EROSION AND ABRASION RESISTANCE OF SOIL-CEMENT AND ROLLER-COMPACTED CONCRETE

by K. D. Hansen, Schnabel Engineering Associates

Research & Development Bulletin RD126

Keywords: Soil-cement, RCC, roller compacted concrete, erosion control, spillways

Abstract: Soil-cement and roller compacted concrete (RCC) have been used in water resources application for over 20 years. Both of these cement based products are increasingly being used in more severe operating conditions where durability against erosion and abrasion is an important design criterion. This publication contains the results of a comprehensive literature search of laboratory tests and field performance studies on erosion and abrasion resistance of soil-cement and RCC. Methods for improving the durability of soil-cement and RCC are discussed along with the design criteria used by various agencies and consultants for specifing the strength and durability requirements for the materials.

Reference: Kenneth D. Hansen, *Erosion and Abrasion Resistance of Soil-Cement and Roller-Compacted Concrete*, RD126, Portland Cement Association, Skokie, Illinois, 2002, 22 pages.

WARNING: Contact with wet (unhardened) concrete, mortar, cement, or cement mixtures can cause SKIN IRRITATION, SEVERE CHEMICAL BURNS (THIRD-DEGREE), or SERIOUS EYE DAMAGE. Frequent exposure may be associated with irritant and/or allergic contact dermatitis. Wear waterproof gloves, a long-sleeved shirt, full-length trousers, and proper eye protection when working with these materials. If you have to stand in wet concrete, use waterproof boots that are high enough to keep concrete from flowing into them. Wash wet concrete, mortar, cement, or cement mixtures from your skin immediately. Flush eyes with clean water immediately after contact. Indirect contact through clothing can be as serious as direct contact, so promptly rinse out wet concrete, mortar, cement, or cement mixtures from clothing. Seek immediate medical attention if you have persistent or severe discomfort.

Portland Cement Association
5420 Old Orchard Road, Skokie, Illinois 60077-1083 USA
847.966.6200, Fax 847.966.9781 www.portcement.org

ISBN 0-89312-210-6

Cover Photos: Top: Photo showing condition of Kerrville RCC Ponding Dam after 1985 overtopping (S#56065)
Bottom left: Soil-cement bank protection after overtopping during 1983 Tucson flood. (S#70037)
Bottomright: Shows condition of Bonny Reservoir soil-cement test section, 49 years after completion (S#70033)

RD126.01

PCAR&D Serial No. 2436a

Erosion and Abrasion Resistance of Soil-Cement and Roller-Compacted Concrete

by K. D. Hansen, Schnabel Engineering Associates

Table of Contents

TABLE OF CONTENTS

Erosion and Abrasion Resistance of Soil-Cement and Roller-Compacted Concrete

by K. D. Hansen, Schnabel Engineering Associates

SUMMARY

Soil-cement may be defined as a highly compacted mixture of portland cement, soil (usually sand), and water. RCC, on the other hand, is a no-slump concrete that is compacted by a roller, usually vibratory.

Soil-cement is used primarily for upstream slope protection for embankments and to protect erodible stream banks during flood events. Exposed RCC applications include mass drop or grade-control structures in water-ways and emergency spillways for existing earth dams, called overtopping protection, as well as emergency spillways for new dams.

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

The main difference between soil-cement and RCC is the aggregate or soil used in the mixture and the resulting properties. Soil-cement for water control projects generally utilizes a pit run sand with little material, if any, greater than 1/4 in. (4.75 mm) in size. RCC uses controlled graded aggregates with the nominal maximum size aggregate (NMSA) averaging about 1-1/2 in. (38 mm) for exposed RCC applications.

Because RCC uses larger, well-graded aggregate, the compressive strength of RCC is invariably greater than soil-cement at the same age. For slope and bank protection, the strength of soil-cement is generally specified to be in the 500 psi to 1,000 psi (3.4 MPa to 6.9 MPa) range at 7 days. The 28-day strength of exposed RCC is usually at least 2,000 psi (13.8 MPa).

While greater compressive strength can be expected with RCC when compared to soil-cement at the same age, the volume of cementitious materials used in RCC is usually less. Even with less cement, the unit cost of RCC is generally more than soil-cement for equal volumes of material to be produced and placed. The difference is due mainly to the added cost of producing and hauling aggregate to the job site.

Mixture proportioning methods to produce adequate durability and/or strength properties have been well-established for both soil-cement and RCC. The adequacy of these designs has also been proven in actual applications subjected to wave action or low velocity water with little suspended solids. However, less is 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 abrasion erosion conditions.

Erosion, as it pertains to soil-cement and RCC water resource applications, may be defined as the progressive disintegration of the material by water in motion. Abrasion erosion can be defined as the wearing away of a surface by rubbing and friction, such as that caused by sand, gravel, and cobbles moving across the surface.

This publication contains the results of a literature search on laboratory tests and field studies on erosion and abrasion resistance of soil-cement and RCC. It is also based on the results of a survey of methods used to design soil-cement and RCC subjected to high velocity or debris-laden flow.

Laboratory Tests–Erosion of Soil-Cement

Tests to assess the erosion resistance of soil-cement when subjected to either high velocity water or a bed load of water-borne particles go as far back as 1942. Test methods were developed to determine the resistance of soil-cement to forces greater than ordinary wave action or low-velocity flow (less than 10 ft / sec [3 m / sec]). In the laboratory, continuously flowing water, water jets, and specially developed test apparatus were used for this purpose.

In order to obtain meaningful results in a relatively short period of time, the test method in the laboratory had to be either (1) severe, (2) accelerated, or (3) conducted on specimens whose strength 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 of soil-cement or RCC that may also be exposed to flowing water in field applications.

Early Research

In 1942, the Civil Engineering Department of Oklahoma A & M College, (now Oklahoma State University) wanted to investigate the use of soil-cement as a lining for open flumes. The researchers applied water flowing at a velocity of 28 ft / sec (8.5 m / sec) in a 10-ft (3-m)-wide soil-cement lined flume. After the high-velocity water flowed continuously for 6 days, an inspection determined no appreciable erosion of the 4-1 / 2-in. (114-mm)-thick slab. A sandy loam soil consisting of 60% sand and 40% silt and clay was stabilized with 8% cement by volume and compacted to produce the soil-cement (PCA, 1943).

