

Report on Soil Cement

Reported by ACI Committee 230



American Concrete Institute®



American Concrete Institute®
Advancing concrete knowledge

First Printing
July 2009

Report on Soil Cement

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI. Proper use of this document includes periodically checking for errata at **www.concrete.org/committees/errata.asp** for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised *ACI Manual of Concrete Practice* (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.

Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

ISBN 978-0-87031-333-2

AVA **Documents**
Document Sharing Hub

Report on Soil Cement

Reported by ACI Committee 230

Mark E. Krebs
Chair

Jan R. Prusinski
Secretary

Wayne S. Adaska
Randall P. Bass
William N. Brabston
Tim Cost

David A. Crocker
William Halczak
Kenneth D. Hansen
Robert H. Kuhlman

Robert V. Lopez
Paul E. Mueller
Ronald L. Peltz
Gerald C. Plunk

Bruce W. Ramme
Wilasa Vichit-Vadakan
David C. Weber
James M. Willson

Soil cement is a densely compacted mixture of portland cement, soil/aggregate, other cementitious materials (possibly), and water. Used primarily as a base material for pavements, soil cement has also been used for slope protection, low-permeability liners, foundation stabilization, and other applications. This report contains information on applications, material properties, mixture proportioning, construction, and quality-control inspection and testing procedures for soil cement. This report's intent is to provide basic information on soil cement technology with an emphasis on current practice regarding design, testing, and construction.

Keywords: aggregates; base courses; central mixing plant; compacting; construction; fine aggregates; fly ash; foundation stabilization; lime, linings; mixing; mixture proportioning; moisture content; pavements; permeability; portland cement; pulverization, slag cement; slope protection; soil cement; soils; soil stabilization; soil tests; tests; vibration.

ACI Committee Reports, Guides, Manuals, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

CONTENTS

Chapter 1—Introduction, p. 230.1R-2

1.1—Scope

Chapter 2—Notation, definitions, and acronyms, p. 230.1R-2

2.1—Notation

2.2—Definitions

2.3—Acronyms

Chapter 3—Applications, p. 230.1R-3

3.1—General

3.2—Pavements

3.3—Slope protection

3.4—Bank protection

3.5—Liners

3.6—Foundation stabilization

3.7—Miscellaneous applications

Chapter 4—Materials, p. 230.1R-9

4.1—Soil

4.2—Portland cement

4.3—Slag cement

ACI 230.1R-09 supersedes ACI 230.1R-90 (Reapproved 1997) and was adopted and published July 2009.

Copyright © 2009, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietor.

- 4.4—Fly ash
- 4.5—Lime
- 4.6—Chemical admixtures
- 4.7—Water
- 4.8—Cementitious materials not conforming to specifications

Chapter 5—Properties, p. 230.1R-11

- 5.1—General
- 5.2—Density
- 5.3—Compressive strength
- 5.4—Flexural and tensile strength
- 5.5—Permeability
- 5.6—Shrinkage and cracking
- 5.7—Structural design

Chapter 6—Mixture proportioning, p. 230.1R-15

- 6.1—General
- 6.2—Proportioning criteria
- 6.3—Special considerations

Chapter 7—Construction, p. 230.1R-17

- 7.1—General
- 7.2—Materials handling and mixing
- 7.3—Compaction
- 7.4—Finishing
- 7.5—Joints
- 7.6—Curing and protection

Chapter 8—Quality-control testing and inspection, p. 230.1R-24

- 8.1—General
- 8.2—Pulverization (mixed in place)
- 8.3—Cement content control
- 8.4—Moisture content
- 8.5—Mixing uniformity
- 8.6—Compaction
- 8.7—Lift thickness and surface tolerance

Chapter 9—References, p. 230.1R-26

- 9.1—Referenced standards and reports
- 9.2—Cited references

CHAPTER 1—INTRODUCTION

1.1—Scope

This report contains information on applications, materials, properties, mixture proportioning, design, construction, and quality-control inspection and testing procedures for soil cement. The intent of this report is to provide basic information on soil cement technology with an emphasis on current practice regarding mixture proportioning, properties, testing, and construction.

This report does not provide information on fluid or plastic soil cement, which has a mortar-like consistency at the time of mixing and placing. Information on this type of material is provided by ACI Committee 229. Roller-compacted concrete (RCC), a type of no-slump concrete compacted by vibratory roller, is not covered in this report. ACI Committees 207 and 327 addressed the subject of roller-compacted concrete (ACI 207.5R and 325.10R).

