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Report on Soil Cement

Reported by ACI Committee 230

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Report on Soil Cement

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Report on Soil Cement

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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.

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

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, and a_3 = layer coefficients of surface, base, and subbase, respectively
D_1, D_2, 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.

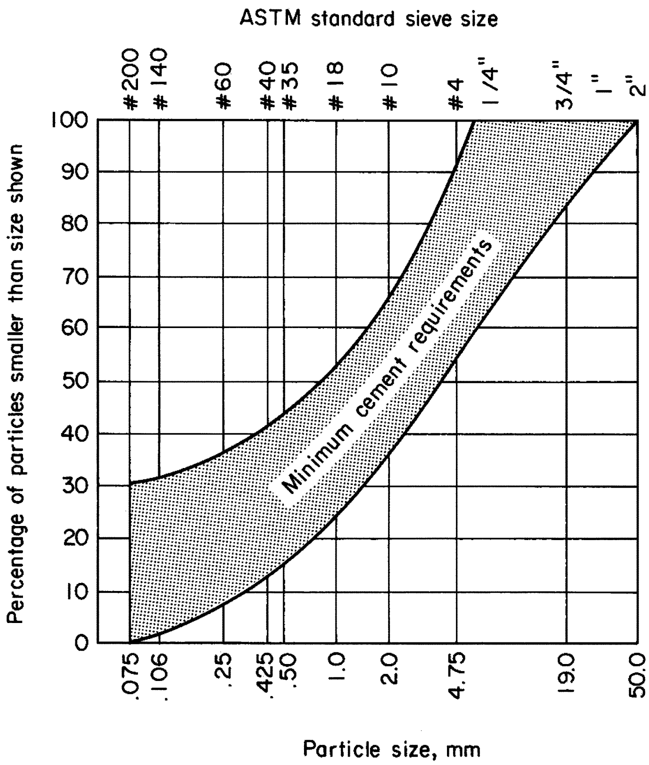

Fig. 2.1—Illustration of aggregate gradation band for minimum binder requirements.

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 offsite before stabilization. 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 yd^2 (250,000 m^2) 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 facing, the USBR constructed a full-scale test section at Bonny

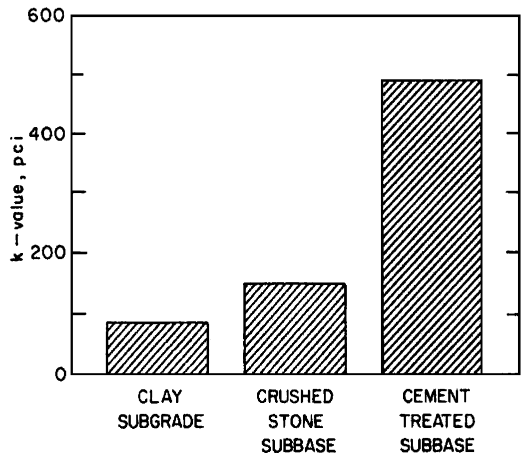

Fig. 3.3—Subgrade modulus improvements using cement-treated subbase for concrete pavements. (Note: 200 pci = 5536 Mg/m^3 = 54 MN/m^3.)

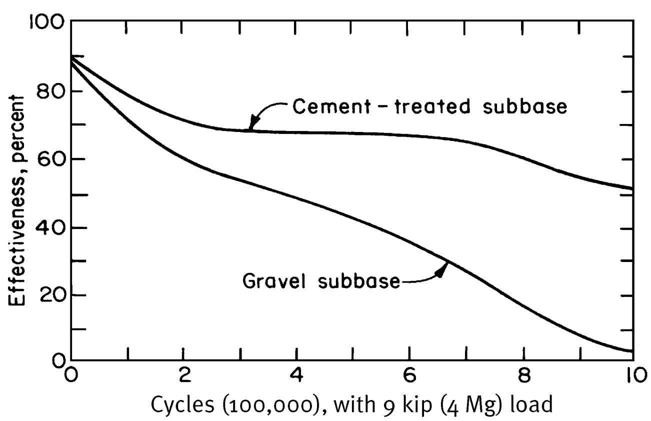

Fig. 3.4—Load transfer effectiveness of using cement-treated subbase for concrete pavements.

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

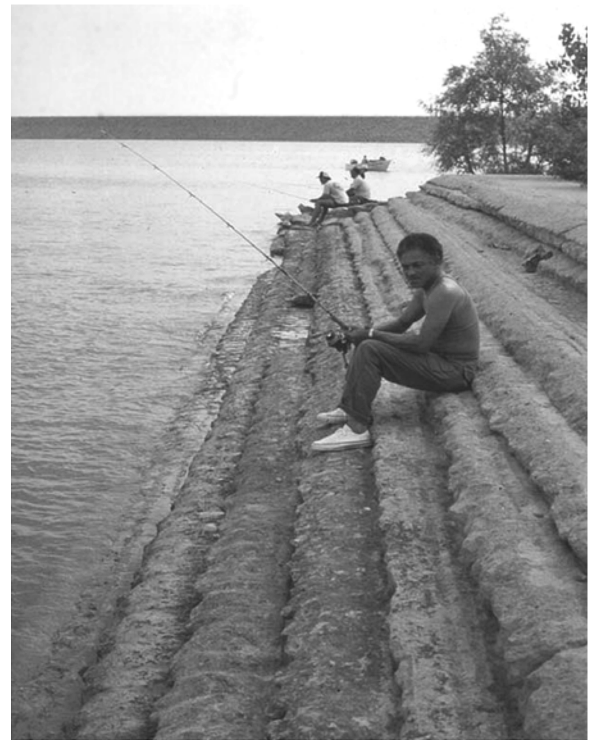

Fig. 3.5—Bonny Reservoir soil cement after 57 years.

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 yd^3 (0.92 million m^3) 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), PCA (1984), and Hansen (1986).

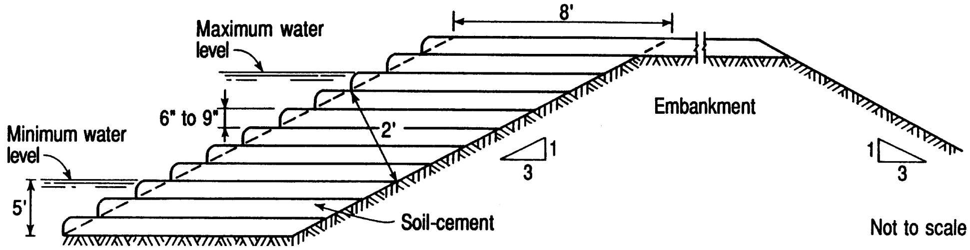

Fig. 3.6—Soil cement slope protection showing layered design.

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 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.

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.

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

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

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:IV 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 1980 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 yd^3 (44,100 m^3) 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 yd^3 (89,800 m^3) 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 whalers. 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 yd^3 (190,000 m^3) 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 yd^3 (11,900 m^3) 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 operations. The berm at the Council Bluffs Power Station in southwestern

Iowa is 840 ft (256 m) long by 36 ft (11 m) high and has steep 55-degree side slopes. It was constructed entirely of soil cement with the interior zone of the berm containing 3% cement. To minimize erosion to the exposed soil cement, the 3.3 ft (1 m) thick exterior zone was stabilized with 6% cement.

At the Louisa Power Plant near Muscatine, IA, only the exterior face of the coal-retaining berm was stabilized with soil cement. The 4 ft (1.2 m) thick soil cement and interior uncemented sand fill were constructed together in 9 in. (230 mm) thick horizontal lifts. A modified asphalt paving machine was used to place the soil cement. A smooth exposed surface was obtained by trailing plates at a 55-degree angle against the edge during individual lift construction.

Several coal-pile storage yards have been constructed of soil cement. Ninety-five acres (38 hectares) of coal storage yard were stabilized with 12 in. (300 mm) of soil cement at the Independence Steam Electric Station near Newark, AK, in 1983. The soil consisted of a processed, crushed limestone aggregate. The 12 in. (300 mm) thick layer was placed in two 6 in. (150 mm) compacted lifts. By stabilizing the area with soil cement, the owner was able to eliminate the bedding layer of coal, resulting in an estimated savings of $3 million. Other advantages cited by the utility include an additional 2% coal recovery, a defined perimeter for its coal pile, reduced fire hazard, and all-weather access to the area for service and operating equipment.

Soil cement has been used to construct compost pads for wastewater treatment operations. In 1992, the City of San Antonio, TX built 8 acres (3.8 hectares) of 8 in. (200 mm) thick soil cement using crushed limestone as an aggregate. The aggregate and cement were mixed in-place and compacted. The yard was unsurfaced and has provided many years of uninterrupted service in daily operations. Soil cement has allowed loaders and dozers to move and turn compost without contamination of the working surface below. Additionally, positive drainage and containment of runoff are easily achieved with the low-permeability soil cement.