Portland Cement Association Studies

Research by the Portland Cement Association (PCA) focused on the abrasion erosion resistance of soil-cement when subjected to 1 / 8 in. to 1 / 4 in. (3.1 mm to 6.3 mm) size gravel-laden water. In addition, researchers Nussbaum and Colley (1971) wanted to determine a means for improving the abrasion erosion resistance (see note on pg. 6) of soil-cement produced from a silty soil.

An AASHTO classification A-1-b sandy gravel and an A-4 silt were stabilized with varying percentages of cement and exposed to an abrasion erosion test after 7 days of fog curing in the laboratory. About 8,000 gal. (36,400 L) of water flowing at a velocity of 3.8 ft / sec (1.2 m / sec) carried 4.2 tons (3,810 kg) of gravel over a soil-cement sample each day.

The results of the test are shown in Figures 1 and 2 as plots of time (in days) to produce a 1-in. (25-mm) depth of erosion. As expected and shown in Figure 1, increasing the cement content of the soil-cement increased its erosion resistance.

Having an even greater effect was the aggregate or soil that was stabilized. 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 in. (25 mm) of the finer A-4 material was less than 2 days, even with a cement content as high as 13.5% by weight. When the coarser A-1-b soil was stabilized with a much lower cement content (5%), it took 15 days to erode the soil-cement to a depth of 1 in. (25 mm).

Because of the better abrasion erosion resistance of the more granular soil, additional tests were made by improving the A-4 silt soil with the addition of gravel greater than 1 / 4 in. (6 mm) in size. The results of these tests indicated the addition of gravel to the fine soil increased its resistance significantly when the gravel component was greater than 20% by weight. At 30% gravel content and 9.5% cement, the modified A-4 soil was nearly as resistant to abrasion erosion as the original A-1-b sandy gravel soil (see Figure 2) with 5% cement.

Also during this test program, it was concluded that a 2,000-psi (13.8-MPa), 28-day-old concrete was more resistant to abrasion erosion than the soil-cement produced by adding 7% cement to the A-1-b sandy gravel. It took 33 days to erode 1 in. (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 significantly improved by using a coarser material as the aggregate or adding gravel to a finer soil. Erosion resistance can also be improved by increasing the cement content. All of these methods increase the strength of the soil-cement, as does delaying exposure to erosive conditions, thus improving the soil-cement's abrasion erosion resistance.

Studies at Universities

Three teams of researchers from universities in the United States and Canada tested the erosion or abrasion erosion of soil-cement for specific applications. At the University of California at Davis, Akky and Shen (1973) were interested in the erosional durability of soil-cement lined channels, while Litton and Lohnes (1982, 1983) at Iowa State University investigated the use of soil-cement for stream channel grade stabilization (drop) structures using loess-derived alluvium found in western Iowa. Oswell and Joshi (1986) at the University of Calgary studied the use of soil-cement for protecting artificial islands in the Beaufort Sea north of Canada and Alaska. The islands, which were planned for oil well drilling, would be subjected to the combined forces of breaking waves and impacting debris, as well as freeze-thaw cycles.

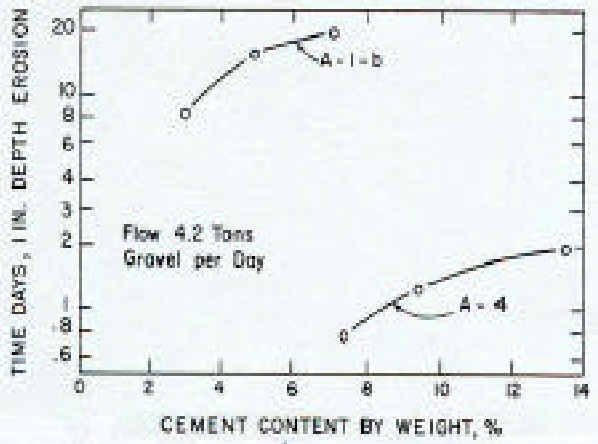

Figure 1. Erosion resistance vs. cement content of soil-cement.

Using a sample of soil-cement inside a rotating cylinder filled with water, Akky and Shen confirmed that erosion resistance increased as cement content, and therefore compressive strength, increased. Subjecting low-cement content soil-cement specimens to freeze-thaw cycles decreased compressive strength, while wet-dry cycles caused very little change in strength. During the first few freeze-thaw cycles, a weakened outer layer was formed that had decreased erosion resistance. This weakened layer may have served as an effective buffer against further deterioration, as the rate of loss or deterioration decreased after the outer layer eroded away.

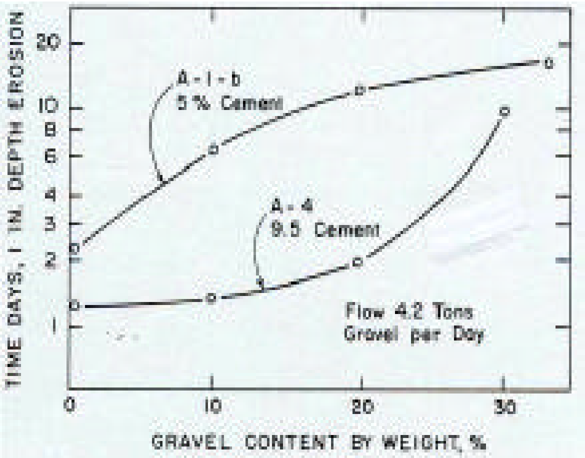

Figure 2. Erosion resistance vs. gravel content of soil-cement.

Litton and Lohnes (1982) developed an erosion testing apparatus designed to produce varying water velocities, and thus the forces anticipated from the free fall of water over a drop structure. Soil-cement made with varying cement contents was tested in addition to varying percentages of sand replacement for the local fine alluvium. Specimens containing 100% sand were also tested.

The results of the tests at Iowa State confirmed previous findings that the erosion resistance of soil-cement increased with increasing cement content and increasing percentages of sand substituted for finer, less erosion-resistant soil. Also, the erosional forces from the drop of water were greater than the boundary shear force produced by water flowing over a compacted soil-cement surface.

The most important portion of their testing came when the researchers compared the cement content required to provide sufficient durability using the freeze-thaw brush test with percent cement required to provide adequate erosion resistance for varying water velocities. Once a certain cement content is established to produce a durable soil-cement, it is assumed the soil-cement produced can withstand many volume changes due to expansion and contraction by freezing and thawing (or wetting and drying) without significant deterioration. However, the cement required to produce adequate erosion resistance depends upon the velocity of the water jet.