CHAPTER 2—NOTATION, DEFINITIONS, AND ACRONYMS

2.1—Notation

- C_w = weight of cement
- R = flexural strength, psi
- f'_c = unconfined compressive strength, psi
- SN = structural number
- $a_1, a_2, \text{ and } a_3$ = layer coefficients of surface, base, and subbase, respectively
- $D_1, D_2, \text{ and } D_3$ = corresponding layer thicknesses

2.2—Definitions

The following terms are used throughout the report:

cement content—cement content is normally expressed in percentage on a weight basis. The cement content by weight is based on the oven-dry weight of soil according to the formula (PCA 1992a)

$$C_w = \frac{\text{weight of cement}}{\text{oven-dry weight of soil}} \times 100$$

cement-modified soil—a soil or aggregate treated with a relatively small proportion of portland cement with the objective of amending undesirable properties of problem soils or substandard materials so that they are suitable for use in construction. The amount of cement added to the soil is less than that required to produce a hardened mass (that is, soil cement), but is enough to improve the engineering properties of a soil (for example, plasticity index reduction, bearing strength improvement). Cement-modified soil is typically not required to achieve this high level of performance, and is normally used in lower load situations (for example, pavement subgrade improvement and plasticity reduction of a marginal aggregate with plastic fines). Cement-modified soil is beyond the scope of, and therefore not included in, this report.

cement-treated base—a form of soil cement that uses graded aggregate, rather than soil, to serve as the inert material bound by cement plus, possibly, pozzolans. Figure 2.1 illustrates the aggregate gradation band for minimum binder requirements. Cement-treated base is also referred to as cement-treated aggregate base, cement-stabilized aggregate base, or other similar terms.

optimum moisture—the water content at which the soil cement can be compacted to a maximum dry density by a given compactive effort.

recycled flexible pavement—recycled flexible pavement is a form of soil cement pavement base that is constructed using existing flexible pavement layers that might consist of a deteriorated bituminous wearing surface, granular base material, and underlying subgrade. Some or all of these materials are blended with cement and possibly other cementitious materials to produce a hardened, durable pavement base for a bituminous surface or subbase for a concrete pavement. This material is also referred to as recycled failed flexible pavement, recycled aggregate base, full-depth reclamation, full-depth recycling, or cement stabilized recycled asphalt pavement.

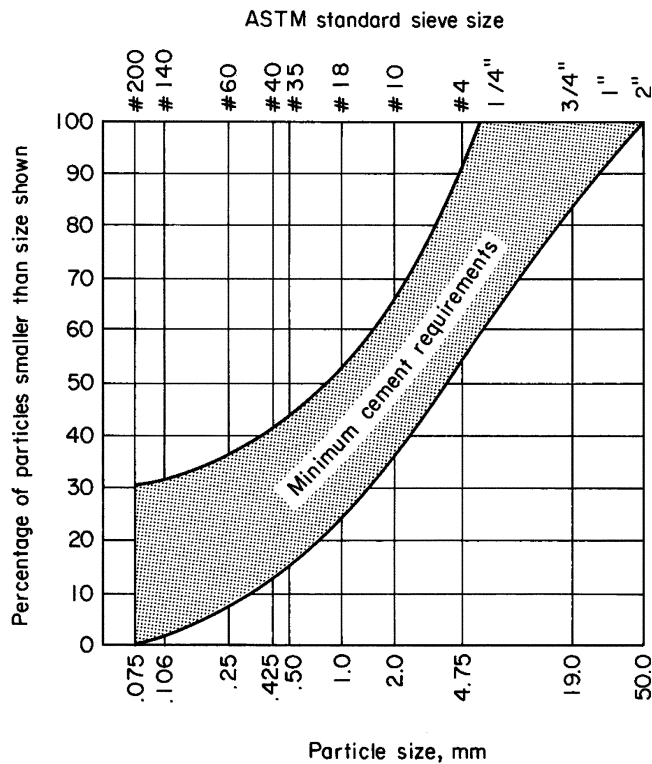


Fig. 2.1—Illustration of aggregate gradation band for minimum binder requirements.

soil cement—“ACI Concrete Terminology” (American Concrete Institute 2009) defines soil cement as “a mixture of soil and measured amounts of portland cement and water, compacted to a high density.” Soil cement can be further defined as a material produced by blending, compacting, and curing a mixture of soil/aggregate, portland cement, possibly other cementitious materials, and water to form a hardened material with specific engineering properties. The soil/aggregate particles are bonded by cement paste, but unlike concrete, the individual particle is not completely coated with cement paste. Soil cement is distinguished from cement-modified soil in that soil cement normally satisfies durability and compressive strength, or both, so that it can effectively resist structural loading (for example, vehicle loads when used as a pavement base) and environmental forces (for example, freezing and thawing, wetting and drying, and erosion under flow conditions).

