Property of
Flood Control District of MC Library
Please Return to
2801 W. Durango
Phoenix, AZ 85009

Laboratory Tests and Field Studies on Erosional and Abrasion Resistance of Soil-Cement and Roller-Compacted Concrete – Results of a Literature Search

Prepared for
Portland Cement Association
April 2000
SEA Contract 998015

Schnabel Engineering

101.502

Laboratory Tests and Field Studies on Erosional and Abrasion Resistance of Soil-Cement and Roller-Compacted Concrete – Results of a Literature Search

April 2000

Prepared by:

Schnabel Engineering Associates, Inc.
1888 Sherman Street, Suit 330
Denver, CO 80203

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES ii

EXECUTIVE SUMMARY 1

A. INTRODUCTION 2

B. DEFINITIONS AND DISCUSSION
1. Erosion and Abrasion Erosion 2
2. Soil-Cement, RCC and the difference 2
3. Methods for Mixture Proportioning for Soil-Cement 3

C. OBJECTIVES OF THE LITERATURE SEARCH 6

D. RESEARCH OF SOIL-CEMENT EROSION-LABORATORY TESTS 6
1. Test at Oklahoma A & M – 1942 6
2. Portland Cement Association research – 1971 7
3. Other Research for Specific Applications 8
a. University of California-Davis research for soil-cement lined channels – 1973 8
b. Iowa State University research for soil-cement drop structures, 1982, 1983 9
c. University of Calgary research for soil-cement protected islands – 1986 11

E. FIELD TESTS OR STUDIES ON SOIL-CEMENT PERFORMANCE 13
1. Bonny Reservoir test section – 1951 13
2. PCA's Study of Projects in California and Arizona – 1979 14
3. Performance of Soil-Cement during the 1983 Tucson Flood 16

F. RESEARCH ON RCC EROSION – LABORATORY TESTS 17
1. Erosion Resistance of Exposed RCC Spillway 17
2. Development of Test for Abrasion of Concrete and Results 18
3. Results of Abrasion Erosion Tests on Concrete 20
a. Tests by Corps of Engineers 20
b. Test for Puget Sound Power and Light 20
4. Comparison of the Abrasion Erosion Resistance of Soil-Cement, Concrete and RCC 21
5. Abrasion Erosion Test for RCC for Rio Salado Project, Arizona 23

G. FIELD PERFORMANCE – EROSION AND ABRASION OF RCC 24
1. North Fork of the Toutle River Debris Retention Structure, Washington 24
2. Kerrville Ponding Dam, Texas 26

H. CONCLUSION 27

I. RECOMMENDATIONS – BASED ON LITERATURE SEARCH 28

J. BIBLIOGRAPHY 30

LIST OF TABLES

Table 1	Abrasion-erosion study for PCC, RCC, and SC Summary of mix designs, compressive strength and abrasion loss	22

LIST OF FIGURES

Figure 1	Durability test results for soil-cement slope protection for South Texas plant cooling water reservoir	4
Figure 2	Relationship between strength and durability of soil-cement	5
Figure 3	Erosion resistance vs. cement content of soil-cement	7
Figure 4	Erosion resistance vs. gravel content of soil-cement	7
Figure 5	Erosion testing apparatus at Iowa State University	10
Figure 6	Erosion testing apparatus at University of Calgary	12
Figure 7	Condition of Bonny Reservoir soil-cement test section – 33 years after completion	13
Figure 8 & 9	Soil-cement bank protection for Roger Road sewage treatment plant Tucson, AZ	15
Figure 10	Soil-cement bank protection after overtopping during 1983 Tucson flood	16
Figure 11	Test apparatus for abrasion resistance of concrete (underwater method)	19
Figure 12	Abrasion erosion of RCC spillway at cold joint at center of slab North Fork of the Toutle River Debris Retention Structure	22
Figure 13	Condition of Kerrville RCC Ponding Dam, after 1985 overtopping	27

EXECUTIVE SUMMARY

In this literature search on the erosion or abrasion erosion resistance as well as basic durability of soil-cement, roller compacted concrete (RCC), and conventional concrete, twenty sources of information were considered pertinent to this study. In addition to Ken Hansen's own files, the literature search consisted of a search on the internet as well as contacts with the Portland Cement Association (PCA) and all three major government water resources agencies (US Army Corps of Engineers, US Bureau of Reclamation, and the Natural Resources Conservation Service).

The twenty sources of information included 18 published papers, one unpublished laboratory study, and one personal communication. The literature search produced testing that went back to 1942.

In order to obtain meaningful results in a relatively short period of time, all laboratory studies of erosion or abrasion erosion of the three cement based materials, the test method had to be either (1) severe, (2) accelerated or (3) conducted on specimens whose strengths was weaker than that usually specified for actual construction. Most laboratory tests were conducted on the compacted surface of the materials and not the unrestrained or possibly poorly compacted edges that may also be exposed to water flowing in the field.

Because soil-cement was developed earlier than RCC and also because soil-cement invariably has a lower compressive strength than conventional concrete (or RCC) more attention was given in the laboratory to assess its erosion resistance. Using flowing water, water jets, together with specifically developed test apparatus, it soon became evident that properly designed soil-cement could withstand relatively high velocities (20 ft/sec = 6m/sec) of water not containing abrasive particles with little erosion.

Examination of soil-cement slope protection projects in service also determined they had a good record with respect to freeze-thaw durability despite having no intentionally entrained air in the mixture.

All laboratory researchers or field investigators determined that for any of the materials produced from the same aggregate, its erosion or abrasion erosion increased as its compressive strength increased. The strength of soil-cement could be improved by (1) using a coarser material as aggregate (2) adding gravel to a fine soil (3) increasing the cement content or (4) delaying exposure to water.

The comparative tests on the three materials showed RCC to have a greater abrasion erosion resistance than conventional concrete of higher strength. This was due to larger percentage of quality aggregate in the mixture and less paste. Both RCC and concrete showed considerably better abrasion erosion resistance than soil-cement. In underwater abrasion tests, (ASTM C 1138) it was determined that abrasion erosion resistance was primarily a function of the aggregate hardness and secondly a function of the strength of the paste. Except in the case of an extremely strong paste, the rate of erosion diminished with time.

With cost as another consideration, RCC was found to provide the greatest benefit vs. cost for abrasion erosion applications for all but the most severe conditions. Improved performance using RCC can be obtained by (1) using the hardest aggregate available (2) providing the highest practical compressive strength and (3) using the largest practical size aggregate so that the volume of aggregate is maximized.

A. INTRODUCTION

Most applications of soil-cement and roller compacted concrete (RCC) in water resources projects involve subjecting the material to waves or low velocity flowing water in addition to weathering. Mixture proportioning methods to produce either adequate durability and/or strength have been well established and proven for these design conditions. However, there is less known about the resistance of soil-cement or RCC to high velocity water flow, water carrying a heavy suspended bed load of sand and gravel or other severe exposure conditions.

This study was authorized by the Portland Cement Association (PCA) to help provide proper guidance to design engineers in determining mixture proportions needed to withstand severe erosional or abrasive forces. The first task associated with this study was a literature search to determine laboratory methods that have been used to assess the erosional durability of soil-cement and RCC. Reports of field performance were also reviewed to determine how actual applications of these materials reacted to severe conditions of erosion or weathering.

Before proceeding with this study, erosion and erosion-abrasion as it pertains to this report needs to be defined. Similarly, soil-cement and RCC need to be defined and the difference between these two similar cement stabilized materials should be discussed. Also, discussed are the design criteria to determine mixture proportions for both soil-cement and RCC.

B. DEFINITIONS AND DISCUSSION

1. Erosion and abrasion erosion

The American Concrete Institute (ACI 116) defines erosion as the progressive disintegration of a solid by the abrasive or cavitation action of gasses, or fluids in motion, while abrasion damage is defined as wearing away of a surface by rubbing and friction. For this study erosion is used to denote the disintegration of soil-cement, RCC, etc. by the action of water while abrasion erosion resistance denotes the action of water together with water borne solid particles acting upon exposed surfaces.

2. Soil-Cement, RCC and the difference

As defined by ACI Committee 116, soil-cement is a mixture of soil and measured amounts of portland cement and water compacted to a high density. Roller-compacted concrete (RCC) is defined as a concrete compacted by a roller compaction; concrete that, in its unhardened state will support a roller while being compacted. In effect, RCC is a no-slump concrete that is compacted by, what usually is a vibratory roller.

The construction methods used to produce soil-cement and RCC are quite similar as both involve proportioning, mixing, transporting, spreading, compacting, and curing a material that contains an aggregate or soil, portland cement, fly ash at times, and water.

The main difference is the aggregate or soil used. Soil-cement for water control projects generally uses pit run sand with little material greater than ¼ - in (4.75 mm) in size. RCC utilizes controlled grading aggregates with the nominal maximum size aggregate (NMSA) averaging about 1 ½" (38 mm).

Because of the use of larger more uniformly graded aggregate the compressive strengths of RCC is invariably greater than soil-cement. For applications exposed to waves or flowing water, the strength of soil-cement is generally in the 500 to 1000 psi. range at 7 days. The soil-cement continues to gain strength with time and proper curing so that its 1-year strength could easily be twice its 7-day strength.

The 28-day strength of RCC exposed to flowing water is generally about 2000 psi. RCC also gains strength with time, but probably not with as great a percentage increase as soil-cement. This is because the early strength of RCC can be attributed to a combination of cement hydration and the interlocking of crushed aggregate. For soil-cement, the strength comes mainly from the cementing action of the usually sand particles. Soil-cement generally contains a greater volume of non-plastic fines passing the No. 200 sieve (0.075 mm), which could help provide some long-term strength gain. When RCC mixtures contain a high percentage of fly ash, considerable strength gain after 28 days can also be expected.

It should be noted that while greater compressive strength can be expected with RCC compared with soil-cement at the same age, the volume of cementitious materials used in RCC is invariably less than that used in soil-cement mixtures. Similarly, for equal volumes of material to be placed the unit cost of RCC is generally more than soil-cement due to the added cost of the aggregate.

A unique situation however occurs in the Phoenix area where the pit-run material, especially in the Salt River contains cobbles greater than 6 inches (150 mm) size, gravel and sand. Here, the plus 3-in. (75 mm) material is screened off and cement added to the well-graded sand/gravel to produce what is locally termed cement-stabilized alluvium (CSA). In this area, the basic principles of soil-cement mixture proportioning are used to produce stream bank protection with properties approaching that of RCC with relatively low percentages of cement.