A number of industrial storage facilities have been constructed of unsurfaced soil cement. A 69,000 yd^2 (58,000 m^2) material storage facility for a Phillips Petroleum PVC pipe storage facility was constructed in Hagerstown, MD, in 1999. The 12 in. (300 mm) thick mat consisted of approximately 50% crushed aggregate (the existing surface material) and 50% subgrade soil, blended with 4% cement. Polypropylene fibers were added to the blend as a trial to help control shrinkage cracking and improve durability. Soil cement construction was staged in sections, and was allowed to return to service quickly so it did not significantly impede plant operations.

CHAPTER 4—MATERIALS

4.1—Soil

Nearly all types of soils can be used for soil cement. Some exceptions include organic soils, highly plastic clays, soils with medium to high levels of sulfates, and poorly reacting sandy soils (Robbins and Mueller 1960; Dunlap et al. 1975). Section 6.3 of this report, which focuses on special design considerations, discusses the subject of poorly reacting sandy soils in more detail. Granular soils are preferred for soil cement. They pulverize and mix more easily than fine-grained soils, and result in more economical soil cement because they require the least amount of cement. Typically, soils containing between 5 and 35% fines passing a No. 200 (75 µm) sieve produce the most economical soil cement. Many soils having a higher fines content (material passing No. 200 [75 µm] sieve) and low plasticity, however, have been successfully and economically stabilized in mixed-in-place operations. Nonplastic silty soils with 60 to 70% material passing the No. 200 (75 µm) sieve have been stabilized with as little as 9% cement in mixed-in-place operations, and have given excellent performance. Soils containing more than 2% organic material and a pH of less than 5.5 are usually considered unacceptable for stabilization (Robbins and Mueller 1960). Types of soil typically stabilized include silty sand, processed crushed or uncrushed sand and gravel, and crushed stone.

Aggregate gradation requirements are not as restrictive as conventional concrete. Many times, the soil is pit-run with little processing, except possibly scalping off oversized rock. Normally, the maximum nominal size aggregate is limited to 2 in. (50 mm), with at least 55% passing the No. 4 (4.75 mm) sieve. Some base applications have specified 3 in. (75 mm) maximum size, with 90% passing the 2 in. (50 mm) sieve. For unsurfaced soil cement exposed to erosive forces, such as slope-protection applications, studies by Nussbaum and Colley (1971) showed improved performance to resist erosion where the soil contains at least 20% coarse aggregate (granular material retained on a No. 4 [4.75 mm] sieve). Figure 2.1 shows the specified gradation recommended by PCA to minimize cement contents.

Fine-grained soils generally require more cement for satisfactory hardening and, in the case of clays, are usually more difficult to pulverize for proper mixing. The presence of fines, however, is not always detrimental. Some nonplastic fines in the soil can be beneficial. In uniformly graded sands or gravels, nonplastic fines including fly ash, cement-kiln dust, and aggregate screenings serve to fill the voids in the soil structure, providing a denser, more stable mixture. The nonplastic fines also help reduce the cement content.

In addition, clay balls (nodules of clay and silt intermixed with granular soil) do not break down during normal mixing. Clay balls have a tendency to form when the plasticity index is greater than 8. For pavements and other applications not directly exposed to the environment, the presence of occasional clay balls may not be detrimental to performance, as long as the clay balls have been prewetted before incorporation of portland cement. For slope protection or other applications where soil cement is exposed to weathering, the clay balls tend to wash out of the soil cement structure, resulting in a “Swiss cheese” appearance, which can weaken the soil cement structure. The USBR requires that clay balls greater than 1 in. (25 mm) be removed, and imposes a 10% limit on clay balls passing the 1 in. (25 mm) sieve (USBR 1986).

4.2—Portland cement

ASTM C150 Type I or II portland cements or ASTM C1157 Type GU or MS portland cements are used for most

Table 4.1—Typical cement requirements for various soil types

AASHTO soil classification	ASTM soil classification	Typical range of cement requirement,* percent by weight	Typical cement content for moisture-density test (ASTM D558), percent by weight	Typical cement contents for durability tests (ASTM D559 and D560), percent by weight
A-1-a	GW, GP, GM, SW, SP, SM	3 to 5	5	3-5-7
A-1-b	GM, GP, SM, SP	5 to 8	6	4-6-8
A-2	GM, GC, SM, SC	5 to 9	7	5-7-9
A-3	SP	7 to 11	9	7-9-11
A-4	CL, ML	7 to 12	10	8-10-12
A-5	ML, MH, CH	8 to 13	10	8-10-12
A-6	CL, CH	9 to 15	12	10-12-14
A-7	MH, CH	10 to 16	13	11-13-15

*Does not include organic or poorly reacting soils. Also, additional cement may be required for severe exposure conditions such as slope protection.

Fig. 4.1—Pulverized asphalt surface and base being mixed in-place in full-depth reclamation process with Class C fly ash.

applications. Cement requirements vary depending on desired properties and type of soils. Cement contents may range from as low as 2% to as high as 16% by dry weight of soil. Generally, as the clayey portion of the soil increases, the quantity of cement required increases. The reader is cautioned that the cement ranges shown in Table 4.1 are not mixture proportioning recommendations. The table provides initial estimates for the mixture proportioning procedures discussed in Chapter 6.

4.3—Slag cement

For use with soils, ground-granulated blast-furnace slag (slag cement) should meet the requirements of ASTM C989, and the allowed Grades 80, 100 and 120 specified. Blended cements containing combinations of slag and portland cement should meet the requirements of ASTM C595 or C1157.

4.4—Fly ash

Fly ash can be used as filler or as a cementitious component in soil cement. Class F fly ashes have been the predominant fly ash used in soil cement (American Coal Ash Association 1993). Class C fly ash has become more accessible in recent years, and has been used successfully in soil cement and recycled flexible pavement base courses (American Coal Ash Association 2008) (Fig 4.1). Fly ash should conform to ASTM C618.

4.5—Lime

For highly plastic clay soils, hydrated lime or quicklime may sometimes be used as a pretreatment to reduce plasticity and make the soil more friable and susceptible to pulverization before mixing with cement.

4.6—Chemical admixtures

Chemical admixtures are rarely used in soil cement. Although research has been conducted in this area, it has been primarily limited to laboratory studies with few field investigations (Ness 1966; Arman and Danten 1969; PCA 1958; Catton and Felt 1943; Wang 1973; Wang et al. 1976).

4.7—Water

Water is necessary in soil cement to help obtain maximum compaction and for hydration of the portland cement. Moisture contents of soil cement are usually in the range of 5 to 13% by weight of oven-dry soil cement.

Potable water or other relatively clean water, free from harmful amounts of alkalis, acids, or organic matter, may be used. Seawater has been used satisfactorily. The presence of chlorides in seawater may increase early strengths.

4.8—Cementitious materials not conforming to specifications

Nonstandard materials have been used in conjunction with portland cement and other cementitious materials in the production of soil cement on occasion. Extreme caution, however, should be used if these materials are contemplated to determine short- and long-term effects. Examples of such materials are cement kiln dust, lime kiln dust, flue gas desulfurization material, and out-of-specification cement, fly ash, and slag. These materials do not conform to any ASTM standard, can vary considerably from source to source, and even can vary from a single source. Testing and quality-control/assurance procedures should be set up to ensure that the nonspecified materials are compatible with the soils and cement used for soil cement. Particular attention should be paid to the level of sulfates in the nonspecified materials, as significant deleterious expansions of soil cement can occur if sulfates are present.

CHAPTER 5—PROPERTIES

5.1—General

The properties of soil cement are influenced by several factors, including: type and proportion of soil; cementitious materials and water content; degree of compaction; uniformity of mixing; curing conditions; and age of the compacted mixture. Because of these factors, a wide range of values for specific properties may exist. This chapter provides information on several properties and how these and other factors affect various properties.

5.2—Density

Density of soil cement is usually measured in terms of dry density, although moist density may be used for field density control. The moisture-density test (ASTM D558 or D1557) is used to determine proper moisture content and density (referred to as optimum moisture content and maximum dry density) to which the soil cement mixture is compacted. For granular soils, particularly in water resources applications, ASTM D1557 is often used to establish the moisture-density relationship. A typical moisture-density curve is shown in Fig. 5.1. Adding cement to a soil generally causes some change in both the optimum moisture content and maximum dry density for a given compactive effort. The direction of this change, however, is not usually predictable. The flocculating action of the cement tends to produce an increase in optimum moisture content and a decrease in maximum density. The addition of portland cement to soil mixtures, with its relatively higher specific gravity, however, will usually cause an increase in dry densities. For a given cement content, the higher the density, the higher the compressive strength of cohesionless soil cement mixtures (Shen and Mitchell 1966).