Litton and Lohnes (1983) determined that for water-jet velocities less than 20 ft / sec (6m / sec), the water-jet erosion tests produced lower weight losses (increased erosion resistance) than those produced by the standard brush durability tests. Thus this research provided designers with laboratory data to support the conclusion that soil-cement designed to provide adequate durability could also withstand clean water velocities up to 20 ft/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 that for any given flow rate, the rate of erosion was relatively great at first and then reached a stable configuration, after which there was minimal material loss. The material lost initially was that loosened during freeze-thaw cycles.

Oswell and Joshi developed a test apparatus that combined the impacting forces of waves and waterborne debris. Using plastic soil-cement mixes, the researchers confirmed that abrasion erosion losses could best be correlated to compressive strength. That is, lower losses were recorded from the higher strength specimens. For the soil-cement used in this study, Oswell and Joshi felt that a compressive strength of about 2,300 psi (16 MPa) was necessary to reduce erosion or abrasion erosion to a negligible amount when subjected to a water pressure of 10 psi (70kPa).

FIELD PERFORMANCE OF SOIL-CEMENT

Bonny Reservoir Test Section

The positive durability of properly designed soil-cement exposed to wave action and weathering has been proven many times in field applications. The best example of the long-term durability and erosion resistance of soil-cement is the test section constructed by the U.S. Bureau of Reclamation (USBR) in 1951 on the south shore of Bonny Reservoir in eastern Colorado.

The purpose of the test section was to determine if soil-cement could be a viable alternative to rock riprap for upstream slope protection for earth dams. A less costly alternative was desired by the USBR at sites where long hauls for rock riprap made the cost of slope protection expensive.

Two different soils were used at the Bonny test section. A fine silty sand required 12% cement by volume while a coarser silty fine to medium sand used 10% cement by volume. The average 28-day laboratory compressive strengths were 1140 psi and 880 psi (7.9 MPa and 6.1 MPa), respectively. After 10 years, cores drilled from the facing had approximately doubled in strength, averaging 2,000 psi and 2,160 psi (13.8 MPa and 14.9 MPa) respectively.

Figure 3. Condition of Bonny Reservoir soil-cement test section, 49 years after completion. (S#70033)

After 49 years of exposure to not only wave action, but also an average of 140 freeze-thaw cycles per year, the soil-cement remains hard and durable (see Figure 3). Erosion of the compacted soil-cement surface has been minor. Tracks from truck tires used for compaction remain visible in places.

There has been greater erosion at the bottom of the nominal 6-in. (150-mm)-thick lifts due to less cement and less density in this area attributed to the in-place mixing process used to produce the soil-cement. Also, there is little evidence of bonding between successive lifts. This lack of bond together with loss of embankment support due to overtoppings and water outflanking the section has caused some collapse and breakage of single layer soil-cement blocks on both ends of the section. Based on the performance at the Bonny test section it can be concluded that successive lifts of soil-cement should be well bonded if the section is to withstand the forces of high waves with little breakage.

Still, the test section proves not only the long-term erosional resistance of the basic soil-cement exposed to moderate to high wave action in the field, but also the freeze-thaw durability of soil-cement without air entrainment. In 1961, after 10 years of exposure, the USBR determined the test section to be a success and started specifying soil-cement in lieu of, or in competition with, rock riprap for slope protection for earth embankments.

FIELD STUDY OF PROJECTS IN THE PACIFIC SOUTHWEST

After its initial applications as upstream slope protection for earth dams, soil-cement started to be used more and more for protecting banks and channels subjected to the longitudinal flow of water. Many of these projects were located in California and Arizona. In 1978, the Pacific Southwest Region of PCA decided to inspect and report on the condition of 12 such projects that had been in service from 2 to 18 years.

In the study (PCA 1979), information was obtained on the frequency and approximate velocity of flow to which the soil-cement was subjected. Little information was available on the relative strength of the soil-cement, except the cement content specified at the time of construction. This was especially true for the strength condition of the usually uncompacted outer edge, which was subjected to water flow.

Each project was given a rating, A – little or no erosion (8 projects); B – minor amount of erosion (2 projects); or C – appreciable erosion (2 projects). Of the 12 projects studied, only 5 of the soil-cement applications were exposed to flow conditions close to those for which they were designed. The projects rated A did not provide much insight into the erosion resistance of soil-cement. The projects were either not subjected to any water flow or to only low velocity flow.

For the two projects that were rated C, the erosion was primarily in the overbuilt and not well compacted outer edge. This lower strength "fluff" is a prime candidate for considerable erosion when subjected to water flow. It has also been established for one of the C-rated projects that in-place mixing was used to produce the soil-cement. As with the Bonny Reservoir test section, this construction method produces a lower strength area at the bottom of the lift that erodes more than the rest of the section.

While this study's recommendations included some basic known methods to improve erosion resistance such as (a) the soil or aggregate to be stabilized should preferably be well-graded sands or sandy gravels, and (b) the cement content should be determined by the standard durability tests for soil-cement, its other conclusions were new.

These new recommendations 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 office recommended that where successive horizontal layers are used, maximum bond can be obtained by methods such as scarification, power brooming, and surface moistening between layers. It was later determined that mortar bedding or dry cement between successive soil-cement lifts was the most effective method to improve cohesion (bond) at the lift line. Another recommendation was to trim or compact outer edges smooth with the slope of the section. This suggestion was to define and expose compacted soil-cement of the design strength at its outer edge.

The most significant recommendation was "where velocities exceed 6 to 8 ft / sec (1.8 to 2.4 m / 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 a waterway could be exposed without modification to the soil or construction method. However, one PCA engineer who was involved with this field study termed this velocity limit "extremely conservative."

The 1983 Flood at Tucson, Arizona

Heavy rains over a 6-day period in late September and early October 1983 caused a record high flow on the Santa Cruz River through Tucson, Arizona. The flood, which exceeded the 1-in-100-year event,

Figure 4. Soil-cement bank protection after overtopping during 1983 Tucson flood. (S#70037)

caused 13 deaths and an estimated $226.5 million in damage in Pima County. Erosion of unprotected bridge abutments and flooding of access roads caused 35 of the 42 major bridges in the county to be closed at one time.