3. Methods for Mixture Proportioning for Soil-Cement

The established method for determining adequate cement content for soil-cement mixtures is the use of laboratory durability tests (ASTM D560 & ASTM D559). Compacted specimens are subjected to 12 cycles of freezing and thawing and/or 12 cycles of wetting and drying. The entire surface area is brushed to remove particles that have become dislodged due to the volume changes imposed on the materials between cycles. The minimum cement content is that which produces specimens that remain within specified limits of weight loss after the 12 cycles of volumes change. The allowable weight loss for soil-cement depends on the type of soil to be stabilized. For sandy or silty-sand materials usually used for water control applications, PCA criteria allow a maximum 14% weight loss after 12 cycles of either of the two durability tests. A lower percentage weight loss is allowed for finer grained soils. The U. S. Bureau of Reclamation (USBR) criteria allow an 8% weight-loss in the freeze-thaw test and 6% weight loss in the wet-dry test. For granular soils, the freeze-thaw test generally produces a greater weight loss than the wet-dry test and, therefore, normally controls. PCA's

"Soil-Cement Laboratory Handbook" (EB 052.075) contains a more detailed explanation of soil-cement durability tests, also called brush tests. A soil or aggregate with a certain cement content is either acceptable or unacceptable using laboratory durability tests.

Once a cement content has been established based on the durability tests, an additional 2 percentage points of cement is specified for construction of water control projects. This is to account for the more severe effects of water exposure as compared to road base construction according to PCA, or to account for field variations in the soil and mixing process according to the Bureau of Reclamation. The USBR has questioned the need for the additional cement recently, but it remains as a part of their criteria until potential construction variations are reduced.

One reason for the possible conservative approach to determining adequate cement content for soil-cement using the brush tests is that the weight loss increases dramatically for lower than adequate cement contents. This is illustrated in Fig. 1. For this project, 10% + 2% = 12% cement by weight was specified. While 8% cement meets PCA weight-loss criteria, most design engineers feel more comfortable with lower percentages of allowable weight-loss and where the plot of weight-loss vs. cement content (see Fig. 1) flattens out. In other words, a cement content is specified where there is little increase in durability with increased cement content.

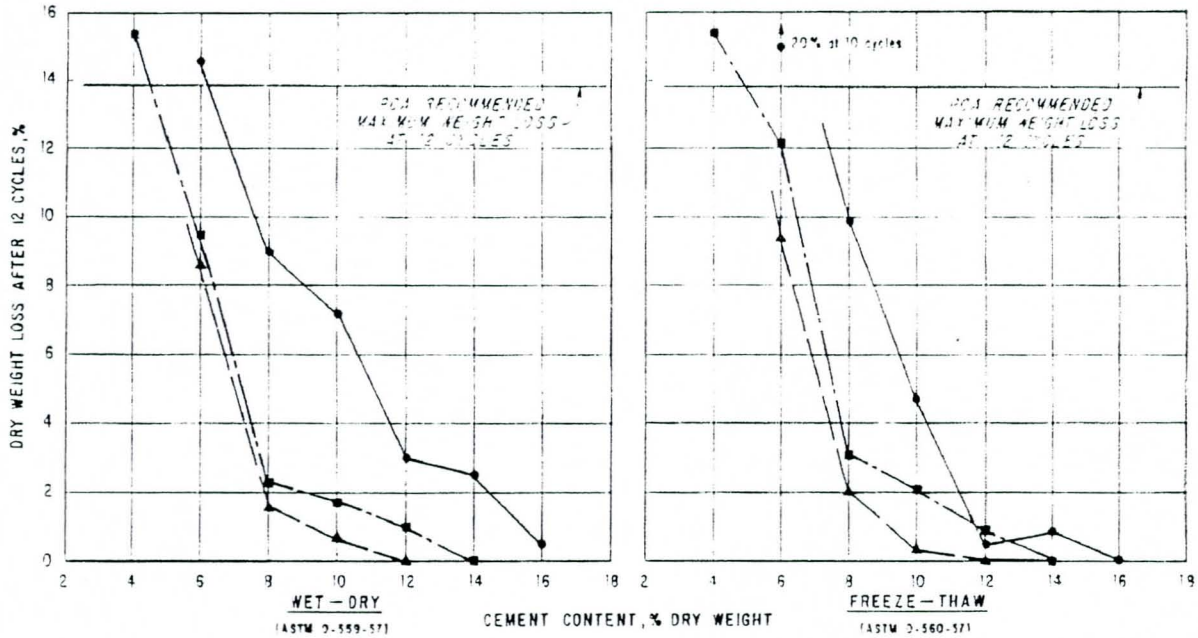


Figure 1 Durability test results for soil-cement slope protection for South Texas Plant cooling water reservoir

Because some agencies and private consulting firms felt the standard durability tests took too long (about 30 days) and were relatively expensive, they started to specify adequate cement content based on 7-day laboratory compressive strength results. Their efforts were aided by PCA research, which correlated durability with 7-day compressive strength (see Fig. 2).

The concept of 7-day compressive strength as an acceptance correlated criteria was initially proposed by the USBR as a secondary requirement based on the results of their 1951 soil-cement test section at Bonny Reservoir in eastern Colorado. Once a cement content was established based on durability tests, the soil-cement specimens at that cement content also needed to attain a minimum compressive strength of 600 psi (4.1 MPa) at 7-days and 875 psi (6.0 MPa) at 28 days. Then the 2 percentage points of cement were added.

At the 600 psi (4.1 MPa) compressive strength level, PCA's strength vs. durability chart indicates that 87% of soil-samples reaching this 7-day strength will pass the durability test. Similarly, about 97% of the soils that achieve 750 psi (5.17 MPa) at 7 days will also be durable per the standard ASTM tests and PCA weight loss criteria. It is felt that soils or aggregates that have high compressive strengths and less than adequate durability are coarse mixtures with poorly graded sand.

Strength criteria are being used in two Arizona metropolitan areas to determine adequate cement content for soil-cement stream bank protection. In Pima County (Tucson), the mixture must attain a 750 psi (5.17 MPa) 7-day compressive strength in the laboratory to assure a minimum of 600 psi (4.14 MPa) is reached in the field. For Maricopa County (Phoenix), the 750 psi (5.17 MPa) strength level is also used for their cement stabilized alluvium designs but the 2 percentages points are added for construction variations and also the fact that bank protection in this area is subjected to more erosive forces from large water borne particles. This is especially true along the crest of grade control structures in the streambed and at the lower elevations of the bank protection along the Salt River.

The strength level of soil-cement can be increased by the design engineer to withstand more severe erosion or abrasion-erosion conditions or a well-graded aggregate used in the mixture to produce RCC.

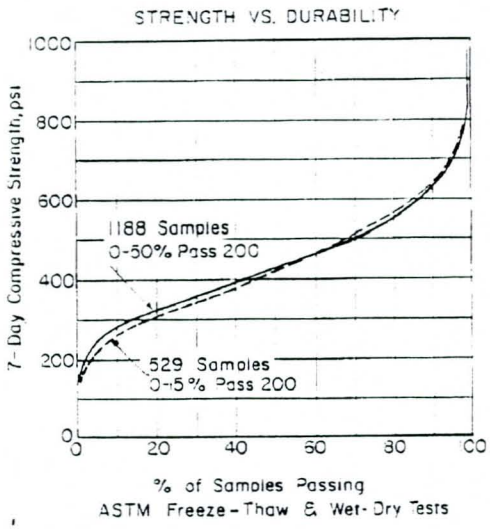


Figure 2 Relationship between strength and durability of soil-cement

C. OBJECTIVES OF THE LITERATURE SEARCH

Now, that we have established that (a) soil-cement invariably has a lower compressive strength than RCC and (b) soil-cement mixtures are generally designed to meet certain durability or 7-day compressive strength criteria, the study is intended to answer the following questions

1. To what degree is soil-cement designed to meet durability and/or strength criteria erosion resistant?
2. How can a soil-cement mixture be modified to improve its erosion or abrasion-erosion resistance?
3. What tests have been used to assess the abrasion-erosion resistance of soil-cement?
4. Under what conditions should RCC be used instead of soil-cement to meet certain abrasion-erosion resistance conditions?
5. Will facing soil-cement or RCC with conventional concrete improve its abrasion erosion resistance?

D. RESEARCH ON SOIL-CEMENT EROSION-LABORATORY TESTS

A literature search was undertaken to better answer these questions. Little research had been accomplished on the erosion resistance of soil-cement during its initial development. This was especially true for soil-cement subjected to (a) high velocity water and (b) bed loads of water-borne particles. Test methods needed to be developed in an attempt to assess the resistance of soil-cement to forces greater than ordinary wave action or low-velocity water flow.

1. Test at Okalahoma A & M – 1942

The first reported test of the erosion resistance of soil-cement to high velocity water goes back to1942 by the Civil Engineering Department of Oklahoma A & M College (now Oklahoma State University). The test consisted of applying water at a velocity of 28 ft/sec (8.5m/sec) and discharge of 150 ft^3/sec (4.2 m^3/sec) to flow on a 10 ft. (3m) wide soil-cement lined flume continuously for six days. The sandy loam soil used in lining the flume consisting of about 60 % sand and 40% silt and clay was stabilized with 8 percent cement by volume. No appreciable erosion of the 4-½ in. (114 mm) thick slab was produced by the flow of clean water devoid of water-borne sand or gravel (PCA 1943).

2. Portland Cement Association research – 1971

The next laboratory research on the erosion resistance of soil-cement was conducted by the Portland Cement Association (Nussbaum & Colley, 1971). Realizing that cement-stabilized banks are at times used at locations where swift-flowing debris-laden streams could abrade the soil-cement protection, they investigated erosion of soil-cement exposed to flows of water carrying 1/8" to 1/4" (3.1 and 6.3mm) – size gravel. Soil-cement produced from two different soils were exposed to an abrasion erosion test after 7 days of fog curing. An AASHTO A-1-b soil (a sand-gravel) and an A-4 soil (a silt) were stabilized with varying percentages of cement. About 8000 gallons (36,400 liters) of water flowing at a velocity of 3.8 ft./sec (1.2 m/sec) and carrying 4.2 tons (3810 kg) of gravel flowed over a small soil-cement sample each day.

The results of the test are shown in Figs. 3 & 4 as plots of time (in days) to produce a 1-inch (25mm) depth of erosion. As expected and shown in Fig. 3 increasing the cement content of the soil-cement increased its erosion resistance.

The effect of the aggregate or soil that was stabilized had an even greater effect. The abrasion erosion resistance of the stabilized sand gravel (A-1-b soil) was extremely good and superior to stabilized silt (A-4 soil) for all cement contents tested. The time required to erode a depth of 1 inch (25 mm) of the finer A-4 material was less than two days even with a cement content as high as 13.5 percent by volume. When the coarser A-1-b soil was stabilized with 5 percent cement, it took 15 days to erode a depth of one–inch (25 mm).