Prolonged delays between the mixing of soil cement and compaction have an influence on both density and strength. Studies by West (1959) showed that a delay of more than 2 hours between mixing and final compaction results in a significant decrease in both density and compressive strength. This can have a significant effect on the contractor's ability to meet specifications in terms of both strength and in-place densities. Catton and Felt (1943) had similar findings for in-place mixing that showed that the effect of time delay could be minimized by intermittently mixing the soil and cement several times an hour, providing that the moisture content during compaction was at or slightly above optimum.

5.3—Compressive strength

Unconfined compressive strength f_c' is the most widely referenced property of soil cement, and is usually measured in accordance with ASTM D1633. It indicates the degree of reaction of the soil cement-water mixture and the rate of hardening. Compressive strength can be used as a criterion for determining minimum cement requirements for proportioning soil cement. Because strength is related to density, this property is affected in the same manner as density by degree of compaction and water content.

Typical ranges of 7- and 28-day unconfined compressive strengths for soaked, soil cement specimens are given in Table 5.1 (Highway Research Board 1961). Soaking specimens before testing is required in ASTM D1633, Section 5.3, because most soil cement structures may become permanently or intermittently saturated during their service life and exhibit lower strength under saturated conditions. The data in the table are grouped under broad textural soil groups, and include the range of soil types normally used in soil cement construction. The range of values given is representative for a majority of soils normally used in the United States in soil cement construction. Figure 5.2 (Highway Research Board 1961) shows that a linear relationship can be used to approximate the relationship between compressive strength and cement content for cement contents up to 15% and a curing period of 28 days.

Curing time influences strength gain differently depending on the types of soils. As shown in Fig. 5.3 (Federal Highway Administration 1979a), the strength increase is greater for soil cement using granular materials than for soil cement produced with fine-grained clayey or silty soils.

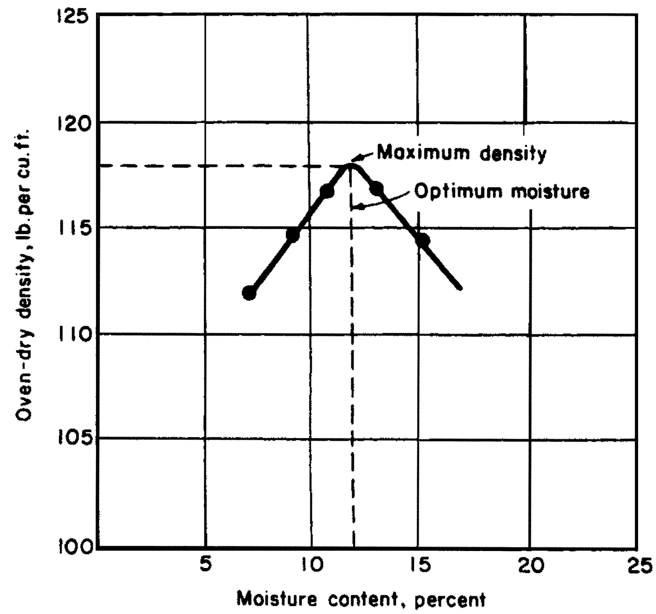

Fig. 5.1—Typical moisture-density curve. (Note: 1 lb/ft^3 = 0.161 Mg/m^3.)

Table 5.1—Ranges of unconfined compressive strengths of soil cement

Soil type	Soaked compressive strength,* psi 7-day	28-day
Sandy and gravelly soils: AASHTO Groups A-1, A-2, A-3 Unified Groups GW, GC, GP, GM, SW, SC, SP, SM	300 to 600	400 to 1000
Silty soils: AASHTO Groups A-4 and A-5 Unified Groups ML and CL	250 to 500	300 to 900
Clayey soils: AASHTO Groups A-6 and A-7 Unified Groups MH and CH	200 to 400	250 to 600

*Specimens moist-cured 7 or 28 days, then soaked in water before strength testing.
Note: 1 psi = 0.0069 MPa.

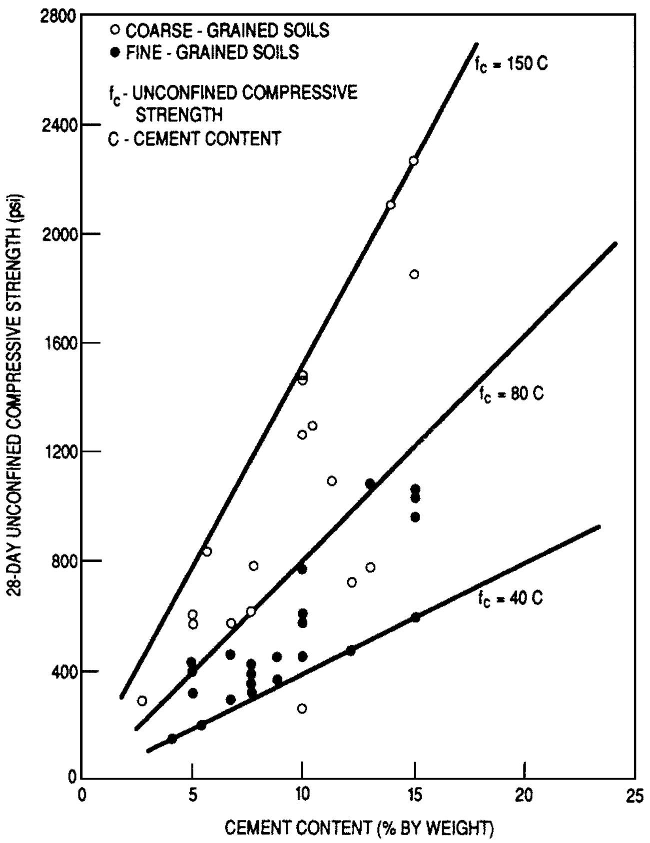

Fig. 5.2—Relationship between cement content and unconfined compressive strength for soil cement mixtures.

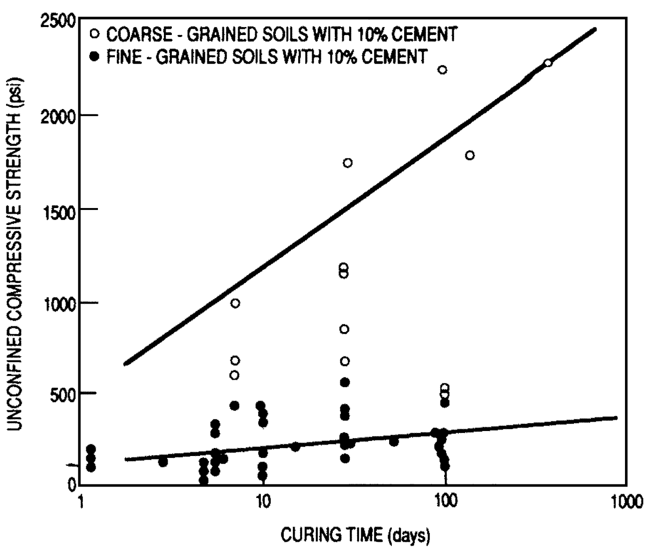

Fig. 5.3—Effect of curing time on unconfined compressive strength of some soil cement mixtures (FHWA 1979a,b).

5.4—Flexural and tensile strength

Flexural-beam tests (ASTM D1635), direct-tension tests, and split-tension tests have all been used to evaluate flexural strength. Flexural strength is approximately 1/5 to 1/3 of the unconfined compressive strength. Data for some soils are shown in Fig. 5.4 (Highway Research Board 1961). The ratio

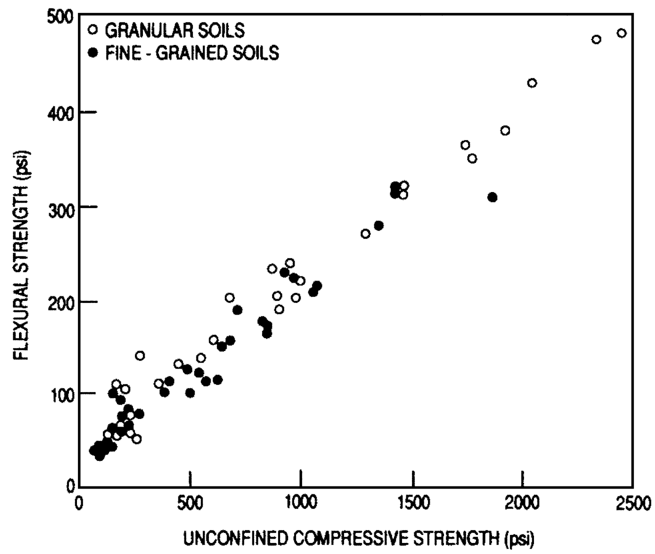

Fig. 5.4—Relationship between unconfined compressive strength and flexural strength of soil cement mixtures (FHWA 1979a,b). (Note: 1 psi = 0.0069 MPa.)

of flexural to compressive strength is higher in low-strength mixtures (up to $1/3f_c'$) than in high-strength mixtures (down to less than $1/5f_c'$). A good approximation for the flexural strength R is

$$R = 0.51(f_c')^{0.88}$$

where

P = flexural strength, psi; and
f_c' = unconfined compressive strength, psi.