2.3—Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACPA	The American Concrete Pavement Association
ASCE	American Society of Civil Engineers
DOT	Department of Transportation
EPA	U.S. Environmental Protection Agency
HDPE	high-density polyethylene
PCA	The Portland Cement Association
RCC	roller-compacted concrete
TxDOT	Texas Department of Transportation

USACE U.S. Army Corps of Engineers
 USBR U.S. Bureau of Reclamation

CHAPTER 3—APPLICATIONS

3.1—General

The primary use of soil cement is as base material underlying bituminous and concrete pavements. Other uses include upstream slope protection for dams; protection of river banks and associated grade-control structures; liners for channels, reservoirs, and lagoons; and mass soil cement placements for dikes and foundation stabilization.

3.2—Pavements

Since 1915, when a street in Sarasota, FL was constructed using a mixture of shells, sand, and portland cement mixed with a plow and compacted, soil cement has become one of the most widely used forms of soil stabilization for highways. More than 125,000 miles (200,000 km) of equivalent 24 ft (7.3 m) wide pavement using a soil cement base have been constructed to date in the United States. Soil cement is used mainly as a base for road, street, industrial, and airport paving. A soil cement base provides a uniform, strong support for the pavement that will not consolidate under traffic. When used in a flexible pavement, a double bituminous chip seal or a hot-mix bituminous wearing surface is normally placed on the soil cement base. Under concrete pavements, soil cement is used as a subbase to improve support between the concrete and subgrade layers, to improve load transfer at joints, and to prevent pumping of fine-grained subgrade soils under wet conditions and heavy truck traffic. It also serves as a firm, stable working platform for construction operations.

Failed flexible pavements have been recycled with cementitious materials, resulting in a new soil cement base (Fig. 3.1). Recycled flexible pavements provide increased base strength without removing the old existing base and subbase materials and replacing them with new, more expensive base materials. In addition, existing grade lines and drainage can be maintained. If an old bituminous surface can be readily pulverized, it can be considered satisfactory for inclusion in the soil cement mixture. If a bituminous surface retains most of its original flexibility, it is often removed because of difficulty in pulverization. Modern mixing equipment, however, is often powerful enough to pulverize most asphalt surfaces (Fig. 3.2). The Portland Cement Association (PCA) recommends that for recycled flexible pavements, the pulverized, mixed material should meet a gradation of 100% passing the 3 in. (75 mm) sieve, at least 95% passing the 2 in. (50 mm) sieve, and at least 55% passing the No. 4 (4.75 mm) sieve (PCA 2005).

Numerous examples exist of recycled flexible pavements stabilized with cement. The Texas Department of Transportation (TxDOT) has recycled more than 500 miles (800 km) of farm-to-market road in the Bryan District. These roads consist of 10 in. (250 mm) of in-place stabilized material that includes the existing base and subgrade. The bituminous surface is normally milled and disposed of separately. For lighter-duty roads, a two-course chip seal is



Fig. 3.1—Initial pulverization of asphalt surface and base.



Fig. 3.2—Complete pulverization of asphalt and base.

placed as the wearing surface directly on the stabilized base. On heavier-duty roads, an additional 4 in. (100 mm) of unstabilized crushed aggregate is added to increase section thickness before chip-seal application. Extensive post-construction monitoring by the Texas Transportation Institute has indicated that, in most cases, these roads are demonstrating excellent performance, with virtually no cracking or distress (Sebesta et al. 1999). Dallas County has used plant-mixed recycled flexible pavement, with the aggregate consisting of 100% recycled asphalt pavement, previously milled from state projects. This material has proven to be economical and highly durable. Also, plant mixing reduces the time the road needs to be closed.