Because of the better abrasion erosion resistance of the granular soil, additional tests were made by improving the A-4 silt soil with the addition of gravel greater than ¼ in (6.3 mm) size. The results of the tests indicated the addition of gravel to the fine soil increased its resistance significantly when the gravel component was greater than 20 percent by weight. At 30% gravel content and 9.5 percent cement, the modified A-4 soil was nearly as resistant to abrasion erosion as the original A-1-b sand gravel (see Fig. 4).

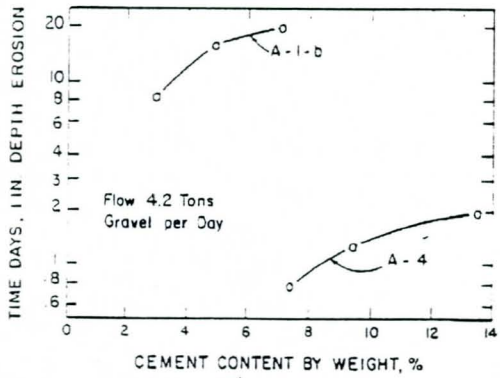


Figure 3 Erosion resistance vs. cement content of soil-cement

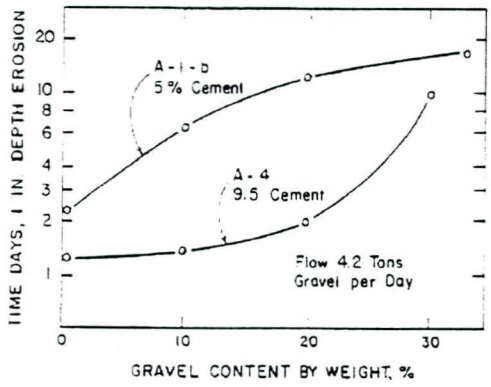


Figure 4 Erosion resistance vs. gravel content of soil-cement

Also, during this test program, it was concluded that a 2000 psi (13.8 MPa) 28 – day old concrete was more resistant to abrasion erosion than the soil-cement produced by adding 7 percent cement to the A-1-b sand gravel. It took 33 days to erode 1 inch (25 mm) of this relatively low-strength concrete.

Another conclusion of the PCA study was that a stream of water not carrying gravel had little or no erosional effect on soil-cement stabilized with low percentages of cement. In summary, the erosion abrasion resistance of soil-cement exposed to water carrying water-borne particles can be improved by (a) using a coarser material as the aggregate, (b) adding gravel to a finer soil or by (c) increasing the cement content.

3. Other Research for Specific Applications

Following the PCA study, three other teams of researchers tested the erosion or abrasion erosion resistance of soil-cement for specific applications and developed unique test procedures for their studies. Akky and Shen (1973) were interested in the erosional durability of soil-cement lined channels; Litton and Lohnes (1982, 1983) investigated the use of soil-cement for stream channel grade stabilization (drop) structures using the loess – derived alluvium found in western Iowa, while Oswell and Joshi (1986) studied using soil-cement for protecting artificial islands in the Beaufort Sea north of Canada or Alaska. The islands, which were planned for oil well drilling, would be subjected to the combined forces of breaking waves and impacting debris. All of these researchers were aware of the earlier work done by Nussbaum and Colley (1971).

a. University of California – Davis research for soil-cement lined channels-1973

In the experimental program by Akky and Shen, a sandy soil mixed with 1, 1 ½, 2 and 3 percent cement by dry weight were tested. The same soil with 4 percent cement produced a soil-cement that was too strong. The purpose of their study was "an effort to characterize the erodibility of cement-stabilized soil under various physical and environmental conditions and to possibly relate erodibility to indexes such as critical shear stress, rate or erosion, and unconfined compression strength so that design guidelines may be established".

The test apparatus used for this study was a rotating cylinder apparatus developed by Masch, Espey, and Moore (1965). This test consists of mounting a stationary cylindrical sample of soil-cement inside a rotating cylinder filled with water. An electric motor could rotate the outer cylinder at speeds ranging from 25 to 2,400 revolutions per minute (up to 40 revolutions per second). As the speed increased the boundary shear stress increased.

Both unconfined compression and erosion tests were performed on soil-cement samples after being subjected to various durability cycles. In this study, samples were initially subjected to either 0, 3, 6, 9, or 12 freeze-thaw (F/T) or wet-dry (W/D) cycles. It should be noted that the cement contents used for the test specimens was considerably less than that required to produce a durable soil-cement using PCA maximum weight – loss criteria, for brush tests.

Because the samples exposed to F/T and W/D cycles did not meet durability criteria for soil-cement specified for water resources applications, it is questionable whether the test results have much relevance.

However, using this method, the researchers confirmed that erodibility decreased as the compressive strength or cement content increased. Subjecting these low-cement content specimens to freeze-thaw cycles decreased its compressive strength, while the wet-dry cycles caused very little change in compressive strength. For the soil-cement containing 3 percent cement, its strength actually increased after 12 wet-dry cycles.

For the samples exposed to freeze-thaw cycles a weakened layer was formed during the first few cycles. Therefore, the strength loss or erosion resistance reduction was most significant in the first few cycles and the rate of loss or deterioration decreased after that. This situation may reflect that the weakened outer layer not removed may have served as an effective buffer against further deterioration of the soil-cement sample due to later freeze-thaw cycles.

b. Iowa State University research for soil-cement drop structures – 1982, 1983

Litton and Lohnes' (1982) research at Iowa State University was aimed at determining if a cement stabilized local material could be used instead of more costly reinforced concrete for drop structures, to control degradation of stream channels. The local soil was a loess-derived alluvium (a loam) from western Iowa. From Nussbaum and Colley's work, they realized that the erosion resistance of cement-stabilized silty soils could be increased by blending sand with the in-place silty soil. They therefore tested the erosion resistance of the cement-stabilized fine local material with 20, 40 and 55% sand replacement. Specimens containing 100% sand was also tested.

Also, as part of their program, the researchers wanted to see if they could develop an alternative method for determining adequate cement content for erosion resistance of soil-cement using exposure to a water jet. Their approach was to compare adequate cement contents determined by the durability brush test with minimum cement contents determined by their erosion test using a water jet.

The researchers developed the erosion testing apparatus shown in Fig. 5. The apparatus was designed to produce varying velocities, and thus the forces anticipated from a free fall of water over a drop structure. The specimens tested were 3 in x 3 in x 7 7/8 in (76 x 76 x 200mm) beams compacted to 100 percent density at optimum moisture content in accordance with the Standard Proctor test (ASTM D 558). The test beams were cured for seven days at 70 degrees F (21 degrees C) and 100% relative humidity.

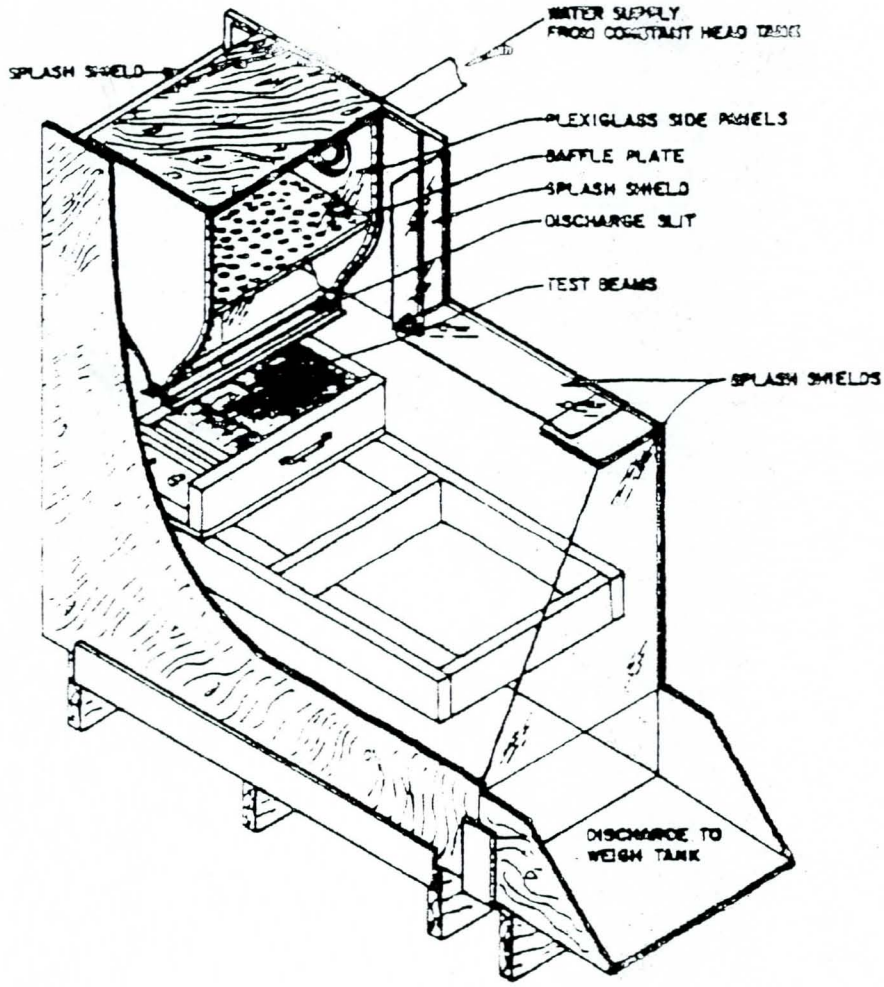


Figure 5 Erosion testing apparature at Iowa State University

In addition to varying the sand content in the mixtures, various cement contents were tested. For the sand-alluvium blends cement contents using Type I portland cement were 5, 7, and 9 percent by dry-weight of aggregate were used. In addition, 11 and 13 percent cement were tested with the loess-derived alluvium alone. Freeze-thaw brush tests (ASTM D 560) were performed on all the soil-cement mixtures.

The results of the testing confirmed previous findings that the erosion resistance of soil-cement increased with increased cement content and increased percentages of sand substituted for finer less erosion resistant soil. Also, the erosional forces from the drop of water was greater than the tractive shear force produced by water flowing over a soil-cement.

The most interesting part of their studies is when the researchers compared the cement content required to provide sufficient durability per freeze-thaw brush tests with the percent cement required to provide adequate erosion resistance for varying water velocities. Once cement content is established for soil-cement to provide adequate durability per the brush tests, the severity of the climate changes is not considered a factor. It is assumed the soil-cement so designed can withstand many volume changes due to expansion and contraction by freezing and thawing or wetting drying. However,

in determining the cement required to provide adequate erosion resistance, the velocity of the water jet is a variable.