Values of flexural and tensile strength deduced from the results of flexure, direct-tension, and split-tension tests may differ due to the effects of stress concentrations and differences between moduli in tension and compression. Research by Radd et al. (1977) has shown that the split-tension test yields values that do not deviate by more than 13% from the direct tensile strength.

5.5—Permeability

Permeability of most soils is reduced by the addition of cement. Table 5.2 (PCA 1986) summarizes results from laboratory permeability tests conducted on a variety of soil types. A large-scale seepage test was performed by the USBR on a section of layered stair-step soil cement facing at Lubbock Regulating Reservoir in Texas (DeGroot 1971). Results indicated a decrease in permeability with time, possibly due to shrinkage cracks in the soil cement filling with sediment and autogenously healing the cracks. Seepage was as much as 10 times greater in the cold winter months than the hot summer months. The reduced summer seepage was probably caused by thermal expansion that narrowed the crack widths and by the presence of algae growth in the cracks.

In multiple-lift construction, higher permeability can generally be expected along the horizontal surfaces of the lifts than perpendicular to the lifts. Research by Nussbaum and Colley (1971) has shown permeabilities for flow parallel

Table 5.2—Permeability of cement-treated soils

ASTM soil classification	Dry density, lb/ft^3	Moisture content, %	Cement content % by weight	*K* coefficient of permeability, ft per year, 10^{-6} cm/s	Gradation analysis, % passing						
					No. 4 (4.75 mm)	No. 10 (2.0 mm)	No. 40 (0.425 mm)	No. 200 (0.075 mm)	0.005 mm	0.0005 mm	Cement* required, % by weight
Standard Ottawa sand	108.2	10.8	0	48,880	100% passing No. 20 (0.85 mm): 0% passing No. 30 (0.6 mm)						—
	112.8	9.4	5.3	6900							
	117.6	9.7	10.5	76							
Graded Ottawa sand	103.2	13.7	0	16,300	100	100	28	2	—	—	—
	104.7	13.6	5.4	470							
	107.4	12.3	10.5	21							
Fine sand (SP)	101.0	12.2	0	750	100	100	91	7	1	—	11.5
	100.9	13.2	3.2	560							
	103.6	12.3	6.5	190							
	105.3	12.0	9.5	21							
Silty sand (SM)	100.8	14.9	0	5000	100	100	96	13	12	2	8.0
	99.9	14.7	3.2	1400							
	104.0	15.1	6.4	60							
Fine sand (SP)	100.1	16.0	0	360	99	99	96	6	6	1	—
	105.8	14.8	6	20							
	109.3	13.5	12.2	1							
Fine sand (SP)	101.0	13.8	0	140	100	100	94	2	—	—	11.0
	106.7	13.3	3.1	33							
	108.2	13.4	6.3	0.3							
	108.8	13.4	9.6	0.02							
Fine sand (SP)	112.5	11.0	0	36	—	97	—	—	11	4	—
	115.8	10.4	5.5	5							
Fine sand (SP)	111.7	12.0	0	23	100	99	—	—	9	3	—
	115.2	11.7	5.5	8							
Silty sand (SM)	121.9	9.3	0	16	98	94	66	20	18	5	—
	125.5	8.0	8.6	0.1							
Silty sand (SM)	117.9	10.8	0	10	99	97	69	16	12	4	—
	123.0	8.1	8.9	2							
Silty sand (SM)	112.5	11.5	0	5	—	98	—	—	12	5	—
	115.0	12.3	5.5	3							
Silty sand (SM)	118.7	11.0	0	5	100	99	88	36	25	7	—
	119.2	10.5	9.1	0.1							
Silty sand (SM)	125.0	—	0	16	100	75	41	13	12	5	5.0
	—	10.1	3.3	0.4							
	—	—	7.3	0.07							

*Cement requirement based on ASTM Standard Freeze-Thaw and Wet-Dry Test for soil mixtures and PCA paving criteria.
Note: 100 lb/ft^3 = 1.6 Mg/m^3.

to the compaction plane were two to 20 times larger than values for flow normal to the compaction plane.

5.6—Shrinkage and cracking

Cement-treated soils undergo shrinkage during drying. The shrinkage and subsequent cracking depend on cement content, soil type, water content, degree of compaction, and curing conditions. Figure 5.5 shows the results of field data on shrinkage cracking from five test locations in Australia (DeGroot 1971). Soil cement made from each soil type produces a different crack pattern. Soil cement made with clays develops higher total shrinkage, but crack widths are smaller and individual cracks more closely spaced (for example, hairline cracks, spaced 2 to 10 ft apart). Soil cement made with granular soils produces less shrinkage, but larger cracks spaced at greater intervals (usually 10 to 20 ft or more apart) (Highway Research Board 1961). George (2002) found that cracking is highly correlated to:

- Volume change (shrinkage) resulting from drying, temperature change, or both;
- Tensile strength of the stabilized material;
- Stiffness and creep of stabilized materials; and
- Subgrade restraint.

Figure 5.6 from George's (2002) study indicates how cracks are related to compressive strength of the soil cement material.

Reflective cracking in asphalt pavements, induced by base cracking in soil cement, may or may not be a performance problem. Many miles of soil cement pavements have performed well even though narrow reflective cracks developed. Kuhlman (1994) and George (2002) both indicate that good construction and quality-control procedures

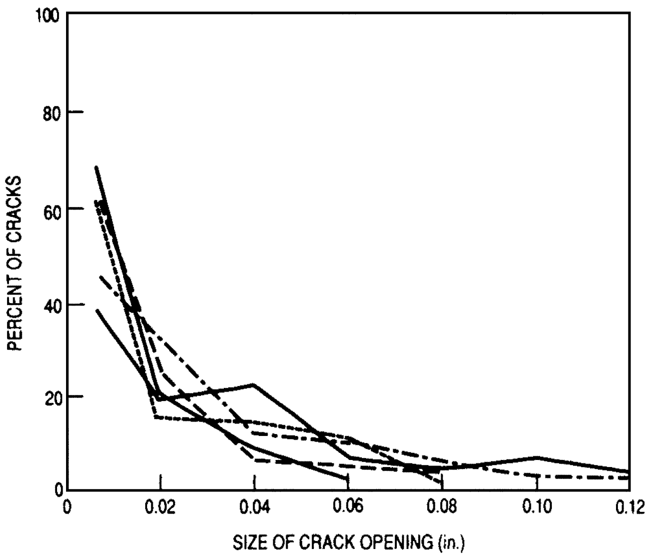

Fig. 5.5—Frequency distribution of various sizes of shrinkage cracks in soil cement (Marchall 1954). (Note: 1 in. = 25.4 mm.)

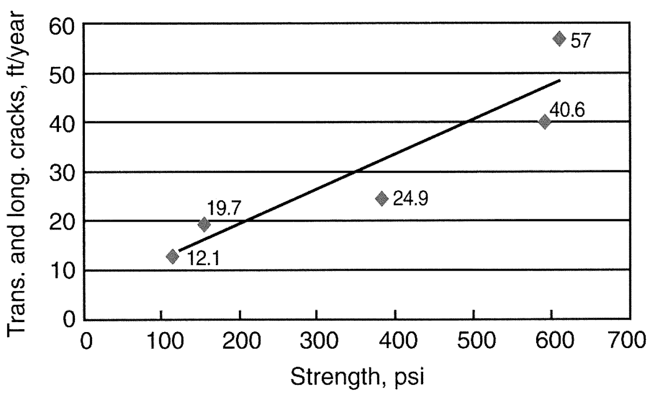

Fig. 5.6—Minimizing cracking in cement-treated materials for improved performance (George 2002). (Note: 1 psi = 0.0069 MPa; 1 ft/year = 0.305 m/year.).

