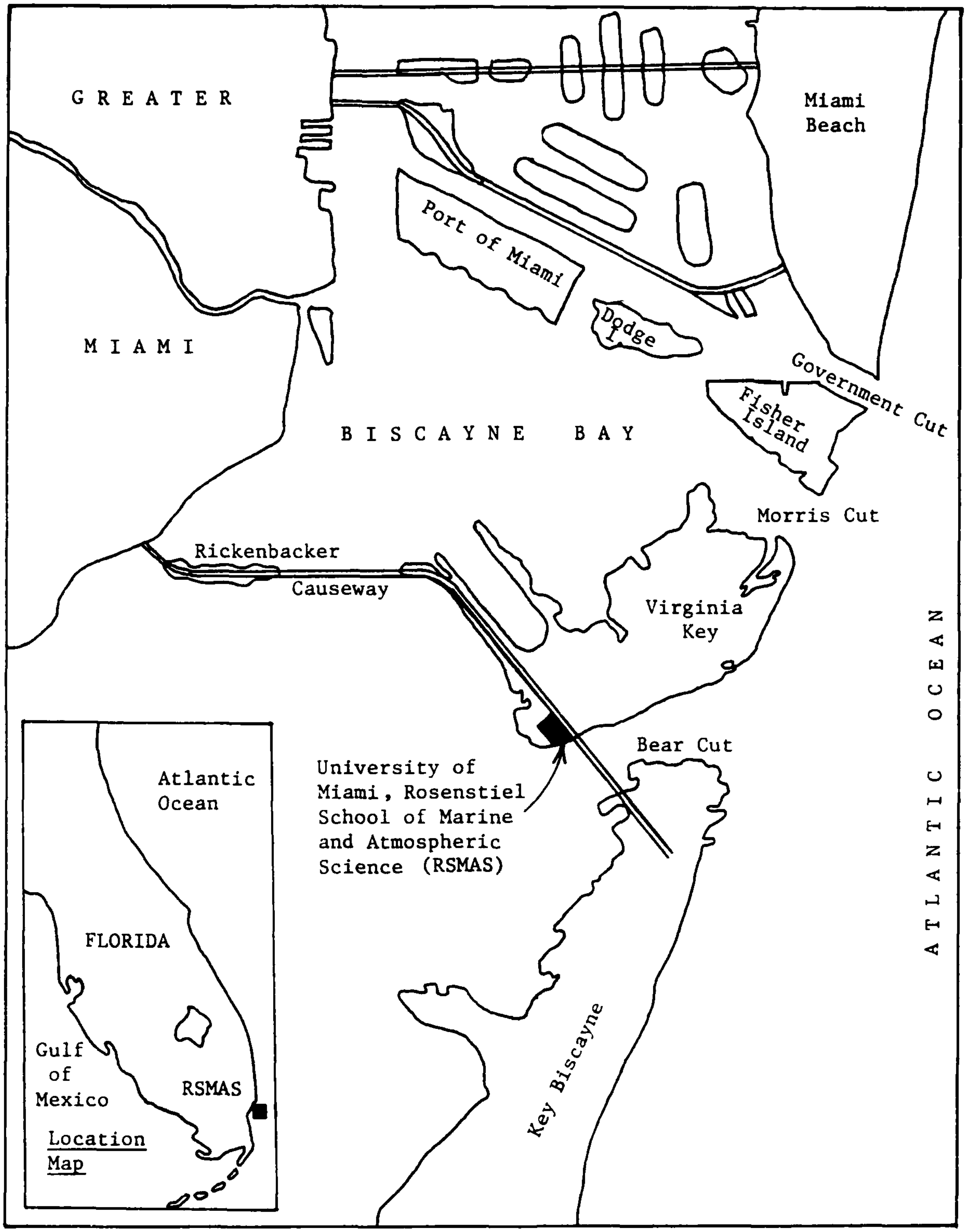


Figure 68. University of Miami, RSMAS, Miami, Florida, long-term durability field station

1 - 10	WES Mixture of Cementitious Sealant
11 - 20	Buhne Point Mixture of Cementitious Sealant
21 - 30	Sodium Silicate-Diacetin Sand Stabilized Mixture
31 - 40	Sodium Silicate-Cement Mixture of Chemical Sealant

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

T - Treat Island, Maine
D - Duck, North Carolina
M - Miami, Florida

Figures 69 through 71 show specimens during placement at Treat Island, Maine; Duck, North Carolina; and Miami, Florida, respectively.