Litton and Lohnes' tests determined that for water jet velocities less than 20 ft/sec (6m/sec) the erosion tests produced lower weight losses than that produced by the brush tests. This research now provides designers with support that soil-cement designed to provide adequate durability could also withstand water velocities up to 20ft/sec (6m/sec) with little deterioration.

In the second phase of their research, Litton and Lohnes (1983) subjected their soil-cement specimens to 12 freeze-thaw cycles prior to testing them for erosion resistance at varying water velocities. The researchers determined for any given flow rate, the rate of erosion was relatively great at first and then reached a stable configuration early after which there was minimal material loss. In their laboratory tests, the soil-cement specimens lost 54 to 97 percent of their total weight loss in the first 30 minutes of a 5-hour test. The material lost initially was that loosened during freeze-thaw cycles.

c. University of Calgary research for soil-cement protected islands -1986

Oswell and Joshi (1986) developed a test apparatus that combined the impacting forces of waves and water borne debris. This research was conducted as part of a program to investigate soil-cement as a possible method for providing shore protection of artificial islands planned for oil well drilling in the Alaskan and Canadian Beaufort Sea.

Prior to initiating their test program, the researchers studied previous approaches to erosion testing on concrete and soil-cement including the work by Nussbaum and Colley (1971) and Akky and Shen (1973). They agreed that the erosion of solid hydraulic structures resulted primarily from abrasion caused by impacted water-borne debris.

Oswell and Joshi also confirmed that most devices used to study erosion involved testing at highly accelerated levels of abrasion. They noted the erosion rate measured in the laboratory may be several orders of magnitude larger than that encountered through natural processes. Their tests were conducted on plastic soil-cement specimens, which are molded at water contents greater than that for compacted soil-cement. For a given cement content, plastic soil-cement will therefore have less strength than compacted soil-cement due to the increased water content (increased water/cement (w/c) ratio). Typically, soil-cement for protecting shores or banks is compacted soil-cement.

The plastic soil-cement mixes were 3 in. x 3 in. blocks approximately 4 in. long (76 x76 x 100mm). Masonry sand was used as the aggregate along with a Class G oil well cement (similar to Type V portland cement) and artificial seawater. Six different plastic soil-cement mixtures were tested. Two of these contained cement only and four contained cement plus fly ash. All specimens were moist cured for a varying number of days (1, 3 and 7) to obtain soil-cement specimens of varying compressive strength. Erosional forces were altered by varying the water pressure.

Fig. 6 shows the water jet and attached pressure regulator, as well as a perforated Plexiglas tube with a wire cage fitted snugly inside the tube. During the test, five small stones are placed within the wire cage and tube assembly. The impinging water jet hits both the specimen directly causing erosion and the stones contained in the wire cage. The stones activated by the water then impact against the sample causing further abrasion

erosion. The water, after impacting the specimen rapidly drains away through the perforations in the tube. The water also removes material loosened by the impacting stones.

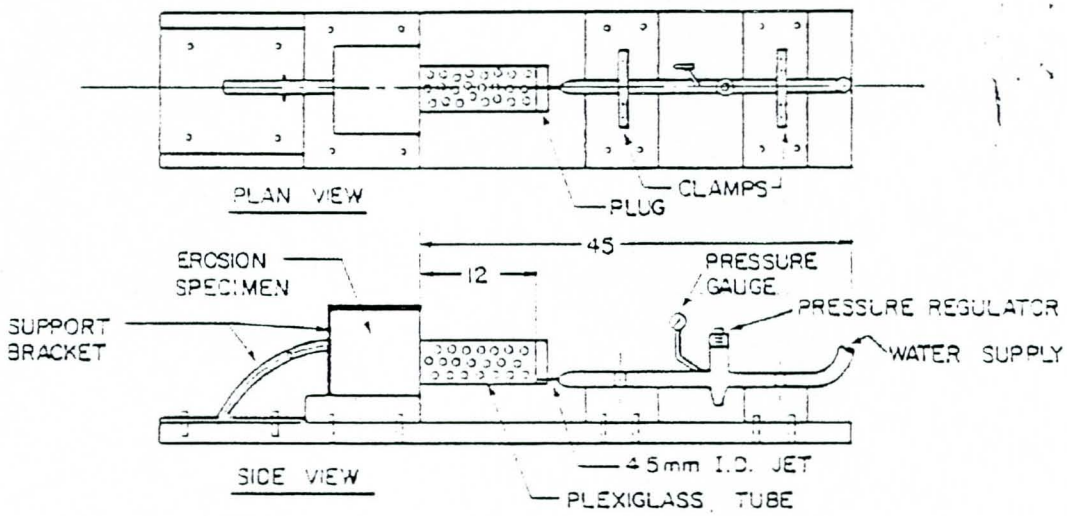


Figure 6 Erosion testing apparatus at University of Calgary
(all dimensions in millimeters) – 12 mm = 0.47 in

The main conclusion from this test program was nothing new. The researchers observed that the erosion losses could be best correlated to compressive strength-greater losses correlated with lower strength. For the soil-cement used in this study, Oswell and Joshi felt that a compressive strength of about 2300 psi (16 MPa) was necessary to reduce erosion or abrasion erosion to neglible amount when subjected to a pressure of 10 psi (70kPa).

In the field, as part of this overall investigation, compacted soil-cement with moisture contents much in excess of optimum was placed and subjected to storm conditions that produced 5 to 8 ft. (1.5 to 2.4m) high waves. Cement contents were in the 10 to 20 % by weight range but only produced a 450-psi (3.0 MPa) compressive strength at 5 days due to the high water content. Long-term erosion resistance of the test sections could not be determined due to the severe under cutting of the soil-cement section. However, it was determined that the test sections containing more than 15% cement were satisfactory. The researchers concluded that this limited scope field test section gave credence to the basic theory of their laboratory erosion test, but felt more comparison of laboratory vs. field-tests was needed to allow development of the apparatus for practical purposes.

E. FIELD TESTS OR STUDIES ON SOIL-CEMENT PERFORMANCE

1. Bonny Reservoir test section – 1951

The U.S. Bureau of Reclamation (USBR) and other designers started specifying soil-cement for the upstream slope protection of earth dams in competition with or in lieu of rock riprap in the early 1960's. This followed the successful long-term performance of a stair-stepped soil-cement test section at Bonny reservoir in eastern Colorado built in 1951. At the Bonny site, the exposed sides and top of the soil-cement have been subjected to not only wave action, but also an average of 140 freeze-thaw cycles per year for the past 50 years. Surface erosion of the soil-cement has been minor and limited to the poorly compacted feathered edges of the layers and to the bottom of the layers where the in-place mixing process produced less than specified cement content and where less density than the top surface was obtained (ICOLD, 1986).

Two different soils were used at the Bonny test section. A fine silty sand (soil A) required 12% cement by volume while a coarser silty fine to medium sand (soil B) used 10% cement by volume. The average 28-laboratory compressive strengths were 1140 and 880 psi (7.9 and 6.1 MPa) respectively. After 10 years, cores drilled from the facing had approximately doubled in strength, averaging of 2000 and 2,160 psi (13.8 and 14.9 MPa) respectively. The test section proved not only the long-term erosional resistance of soil-cement exposed to moderate wave action in the field but also the freeze-thaw durability of soil-cement without air-entrainment. Fig. 7 shows the condition of the Bonny soil-cement test section after 33 years of exposure.

Figure 7 Condition of Bonny Reservoir soil-cement test section – 33 years after completion

2. PCA's Study of Projects in California and Arizona-1979

The Pacific Southwest Region of PCA (1979) inspected 12 soil-cement projects located in California and Arizona in mid-1978. The purpose of the study was to determine the field performance of soil-cement when subjected to longitudinal water flow, such as in a channel or protected stream bank. At the time of the inspections, the age of the projects ranged from 2 to 18 years. The reported cement contents used for soil-cement for the projects when constructed were from 6.5% to 13% by weight (5 projects) and 7% to 12% by volume (7 projects).

For a soil weighing 94 lb/cu.ft, cement by weight and volume are the same percentage. However, for a soil-weighing 125 lb/cu.ft, 10 percent by weight equals 13.3 percent by volume. For early soil-cement projects, using in-place mixing for a single soil-cement layer, cement content was invariablely expressed as a percent by volume. In this manner, the engineer or contractor did not have to know the unit-weight of the soil, only the depth of mixing to calculate the cement to be added. Recently, nearly all soil-cement is central plant mixed and cement is expressed as percent cement by dry weight of soil or aggregate. Plant mixed soil-cement is nearly always used for multiple layer construction that is prevalent in water resources projects. It is assumed the cement contents used for the projects studied were adequate for the soil or aggregate that was stabilized. For the projects studied, very few freeze-thaw cycles can be expected.

Following the field inspections and gathering of information concerning the flows to which each project had been subjected, each project was given a condition rating. The ratings were as follows:

A. Little or no erosion; perfect or near-perfect condition (8 projects)
B. Minor amount of erosion; condition still excellent (2 projects)
C. Appreciable erosion; condition still serviceable (2 projects)

Of the 12 projects studied only 5 of the soil-cement applications were exposed to flow conditions close to that for which they were designed. The projects rated A do not provide much insight into the erosion resistance of soil-cement. The projects were either not subjected to any water flow or only low velocity flow.

While the study contained some information as to the hydraulic action on the soil-cement (velocity and frequency of water flow), there is little information as to the resisting properties of the soil-cement except cement content. No information was provided as to the compressive strength of the basic soil-cement or at its outer edge. It was determined that for most of the bank protection projects studied, the soil-cement was over built and not well compacted at the outer edge. This was due in part to lack of restraint of the outer edge and the specifications did not require edge compaction or trimming. This would produce some sacrificial soil-cement of lower strength at the outer edge of the soil-cement mass. This low strength "fluff" is then a prime candidate for considerable erosion when subjected to water flow.

In the field, a new factor is introduced into the study of soil-cement. For many of the projects, studied soil-cement was placed in 6 in. (150 mm) compacted horizontal lifts. This produced, in most cases, an unbonded or poorly bonded lift line that was or could be exposed to water flow. It is assumed that nothing special was done to improve bond between successive layers for these projects and construction during warm, dry weather did not help the bonding situation.

The field study provided some basic recommendations for soil-cement design to improve erosion resistance. That is (a) the soil or aggregate to be stabilized should preferably be well-graded sands or sandy gravels and (b) the cement contents should determined by the durability tests previously described in this report.