(proper moisture, density, mixing, cement content/distribution, and curing) are essential to minimizing cracking. When a crack remains narrow, load transfer continues across the crack, and little water is admitted through the crack to the pavement and subgrade below. This results in good crack performance. George (2002) proposed that desirable cracking occurs when cracks are closely spaced and narrow. Cracking can be a performance problem, however, when the cracks are larger, therefore admitting moisture—which can degrade base and subgrade—and reducing load transfer. These cracks will cause raveling, pumping/loss of subgrade material, pavement faulting, surface deterioration, and poor ride qualities. Methods of controlling cracking to achieve good performance include proportioning to minimize shrinkage, use of secondary additives, observing quality construction procedures, and controlling the cracking through the bituminous surface. Specific techniques (beyond quality construction procedures previously mentioned) include:

- Compacting at slightly less than optimum moisture content because higher moisture results in greater shrinkage;
- Limiting the fines content in the soil or aggregate;
- Using interlayers to inhibit propagation of cracks from the base layer. The following types of interlayers have been found to be successful:
  - Chip seal between the base and asphalt surface. Chip seals can also serve as the riding surface for some time, with an asphalt surface provided later as traffic and surface quality dictate;
  - 2 to 4 in. (50 to 100 mm) unstabilized aggregate interlayer between the base and surface, sometimes termed “upside down” design; and
  - Geotechnical fabric tack-coated to base;
- Delayed surfacing and prolonged curing (either through water application or placement of a bituminous curing compound) for 14 to 28 days to allow initial cracks to form. Subsequent placement of asphalt tends to bridge these cracks and reduce their reflectivity and size;
- Using a thicker base slab with reduced cement content;
- Prescribing materials/methods that promote numerous microcracks. These methods include:
  - Quick placement of asphalt pavement on the base layer (within 7 days), followed by immediate trafficking. This not only aids in providing a moisture barrier to reduce shrinkage due to moisture loss, the stressing in the young soil cement induces microcracks that promote a desirable crack pattern;
  - Precracking the pavement by systematic application of compaction equipment within 24 to 48 hours after final compaction; and
  - Precracking the pavement by forming a partial-depth, narrow channel into mixed but uncompacted soil cement, and filling this channel with asphalt emulsion to induce a weakened plane (analogous to saw-cutting/sealing in concrete pavements). This technique has been successful in France and Great Britain (Shahid and Thom 1996), where spacing of 9.8 ft (3 m) has eliminated reflective cracking;
- Adding fly ash to reduce overall shrinkage. George’s (2002) study showed that drying shrinkage can be reduced by replacing a portion of cement with fly ash;
- Use of expansive cement; and
- Using specification parameters that help provide a desirable crack pattern. George (2002) proposed the following 7-day strength and shrinkage criteria:
  - Fine grained soils: Unconfined compressive strength of 300 to 350 psi (2070 to 2410 KPa), with a maximum drying shrinkage of 525 microstrain; and
  - Coarse-grained soils: Unconfined compressive strength of 450 psi (3100 KPa) with a maximum drying shrinkage of 300 microstrain.

Again, quality construction is generally the first and most important way to promote a desirable crack pattern; many miles of well-performing soil cement has been placed with nothing more than good construction procedures. One or more of the aforementioned techniques, however, may be helpful, as the local materials and practices indicate.

Table 5.3—Examples of AASHTO layer coefficients for soil cement used by various state DOTs

State	Layer coefficient a	Compressive strength requirement
Alabama	0.23	650 psi minimum
	0.20	400 to 650 psi
	0.15	Less than 400 psi
Arizona	0.28	For cement-treated base with minimum 800 psi (plant mixed)
	0.23	For cement-treated subgrade with 800 psi minimum (mixed in place)
Delaware	0.20	—
Florida	0.15	300 psi (mixed in place)
	0.20	500 psi (plant mixed)
Georgia	0.20	350 psi
Louisiana	0.15	200 psi minimum
	0.18	400 psi minimum
	0.23	Shell and sand with 650 psi
Montana	0.20	400 psi minimum
New Mexico	0.23	650 psi minimum
	0.17	400 to 650 psi
	0.12	Less than 400 psi
Pennsylvania	0.20	650 psi minimum (mixed in place)
	0.30	650 psi minimum (plant mixed)
Wisconsin	0.23	650 psi minimum
	0.20	400 to 650 psi
	0.15	Less than 400 psi

Note: 1 psi = 0.0069 MPa.

5.7—Structural design

The thickness of a soil cement base depends on various factors, including: subgrade strength; pavement design period; traffic and loading conditions, including volume and distribution of axle weights; and thickness of concrete or bituminous wearing surface. The Portland Cement Association (PCA 1975a, 1992b), the American Association of State Highway and Transportation Officials (AASHTO 1993), and the U.S. Army Corps of Engineers (USACE TM5-822-13 1994) have established methods for determining design thickness for soil cement bases. For light-duty aircraft, the PCA has also published a design guide (PCA 1998).

Most in-service soil cement bases are 6 in. (150 mm). This thickness has proved satisfactory for service conditions associated with secondary roads, residential streets, and light-traffic air fields. Some 5 in. (125 mm) thick bases have given good service under favorable conditions of light traffic and strong subgrade support. Many miles of 7 and 8 in. (175 and 200 mm) thick soil cement bases are providing good performance in primary and high-traffic secondary pavements. Soil cement bases more than 9 in. (225 mm) thick are less common; a few airports and heavy industrial pavement projects have been built with multi-layered thicknesses up to 32 in. (0.8 m).

In the AASHTO (1993) method for flexible pavement design, layer coefficient a_i values are assigned to each layer of material in the pavement structure to convert actual layer thicknesses into a structural number *SN*. This layer coefficient expresses the empirical relationship between *SN* and thickness *D*, and is a measure of the relative ability of the material to function as a structural component of the pavement.

The following general equation for structural number reflects relative impact of the layer coefficient and thickness

$$SN = a_1/D_1 + a_2D_2 + a_3D_3$$

where a_1, a_2, and a_3 = layer coefficients of surface, base, and subbase, respectively; and D_1, D_2, and D_3 = corresponding layer thicknesses.

The layer coefficients are actually the average of a set of multiple regression coefficients that indicate the effect of the wearing course, the base course, and the subbase on the pavement's performance. Typical soil cement layer coefficient a_1 values used by state each Department of Transportation (DOTs) is given in Table 5.3.

CHAPTER 6—MIXTURE PROPORTIONING

6.1—General

The principal structural requirements of a hardened soil cement mixture are based on adequate strength and durability. For some applications, such as liners, permeability may be the principal requirement. Laboratory testing should always be performed using the specific materials to be employed in the actual application. Table 4.1 indicates typical cement contents for pavement applications. Detailed test procedures for evaluating mixture proportions are given in the PCA Handbook (1992a) and by the following ASTM test standards: ASTM D558, D559, D560, D1557, D1632, D1633, D2901, and D5982.

6.2—Proportioning criteria

Various criteria are used by different organizations to determine acceptable mixture proportions. The PCA criteria are summarized in Table 6.1 (PCA 1992a). Cement contents sufficient to prevent weight losses greater than the values indicated after 12 cycles of wetting, drying, and brushing or freezing, thawing, and brushing are considered adequate to produce a durable soil cement.

The U.S. Army Corps of Engineers (USACE) follows its technical manual, *Soil Stabilization for Pavements* (USACE 1994b). The durability and strength requirements for portland cement stabilization are given in Tables 6.2 and 6.3, respectively. The USACE requires that both criteria be met before a stabilized layer can be used to reduce the required surface thickness in the design of a pavement system. The USACE frequently increases the cement content by 1 or 2% to account for field variations. For bank protection, the USACE has an unnumbered draft engineer technical letter for interim guidance (USACE 2000).

The USBR design criteria for soil cement slope protection on dams (USBR 1986) allow maximum losses during freezing-and-thawing and wetting-and-drying durability tests of 8 and 6%, respectively. These criteria were developed specifically for soil cement slope protection using primarily silty sands. In addition, USBR requires a minimum compressive strength of 600 psi (4140 kPa) at 7 days, and 875 psi (6040 kPa) at 28 days. To allow for variations in the field, it is USBR's practice to add two percentage points to the minimum cement content that meets all of the preceding design criteria.

Table 6.1—PCA criteria for soil cement as indicated by wetting-and-drying and freezing-and-thawing durability tests (PCA 1971)

AASHTO soil group	Unified soil group	Maximum allowable weight loss, %
A-1-a	GW, GP, GM, SW, SP, SM	14
A-1-b	GM, GP, SM, SP	14
A-2	GM, GC, SM, SC	14*
A-3	SP	14
A-4	CL, ML	10
A-5	ML, MH, CH	10
A-6	CL, CH	7
A-7	OH, MH, CH	7

*Ten percent is maximum allowable weight loss for A-2-6 and A-2-7 soils.
Additional criteria:
1. Maximum volume changes during durability test should be less than 2% of initial volume.
2. Maximum water content during test should be less than quantity required to saturate sample at time of molding.
3. Compressive strength should increase with age of specimen.
4. Cement content determined as adequate for pavement, using the aforementioned PCA criteria, will be adequate for soil cement slope protection that is 5 ft (1.5 m) or more below the minimum water elevation. For soil cement that is higher than that elevation, cement content should be increased two percentage points.