119. 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 of each sealant type (WES mixture of cementitious sealant, Buhne Point mixture of cementitious sealant, sodium silicate-cement mixture of chemical sealant, and sodium silicate-diacetin mixture of chemical sealant with stabilized sand) were placed in each of four baskets, which would correspond to one sealant type per water level (Figure 72). The sand-asphalt mixture samples (Figure 73) were housed in a pvc pipe apparatus to ensure that deformation would not occur either during shipping or in the field (Figure 74). Shape retention of the asphaltic specimens was crucial for accurate testing results. Each housing contained four sand-asphalt specimens. Eight housings were placed at each of the two water levels at each field station.

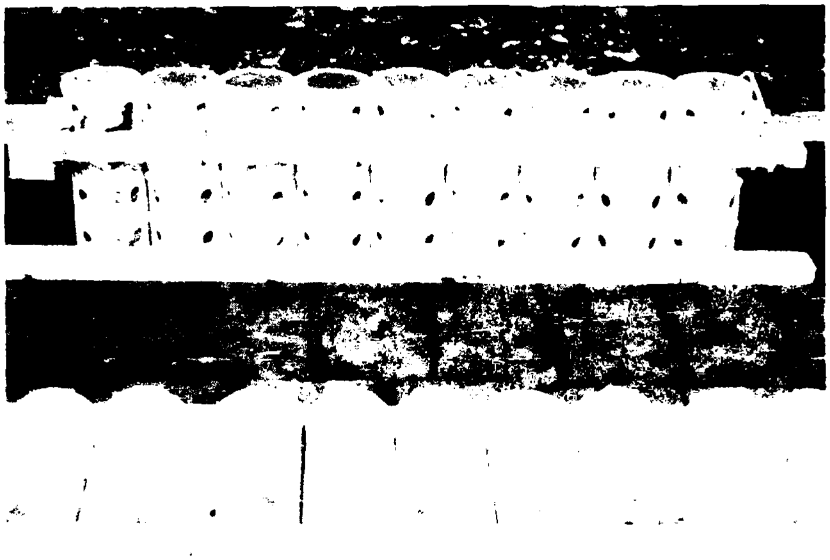


Figure 69. Placement of long-term time-dependent sealant specimens for durability testing at Treat Island, Maine

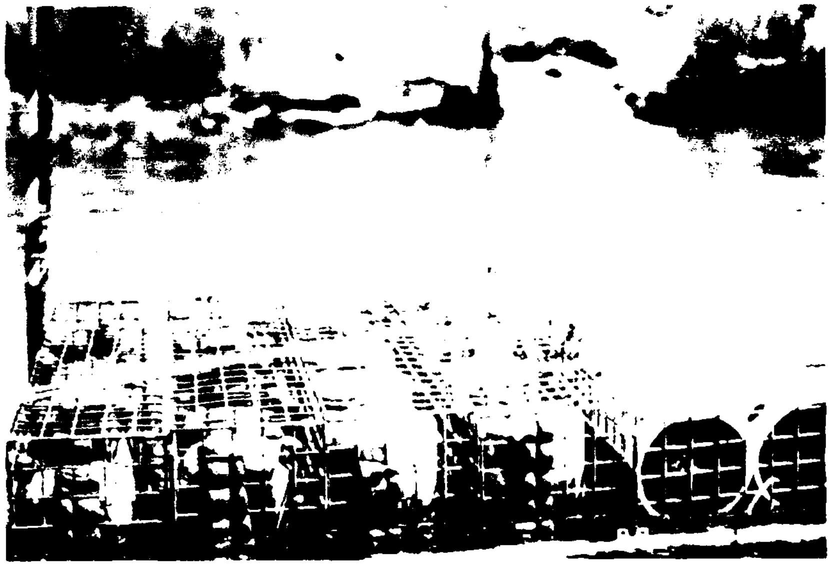


Figure 70. Placement of long-term time-dependent sealant specimens for durability testing at Duck, North Carolina

Figure 71. Placement of long-term time-dependent sealant specimens for durability testing at Miami, Florida