The other conclusions had to do with the effect of water flow on poorly compacted outer edges and unbonded lift lines of a soil-cement mass. The PCA regional investigator recommended that where successive horizontal layers are used, maximum bond be obtained by several methods, such as by scarification, power brooming, and surface moistening between layers. Another recommendation was to trim or compact outer edges smooth with the slope of the section. The latter suggestion was to help define what was compacted soil-cement of the design strength. Some designers like the natural appearance of the poorly compacted exposed soil-cement, but may have a difficult time explaining the erosion after a flood. Fig. 8 & 9 shows the soil-cement bank protection of Santa Cruz River at the Roger Road Sewage Treatment Plant at Tucson, AZ. This project was rated C (appreciable erosion) after the soil-cement was subjected to heavy flow in the 10 to 12 ft/sec (3 to 3.6m/sec) range about 15 times per year. Subsequent excavation of the eroded area by a backhoe confirmed the erosion took place in the low-strength overbuilt outer edge and well-compacted soil-cement was less than 1 ft (300mm) back from the surface.

The most significant recommendation was "where velocities exceed 6 to 8 ft/sec or where water carrying large amounts of debris is expected, consideration should be given to higher-strength soil-cement or other design modifications..." It appears this was the first time anyone had tried to establish a limit on the water velocity to which soil-cement in waterway could be exposed without modification to the soil used or construction method. However, one PCA engineer (Mueller, 2000) who was involved in this field study termed the velocity limit "extremely conservative". In addition, he confirmed that nearly all the erosion that was evident in the stair-stepped soil-cement section occurred in the low-strength soil-cement at the outer edge, which was intended to be a sacrificial zone.

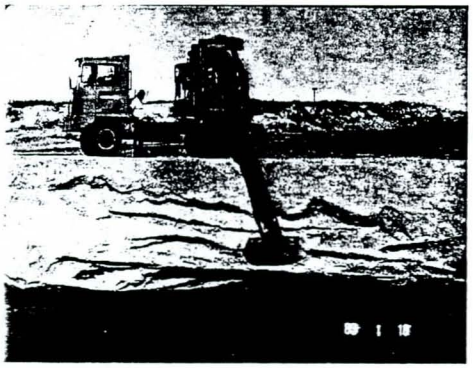


Figure 8

Figure 9

Soil-cement bank protection for Roger Road sewage treatment plant, Tucson, AZ

3. Performance of Soil-Cement During the 1983 Tucson Flood

Heavy rains in the Tucson, Arizona area during a six-day period in late September and early October 1983 totaled 6.7 in (170mm). This heavy rainfall which was more than 60% of Tucson's annual average precipitation produced a record high flow (since 1915) estimated at 45,000 ft^3/sec (1270m^3/sec) on the Santa Cruz River west of downtown Tucson. This flow was determined to be greater than the 1 in 100 year flood event and has been described as "The Big One".

In addition to the flood causing 4 deaths, 154 destroyed residences, and 400 damaged homes and businesses, the erosion of unprotected bridge abutments and flooding of access roads caused 35 of the 42 major bridges in Pima County to be closed at one time. Soil-cement protected banks withstood the floodwaters very well.

One such project that was protected by soil-cement banks was the Rio Nuevo project on the west side of the Santa Cruz as it flowed through the city. The soil-cement bank protection was constructed to the 25-year flood level. Because the water level rose to a greater elevation than the protected banks, the soil-cement was overtopped and some soil support behind the armored banks washed away. The soil-cement section remained in place with little if any noticeable erosion (see Fig. 10). The water velocity in this area was estimated to be greater than 20 ft/sec (6m/sec) (Hansen & Lynch, 1995).

The flood at Tucson provided a higher level of confidence for the erosion resistance of properly designed soil-cement bank protection subjected to water not carrying abrasive particles. The 20-ft/sec-velocity limit concurs with the laboratory research conclusion of Litton and Lohnes (1982).

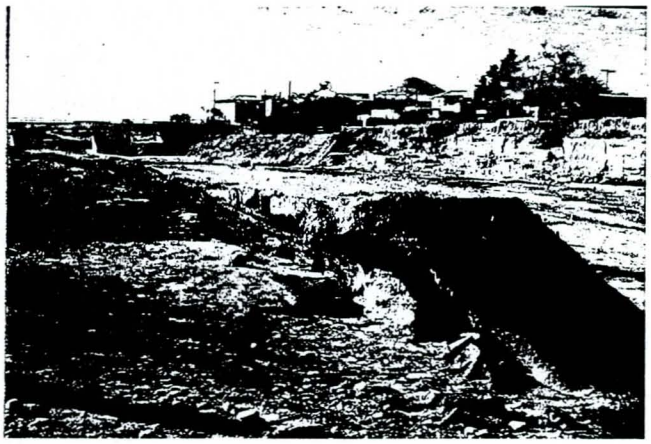


Figure 10 Soil-cement bank protection after overtopping during 1983 Tucson flood

E. RESEARCH ON RCC EROSION – LABORTORY TESTS

The U.S. Army Corps of Engineers took the lead in researching the erosion and abrasion erosion resistance of roller-compacted concrete (RCC). Their research was conducted in four phases in order to address specific project needs. The Corps desired to determine (1) the erosion resistance of an exposed spillway for an RCC gravity dam (2) the abrasion erosion resistance of conventional concrete and modified concretes used to repair abraded stilling basins (3) compare the abrasion erosion resistance of soil-cement, RCC, and conventional concrete for use as bank protection for waterways and (4) determine RCC mixture proportions for a bank protection project in Arizona based on the results of the underwater abrasion erosion test.

1. Erosion Resistance of Exposed RCC spillway

The design by the Corps of Engineers Walla Walla District for the 127 ft (39m) high Zintel Canyon Dam at Kennewick, WA called for an exposed RCC spillway on a 0.8 H: 1V downstream slope. Zintel Canyon was to be the first RCC gravity dam built in the USA. However, this honor ultimately fell to the 169 ft (52m) high Willow Creek Dam near Heppner, OR in 1982 designed by the same Corps District. Zintel Canyon was built as an RCC dam ten years later in 1992 after local support for the flood control structure resurfaced.

As part of the design process, the Corps wanted to investigate the effect of high velocity water flow on RCC of about 2000 psi (13.8 MPa) compressive strength. Their tests were conducted in 1976 at Detroit Dam, OR and the Waterways Experiment Station, MS, both Corps of Engineers facilities. The summary of the tests were included in Design Memorandum No. 3 for Zintel Canyon Dam (1980, a & b), and were subsequently used for the Willow Creek design.

For the tests at the high-head Detroit Dam facility, six 21 in (.53m) wide RCC panels 5 ft (1.5m) long were cast. The surface of the RCC test specimens was finished to produce both smooth and rough surfaces. The surface of three specimens were given a float finish to produce a smooth surface, while the other three were finished with a pneumatic hammer, which gave a very rough surface. The RCC containing 200 lbs of cement per cubic yard (119 kg/m^3) when mixed with a combination of pit-run and blended sand produced an average strength for the test sample of about 2000 psi (13.8 MPa).

Velocity of water was varied by placing the test slab a varying distance downstream from the control gate. For example, if the slab was placed 10 ft (3.0m) from the opening the anticipated velocity was 85 ft/sec (26m/sec) while at 30 ft (9m) the maximum velocity reduced to 74 ft/sec (23m/sec). At this facility, the head could also be varied from a maximum of 134 ft (41m) to less than 100 ft (30m).

Two of each type specimens (smooth and rough) were used to form a 10 ft (3.0m) long slab. The set having the smooth surface was placed with its upstream end 10 ft (3.0m) downstream of the test control gate while the set having the rough surface was placed with its upstream end 30 ft (9m) from the control gate. The facility was operated for 75.4 hours, 63.5 hours at 134 ft (41m) head, 2.6 hours at heads greater than 100 ft (30m) and 9.3 hours at heads less than 100 ft (30m).

For the smooth RCC slab, small aggregate became exposed after 37 minutes of operation at maximum head that produced a velocity of 85 ft/sec (26 m/sec). After 63.5 hours, these same areas had increased to 80 percent of the slab area showing exposed aggregate with some small stones having been plucked out.

The roughened slab, even though subjected to a lower velocity due to its location further downstream of the control gate showed greater erosion than the smooth slab. An overall erosion of nearly ¾-in (19mm) occurred after 63.5 hours at the maximum test head. The progression of the erosion seemed to be one of slow unraveling in a uniform pattern. In the first 37 minutes, the already exposed aggregate resulting from the manufacturing process was removed resulting in several holes and irregularities. Still, after the test the deepest hole was only 1 1/8 in (29mm) from its surrounding surface.

The erosion tests conducted at the Corps Waterways Experiment Station at Vicksburg, MS consisted of a 1" by 8" (25 by 200mm) water jet impinging on four RCC specimens held at an angle of 5 degrees from the horizontal. The center of the specimen was placed 12 in (300mm) from the water source that fluctuated at a velocity between 30 to 35 ft/sec. (9.1 to 10.6m/sec).

The specimens were about 11.5 in (290mm) square. The RCC from which the specimens were sawed consisted of a 3-in (75mm) maximum size crushed aggregate, 100 lbs (45kg) cement and 100 lb (45kg) of fly ash per cu. yd. with a reported water-cement ratio by weight of 0.70. Two of the specimens had a cast surface exposed to the water jet, while two were rolled – one with a smooth surface, and one with a rough surface.

The results of the tests indicated there was very little erosion of any of the four tests specimens after 14 hours of continuous flow. As with other laboratory tests conducted on soil-cement, the rate of erosion decreased with time.

Visual observation indicated the material lost due to erosion consisted of small amounts of week mortar adjacent to voids on the surface of the test specimens. The rolled smooth specimen had the least erosional weight loss, followed by the rolled rough specimen and then the two with the cast surfaces.