Table 6.2—USACE durability requirements (USACE 1994a)

Type of soil stabilized	Maximum allowable weight loss after 12 wetting-and-drying or freezing-and-thawing cycles, % of initial specimen weight
Granular, *PI* < 10	11
Granular, *PI* > 10	8
Silt	8
Clays	6

Table 6.3—USACE minimum unconfined compressive strength criteria (USACE 1994a)

Stabilized soil layer	Minimum unconfined compressive strength at 7 days, psi	
	Flexible pavement	Rigid pavement
Base course	750	500
Subbase course, select material or subgrade	250	200

In Arizona, Maricopa and Pima Counties use a considerable amount of soil cement for stream bank slope protection. Both counties require the soil cement to have a minimum 7-day compressive strength of 750 psi (5.2 MPa). The cement content for the project as determined in laboratory tests is sometimes increased 2% for additional erosion resistance and to compensate for field variation. This additional cement increases the 7-day compressive strength to approximately 1000 psi (6.9 MPa). Field control tests for plant-mixed soil cement often include making a set of four molded samples twice daily during production. Three of the samples are tested in compression at an age of 7 days for verification of specified strength. The fourth sample is tested after 1 day as a quick indicator of the quality of the production mixing. The 1-day compressive strength results are usually approximately 50 to 60% of the 7-day design strength. This test provides a good indication of the product without having to wait an additional 6 days to determine if corrections to the mixture should be made.

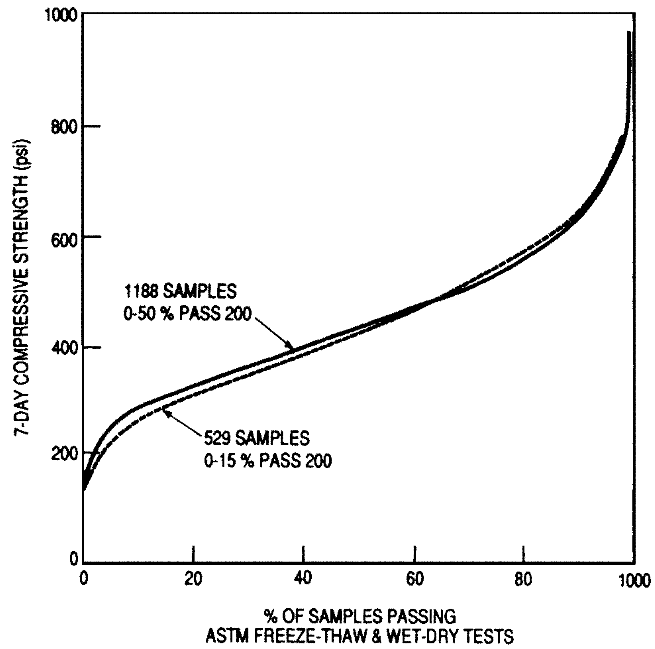

Fig. 6.1—Relationships between compressive strength and durability of soil cement based on PCA durability criteria (PCA 1971). (Note: 1 psi = 0.0069 MPa.)

PCA (1992a) describes a shortcut test procedure that can be used to determine the cement content for sandy soils. The procedure uses charts developed from previous tests on similar soils. The only tests required are a sieve analysis, a moisture-density test, and a compressive strength test. Relatively small samples are needed. All tests can be completed in 1 day, except the 7-day compressive strength test. The Handbook also describes a rapid test procedure—also referred to as the pick and click test—for use in small jobs or emergency situations where conventional testing is impractical. This test can be accomplished in 1 to 3 days with equipment available on most construction sites.

6.3—Special considerations

6.3.1 *Strength versus durability*—In many soil cement applications, both strength and durability requirements need to be met to achieve satisfactory service life. ASTM D559 and D560 are standard test methods that are conducted to determine, for a particular soil, the amount of cement needed to hold the mass together permanently and to maintain stability under the shrinkage and expansive forces that occur in the field. It is common practice, however, to use compressive strength to determine the minimum cement content. Figure 6.1 illustrates the general relationship between compressive strength and durability for soil cement. It is apparent from these curves that a compressive strength of 800 psi (5.5 MPa) would be adequate for all soils, but this strength would be higher than needed for most soils and would result in a conservative design and more costly project. The determination of a suitable design compressive strength is simplified when materials within a narrow range of gradations, soil types, or both, are used. As a result, some agencies have determined and successfully used, for a particular type of material, a compressive strength requirement generally based on results of the wetting-and-drying and freezing-and-thawing tests. A minimum compressive strength is set by specification, and the laboratory determines the minimum cement content necessary to achieve that strength under a specific compaction criterion. Compressive strength requirements vary depending on an agency's experience and soil conditions. Several compressive strength criteria for state DOTs are shown in Table 6.3.

6.3.2 *Compressive strength specimen size*—Compressive strength tests are frequently conducted on test specimens obtained from molds commonly available in soil laboratories and used for other soil cement tests. These test specimens are 4.0 in. (100 mm) in diameter and 4.58 in. (116 mm) in height, with a height-diameter (h/d) ratio of 1.15. This differs from conventional concrete molds, which use an h/d of 2. The h/d of 2 provides a more accurate measure of compressive strength from a technical viewpoint, because it reduces complex stress conditions that may occur during crushing of lower h/d specimens. In soil cement testing, however, the lower h/d (1.15) specimens are frequently used. Most of the compressive strength values given in this report are based on $h/d = 1.15$. Using the correction factor for concrete given in ASTM C42, an approximate correction can be made for specimens with h/d of 2 by multiplying the compressive strength value by a factor of 1.10.

6.3.3 *Poorly reacting sandy soils*—Occasionally, certain types of sandy soils are encountered that cannot be treated successfully with normal amounts of portland cement. Early research by Robbins and Mueller (1960) showed that acidic organic material often had a very adverse effect on strength development in soil cement mixtures. The study showed that organic content and pH do not in themselves constitute an indication of poorly reacting sand. A sandy soil with an organic content greater than 2% or having a pH lower than 5.3, in all probability, will not react normally with cement. These soils require special studies before use in soil cement.

6.3.4 *Sulfate resistance*—As with conventional concrete, sulfates will generally attack soil cement. The attack usually takes the form of deleterious expansion of the material through the formation of ettringite or other expansive sulfoaluminate minerals. Studies by Cordon (1962), Sherwood (1962), and Huntington et al. (1995) have indicated that the resistance to sulfate attack differs for cement-treated coarse-grained and fine-grained soils and is a function of the clay and sulfate concentrations. Studies showed that sulfate-clay reactions are more detrimental than sulfate-cement reactions, resulting in deterioration of fine-grained soil cement more rapidly than coarse-grained soil cement. Also, increasing the cement content of soil cement mixtures may be more beneficial than changing to a sulfate-resistant type of cement.

All calcium-based stabilizers, such as cement, lime, Class C fly ash, and slag cement, have the potential to experience deleterious expansions when exposed to sulfates, particularly when clay minerals are present. Much of the research has centered on lime stabilization, because most of the instances of sulfate attack on stabilized soils have occurred on projects where lime has been used. Some guidelines have been developed for lime, which should be conservative when used with cement. Sulfate levels less than 3000 parts per million (ppm) pose very low risk; 3000 to 5000 ppm pose low to moderate risk; 5000 to 8000 ppm pose moderate to high risk; and levels greater than 8000 ppm pose very high risk. These concentrations should be based on a 1:10 soil/water ratio when determining sulfate concentrations (other ratios will yield different concentrations with the same soil). Generally, any soil cement expected to be exposed to more than 3000 ppm sulfates should be tested for swell potential (TxDOT 2005).

CHAPTER 7—CONSTRUCTION

7.1—General

In the construction of soil cement, the objective is to obtain a thoroughly mixed and adequately compacted and cured material. Several references are available (Hansen 1986; American Coal Ash Association 1993, 2008; PCA 1992c, 1998; Federal Highway Administration 1979a, 2003; Cement and Concrete Promotion Council of Texas 1995) that discuss soil cement construction methods for various applications. Specifications on soil cement construction are also available (PCA 2001a, 1975b, 1976; Federal Aviation Agency 2008).

Soil cement should not be mixed or placed when the soil or subgrade is frozen or when the air temperature is below 45 °F (7 °C). A common practice, however, is to proceed with construction when the air temperature is at least 40 °F (4 °C) and rising. When the air temperature is expected to reach the freezing point, the soil cement should be protected from freezing for at least 7 days. A light rainfall should not delay construction. A heavy rainfall that occurs after most of the water has been added, however, can be detrimental. If rain falls during cement-spreading operations, spreading should be stopped, and the cement already spread should be quickly mixed into the soil mass. Compaction should begin immediately and continue until the soil cement is completely compacted. After the mixture has been compacted, rain will usually not harm it.

7.2—Materials handling and mixing

Soil cement is either mixed in-place using a transverse single-shaft mixer or in a central mixing plant using a rotary drum mixer or a continuous flow or batch-type pug mill.

7.2.1 *Mixed in-place*—Mixing operations with subgrade materials are performed with transverse single-shaft-type mixers (Fig. 7.1 and 7.2). Mixing with borrow materials may also be performed with single-shaft mixers. Almost all types of soil, from granular to fine-grained, can be adequately pulverized and mixed with transverse single-shaft mixers; however, some soils may require multiple passes of the mixer to achieve adequate pulverization.