On another project, the TxDOT Amarillo District used a full-depth reclamation process to reconstruct almost 13 miles

(21 km) of Interstate 40. The paving train consisted of a milling machine, followed by a trailer-mounted screening/crushing unit. A cold mixing unit with a belt scale added cement and water, and the materials subsequently remixed. The existing pavement consisted of 11 in. (270 mm) asphalt plus 19 in. (475 mm) of crushed aggregate base. For this project, the top 4 in. (100 mm) of asphalt was removed. The final base consisted of 7 in. (175 mm) of asphalt plus 3 in. (75 mm) of aggregate base stabilized with 3 to 4% cement. The TxDOT indicated that it saved about a month of construction time by using this method, as well as avoiding removing 265,000 tons (240,000 metric tons) of paving materials (*Asphalt Contractor Magazine*). Deteriorating residential bituminous-surface streets are ideal candidates for recycled pavements. A recycling project in Spokane County, WA, realized a 32% savings in construction costs versus removal and replacement with virgin aggregates (Spokane). Projects in Colonial Heights, VA; Endicott, NY; and Westminster, CA, are three more examples where recycling pavements with cement was found to be an economical and effective alternative.

Airfield runways have used considerable amounts of soil cement. General aviation airports, in particular, have benefited from soil cement. For instance, in the early 1980s, four general aviation airfields in Arizona used soil cement to reconstruct existing runways after the original bituminous pavements failed (PCA 1985). Dallas-Fort Worth Airport, Atlanta's Hartsfield International Airport, and Denver International Airport have used soil cement and cement-treated base extensively beneath concrete pavement. Alliance Airport in Fort Worth included over 300,000 yd² (250,000 m²) of 9 in. (225 mm) cement-treated base upon which 14 in. (350 mm) of portland-cement concrete pavement was placed. The clay subgrade on this project was also stabilized with cement.

Soil cement and cement-treated base have been found to be particularly effective for use as a subbase for concrete pavements. The American Concrete Pavement Association (ACPA) cites high support values, load transfer effectiveness, and nonpumping properties as reasons for selecting soil cement for concrete subbases. Figures 3.3 and 3.4 illustrate the lower strain, higher subgrade modulus, and higher load transfer effectiveness, respectively, of cement-treated subbases (ACPA 1991).

3.3—Slope protection

Following World War II, there was a rapid expansion of water resource projects in the Great Plains and South Central regions of the United States. Rock riprap of satisfactory quality for upstream slope protection was not locally available for many dam projects. High costs for transporting riprap from distant quarries to these sites threatened the economic feasibility of some projects.

In the late 1940s, the U.S. Bureau of Reclamation (USBR) initiated a major research effort to study the suitability of soil cement as an alternative to conventional riprap. Based on laboratory studies that indicated soil cement made with sandy soils could produce a durable erosion-resistant surface, the USBR constructed a full-scale test section at Bonny

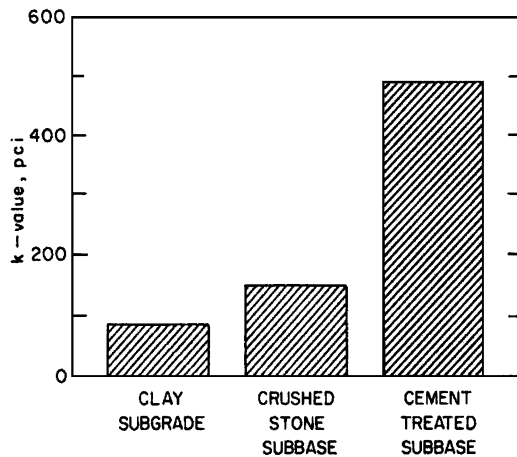


Fig. 3.3—Subgrade modulus improvements using cement-treated subbase for concrete pavements. (Note: 200 pci = 5536 Mg/m³ = 54 MN/m³.)

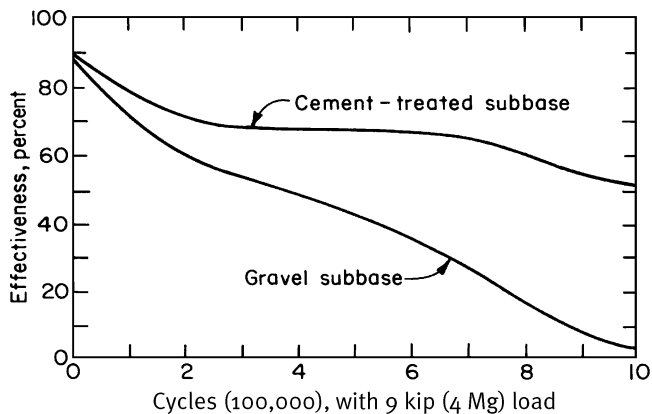


Fig. 3.4—Load transfer effectiveness of using cement-treated subbase for concrete pavements.