2. Development of Test for Abrasion Erosion Resistance of Concrete and Results

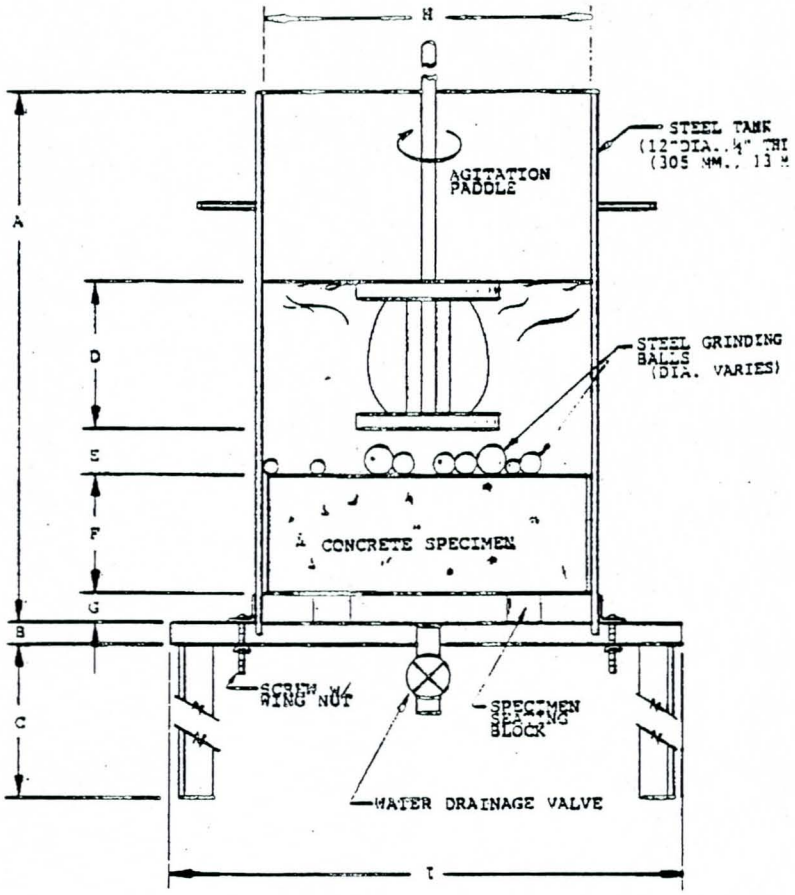
From the results of the high velocity water tests on RCC specimens at both Detroit Dam, OR and the Waterways Experiment Station, MS., the Corps was convinced that RCC for exposed spillways had adequate erosion resistance. Theses tests were conducted at a higher velocity and for a longer period of time than clean water spillway flows were anticipated for either Zintel Canyon or Willow Creek Dams.

Now, the Corps had a new problem to address with respect to the abrasion erosion resistance of concrete. A number of stilling basins and other structures at existing Corps dams had been damaged due to abrasion of the concrete caused by turbulent water flow that contained rock particles and other materials such as pieces of steel reinforcing bars.

Their goal was to evaluate the abrasion erosion resistance of various materials considered for repair of their concrete structures. In order, to evaluate (a) conventional concrete (b) fiber-reinforced concrete and (c) polymer concrete they needed to develop an underwater abrasion erosion test method.

The method developed by Liu (1980) consists of a paint mixing paddle that rotates creating agitation of both the water and 70 steel balls of three sizes ranging from ½ in to 1 in. (12.7 to 25.4 mm) in diameter (see Fig. 11). The test has been adopted at

ASTM designation C1138 "Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)". While the test was initially developed to test the concrete types noted above, the test was subsequently used to test both soil-cement and RCC as described later in this report.



	in.	mm
A	18.0	457
B	0.75	19
C	Optional - to suit	
D	5.0	127
E	1.5	38
F	4.0	102
G	1.0	25.4
H	12.0	305
I	18.0	457

Figure 11 Test apparatus for abrasion resistance of concrete (underwater method)

3. Results of Abrasion Erosion Tests on Concrete

a. Tests by Corps of Engineers

In the initial tests of concrete using the underwater abrasion erosion test by the Corps, the variables were seven aggregate types, three water/cement ratios, and six types of surface treatment in addition to the three types of concrete previously mentioned.

The recommendations from the Corps study with some discussion (Holland, 1983) are:

- Use the hardest available aggregate, but hard aggregate may not always be available close to the project site.
- Use the lowest practical water-cement ratio, which produces the highest practical compressive strength. The highest practical compressive strength has been about 6000 psi (41 MPa), which is not high enough to overcome problems with weak aggregates.
- Do not use fiber-reinforced concrete for this purpose. In the laboratory steel fiber-reinforced concrete had less resistant to abrasion erosion than conventional concrete made with the same aggregate type and water cement ratio. Fiber-reinforced concrete also did not perform well for an overlay of the stilling basin at Kinzua Dam, PA.
- The abrasion-erosion resistance of polymer-impregnated concrete (PIC) was significantly superior to the companion unpolymerized concrete. The same can be said for polymer concrete (PC) and polymer portland cement concrete (PPCC). However, these exotic concretes can be quite expensive and may be difficult to handle and place in the field.

Later tests reported by Holland (1983) involved production concretes with very high compressive strength (about 15, 000 psi (103 MPa)) using silica flume. As expected they performed very well with respect to abrasion-erosion resistance. For these high strength concretes, the hardened paste apparently assumes a greater role in resisting damage due to abrasion than the aggregate quality.

Based on the work by the Corps at WES, the optimum amount of silica fume was closer to 20 percent by weight than the 30 percent initially tested. Silica fume will not work as well in soil-cement or RCC due to the lower water content in these mixes. There is also a high tendency for plastic shrinkage cracking using silica fume concrete.

Of the concrete coatings tested underwater with the steel balls, two types of polyurethane coatings gave excellent abrasion erosion results while an iron aggregate topping gave the poorest results.

b. Test for Puget Sound Power and Light

Simons (1992) also investigated abrasion erosion resistance of concrete as part of a project to replace an existing water flume that had originally been built of wood timbers and planks. The abrasive effects of sand and rocks carried by water on the wood had caused maintenance cost of the structure to be excessive. A steel liner was initially proposed to the owner of the Puget Sound Power and Light, but its estimated cost exceeded the owners budget. Concrete was then favored by the owner's consultant, but there was concern about its resistance to severe abrasional forces.

Simons investigated the applicability of several existing test methods to assess the abrasion resistance of concrete. Apparently, he was unaware of the Corps development of its underwater test. The investigator then developed a low-cost test that combined concepts from ASTM C779-Abrasion Resistance of Horizontal Concrete Surfaces and ASTM C944-Abrasion Resistance of Concrete or Mortar by the Rotating-Cutter Method. The method consisted of placing an 8 in. (203 mm) diameter drum sander on a test panel and running it continuously for 8 hours. Every 30 minutes, the twenty-grit Carborundum sandpaper was changed.

Although the test was not expected to simulate the magnitude and rate or wear that the structure would actually be subjected to, it would provide some index of resistance of several materials to abrasion forces. The materials tested were (a) steel plate (b) silica fume high strength concrete 11,620 psi (80 MPa) at 28 days (c) fly ash high strength concrete – 10, 210 psi (70 MPa) (d) conventional concrete 8050 psi (55 MPa) and (e) conventional concrete with metallic topping.

The results of the tests produced the following anticipated conclusions:

- The two high strengths concrete showed abrasion resistance superior than either the conventional concrete or a similar mix with metallic topping. The relative rates of wear for the high-strength concretes was about 30 percent of that of the two other concretes.
- Steel displayed the least amount of abrasion.

However, the test program provided the following somewhat unexpected results:

The concrete mix with the fly ash proved to have superior relative abrasion resistance than the silica fume concrete despite having a lower compressive strength. This was determined to be the result of the fly ash mix containing a slight overdose of a high-range water-reducing admixture (a super plasticizer). It was discovered that the overdose of the superplasticizer caused some segregation that placed a greater volume of high quality of aggregate at the test surface.

4. Comparison of the Abrasion Erosion Resistance of Soil-Cement, Concrete and RCC

Omoregie, Gutschow and Russell (1994) expanded the scope of the Corps developed underwater abrasion-erosion test to include soil-cement and RCC in addition to conventional concrete. The Los Angeles District of the Corps was starting to adopt these new materials for protecting channel banks and channel invert stabilizers (also called grade control or drop structures) mainly in Arizona. The grade control structures especially could be abraded by water-borne particles.

Four mixes of each material (soil-cement, RCC, and conventional concrete) were tested. Information concerning the mixes is shown in Table 1.

Table 1 — Abrasion-erosion study for PCC, RCC, and SC; Summary of mix designs, compressive strength and abrasion loss

	Portland cement concrete				Roller compacted concrete				Soil cement			
Mix number	1	2	3	4	5	6	7	8	9	10	11	12
Mix design data												
Maximum aggregate size, in.	3/4	3/4	1	1	1	1	1	1				
No-air cement factor, lbs/cy or %	495	705	480	705	350	450	550	650	6	8	10	12
Pozzolan replacement, %	0	0	0	0	30	30	30	30	0	0	0	0
Water-cement ratio	0.61	0.43	0.63	0.43	0.56	0.49	0.357	0.302	—	—	—	—
Moisture as batched, %	—	—	—	—	6.5	7.0	6.4	6.3	8.3	8.3	8.3	8.3
Sand-aggregate ratio	46	43	44	41	40	40	40	40	—	—	—	—
Slump, in.	1.25	2.50	2.75	3.00	0	0	0	0	—	—	—	—
Air content, %	2.4	2.4	2.2	2.0	—	—	—	—	—	—	—	—
Average percent of voids	—	—	—	—	5.8	2.2	4.5	3.9	—	—	—	—
Water reducer, oz/cwt	2.5	2.5	2.5	2.5	0	0	0	0	—	—	—	—
Average unit weight, lbs/cu ft	143.0	144.3	143.1	144.9	142.0	146.5	144.6	146.0	129.1	129.7	130.3	130.1
Strength and abrasion loss												
7-day compressive strength, psi	3020	5870	2835	5495	1005	1850	2620	3640	565	775	1180	1220
28-day compressive strength, psi	4610	7255	4440	7625	1525	3050	3960	5010	875	1400	1605	1830
72-hours equivalent loss, %	8.7	6.0	8.7	6.8	10.1	5.2	5.4	6.4	96.5	59.0	36.3	32.0
72-hours equivalent loss, cc/sq cm	1.0	0.7	1.0	0.7	1.1	0.6	0.6	0.7	8.0	6.7	4.1	3.7

NOTE: 72 hour loss equivalent for soil cement is based on the time for 95% of erosion established during the midpoint of the test. Cement content in soil cement is based on the dry weight of the aggregate.

All abrasion tests were initiated after 28 days of wet curing. For both the portland cement concrete (PCC) and RCC the weight loss was measured every 12 hours throughout the 72-hour test. Because the soil-cement samples were of lower strength and eroded at a faster rater, the loss from the soil-cement was measured at 2-hour intervals. In addition, at this time interval, debris that had eroded had to be removed to keep from jamming the sample in the test apparatus.