Soil-cement protected banks withstood the floodwaters very well. The $4 million Rio Nuevo project on the Santa Cruz and some bank protection along Rillito Creek prevented an estimated $15 to $20 million in damage.

For the Rio Nuevo project, 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 Figure 4). The water velocity in this area was estimated to be greater than 20 ft/sec (6 m/sec) (Hansen and 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 large abrasive particles. Field performance during this flood event verified laboratory research results of Litton and Lohnes (1982).

LABORATORY TESTS–ABRASION EROSION RESISTANCE OF RCC

Early Research for Exposed RCC Spillways

As part of the design process for Zintel Canyon Dam in Washington and Willow Creek Dam in Oregon, the U.S. Army Corps of Engineer (Corps) wanted to investigate the effect of high velocity flow on exposed RCC spillways. Tests were conducted in 1976 at two Corps facilities, at Detroit Dam in Oregon and at their Waterways Experiment Station (WES) in Mississippi.

In both tests, (U.S. Army Corps of Engineers, 1980) [a] & [b] water jets impinged on the compacted surface of RCC specimens even though the flow in the planned spillways was over the edges of exposed RCC lifts on a 0.8H: 1.0V downstream slope. RCC test slabs of about 2000 psi (13.8 MPa) compressive strength were subjected to water jet velocities ranging from 30 ft/sec (9m/sec) to 85 ft/sec (26m/sec). Various surface finishes were tested, including smooth and rough surfaces and a cast vs. rolled surface.

The results of the testing convinced the Corps that exposed RCC spillways had adequate erosion resistance. The tests were conducted at a higher velocity and for a longer period of time than clean water spillway flows were anticipated for either dam.

With respect to surface texture, smooth surfaces showed less erosion than rough surfaces. Similarly, rolled surfaces had better erosion resistance than cast surfaces. As with laboratory tests on soil-cement, the rate of erosion decreased with time.

Development of an Abrasion Erosion Test

A number of stilling basins and other structures at existing Corps dams had been damaged due to abrasion of concrete caused by turbulent water flow that contained large rock particles and other materials, such as pieces of steel. In order to evaluate the abrasion erosion resistance of various materials considered for repair of these concrete structures, the Corps developed an underwater abrasion erosion test method.

An apparatus developed by Liu (1980) was initially used to evaluate (a) conventional concrete, (b) fiber-reinforced concrete, and (c) polymer concrete. However, the apparatus was later used to determine the erosion resistance of both soil-cement and RCC and how these rolled no-slump materials compared with cast conventional concrete.

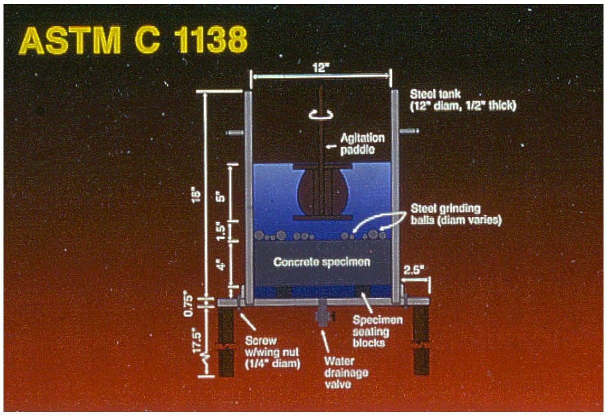

Figure 5. Section of apparatus for underwater abrasion test.

The apparatus consisted of a paint mixing paddle that rotated, creating agitation of both the water and 70 steel balls of three sizes ranging from 1/2 in. to 1 in. (12.7 mm to 25.4 mm) in diameter (see Figure 5). The test has been adopted as ASTM C 1138 Standard Method for Abrasion Resistance of Concrete (Underwater Method).

Results of Abrasion Erosion Test on Various Concretes

Tests to determine the abrasion erosion resistance of various concretes subjected to severe wear conditions were conducted by the Corps (Holland 1983) and for Puget Sound Power and Light (Simons 1992). The Corps used their underwater abrasion erosion test (ASTM C 1138) while Simons ran an 8-in. (203 mm) diameter drum sander on a test panel continuously for 8 hours. Every 30 minutes, the 20-grit Carborundum sandpaper was changed.

In the initial tests of concrete by the Corps using their ASTM C 1138 test method, the variables were seven aggregate types, three water/cement ratios and six types of surface treatments in addition to three types of concrete mentioned in the preceding section. Later they tested concrete with very high compressive strength using silica fume (about 15,000 psi [103 MPa]).

The conclusions and recommendations from the Corps studies included:

- Use the hardest available aggregate.
- Use the lowest practical water-cement ratio, which produces the highest practical compressive strength. The highest practical compressive strength in the early 1980s was about 6,000 psi (41 MPa), which was not high enough to overcome problems with weak aggregates.
- Fiber-reinforced concrete does not improve erosion resistance of concrete. In the laboratory, steel-fiber-reinforced concrete had less resistance 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, Pennsylvania.
- 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 so-called "exotic concretes" can be quite expensive and may be difficult to handle and place in the field.
- Very-high-strength concrete, (greater than 10,200 psi [70 MPa] at 28 days) as expected, showed very good abrasion erosion resistance with the hardened paste assuming a greater role than aggregate quality in resisting damage due to abrasion. For these high-strength mixes the optimum amount of silica fume by weight was determined to be closer to 20% than 30%, as initially tested. The Corps also noted 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.

The study for Puget Sound Power and Light (Simons 1992) attempted to find a lower cost alternative to a steel liner for replacing an existing wood water flume subjected to severe abrasion by water-borne sand and rocks. Although the test method used was not expected to simulate the magnitude and rate of wear that the structure would be subjected to, it would provide some indication of the abrasion erosion resistance of several materials.

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 8,050 psi (55 MPa) and, (e) a similar conventional concrete mixture with metallic topping.

The results of the tests produced the following conclusions:

- The two high-strength concretes showed abrasion resistance superior to either the conventional concrete or a similar mix with metallic topping. The relative rates of wear for the high-strength concretes were about 30% of that of the two lower strength concretes.
- The concrete mix with the fly ash proved to have superior relative abrasion resistance to 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 aggregate at the test surface.

- Steel displayed the least amount of abrasion, but cost the most.