Reservoir in eastern Colorado in 1951 (Holtz and Walker 1962). The test-section location along the southeast shore of the reservoir was selected because of severe natural service conditions created by waves, ice, and more than 140 freezing-and-thawing cycles per year. After 10 years of observing the test section, the USBR was convinced of its suitability and specified soil cement in 1961 as an alternative to riprap for slope protection on Merritt Dam, NE, and later at Cheney Dam, KS (Coffey and Jones 1961). Soil cement was bid at less than 50% of the cost of riprap, and produced a total savings of more than \$1 million for the two projects.

Performance of these early projects has been good (Casias and Howard 1984). Although some repairs have been required for both Merritt and Cheney Dams, the cost of the repairs was far less than the cost savings realized by using soil cement over riprap. In addition, the repair costs may have been less than if riprap had been used (Casias and Howard 1984). The original test section at Bonny Reservoir has required very little maintenance and still exists today, over 50 years later (Fig. 3.5).

Since 1961, more than 400 major soil cement slope protection projects have been built in the United States and Canada. In

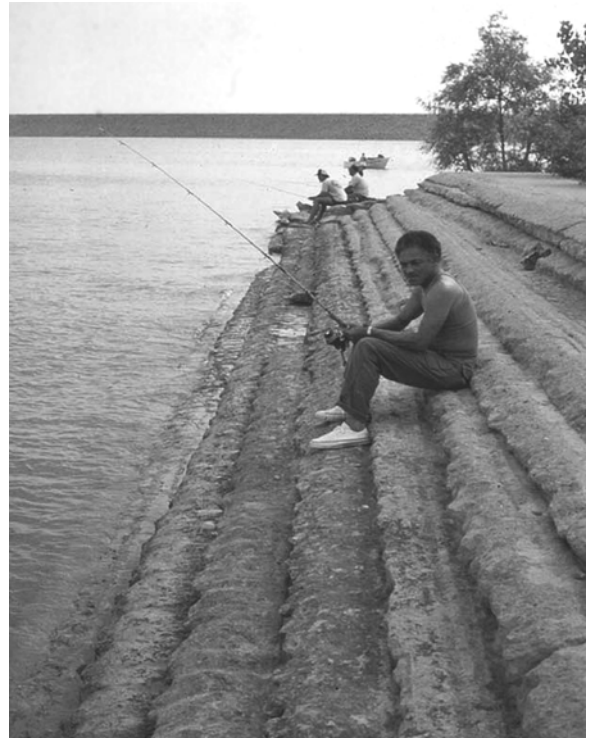


Fig. 3.5—Bonny Reservoir soil cement after 57 years.

addition to upstream facing of dams, soil cement has provided slope protection for channels, spillways, coastal shorelines, and highway and railroad embankments.

For slopes exposed to moderate to severe wave action (effective fetch greater than 1000 ft [300 m]) or debris-carrying, rapid-flowing water, the soil cement is usually placed in successive 6 to 9 in. (150 to 230 mm) thick horizontal layers 6 to 9 ft (1.8 to 2.7 m) wide, adjacent to the slope. This is referred to as stair-step slope protection (Fig. 3.6). For less severe applications, such as those associated with small reservoirs, ditches, and lagoons, the slope protection may consist of single or multiple 6 to 9 in. (150 to 230 mm) thick layers of soil cement placed parallel to the slope face. This method is often referred to as plating (Fig. 3.7).

The largest soil cement project worldwide involved 1.2 million yd³ (0.92 million m³) of soil cement slope protection for a 7000 acre (2830 hectare) cooling-water reservoir at the South Texas Nuclear Power Plant near Houston. Completed in 1979, the 39 to 52 ft (12 to 16 m) high embankment was designed to contain a 15 ft (4.6 m) high wave action that would be created by hurricane winds of up to 155 mph (250 km/h) (Adaska and Dinchak 1980). In addition to the 13 miles (21 km) of exterior embankment, nearly 7 miles (11 km) of interior dikes, averaging 27 ft (8.2 m) in height, guide the recirculating cooling water in the reservoir. To appreciate the size of this project, if each 6.75 ft (2.1 m) wide by 9 in. (230 mm) thick lift were placed end-to-end rather than in stair step fashion up the embankment, the total distance covered would be more than 1200 miles (2000 km).