7.2.1.1 *Soil preparation*—During grading operations, all soft or wet subgrade areas are located and corrected. All deleterious material such as stumps, roots, organic soils, and aggregates larger than 3 in. (75 mm) should be removed. For single-shaft mixers, the soil is shaped to the approximate final lines and grades before mixing. Proper moisture content aids in pulverization. For granular soils, mixing at less than

Fig. 7.1—Transverse single-shaft mixer processing soil cement in place; multiple passes are required.

Fig. 7.2—Mixing chamber of transverse single-shaft mixer.

Fig. 7.3—Calibrated spreader truck placing cement on pre-pulverized material.

Fig. 7.4—Mechanical cement spreader attached to bulk cement transport truck.

optimum moisture content minimizes the chances for cement balls to form. For fine-grained soils, moisture content near optimum may be necessary for effective pulverization.

7.2.1.2 *Cement application*—Cement is generally distributed in bulk using a mechanical spreader (Fig. 7.3 and 7.4) or, for small projects, by hand-placing individual cement bags. Where dusting is a concern, cement can be applied as a slurry (Fig 7.5). The primary objective of the cement-spreading operation is to achieve uniform distribution of the cement in the proper proportions.

To obtain a uniform cement spread, the mechanical spreader should be operated at uniform speed with a relatively constant level of cement in the hopper. The spreader should have adequate traction to produce a uniform cement spread. Traction can be aided by wetting and rolling the soil before spreading the cement. When operating in loose sands or gravel, slippage can be overcome by using cleats on the spreader wheels. The mechanical cement-spreader can also be attached directly behind a bulk-cement truck. Cement is moved pneumatically from the truck through an air-separator cyclone that dissipates the air pressure; it then falls into the hopper of the spreader. Although pipe cement-spreaders attached to cement-transport trucks have been used in some areas with mixed results, mechanical spreaders are generally preferred. For slurry application, cement and water are thoroughly mixed in a slurry pump that thoroughly combines the water and cement (Fig 7.6). Many projects have been placed with a 50/50 blend (by weight) of water and cement. The slurry is then piped into a liquid tanker truck equipped with internal agitation devices or recirculation pumps to keep the cement in suspension. Slurry is discharged through the spreader bar of the tanker (Fig 7.5). The amount of cement required, whether dry or slurry, is specified as a percentage by weight of oven-dry soil, or in pounds of cement per cubic foot of compacted soil cement. Table 7.1 can be used to determine quantities of cement per square yard of soil cement placement.

7.2.1.3 *Pulverization and mixing*—Single-shaft mixers are typically used to pulverize and mix cement with subgrade soils. Agricultural-type equipment is not recommended due to relatively poor mixing uniformity. Pulverization and mixing difficulties increase with higher fines content and plasticity of the soils being treated. In-place mixing efficiency, as measured by the strength of the treated soil, may be less than

Fig. 7.5—Slurry application of 50/50 blend of cement and water.

Fig. 7.6—Cement-water slurry being mixed and pumped into a water truck.

that obtained in the laboratory. This reduced efficiency is sometimes compensated for by increasing the cement content by one or two percentage points from that determined in the laboratory testing program. The more powerful single-shaft mixers available today often overcome the limitations of less powerful mixers, and are able to pulverize even higher plasticity soils adequately.

7.2.2 *Central plant mixing*—Central mixing plants are normally used for projects involving borrow materials. Granular borrow materials are generally used because of their low cement requirements and ease in handling and mixing. Clayey soils or materials containing clay lenses should be avoided because they are difficult to pulverize. There are two basic types of central plant mixers: pug mill mixers (either continuous-flow or batch) and rotary-drum mixers. Although batch pug mills and rotary-drum mixers have been used satisfactorily, the most common central plant mixing method is the continuous-flow pug mill mixer. Production rates with this type of mixer vary between 200 and 800 tons/hour (180 and 725 Mg/hour).

7.2.2.1 *Borrow material*—Natural soil deposits are frequently located near the construction site. Uniformity of the soil material throughout the borrow site should be monitored for purposes of quality control for cement requirements, optimum moisture, and density.

Table 7.1—Cement spread requirement (PCA 1980)

Cement content, lb/ft^3 (kg/m^3) of compacted soil cement	Cement spread, lb/yd^2/in. (kg/m^2/cm) of thickness of compacted soil cement
4.5 (72)	3.38 (0.72)
5.0 (80)	3.75 (0.80)
5.5 (88)	4.13 (0.88)
6.0 (96)	4.50 (0.96)
6.5 (104)	4.88 (1.04)
7.0 (112)	5.25 (1.12)
7.5 (120)	5.63 (1.20)
8.0 (128)	6.0 (1.28)
8.5 (136)	6.38 (1.36)
9.0 (144)	6.75 (1.44)
9.5 (152)	7.13 (1.52)
10.0 (160)	7.5 (1.60)
10.5 (168)	7.88 (1.68)
11.0 (176)	8.25 (1.76)
11.5 (184)	8.63 (1.84)
12.0 (192)	9.0 (1.92)
12.5 (200)	9.38 (2.00)
13.0 (208)	9.75 (2.08)
13.5 (216)	10.13 (2.16)
14.0 (224)	10.50 (2.24)
14.5 (232)	10.88 (2.32)
15.0 (240)	11.25 (2.40)
15.5 (248)	11.63 (2.48)
16.0 (256)	12.0 (2.56)

The USBR recommends the following procedure for handling borrow material. If the material in the borrow area varies with depth, full-face cuts should be made with the excavation machinery. This selective excavation ensures that some material from each layer is obtained in each cut. If the material varies laterally across the borrow area, or differs from one spot to another, loads from different locations in the borrow area should be mixed. After the material has been excavated, soil can be further blended at the stockpile. Alternating the loads from different parts of the borrow area helps to blend soil gradations in the stockpile. Mixing for uniformity of gradation and moisture can also be done as the material is pushed into the stockpile. For example, if excavated material is dumped at the base of the stockpile, it can be pushed up the stockpile with a bulldozer. A front-end loader can then be used to load the soil feed. This tends to mix a vertical cut of the stockpile, which causes further mixing of any layers that might exist in the pile.

As the borrow material is excavated, it should be checked for unsuitable material such as clay lenses, cobbles, or cemented conglomerates. Such materials do not adequately break down in a pug mill mixer. Removal of some oversize clay balls and other large particles can be done by screening through 1 to 1-1/2-in. (25 to 37.5 mm) mesh (Fig. 7.7). In some cases, selective excavation may be necessary to avoid excessive clay lenses.

7.2.2.2 *Mixing*—The objective is to produce a thorough and intimate mixture of the soil, cement, and water in the correct proportions. A diagram of a continuous-flow pug mill plant is shown in Fig. 7.8. A typical plant consists of at least one soil bin, a cement silo with surge hopper, a conveyor belt to deliver the soil and cement to the mixing chambers, a mixing chamber, a water-storage tank for adding water during mixing, and a holding or gob hopper to temporarily store the mixed soil cement before loading (Fig. 7.9).

A pug mill mixing chamber consists of two parallel shafts equipped with paddles along each shaft (Fig. 7.10). The twin shafts rotate in opposite directions, and the soil cement is moved through the mixer by the pitch of the paddles.

Material feed, belt speed, pug mill tilt, and paddle pitch are adjusted to optimize the amount of mixing in the pug mill. Thorough blending in the mixer is very important. The length of mixing time is used to control this factor. Some specifications dictate the minimum blending time. Usually 15 to 30 seconds is specified, depending on the efficiency of the mixer.

7.2.2.3 *Transporting*—To reduce evaporation losses during hot, windy conditions and to protect against sudden showers, rear and bottom dump trucks are often equipped with protective covers. No more than 60 minutes should elapse between the start of moist mixing and the start of compaction. Haul time is usually limited to 30 minutes.

Fig. 7.7—Vibrating screen removing oversized material from soil portion of mixture.

For multiple-layer stair-step construction, as used for slope protection, earthen ramps are constructed at intervals along the slope to enable trucks to reach the layer to be placed. These are constructed at a 45-degree horizontal angle to the slope, normally 2 ft (600 mm) thick and spaced approximately 300 to 400 ft (90 to 120 m) apart.

At large-volume projects, such as the South Texas Nuclear Power Plant, a conveyor system can be used to deliver the soil cement to the spreader. This removes the necessity for ramp construction and truck maneuvering, and provides a cleaner end-product. Narrower layers can also be placed using the conveyor system, because the width needed to facilitate the haul trucks is eliminated. The soil cement can be delivered either from above or below directly to a spreader box.

7.2.2.4 *Placing and spreading*—The mixed soil cement should be placed on a firm subgrade, without segregation, and in a quantity that will produce a compacted layer of uniform thickness and density conforming to the design grade and cross section. The subgrade and all adjacent surfaces should be moistened before placing soil cement.