Some of the conclusions derived from these two laboratory tests on various concretes may also be applied to soil-cement and RCC. The results of the testing also provide guidance to designers for projects subjected to extreme abrasion erosion conditions and for repair of abrasion damaged concrete.

Comparison of the Abrasion Erosion of Three Materials

The Los Angeles District of the Corps of Engineers expanded the application of the underwater abrasion erosion test to include soil-cement and RCC. Omoregie, Gutschow, and Russell (1994) also tested the abrasion erosion of conventional concrete in order to compare the three materials. The Corps wanted to apply this laboratory research to their use of soil-cement and RCC for protecting riverbanks and building channel invert stabilizers (also called grade control or drop structures).

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

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 rate, the loss from the soil-cement was measured at 2-hour intervals. In addition, debris that had eroded from the soil-cement sample had to be removed to keep from jamming the sample in the test apparatus.

The results of the test confirmed previous studies of abrasion erosion that wear progression is non-linear. Greater wear occurred earlier in the test than later on, except for the PCC containing 3/4-in. (19-mm) maximum size aggregate and the highest cement content (705 lb/yd3 [418 kg/m3]). This concrete had a 28-day compressive strength of 7,255 psi (50 MPa).

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 than conventional concrete, its exposed surface had a greater volume of aggregate exposed 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

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 agregate 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 onthe 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.

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 resistant than the conventional concrete (PCC), especially during the first 36 hours. In one case, an RCC with a 28-day compressive strength of 3,050 psi had a 5.2% weight loss, while a 4440 psi conventional concrete exhibited an 8.7% loss when tested in accordance with ASTM C 1138.

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, the soil-cement needs to be stronger or of a 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 (2.4 m). 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 strength through the addition of larger stone particles to the mixture, increasing cement content, or both.

The authors also introduced cost into their study because while soil-cement had the greatest rate of erosion, it was also the least costly. In doing their cost studies, they chose a soil-cement thickness of 5 ft 8 in. (1.7 m) perpendicular to the 1H: 1V slope. For PCC, an 8-in. (200-mm)-thick slab was placed on a 2H: 1V slope. Similarly, RCC of two strengths (by varying cement content) were 12 in. (300 mm) 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, plus estimated costs based on actual bid prices, the authors concluded that RCC appeared to be the most cost-effective material. However, when real estate and other items were considered, due to the flatter slope that RCC required to be placed for stream bank protection, soil-cement became more attractive.

Until this study, it was perceived by some engineers that RCC was an inferior product to PCC. With respect to abrasion erosion resistance, these tests now show the opposite, and even more so when cost is included in the analysis.

Abrasion Erosion Tests for Phoenix Area Projects

The underwater abrasion erosion test (ASTM C 1138) was used to test the wear of RCC mixtures planned for two flood control projects in the Phoenix, Arizona area. The U.S. Bureau of Reclamation tested RCC mixtures for the Rio Salado project on the Salt River, through Phoenix. This work was done for the Corps of Engineers' Los Angeles Districts (U.S. Army Corps of Engineers, 1999). Also, AGRA Earth & Environmental (1996) applied the test to "soil-cement" mixtures planned for the Reata Pass Wash project at Scottsdale, Arizona for the Flood Control District of Maricopa County.

Although the material tested by AGRA was called soil-cement, it contained aggregate whose maximum size was 1-1/2 in. (38 mm) and was artificially graded to meet a specified grading band. The material could better be classified as RCC, considering that its 7-day compressive strength using this well-graded aggregate averaged 2060 psi (14.2 MPa).

For the Rio Salado project, four mixtures were tested: two with portland cement only and two with cement plus the addition of fly ash (FA). Also, several aggregate gradations up to 1-1/2-in. (38-mm) maximum size aggregate (MSA) were tested including a 3/4-in. (19-mm) maximum size Arizona base course.

Generally, the abrasion resistance of the RCC specimens increased with increasing strength and maximum size aggregate. However, for the 1-1/2-in. (38-mm) NMSA C + FA mixtures, the specimen with the lower strength had a greater abrasion resistance (less wear) than the higher strength mix.

In the abrasion testing for the Reata Pass Wash project, cement contents varied from 5% to 10% by dry weight of aggregate in 1% increments. In all cases, increased cement content produced higher 7-day compressive strength. However, there were some inconsistencies in the results of the underwater abrasion tests. Similar to the one situation in the Rio Salado test program, there were several cases where the lower cement content (lower compressive strength) RCC showed less erosion than a higher strength specimen produced with a greater cement percentage. Because this unanticipated result occurred in both test programs, it provided evidence that aggregate properties are a larger factor in abrasion erosion resistance than compressive strength of RCC.

The results of the Reata Pass Wash test program produced another interesting result in that there was a definite break in the erosion resistance of specimens after reaching a 6% cement content. For the samples containing 7%, 8%, 9%, and 10% cement, the wear after 48 hours of testing was nearly identical. This phenomenon may be explained by the fact that the abrasion resistance of the aggregate controls once a certain level of compressive strength is reached. In this case it was 1,100 psi (7.6 MPa) at 7 days.

Field Performance of Roller-Compacted Concrete

Schrader and Stefanakos (1995) and Hansen (1996) independently reported on the field performance of RCC structures that had been exposed to erosion from water flow both with and without waterborne particles. Both papers concluded that RCC had very good erosion or abrasion erosion resistance when exposed to over-topping or large volume or high velocity water flow, citing the field performance of a total of 13 projects.

The following two projects provide the best case histories with respect to erosion or abrasion erosion resistance of RCC.

North Fork of the Toutle River Spillway

The most severe case of RCC exposed to abrasion erosion was the spillway for the North Fork of the Toutle River Debris Retention Structure in the southwest corner of the State of Washington. Following the eruption of Mt. St. Helens in 1980, the Corps of Engineers' Portland District built a debris basin to retain mud, rocks, volcanic ash, and trees sent downstream by the volcano.

The original design for the 38-ft (11.6-m) high embankment dam included a 300-ft (91-m)-long uncontrolled shotcrete-coated gabion spillway. Because this temporary dam had no outlet conduit, the entire river flow came over the spillway once the reservoir filled. Abrasive flow caused erosion of the thin shotcrete coating and then the wires forming the gabion baskets, eventually causing a failure of the entire spillway one month after completion.