The results of the test confirmed some previous studies of abrasion erosion in that the progression of wear was not linear. Greater wear occurred earlier in the test than later on, except for the PCC containing ¾ in (19mm) maximum size aggregate and the highest cement content (705 lb/yd^3 = 418 kg/m^3

For the lower-strength specimens, the initial wear was on the paste and mortar (paste and sand) until the larger aggregate was exposed. For soil-cement, this occurred during the first few hours. However, for PCC and RCC this initial erosion of paste and mortar happened in the first 12 to 24 hours. Once, the larger aggregate was exposed, the wear represented the entire mixture.

Because the RCC had a lower paste content (greater volume of aggregate) and had an aggregate grading designed to fill voids, the exposed surface was one of exposed rock that remained hard and smooth. At the other extreme, erosion of weaker soil-cement with few large aggregate particles produced a quite irregular surface that captured the steel balls causing further deterioration. This effectively caused the test to be terminated after 12 to 36 hours.

From the results of their work, the researchers concluded that abrasion-resistance of the cement stabilized materials tested was primarily a function of the aggregate hardness and secondarily a function of the strength of the cement paste. Of the three materials, RCC even at a lower strength was more abrasion erosion resistance than the conventional concrete (PCC), especially during the first 36 hours. The soil-cement had considerably less resistance than either the RCC or PCC. Therefore, if a typical soil-cement mixture is to be used to withstand abrasion from water-borne particles in the water, the soil-cement needed to be of greater thickness than either of the other two materials. The greater thickness is typical of soil-cement bank protection placed in stair-

step fashion on a relatively steep bank. In this case, the soil-cement layer has a horizontal width of about 8 ft (2.4m). If thinner soil-cement sections are to be used such as for plating a channel consideration needs to be given to increasing the soil-cement strengths through the addition of larger stone particles to the mixture, increasing cement content, or both.

The authors also introduced cost into their study, because in part that while soil-cement had the greatest rate or erosion, it was also the least costly per cubic yard. In doing their cost studies, they chose a soil-cement thickness of 5'8" perpendicular to the 1H:1V slope. For PCC, an 8-inch (200mm) thick slab was placed on 2H:1V slope. Similarly, RCC of two strengths (by varying cement content) were 12 inches (300mm) thick and placed on a 3H:1V slope. The slopes selected for each material therefore took into account the construction method for each material. The soil-cement section needed to be constructed using successive horizontal layers built in stair-step fashion up the steeper slope. For both the PCC and RCC, the material was to be placed directly on the slope, called the plating method of construction.

From their abrasion erosion resistance tests, which established a relative erosion rate plus estimated costs based on actual bid prices, the authors concluded RCC appeared to be the most cost effective material. However, when real estate and other items are considered due to the flatter slope that RCC had to be placed for stream bank protection, soil-cement became more attractive.

Up until this study, some engineers had a perception that RCC was an inferior product to PCC. These tests now showed that opposite with respect to abrasion erosion resistance and even more so when cost was included in the analysis.

5. Abrasion Erosion Tests for Rio Salado Project, Arizona

The Rio Salado project consists of bank protection and grade control structures along the Salt River as it passes through Phoenix, AZ. Natural flows and floodwaters here can contain large amounts of abrasive sand, gravel and cobbles. In order to test the abrasion erosion resistance of specific RCC mixtures being planned for the project, the Corps of Engineers Los Angeles District contracted with the U.S. Bureau of Reclamation (USBR), laboratory in Denver to conduct the underwater abrasion test (ASTM C 1138).

Four mixtures were tested; two with portland cement only and two with cement with the addition of fly ash (FA). Several aggregate gradings were tested, including a ¾ inch (19mm) nominal maximum size aggregate (NMSA) Arizona road base course. All the other mixtures had a Vebe time between 24 to 50 seconds and used 1 ½ in (38mm) NMSA aggregate. The W/C + FA for the cement only mixtures was 0.83 while the same ration for the C + FA mixtures was less (0.63 and 0.60) due mainly to the addition of the fly ash as a cementitious material.

With respect to abrasion resistance, the cement-only mixtures were tested at 28 days while the mixture containing cement plus fly ash were tested at about 90 to 100 days to allow for some strength gain from the pozzolan. The cement only mixture had compressive strength from 2060 to 2200 psi (14.2 to 15.2 MPa) at 28 days. The 90 to 100 day strength of C + FA mixtures were 3125 and 3890 psi (21.6 & 26.8 psi)

Generally, the abrasion resistance of the RCC specimens increased with increased strength and increased maximum size aggregate. However, for the 1½ inch (38mm) NMSA C + FA mixtures, the specimen with the lower strength had a greater abrasion

resistance (less wear) than the higher strength mix. This may be attributed to greater coarse aggregate packed into the mixture. Having a greater volume of high quality aggregate (mainly coarse aggregate) in a mixture helps explain why RCC has better abrasion erosion resistance than conventional concrete.

G. FIELD PERFORMANCE OF EROSION OF RCC

Schrader and Stefanakos (1995) and Hansen (1996) working independently reported on the field performance of RCC structures that had been exposed to erosion from water flow both with and without water-borne particles. In their paper "Roller Compacted Concrete – Cavitations & Erosion Resistance" borne particles, Schrader and Stefanakos reported on the field performance of 12 projects and 4 laboratory tests. Hansen in his paper "Erosion Resistance of Roller Compacted Concrete" reported on five projects in service and one laboratory test.

Both papers reported on the laboratory tests by Omoregie, Gutschow, and Russell (1995), which indicated a greater abrasion erosion resistance of a lower strength RCC compared to conventional concrete. Field performance of three projects were covered in both papers, namely Tarbela Dam in Pakistan, Ocoee No. 2, Tennessee, and Kerrville Ponding Dam, Texas. Both papers concluded that RCC, both in the field and the laboratory had very good erosion or abrasion resistance when exposed to overtopping or to large volume or high velocity water flow.

Probably the most severe case of RCC exposed to abrasion erosion was the spillway for the North Fork of the Toutle River Debris Retention Structure reported by Hansen. Another project with definitive data with respect to performances of RCC subjected to high depths of overflow was the Kerrville Ponding Dam in Texas. Its field performance was described in both papers.

1. North Fork of the Toutle River Debris Retention Structure, Washington

Following the volcanic eruption of Mt. St. Helens, in the southwest corner of the State of Washington in 1980, the US Army Corps of Engineers needed to build a debris retention basin. The purpose of the 38 ft (11.6m) high dam was to retain mud, rocks, volcanic ash and trees and keep the debris from clogging the Cowlitz and Columbia Rivers downstream.

The original design for the embankment included a 300 ft (91m) long shotcrete coated gabion spillway. In addition, this temporary structure had no outlet conduit. Therefore, once the reservoir filled, the entire river flow came over the spillway. The abrasive flow caused erosion of the thin shotcrete coating and then the wires forming the gabion baskets causing the entire spillway to fail one month after completion.

The new replacement spillway was constructed of steel-mesh reinforced RCC as it could be built quickly. The 4 ft (1.2m) thick RCC spillway placed in 5 lifts consisted of a 4H: 1V sloped portion with a horizontal crest as well as downstream apron. Side training walls for the spillway were also constructed of mass RCC. The new spillway requiring 18,000 cu. yd (13, 800m^3) of RCC was placed in 60 hours in a 6-day construction period.

Because abrasive flow was anticipated, the RCC mixture was designed for a relatively high compressive strength – 5500 psi (38 MPa) in 45 days. The velocity of the

water flowing over the exposed RCC was calculated to be in the 40 ft/sec (12.2 m/sec) range for the first six months following completion in 1981. Then, after the reservoir filled with sediment and debris, ash laden water and rocks up to 2 ft (0.6m) in size passed over the surface at high velocities for another 5 months.

In March 1982, another eruption of the volcano brought additional flows down the river causing the embankment to be overtopped and breached on both sides of the spillway. The condition of the spillway surface could now be inspected as water was flowing through the two embankment breaches and not over the spillway. After 11 months of high velocity abrasive flow, about 6 inch (150 mm) of RCC had eroded down to the steel mesh at one location. Also, a greater than 6-inch (150 mm) deep abrasion erosion groove occurred at the cold joint in the center of spillway as the structure was built in two sections working from the bottom up (see Fig. 12). The steel reinforcing was also easily abraded in this area. Because this area had dried out prior to placing the adjacent RCC and was poorly compacted due to lack of edge restraint, it had less strength and therefore less abrasion resistance than the rest of the RCC. Still the RCC performed quite well considering the severe conditions to which it was subjected.

Figure 12 Abrasion erosion of RCC spillway at cold joint at center of slab
North Fork of the Toutle River Debris Retention Structure

2. Kerrville Ponding Dam, Texas

This 21 ft (6.4m) high RCC gravity dam was completed in 1985 to replace a concrete capped compacted clay embankment structure that had been damaged extensively following a 10 ft (3m) overtopping in late 1984. Most of the downstream portion of the concrete cap plus about one-third of the embankment was washed away during this event.

The replacement dam was an RCC gravity section of the same height as the original dam constructed immediately downstream of the partially failed dam. In both designs, the 198 ft (60m) portion at the left abutment of the 598 ft (182m) long dam was depressed by 1 foot (300mm) to act as a service spillway. The entire dam was then planned to be overtopped during flood conditions.

Most of the undamaged upstream portion of the original dam was left in place to act as the cofferdam. RCC placement started on the limestone foundation rock and was placed adjacent to what was now a near vertical downstream face of the original embankment. A 2 ft (0.6m) thick apron of conventional concrete extended 20 ft (6.1m) downstream of the RCC section to prevent under cutting during overtopping.

The RCC mixture consisted of a 3-½ inch (89mm) MSA pit run sand and gravel to which 10% by dry weight of aggregate had been added. This mix was used for the base of the section and at the crest with a 5% mix in between. The richer mix produced an average compressive strength of more than 2100 psi (14.5 MPa) at 28 days.

Thirty days after completion of the RCC section it was subjected to a severe hydraulic test as up to 11 inches (280mm) of rain fell upstream of the dam in October 1995. This caused the RCC replacement dam to be overtopped by as much as 14.4 ft (4.4m). Flow over the entire dam lasted for more than four days and then as the flow diminished water flowed continuously over the depressed service spillway portion for nearly three weeks.

Except for washing away poorly compacted material at the downstream face of the broad-crested weir, there was no noticeable erosion of the RCC (see Fig.13). The maximum flow calculated to be 125,000 cfs (3540 m^3/s) was determined to be the one in 50 year event.

Then, less than two years later in July 1987, the RCC section was subjected to an even greater flood, which overtopped the dam, by a maximum of 16.2 ft (4.9m). Again, after this 1 in a 100 year event, no further erosion or other distress was evident. Except for several years, the Kerrville Ponding Dam has been overtopped by at least 7 ft (2.1m) each year since the two major overtoppings.