More detailed design information on soil cement slope protection can be found in USBR (1986), and Hansen (1986).

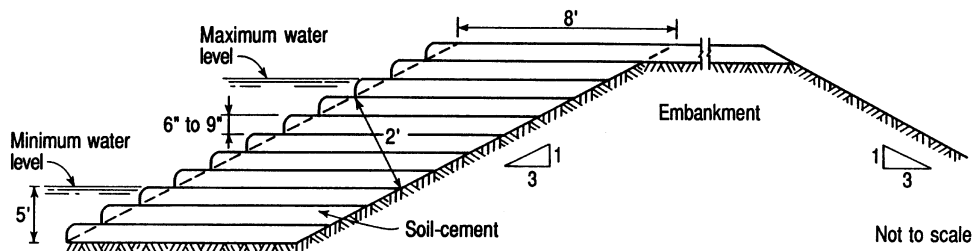


Fig. 3.6—Soil cement slope protection showing layered design.



Fig. 3.7—Soil cement slope plating for cooling water flume at Florida power plant.

3.4—Bank protection

Bank protection is similar to slope protection except the soil cement section will withstand high velocity and sometimes abrasive flows parallel to the protected banks. The use of soil cement bank protection has gained its greatest acceptance in protecting usually sand river banks through urban areas in the southwestern part of the United States. Based on its excellent performance during major flow events in Tucson, AZ, in 1983 and both the Tucson and Phoenix areas in 1993, soil cement bank protection has been used almost exclusively in these metropolitan areas.

A typical soil cement section consists of 7 to 9 ft (2.1 to 2.7 m) wide horizontal layers, but typically at a steeper slope than that used for upstream slope protection for dams or other water impoundments. The slope generally ranges from 1:1 to 1.5:1 (horizontal to vertical). To withstand scour of the river and possible subsequent undermining of the soil cement, the section often starts 8 ft (2.4 m) or more below the existing, and usually dry, river bottom. The top elevation is generally determined by the river level for the 1-in-100 year storm event, or less in protecting areas of lesser value. The ends of a bank protection section either abut previously placed soil cement bank protection or are turned perpendicular to the river for a distance approximating 50 ft (15 m) to prevent washing out behind the section. The outer face of the soil



Fig. 3.8—Outer face of soil cement can be trimmed smooth and compacted immediately following placement to improve hydraulic considerations or create desired appearance.

cement section can be either trimmed smooth or compacted immediately following placement to improve hydraulic considerations (Fig. 3.8), left as is to make a more natural look, or compacted to produce definite stair-steps for better appearance or easier access out of the river bottom. Refer to USBR (1986) and PCA (1984) for additional information on design of the section and mixture proportions for soil cement bank protection.

3.5—Liners

Soil cement has served as a low-permeability lining material for more than 40 years. During the mid-1950s, a number of 1 to 2 acre (0.4 to 0.8 hectare) farm reservoirs in southern California were lined with 4 to 6 in. (100 to 150 mm) thick soil cement. The largest soil cement-lined lake project is Lake Cahuilla, a terminal-regulating reservoir for the Coachella Valley County Water District irrigation system in southern California. Completed in 1969, the 135 acre (55 hectare) reservoir bottom has a 6 in. (150 mm) thick soil cement lining, and the sand embankments forming the reservoir are faced with 2 ft (0.6 m) of soil cement normal to the slope.

In addition to water-storage reservoirs, soil cement has been used to line wastewater-treatment lagoons, sludge-drying beds, ash-settling ponds, and solid waste landfills. The U.S. Environmental Protection Agency (EPA) sponsored laboratory tests to evaluate the compatibility of a number of lining materials exposed to various wastes (Office of Solid Waste and Emergency Resources 1983). The tests indicated that after 1 year of exposure to leachate from municipal solid wastes, the soil cement hardened considerably and cored like portland cement concrete. In addition, the liner's permeability decreased during the exposure period. The soil cement was also exposed to various hazardous wastes, including toxic pesticide formulations, oil refinery sludges, toxic pharmaceutical wastes, and rubber and plastic wastes. Results showed that for these hazardous wastes, no seepage had occurred through soil cement following 2-1/2 years of exposure. After 625 days of exposure to these wastes, the compressive strength of the soil cement exceeded the compressive strength of similar soil cement that had not been exposed to the wastes. Soil cement was not exposed to acid wastes. It was rated "fair" in containing caustic petroleum sludges, indicating that the specific combination of soil cement and certain waste materials should be tested and evaluated for compatibility before making a final design decision.