The replacement spillway was a 4-ft (1.2 m) thick slab of steel-meshed reinforced RCC, as it could be built quickly. The new spillway requiring 18,000 yd3 (13,800 m3.) of RCC was placed in 60 hours during a 6-day construction period. The RCC was placed in five lifts with a horizontal crest and downstream apron and a 4H: 1V sloping portion in between. The training walls for the spillway were also constructed of mass RCC.

Because abrasive flow was anticipated, the RCC mixture was designed for a relatively high compressive strength—5,500 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 its completion in 1981. Then, after the reservoir filled with sediment and debris, ash-laden water and rocks up to 2 ft (0.6 m) in size passed over the surface at high velocities for another five 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 eleven months of high velocity abrasive flow, about 6 in. (150 mm) of RCC had been eroded down to the steel mesh at one location (see Figure 6). Also, a greater than 6-in. (150-mm) deep abrasion erosion groove occurred at the cold joint in the center of the spillway, as the structure was built in two sections working from the bottom up. The steel reinforcement was also easily abraded in this area.

Figure 6. Aftermath of RCC Spillway at North Fork of the Toutle River following 11 months of high velocity flow. Note severe washout behind sheet pile end sill. (S#70046)

Because the area had dried out prior to placing the adjacent RCC and had lower density 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.

Kerrville Ponding Dam

The greatest depth of overtopping for a small exposed RCC dam occurred over this replacement dam located on the Guadalupe River at Kerrville, Texas. The 21-ft (6.4 m)-high RCC gravity was completed in 1985 to replace a concrete-capped clay embankment that had been severely damaged following an overtopping of about 10 ft (3 m) in late 1984. About one third of the embankment and most of the downstream portion of the concrete cap were damaged during this event.

The replacement dam was an RCC gravity section constructed immediately downstream of the partially failed dam. In both designs, a 198-ft (60-m) portion at the left abutment of the 598-ft (182-m) long dam was depressed by 1 ft (300 mm) to act as a service spillway. The entire dam was then prepared 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 (0.6-m)-thick apron of conventional concrete extended 20 ft (6.1 m) downstream of the RCC section to prevent undercutting during overtopping.

The RCC mixture consisted of a 3-1/2 in. (89-mm) MSApit run sand and gravel to which 10% cement 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% cement mix in between. The richer mix produced an average compressive strength of more than 2,100 psi (14.5 MPa) at 28 days.

Thirty days after completion of the RCC section, it was subjected to a severe hydraulic test when up to 11 in. (280 mm) of rain fell upstream of the dam in October 1985. This caused the RCC replacement dam to be overtopped by as much as 14.4 ft (4.4 m). Flow over the entire dam lasted for more than 4 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 Figure 7). The maximum flow of 125,000 cfs (3,540 m3/s) was determined to be the 1-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 (4.9 m). In each of these major overtoppings, portions of trees were part of the overtopping flood. Again, after this 1-in-100-year event, no further erosion or other distress was evident. The Kerrville Ponding Dam has been overtopped by at least 7 ft (2.1 m) on a number of other occasions since the two major overtoppings.

Figure 7. Condition of Kerrville RCC Ponding Dam after 1985 overtopping. (S#56065)

Salt River Bank Protection

An example of severe abrasion erosion of cement stabilized alluvium (CSA) bank occurred during the 1993 flooding in the Phoenix area. The CSA containing pit-run aggregate of 3-in. (75 mm) size or larger may be better termed RCC than soil-cement.

Fourteen straight days of rain in January 1993 produced a maximum flow of 124,000 cfs (3,510 m3/s) on the Salt River through Phoenix. Basically, the CSA-protected banks performed well, but there were a few cases of significant abrasion erosion. One instance of erosion was on the south side of the river and downstream (west) of the McClintock Rd. Bridge at Tempe, Arizona (see Figure 8). The flood flows were reportedly channelized to this side. Note the size of the boulders and cobbles in the river that contributed to abrasion erosion of the banks. Large eroded areas in this area were subsequently repaired by infilling with a lean concrete.

Considering the severity and frequency of this extreme abrasion erosion condition in a relatively short stretch, repair was probably a more cost-effective solution than specifying a higher strength mix for protecting many miles of banks on both sides of the river. Also, it would be difficult to determine an adequate strength level to avoid no damage requiring repair for this extreme condition.

Figure 8. Erosion of cement-stabilized alluvium (CSA) bank protection on south side of Salt River at Tempe, Arizona following 1993 flood.

Methods for Mixture Proportioning for Soil-Cement

For early soil-cement upstream slope protection applications for earth embankments, an adequate cement content was determined using standard durability tests (freeze-thaw and wet-dry). However, most soil-cement bank protection cement content determinations have used a 7-day compressive strength as the basic design criterion.

Durability Tests for Determining Cement Content

The laboratory durability tests (ASTM D 560 and ASTM D 559) consist of subjecting compacted soil-cement specimens to 12 cycles of freezing and thawing (F/T) and/or 12 cycles of wetting and drying (W/D). The entire surface area is brushed after each cycle to remove loose particles that have become dislodged due to the volume changes imposed on the material. The minimum cement content is that which produces specimens that remain within specified limits of weight loss after the 12 F/T or W/D cycles. 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 (1992) criteria suggest a maximum 14% weight loss after 12 cycles of either of the two durability tests. A lower percentage weight loss (10% or 7%) is allowed for finer grained soils. 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 prevails. PCA’s Soil-Cement Laboratory Handbook (EB052.07S) 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% of cement is generally 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 USBR.

Some agencies will specify the additional 2% of cement initially. However, if field tests during construction show higher than anticipated compressive strength, the cement content is often reduced.

Compressive Strength for Determining Cement Content

A 7-day compressive strength criterion to determine an adequate cement content for soil-cement was adapted because strength tests can be run by all testing laboratories, take less time, and cost less than durability tests. The Portland Cement Association (1992) developed a correlation between 7-day compressive strength and durability. PCA compared results of more than 1,700 different soil-cement samples tested for both strength and durability. Results of the study are shown in Figure 9. Design engineers now had sufficient data to aid in specifying an acceptable strength level for exposed soil-cement in water control projects.

The concept of 7-day compressive strength as a criterion 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 were also required 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% of cement was added.