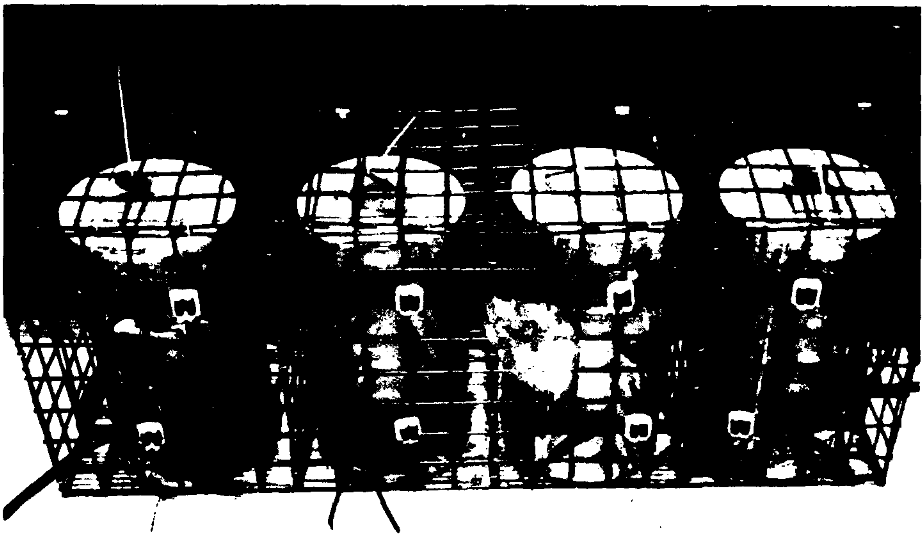


Figure 72. Cementitious sealant specimens in gabion-type cages for long-term time-dependent durability evaluations

Figure 73. Sand-asphalt mixture of sealant specimens cast for long-term time-dependent durability testing

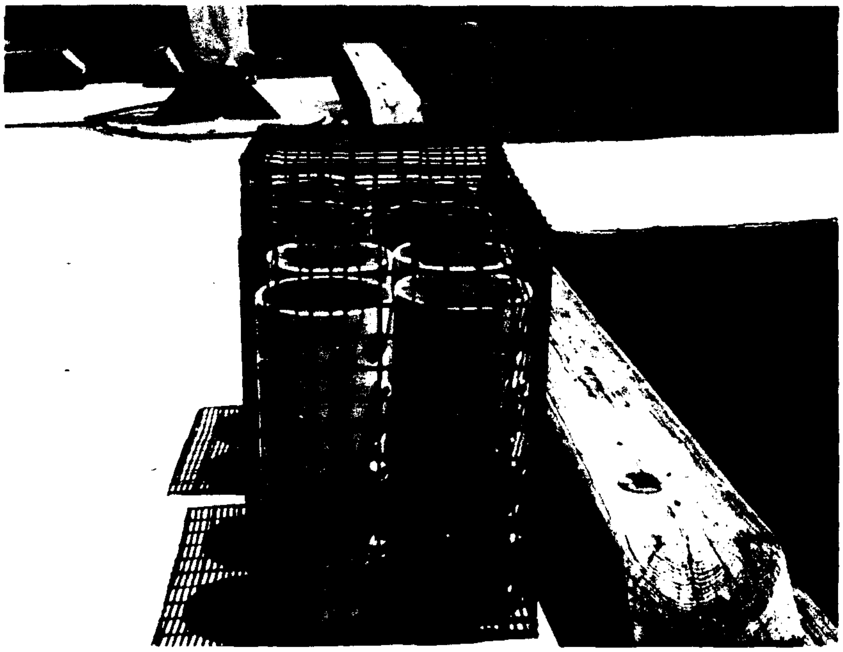


Figure 74. Sand-asphalt mixture of sealant specimens in gabion-type cages for long-term durability testing

PART VIII: ENVIRONMENTAL EFFECTS OF SEALANTS

Aquatic Toxicity Assessment

120. The materials under consideration as sealants must be easily pumped or injected, resistant to dilution and erosion when placed in flowing water, and safe in the aquatic environment. Sealants can be shown to be safe in the aquatic environment by using standard laboratory bio-assay 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 to aquatic organisms, would be to conduct static, short-term bio-assays 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.

121. 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.

122. 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 various 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, and using standardized test conditions. No chemical analyses of the sealants or sealant-water mixtures are necessary unless toxicity is observed.

Toxicity Bio-Assay Analyses

123. The WES Environmental Laboratory performed preliminary toxicity bio-assay analyses of three sealant mixtures, including (a) the WES mixture of cementitious sealant containing the variety of admixtures, (b) the sodium silicate-diacetin mixture of chemical sealant, and (c) a sand-asphalt mixture. The sand-asphalt mixture was delivered to the 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 cement-like slurry rather than a solid. The sodium silicate-diacetin mixture was transported in separate bottles, both being in liquid form. Prior to conducting the bio-assay 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-asphalt mixture. All of these materials were received by the bio-assay 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 the Environmental Laboratory because the mixture hardens quickly. The sodium silicate-diacetin mixture was prepared immediately prior to being used in the *Daphnia* bio-assays. The *Daphnia* were exposed for 96 hr to a range of sealant concentrations.

124. These initial bio-assays 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 mg/ℓ of test water) to 100,000 ppm. The animals were exposed to different concentrations of the sealant materials, which were placed on the bottom of glass exposure beakers. The sand-asphalt mixture was broken into 1-cm pieces before being weighed and added to the beakers. The WES and the sodium silicate-diacetin mixtures 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 data of the test animals are shown in Table 9, and statistics of these means are presented in Table 10.

125. These data are an initial indication that two of the sealant mixtures (the WES and the sodium silicate-diacetin) 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-asphalt 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-asphalt 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-asphalt 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 11 through 13 for the WES mixture, the sand-asphalt mixture, and the sodium silicate-diacetin mixture, respectively.