Mixture proportions for liner applications have been tested to reduce permeability of the mixture by adding fly ash, lime, or both, to portland cement. Permeabilities significantly less than 4×10^{-9} in./s (1×10^{-8} cm/s) have been measured for such fly ash-lime-cement mixtures. Also, the unconfined compressive strengths before and after vacuum saturation indicate good freezing-and-thawing durability (Moretti 1987). A similar evaluation has been made for liners incorporating fly ash, cement, and bentonite (Usmen 1988).

For hazardous wastes and other impoundments where maximum seepage protection is required, a composite liner consisting of soil cement and a synthetic membrane can be used. To demonstrate the construction feasibility of the composite liner, a test section was built in 1983 near Apalachin, NY (Fig. 3.9). The section consisted of a 30 to 40 mil (96 to 1.0 mm) high-density polyethylene (HDPE) membrane placed between two 6 in. (150 mm) layers of soil cement on a 3H:1V slope. After compacting the soil cement cover layer, the membrane was inspected for signs of damage. The membrane proved to be puncture-resistant to the placement



Fig. 3.9—Spreading soil cement on membrane at 3:1 slope Apalachin, NY.

and compaction of soil cement even with 3/4 in. (19 mm) aggregate scattered beneath the membrane (PCA 1986).

Actual soil cement/geomembrane composite liners constructed to date have used a single layer of soil cement placed either below or above the membrane. Experience with geomembranes placed directly on the slope of large open reservoirs indicates they do not perform well when subject to significant wave action produced by high winds. The use of soil cement as a rigid backing for a membrane lining was used at two open municipal water-storage reservoirs completed in 1991 at Lubbock and Midland, TX. To provide an incompressible backing for the 60 mil (1.5 mm) thick HDPE liner, a 12 in. (300 mm) thick layer of compacted soil cement on the 3H:1V side slope was placed for both reservoirs (Midland and Lubbock).

For another reservoir at Midland, TX, built in 1994, the soil cement was placed on top of a 60 mil (1.5 mm) thick HDPE liner for the entire 8.5 acre (3.4 hectare) reservoir. A 6 in. (150 mm) thickness of compacted soil cement was used for the reservoir floor, while a 9 in. (230 mm) thickness was used on the 3H:1V side slopes. In this case, in addition to protecting the impermeable liner from wind and wave damage, the soil cement surface could support vehicles for occasional silt cleanout of the reservoir.

3.6—Foundation stabilization

Soil cement has been used as a massive fill to provide foundation strength and uniform support under large structures. In Koeberg, South Africa, for example, soil cement was used to replace an approximately 18 ft (5.5 m) thick layer of medium-dense, liquefiable saturated sand under two 900 MW nuclear power plants. An extensive laboratory testing program was conducted to determine static and dynamic design characteristics, liquefaction potential, and durability of the soil cement. Results showed that with only 5% cement content by dry weight, cohesion increased significantly, and it was possible to obtain a material with enough strength to prevent liquefaction (Dupas and Pecker 1979).

Soil cement was used instead of a pile or caisson foundation for a 38-story office building completed in 1981 in Tampa, FL. A soft limestone layer containing several cavities

immediately below the building made the installation of piles or caissons difficult and costly. The alternative to driven foundation supports was to excavate the soil beneath the building to the top of limestone. The cavities within the limestone were filled with lean concrete to provide a uniform surface before soil cement placement. The excavated fine sand was then mixed with cement and returned to the excavation in compacted layers. The 12 ft (3.7 m) thick soil cement mat saved \$400,000 compared with either a pile or caisson foundation. In addition to providing the necessary bearing support for the building, the soil cement doubled as a support for the sheeting required to stabilize the excavation's walls. The soil cement was ramped up against the sheeting and cut back vertically to act as formwork for the mat pour. As a result, just one brace was needed for sheeting rather than eight (*Engineering News Record* 1980).

At the Cochiti Dam site in north-central New Mexico, a 35 ft (10.7 m) deep pocket of low-strength clayey shale under a portion of the outlet works conduit was replaced with 57,650 yd³ (44,100 m³) of soil cement. The intent of the massive soil cement placement was to provide a material with physical properties similar to the surrounding sandstone, thereby minimizing the danger of differential settlement along the length of the conduit. Unconfined 28-day compressive strengths for the soil cement were just over 1000 psi (6.9 MPa), closely approximating the average unconfined compressive strength of representative sandstone core samples.