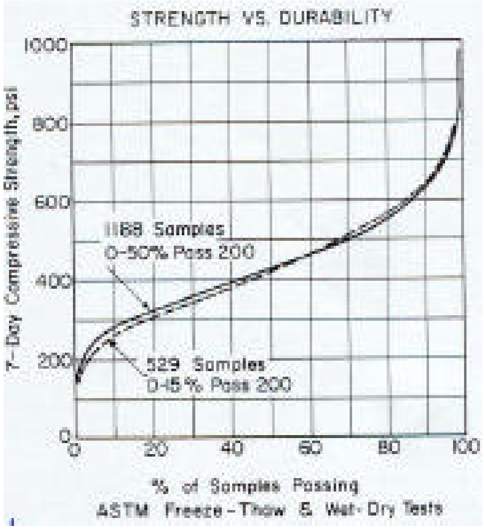

Figure 9. Relationship betweena strength and durability of soil-cement (PCA 1992).

At the 600-psi (4.1-MPa) compressive strength level, PCA's strength vs. durability chart (Figure 9) 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 (5.2 MPa) at 7 days will also be durable per the standard ASTM tests and PCA weight-loss criterion. It is believed that soils or aggregates that have high compressive strengths and less than adequate durability are poorly graded coarse sands and gravels (Hansen and Lynch 1995).

Compressive strength criteria used by five agencies in the Southwest to determine cement content for soil-cement bank protection as well as grade control structures are given in Table 2.

Table 2. Minimum 7-day Compressive Strength Requirements—for Soil-cement Banks and Grade Control Structures (145 psi = 1 MPa)

Agency	Soil-Cement Banks	Grade Control Structures	Comments
Pima County Tucson, AZ	750 psi	4-ft (1.2-m)-thickRCC cap ovr soil-cement structure	Grade control structures designed by USACE-LA
Maricopa County Phoenix, AZ (cement stabilized alluvium	750 psi	1,000 psi + 2%	Greater bed load conditions than other areas
AMAFCA Albuquerque, NM	750 psi + 2% (2)	1,000 psi + 2%	Coarser grading for agg. For grade control structures
Orange County, CA	700 psi + 2%	1,000 psi + 2%	
U.S. Corps of Engineers LA (1)	1,000 psi	2,000 psi	Crushed aggregate to produce RCC

(1) For use in Maricopa County, Arizona
(2) Minimum 7% by weight

It can be seen from Table 2 that the minimum compressive strength requirements for soil-cement bank protection by the various agencies are similar. In Tucson, 750-psi (5.2-MPa) minimum strength at 7 days is required in the laboratory in order to be assured of achieving a minimum of 600 psi (4.1 MPa) at 7 days for the banks as placed in the field. Somewhat higher strength is required in the Phoenix area due to the potential for a more severe bed-load abrasion situation.

All the agencies realize that the material used for grade control structures needs to be of a higher compressive strength than soil-cement bank protection, due to a more severe design condition. The top surface of the structures in the bed of the river can be subjected not only to relatively high water velocities, but also to bed load being transported downstream. The suspended bed load can tend to abrade lower portions of the soil-cement protected banks. In some cases, RCC with controlled graded aggregate is used instead of enriched soil-cement for grade control structures.

The three main factors affecting the compressive strength of compacted cement-stabilized mixtures are cement content, aggregate quality, and aggregate grading. Therefore, most agencies realize that the higher strength desired for more erosion-resistant structures can be more cost effectively obtained by requiring a coarser aggregate grading in addition to possibly an increased cement content. This realization was based on experience as well as PCA research (Nussbaum and Colley, 1971). Table 3 provides examples of aggregate gradings required by a few agencies for cement-stabilized bank protection. The best examples of a grading for greater erosion resistance are given by Albuquerque (Mixture A) and Maricopa County, where at least 30% and 35% of coarse aggregate retained on the #4 (4.75 mm) sieve is required. In these areas, the material to be stabilized is usually on site, with little or no processing needed to meet the coarser aggregate grading requirement.

Table 3. Aggregate Grading Specifications for Bank Protection (percent passing)

	PCA-1976 (suggested)	Orange Co., CA	Albuq., NM	Albuq., NM	Pima Co., AZ	Maricopa Co., AZ
Sieve Size	soil-cement	soil-cement	"B" soil-cement	"A" soil-cement	soil-cement	CSA (1)
2 in. (50 mm)	100	100	100			100
1-1/2 in. (38 mm)		98–100		100	90–100	
3/4 in. (19 mm)				80–95		
#4 (4.75 mm)	55–100	60–90	55–100	50–70	60–90	30–65
#200 (0.075 mm)	5–35	5–20	5–35	5–20	5–15	0–8
Plasticity Index (PI)			10 max	10 max	3 max	25 max
Sand Equivalent (2)		15 min. (1 test) 20 min. average				

(1) CSA = Cement Stabilized Alluvium–could be considered RCC

(2) A measure of the relative proportions of detrimental fine dust or claylike material or both in soils (Calif. Test Method 217).

RCC Compressive Strength Requirements

The compressive strength specified for exposed RCC spillways in embankment dams is generally higher than that required for interior mass RCC used in gravity dams. This is because the RCC spillways are exposed to weather and occasional flows, whereas this interior RCC mass is protected from these conditions. RCC placed on the downstream slope of an existing earth dam to increase the structure's ability to safely accommodate infrequent flood flows is called over-topping protection.

A survey of three major consulting engineering firms and two government agencies found four of the five respondents required a minimum 28-day compressive strength of 3,000 psi (20.7 MPa) for RCC spillways. One consulting firm felt 2,500 psi (17.2 MPa) at 28 days would be sufficient. One government agency thought that 4,000 psi (27.6 MPa) should be the lower level of durability for exposed RCC spillways located in areas where many freeze-thaw cycles could be anticipated yearly. Field experience seems to indicate RCC proportioned to achieve a minimum 28-day compressive strength in the range noted above has performed well except for the most severe abrasion conditions.

One reference for determining mixture proportions for RCC is the Corps of Engineers manual Roller-Compacted Concrete (EM 1110-2-2006). Another method is to add varying amounts of portland cement or portland cement plus fly ash to a well-graded aggregate and determine the compressive strength at various ages. The usual 6-in. x 12-in. (152-mm x 304-mm) RCC cylinders are prepared at or wetter than optimum moisture consistent with modified Proctor compactive effort (ASTM D 1557). Another method of preparing cylinders is in accordance with ASTM C 1435 Molding Roller-Compacted Concrete in Cylinder Molds Using A Vibrating Hammer.