126. 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 9

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

Treatment	Initial No.	WES Mixture			Sand-Asphalt Mixture			Sodium Silicate-Diacetin Mixture		
		24 hr	48 hr	96 hr	24 hr	48 hr	96 hr	24 hr	48 hr	96 hr
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 10

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

	Mean Number of Survivors		
Treatment	WES Mixture	Sand-Asphalt Mixture	Sodium-Silicate Diacetin Mixture
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

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

Table 11

Variation of DO and pH of WES Mixture of Cementitious Sealant Bio-Assay with *Daphnia*

	Test Date							
	29 June 87		30 June 87		1 July 87		2 July 87	
Treatment	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 12

Variation of DO and pH of Sand-Asphalt Mixture of Sand Stabilization Sealant, Bio-Assay with *Daphnia*

	Test Date							
	6 July 87		7 July 87		8 July 87		9 July 87	
Treatment	DO	pH	DO	pH	DO	pH	DO	pH
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 13

Variation of DO and pH of Sodium Silicate-Diacetin Mixture of Chemical Sealant, Bio-Assay with *Daphnia*

	Test Date							
	7 July 87		8 July 87		9 July 87		10 July 87	
Treatment	DO	pH	DO	pH	DO	pH	DO	pH
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: CONCLUSIONS AND RECOMMENDATIONS REGARDING VOID SEALING OF RUBBLE-MOUND STRUCTURES

Conclusions

127. 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 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 fills 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 used to fill the voids in the sand layer did not completely solidify (harden) the sand in Section D.

128. The disassembled sections showed concrete can form a bulbous mass in a rubble structure when injected under water. 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 in. 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.

129. 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.

130. Sand-asphalt 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-in.- or 6-in.-diam pipes are required. Sand-asphalt 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.

Recommendations

Materials

131. 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.

132. The Buhne Point mixture was simpler to batch and, in some cases, showed flow and bonding characteristics quite similar to the WES mixture. It should be noted that the Buhne Point mixture in the lowermost lift in Hole F3 did not set up properly. For reasons not fully understood, it appears the strength of the Buhne Point mixture was more susceptible to site factors than the WES mixture. Perhaps, coincidentally, the region in Hole F3 having slightly less concrete strength than the WES mixture was where REVERT had been injected a week earlier. According to other experimenters, no effect of the REVERT should have been found after 2 days. Injection in the field,

followed by onsite coring, will better ascertain the sealant's consistency.

133. The sodium silicate sealants have extensive records of successful applications. 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. With improved understanding of set time requirements and proportioning of constituents, the sodium silicate-cement mixture and the sodium silicate-diacetin mixture are recommended for field experimentation.

Methods of application

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

135. Concrete pumps are ideal for emplacing both the WES mixture and the Buhne Point mixture of cementitious sealants, confirmed by field experience of US Army Engineer Division, North Central (NCD) during sealing of the Milwaukee Harbor, Wisconsin, north detached breakwater. While the intent of NCD was strictly to fill the void beneath the cap, cementitious sealant penetrated up to 1 ft into the core stone in 25 percent of the cores retrieved. 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.

136. Positive displacement pumps are a standard type of pump for injecting chemical sealants in large spaces. Comparison between laboratory samples that were created by a static in-line mixer and samples of model injections that 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.

137. The field experience of NCD 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. It is possible that the faster pumping rates used by NCD eliminated the need for the static mixers. The effect of wave conditions during injection was not addressed. Phase I was impacted by excessive waves and, during Phase II, limitations on wave height during which sealing operations could be conducted were established.

Specifications

138. Contract specifications for experimental prototype rubble-mound structure field sealing should be prepared to give the broadest possible decision-making powers to the Contracting Officer's Representative (COR). In developing such contract specifications, guidance may be obtained from Parts IV through VI of REMR Technical Report "State-of-the Art Procedures for Sealing Coastal Structures with Grouts and Concretes" (Simpson 1989). 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, and the work unit Principal Investigator should be onsite during the prototype field test sealing.

Environmental effects

139. The potential danger to the environment and to aquatic organisms from sealant material placement in rubble-mound structures exposed to open water was evaluated by a series of static, short-term bio-assays 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. Costs associated with conducting such bio-assays would include purchase of test animals and laboratory equipment, labor for holding the animals and conducting the tests, and computer time for extensive statistical analysis of data.

140. 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 bio-assay analysis for toxicity effects. Also, representative samples of attaching marine organisms from both the sealed and nonsealed portions of the Buhne Point, California, groin structure will be obtained and similarly analyzed, since breakwaters and jetties to which this research is directed are primarily located in marine environments.

141. 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.

142. 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 of 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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