In 1984, soil cement was used instead of mass concrete for a 1200 ft (366 m) wide spillway foundation mat at Richland Creek Dam near Ft. Worth, TX. About 10 ft (3 m) of overburden above a solid rock strata was removed and replaced with 117,500 yd³ (89,800 m³) of soil cement. To satisfy the 28-day 1000 psi (6.9 MPa) compressive strength criteria, 10% cement content was used. The substitution of soil cement for mass concrete saved approximately \$7.9 million.

3.7—Miscellaneous applications

Rammed earth is another name for soil cement used to construct wall systems for residential housing. Rammed-earth walls, which are generally 2 ft (0.6 m) thick, are constructed by placing the damp soil cement into forms commonly made of plywood held together by a system of clamps and walers. The soil cement is then compacted in 4 to 6 in. (100 to 150 mm) thick lifts with a pneumatic tamper. After the forms are removed, the wall can be stuccoed or painted to look like any other house. Rammed-earth homes provide excellent thermal mass insulation properties; however, the cost of this type of construction can be greater than comparable wood-frame houses. A typical rammed-earth soil mixture consists of 70% sand and 30% noncohesive fine-grained soil. Cement contents vary from 4 to 15% by weight, with the average around 7% (Berglund 1986).

Soil cement has been used as stabilized backfill. At the Dallas Central Wastewater Treatment Plant, soil cement was used as economical backfill material to correct an operational problem for 12 large clarifiers. The clarifiers are square tanks, but use circular sweeps. Sludge settles in the corners

beyond the reach of the sweep, resulting in excessive downtime for maintenance. To operate more efficiently, sloped fillets of soil cement were constructed in horizontal layers to round out the four corners of each tank. A layer of shotcrete was placed over the soil cement face to serve as a protective wearing surface.

The Texas State Department of Highways and Public Transportation specifies an option that allows the fill behind retained earth-wall systems for highway overpass approaches to be cement-stabilized sand. This is done primarily as a precautionary measure to prevent erosion from behind the wall, under the adjacent roadway, or both. On some projects, cement-stabilized sand is chosen—even when good granular material is readily available—because of cost and ease of construction.

Soil cement has been used for embankment stabilization for home developments in southern California. In one housing development where homes were built along the face of hills, 250,000 yd³ (190,000 m³) of soil cement was used instead of an unstabilized, compacted fill material. Soil cement could be placed at a 1.5:1 slope instead of a 3:1 slope for the unstabilized material, thus saving considerable material.

At some locations, especially where clay is not available, embankments and dams have been constructed entirely of soil cement. A monolithic soil cement embankment serves several purposes. It provides upstream slope protection, its erosion-resistant downstream face acts as an impervious core, and it can be built on relatively steep slopes due to its inherent shear strength properties. A monolithic soil cement embankment was used to form the 1100 acre (445 hectare) cooling water reservoir for Barney M. Davis Power Plant near Corpus Christi, TX. The reservoir consisted of 6.5 miles (10.5 km) of circumferential embankment and 2.1 miles (3.4 km) of interior baffle dikes. The only locally available material for construction was a uniformly graded beach sand. The monolithic soil cement design provided both slope protection and served as the impervious core. By using the increased shear strength properties of the compacted cement-stabilized beach sand, the 8 to 22 ft (2.4 to 6.7 m) high embankment was constructed at a relatively steep slope of 1.5H:IV.

Coal-handling and storage facilities have used soil cement in a variety of applications. The Sarpy Creek coal mine, near Hardin, MT, used soil cement in the construction of a coal storage slot. Slot storage basically consists of a long V-shaped trough with a reclaim conveyor at the bottom of the trough. The trough sidewalls should be at a steep and smooth enough slope to allow the stored coal to remain in a constant state of gravity flow. The Sarpy Creek storage trough is 750 ft (230 m) long and 20 ft (6.1 m) deep. The 15,500 yd³ (11,900 m³) of soil cement were constructed in horizontal layers 22 ft (6.7 m) wide at the bottom to 7 ft (2.1 m) wide at the top. During construction, the outer soil cement edges were trimmed to a finished side slope of 50 degrees. A shotcrete liner was placed over the soil cement to provide a smooth, highly wear-resistant surface.

Monolithic soil cement and soil cement-faced berms have been used to retain coal in stacker-reclaimer systems. The berm at the Council Bluffs Power Station in southwestern