SUMMARY AND DISCUSSION

In order to design for erosion or abrasion erosion resistance of soil-cement or RCC, one needs to understand the basics of erosion as well as the erosion or abrasion process. Basically the erosion resistance of compacted cement-stabilized materials depends on three factors (1) the compressive strength of the material, (2) the quality of the aggregate, and (3) the quantity and gradation of aggregate in the mixture. All other factors being equal, the erosion resistance of soil-cement and RCC increases with increased compressive strength, harder aggregates, and a greater percentage of mainly coarse aggregate in the mixture.

Which factor controls depends on the strength of the paste or the hardness of the aggregate. The strength of the paste increases with time, while aggregate hardness remains the same during the life of the structure.

With conventional slump concrete, there is excess paste at the surface due to bleeding and finishing of the concrete. This paste needs to be worn away before the erosion process can start on the entire mixture, most notably the aggregate. Except for very-high-strength concrete where the paste is stronger than the aggregate, the hardness of the aggregate controls the rate of wear. Invariably the rate of erosion of concrete diminishes with time, with stable, hard aggregates.

Because soil-cement and RCC are no-slump mixtures, there is little if any paste at the surface. Still, it has been found in both the laboratory and the field that the rate of erosion of these materials also diminishes with time.

Abrasion erosion of soil-cement or RCC due to water-borne materials is a more critical situation than erosion due to clean water running over the surface, even at relatively high velocities. Also rolled, smooth surfaces have been shown to be more erosion resistant than rough surfaces, especially uncompacted edges of either soil-cement or RCC lifts.

Erosion Resistance of Soil-Cement

Because soil-cement contains very little, if any, coarse aggregate, its erosion resistance is invariably controlled by the compressive strength of the cement paste. The method for determining adequate cement content for soil-cement is based on durability tests or a minimum 7-day compressive strength that correlates to durability. In most areas, a minimum 7-day compressive strength of 750 psi (5.2 MPa) is specified. An additional 2% of cement is then usually added to the cement content derived from either durability or compressive strength laboratory testing to account for construction-related variations or the fact that durability decreases sharply for mixes containing inadequate cement contents.

It has been shown in both the laboratory and the field that properly designed soil-cement can withstand the flow of clean water up to a velocity of 20 ft / sec (6 m / sec) with little erosional damage. Also, soil-cement designed for adequate durability without air entrainment can withstand the long-term action of waves and freeze-thaw cycles with little deterioration.

For higher flow velocities or abrasion erosion conditions, the compressive strength of soil-cement needs to be increased or RCC used. Means for increasing the strength of soil-cement exposed to more severe erosion conditions include modification to the mixture proportions, increased degree of compaction on exposed soil-cement surfaces, and extending the curing period. Methods for increasing compressive strength of the soil-cement due to mix adjustments include increasing the cement content, changing to a coarser, more well-graded aggregate, or adding coarse aggregate to a finer sand or silty sand.

Erosion Resistance of Roller-Compacted Concrete

The criterion for mixture proportioning of RCC to withstand erosion or abrasion erosion is to specify a certain minimum compressive strength at a certain age. The lower limit for RCC strength has been in the 2,000 psi to 2,500 psi (13.8 MPa to 17.2 MPa) range at 28 days. Most designers specify a minimum compressive strength of 3,000 psi (20.7 MPa) at 28 days for exposed RCC spillways that will carry infrequent clean water flows.

For continuous or very abrasive flow, or an extreme freeze-thaw durability condition, higher compressive strengths are needed. However, there is ultimately a strength level at which the hardness and amount of aggregate in the mix control its erosion resistance rather than its compressive strength. It appears this strength level is variable depending mainly on the hardness of the aggregate.

Therefore, for extreme exposure conditions, the most effective way to improve erosion or abrasion erosion resistance of RCC is to adjust mixture proportions. Assuming an adequate cement or cementitious content, the adjustment involves the aggregate. It has been shown that improved erosion resistance can be obtained by using the hardest available aggregate, increasing the NMSA of the aggregate, and increasing the volume of aggregate in the mix. Care should be taken that these mix adjustments do not contribute to increased segregation during construction.

No-slump RCC has a greater volume of aggregate in the mixture and less paste than conventional slump concrete. This helps explain why RCC has been shown in laboratory tests to have a greater abrasion erosion resistance than conventional concrete of greater compressive strength. Cost also favors RCC over conventional concrete of equal thickness.

ACKNOWLEDGMENT

The research reported in this paper (PCA R&D Serial No. 2436a) was conducted by Schnabel Engineering Associates with the sponsorship of the Portland Cement Association (PCA Project Index No. 00-03). The contents of this paper reflect the views of the author, who is responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

This publication is based on the following report prepared by Schnabel Engineering Associates for the Portland Cement Association:

"Laboratory Tests and Field Studies on Erosional and Abrasion resistance of Soil-Cement Concrete-Results of a Literature Search," (PCA Serial No. 2436) November 2000.

REFERENCES

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

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, Neveda, June, 1995.

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

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

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

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

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

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

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.

*Report on Reata Pass Abrasion Testin*g, AGRAEarth & Environment, Phoenix and Scottsdale, Arizona, for the Flood Control District of Maricopa County (unpublished), August 1998.

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

Roller-Compacted Concrete, U.S. Army Corps of Engineers, EM 1110-2-2006, January 2000.

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

Suggested Specifications for Soil-Cement Slope Protection for Earth Dams (Central-Plant-Mixing Method), Portland Cement Association . IS 052.02W,1976

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

Soil-Cement Laboratory Handbook, Portland Cement Association EB 052.07S, 1992.

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

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. (a)

U.S. Army Corps of Engineers, *Summary of Erosion Study at Detroit Dam for Zintel Canyon Dam*, Design Memorandum, No.3-Exhibit 16. Zintel Canyon Dam, Walla Walla District, September 1980.(b)

PORTLAND CEMENT ASSOCIATION

5420 Old Orchard Road
Skokie, Illinois 60077-1083 USA

Phone: 847.966.6200
Fax: 847.966.9781
Internet: www.portcement.org

An organization of cement companies to improve and extend the uses of portland cement and concrete through market development, engineering, research, education, and public affairs work.