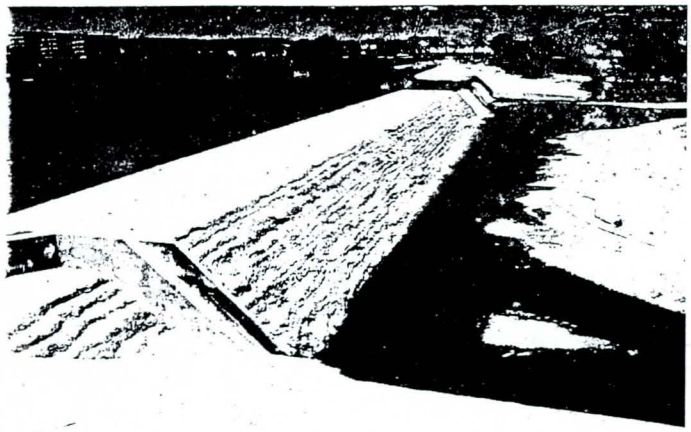


Figure 13 Condition of Kerrville RCC Ponding Dam, after 1985 overtopping

H. CONCLUSIONS

1. In reviewing all the material uncovered in the literature search, the following became apparent from many of the papers.

- In all laboratory studies of erosion or abrasion erosion of soil-cement, RCC, or conventional concrete, the test method either had to be (1) severe (2) accelerated or (3) conducted on specimens produced with cement contents less than usually specified for actual construction. Only in this manner could the researchers obtain any meaningful results in a relatively short period of time.
- The surface of the soil-cement or RCC surface in the laboratory was generally the rolled compacted surface. In field performance studies, hydraulic forces acted upon both compacted surfaces and on edges that were not directly compacted. The latter situation is encountered when water flows parallel to soil-cement stream bank protection or overflows exposed RCC downstream slopes on gravity dams or grade-control structures. These structures are constructed of multiple horizontal layers with slopes built in stair-step fashion.
- The erosion or abrasion erosion resistance of soil-cement or any concrete relates directly to the compressive strength of the material. Thus, for a soil-cement, concrete, or RCC made from the same aggregate, its abrasion erosion resistance increased as its strength increased.

2. In order to properly evaluate the results of erosion or abrasion erosion tests of cement stabilized materials, one needs to understand the main factors involved in the erosion process and the rate of erosion with time. Throughout this study, it became apparent that abrasion erosion resistance is primarily a function of the aggregate hardness and secondarily a function of the strength of the paste. The strength of the paste comes into play first. The mortar surface needs to be eroded first before the erosion of the mixture (mainly the coarse aggregate) is subjected to erosion or abrasion erosional forces.

If the paste is very strong, it takes a longer time to expose the aggregate while a surface that has been weakened by freeze-thaw cycles erodes very quickly.

Except for the case of a very strong paste (stronger than the aggregates), the rate of erosion diminishes with time.

3. From the literature review, the following conclusions can also be made:
    - The erosion resistance of soil-cement exposed to clean water not carrying water-borne particles has been exceptional. In addition, soil-cement in the field has been shown to have good long-term freeze-thaw durability without air-entrainment.
    - The soil-cement subjected to freeze-thaw and wet-dry durability brush tests and meeting PCA weight loss criteria had lower weight losses than that produced from water jets with velocities up to 20 ft/sec (6m/sec).
    - The erosional forces from the drop of water was greater than the tractive shear forces produced by water flowing over a soil-cement surface.
    - The most widely accepted test method for determining abrasion erosion resistance of cement-stabilized materials is ASTM C 1138 "Standard Test Method for Abrasion Resistance of Concrete (Underwater Method) developed by the US Army Corps of Engineers.
    - Because soil-cement invariably has a lower compressive strength than RCC or conventional concrete, it has less erosion or abrasion erosion resistance than either of the concretes.
    - RCC, even at a lower compressive strength, had a better abrasion erosion resistance than conventional concrete. This is due to a larger percentage of quality aggregate in the mixture and less paste.
    - Where soil-cement or RCC has experienced some erosion or abrasion erosion on actual structures it has occurred in areas of low strength such as a poorly compacted outer edge, or at the bottom of a lift where there is less density from the compaction process or in the case of in-place mixing where the cement content can be less. In addition, at a vertical cold joint there can be less strength due to less compactive effort at the edge and drying out of the material prior to placing and compacting the adjacent layer.
    - Where RCC surfaces are exposed to high-velocity water flow, smooth surfaces perform better than rough surfaces. In addition, compacted surfaces have better erosion resistance that cast surfaces as there is more aggregate and less paste closer to the surface exposed to water flow.

I. RECOMMENDATIONS – BASED ON LITERATURE SEARCH

1. Soil-cement designed for durability or equivalent compressive strength can withstand flows of clean water velocities up to 20 ft/sec (6m/sec) with little damage.

2. The erosion resistance of soil-cement can be improved by increasing its strength by one or more of the following means:
    a. Using a coarser material as the aggregate
    b. Adding gravel (at least 20% by weight) to a finer soil
    c. Increasing cement content

d. Delay water flow on the soil-cement until a later age.

3. Where greater abrasion erosion resistance is required, the following can be considered
   a. Roller-compacted concrete (RCC)
   b. High strength concrete (> 10,000 psi (69 MPa) @ 28 days) using fly ash or silica fume as an additive
   c. So-called exotic concretes such as polymer-impregnated concrete (PIC), polymer concrete (PC), and polymer-portland cement concrete (PPCC).
   d. Applied coatings
4. Cost, as well as ease of placement and performance anticipated for the conditions to be encountered should be considerations in selection of materials subjected to severe abrasion erosion forces or caxitation.
5. RCC will usually provide the greatest benefit vs. cost for abrasion erosion applications for all but the most severe conditions. Improved performance using RCC can be obtained by:
   a. Using the hardest aggregate available
   b. Providing the highest practical compressive strength (lowest w/c ration plus high degree of compaction)
   c. Use the largest practical NMSA in order to maximize the volume of aggregate and minimize paste.
   d. Design the structure so that the abrasive flow acts upon a well-compacted surface. For grade control structures, the protected banks adjacent to the structure need to have an equivalent abrasion erosion resistance as the structure itself.
6. Fiber-reinforced concrete or concrete with an iron metallic topping have not performed as well as other alternatives when subjected to abrasion erosion tests. Polyurethane coatings provided the best results of the coatings tested.

J. BIBLIOGRAPHY

Akky and Shen, 1973
Akky, M.R. and Shen, C.K., "Erodibility of a Cement-Stabilized Sandy Soil", Soil Erosion: Cause and Mechanisms – Prevention and Control – *Highway Research Board, National Academy of Science,* Washington, D.C., 1973.

Hansen, 1996
Hansen, K.D., "Erosion Resistance of Roller-Compacted Concrete", presented at 1996 Spring Convention, American Concrete Institute, Denver, CO, March 1996.

Hansen and Lynch, 1995
Hansen, K.D. and Lynch, J.B. "Controlling Floods in the Desert with Soil-Cement" Proceedings Second CANMET/ACI International Symposium on Advances in Concrete Technology, Las Vegas, NV, June, 1995.

Holland, 1983
Holland, T.C., "Abrasion – Erosion Update" *Concrete Structures Repair and Rehabilitation, Information Exchange Bulletin Vol. C-83-1*, August 1983.

ICOLD, 1986
International Commission on Large Dams, "Soil-Cement for Embankment Dams" Bulletin 54 prepared by Kenneth D. Hansen, *USCOLD*, 1986

Lilton and Lohnes, 1982
Lilton, L.L and Lohnes, R.A., " Soil-Cement for Use in Stream Channel Grade – Stabilization Structures" *Transportation Research Record 839,* 1982.

Lilton and Lohnes, 1983
Lilton, L.L and Lohnes, R.A., "Attrition Rates of Soil-Cement Subject to Water Jets" *Transportation Research Record 941*, 1983.

Liu, 1980
Liu, Tony C., Maintenance and Preservation of Concrete Structure: Report 3, Abrasion-Erosion Resistance of Concrete, *US Army Engineer Water Ways Experiment Station Technical Report C-78-4* July 1980.

Masch, Espey, and Moore, 1965
Masch, F.D., Jr., Espey, W.H., Jr., and Moore, W.L. "Measurements of the Shear Resistance of Cohesive Sediments" *Agricultural Research Service*, Publication 970, 1965

Mueller, 2000
Mueller, P.E. – personal communication

Nussbaum and Colley, 1971
Nussbaum, P.J. and Colley, B.E., "Dam Construction and Facing with Soil-Cement", *Portland Cement Association*, 1971.

Omoregie, Gutschow and Russell, 1994
Omoregie, F.A., Gutshow, R.A and Russell, M.L.: "Cement-Hardened Materials for Abrasion-Erosion in Hydraulic Structures", *Concrete International*, July 1994

Oswell and Joshi, 1986
Oswell, J.M. and Joshi, R.C., "Development of an Erosion Test for Soil-Cement", *ASTM Geotechnical Testing Journal, Vol. 9, Number 1*, March 1986

PCA, 1943
Portland Cement Association, "Soil-Cement for Flume Lining Gets a Tryout". *Soil-Cement News* 1943

PCA, 1979
Portland Cement Association, Pacific Southwest Region, "Resistance of Soil-Cement to Erosion by Longitudinal Flow of Water and Debris," April 1979.

Schrader and Stefanakos, 1995
Schrader, E. and Stefanakos, J.: "Roller Compacted Concrete Cavitation & Erosion Resistance" *Proceeding of International Symposium on Roller Compacted Concrete Dams*, Santander, Spain October 1995.

Simons, 1992
Simons, B.P., "Abrasion Testing for Suspended Sediment Loads", *Concrete International* March 1992.

U.S. Army Corps of Engineers, 1980 (a)
U.S. Army Corps of Engineers, "Summary of Erosion Study at Detroit Dam for Zintel Canyon Dam." *Design Memorandum, No.3-Exhibit 15. Zintel Canyon Dam*, Walla Walla District, September 1980.

U.S. Army Corps of Engineers, 1980 (b)
U.S. Army Corps of Engineers, "Erosion Test of Roller-Compacted Concrete (RCC)." *Design Memorandum, No.3-Exhibit 15. Zintel Canyon Dam* Walla Walla District, September 1980.

U.S. Bureau of Reclamation, 1999
Test Results of Roller Compacted Concrete Mixtures; Rio Salado Project: U.S. Army Corps of Engineers, Los Angeles District (unpublished), October 1999.