There is a wide variety of spreading devices and methods. Using a motor grader or spreader box attached to a dozer are the most commonly used means (Fig. 7.11). Spreading may also be done with asphalt-type pavers (Fig. 7.12). Some pavers are equipped with one or more tamping bars that provide initial compaction. Soil cement is usually placed in a layer 10 to 30% thicker than the final compacted thickness. For example, an 8 to 9 in. (200 to 225 mm) loosely placed layer will produce a compacted thickness of approximately 6 in. 150 mm). This relationship varies slightly with the type of soil, method of placement, and degree of compaction. The actual thickness of the loosely spread layer is determined from contractor experience or trial-and-error methods. Compacting, finishing, and curing follow the same procedures as for mixed-in-place construction.

7.2.2.5 *Bonding successive layers*—Bonding successive layers of soil cement is an important requirement for appli-

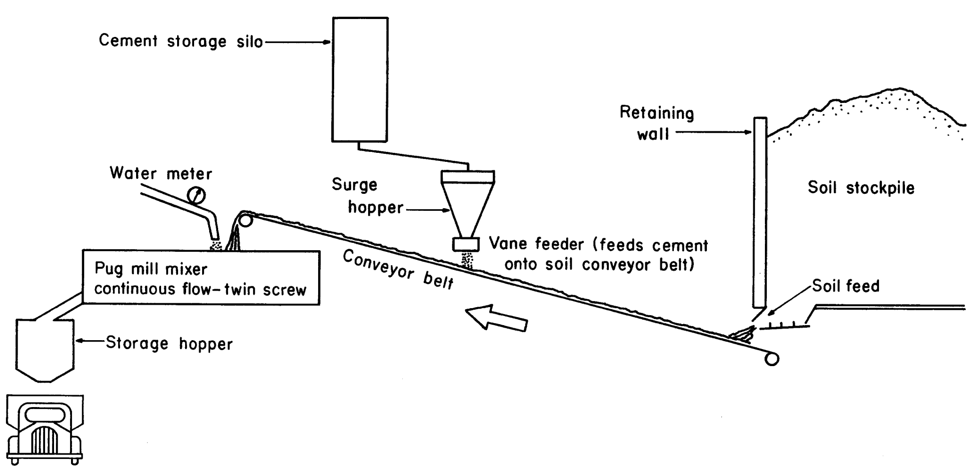

Fig. 7.8—Diagram of continuous-flow central plan for mixing soil cement.

Fig. 7.9—Typical continuous-flow central mixing plant.

Fig. 7.10—Mixing paddles of a twin-shaft, continuous-flow central mixing plant.

cations such as slope protection. It is essential that each completed surface remain clean and moist, but not wet, until it is covered with the next layer. Mud and debris tracked onto a surface will significantly reduce bonding. Other methods that have been effective in improving bond between layers include the following:

1. Minimizing time between placement of successive layers;

2. Using either dry cement or cement slurry. The dry cement should be applied at approximately 1 lb/yd^2 (0.54 kg/m^2) to a moistened surface immediately before placement. The cement slurry mixture should have a water-cement ratio (*w/c*) of about 0.70 to 0.80;

3. Brushing or blowing the surface with air to remove contaminants after the soil cement has set; and

4. Using chemical retarding agents.

7.3—Compaction

Compaction begins as soon as possible, and is generally completed within 2 hours of initial mixing. The detrimental effects of delayed compaction on density and strength have already been described in Section 5.2. No section is left unworked for longer than 30 minutes during compaction operations. The principles governing compaction of soil cement are the same as those for compacting the same soil

Fig. 7.11—Pug-milled soil cement placed with a Jersey spreader.

Fig. 7.12—Pug-milled soil cement placed with a high-density asphalt paver.

without cement treatment. For maximum density, the soil cement mixture should be compacted at or near optimum moisture content as determined by ASTM D558 or D1557. Most specifications require soil cement to be uniformly compacted to a minimum of between 95 and 100% of maximum density. Moisture loss by evaporation during compaction, indicated by a graying of the surface, should be replaced with light applications of water.

Various types of rollers have been used for soil cement. Tamping or sheepsfoot rollers are used for initial compaction of fine-grained soils (Fig. 7.13). The sheepsfoot roller is often followed by a multiple-wheel, rubber-tired roller for finishing (Fig. 7.14). For granular soils, vibratory steel-wheeled (Fig. 7.15) or heavy rubber-tired rollers are generally used. To obtain adequate compaction, it is sometimes necessary to operate the rollers with ballast to produce greater contact pressure. The general rule is to use the greatest contact pressure that will not exceed the bearing capacity of the soil cement mixture. Compacted layer thicknesses generally range from 6 to 9 in. (150 to 225 mm). Greater thicknesses, particularly for granular soils, can be compacted with heavy equipment designed for thicker lifts. Regardless of the lift thickness and compaction equipment

Fig. 7.13—Sheepsfoot rollers are typically used on fine-grained soil cement.

Fig. 7.14—Rubber-tired roller provides smooth-surfaced soil cement.

Fig. 7.15—Steel-drum vibratory roller is typically used on granular soil cement.

used, the fundamental requirement is that the compacted layer achieves the specified minimum density throughout the lift.

7.4—Finishing

As compaction nears completion, the surface of the soil cement is shaped to the design line, grade, and cross section.

Fig. 7.16—Scarification of final soil cement surface to eliminate compaction planes.

Frequently, the surface may require lift scarification to remove imprints left by equipment or potential surface compaction planes. Surface compaction planes are smooth areas left near the surface by the wheels of equipment or by motor grader blades. A thin surface layer of compacted soil cement may not adhere properly to these areas, and in time may fracture, loosen, and spall. For good bond, the base layer should be rough and damp.

The scarification can be done with a weeder, nail drag, spring tooth, or spike tooth harrow (Fig. 7.16). For soils containing an appreciable quantity of gravel, scarification may not be necessary. Following scarification, final surface compaction is performed using a nonvibrating steel-wheeled roller or a rubber-tired roller. Electronic, automatic fine graders may be used on soil cement bases for pavements when very tight tolerances are required. For stair-stepped embankment applications, several methods have been used to finish the exposed edges of each lift, including cutting back the uncompacted edges and using special attachments on compaction equipment (Fig. 7.17).

7.5—Joints

When work stoppages occur for intervals longer than the specified time limits for fresh soil cement, transverse joints are trimmed to form straight vertical joints (Fig. 7.18). This is normally done using the toe of a motor grader or dozer. Joints made in this way will be strong and easy to clean before resuming placement. When the freshly mixed soil cement is ready for placement against the construction joint, a check is made to assure that no dry or unmixed material is present on the joint edge. Retrimming and brooming may be necessary. Freshly mixed soil cement is then compacted against the construction joint. The fresh soil cement is left slightly high until final rolling, when it is trimmed to grade with the motor grader and rerolled. Joint construction requires special attention to ensure that joints are vertical and that material in the joint area is adequately mixed and thoroughly compacted. For multiple-layer constructions

Fig. 7.17—Compacting outer edge with rounded steel flange welded to steel-wheel roller.

Fig. 7.18—Properly prepared construction joint is cut vertically.

Fig. 7.19—Water curing keeps soil cement surface moist.

Fig. 7.20—Bituminous curing compound seals moisture in soil cement.

such as stair-stepped embankments, joints are usually staggered to prevent long continuous joints through the structure.

7.6—Curing and protection

Proper curing of soil cement is important because strength gain is dependent upon time, temperature, and the presence of water. Generally, a 3- to 7-day curing period is required, during which time equipment heavier than rubber-tired rollers is prohibited. Light local traffic, however, is often allowed on the completed soil cement immediately after construction provided that the curing coat is not damaged.

Water-sprinkling and bituminous coating are two popular methods of curing. Sprinkling the surface with water (Fig. 7.19) until a bituminous cure coat or until the 3- to 7-day curing period is complete has proven successful. In bituminous curing, the soil cement is commonly sealed with emulsified asphalt (Fig. 7.20). The rate of application is dependent on the particular emulsion, but typically varies from 0.15 to 0.30 gal./yd^2 (0.68 to 1.36 L/m^2) Some agencies use a 50/50 diluted emulsion spread at a rate of 0.08 to 0.12 gal./yd^2 (0.36 to 0.54 L/m^2). Rapid- or medium-set emulsions are less prone to pick-up than slow sets if traffic is applied before surfacing. Before the bituminous material is applied, the surface of the soil cement should be moist and free of dry, loose material. In most cases, a light application of water precedes the bituminous coating. If traffic is allowed on the soil cement during the curing period, it is desirable to apply sand over the bituminous coating to minimize tracking of the bituminous material. Bituminous material should not be applied to any surfaces where bonding of subsequent soil cement layers is required. Additionally, bituminous curing should not be applied on soil cement linings for ponds or reservoirs that will be used to hold aquatic life. Concrete curing compounds can be used to cure soil cement, and should be applied at a rate of 1-1/2 times normal application rates for concrete. It should be placed on a tightly-compacted surface.

Curing can also be accomplished by covering the compacted soil cement with wet burlap, plastic tarps, or moist earth.

Soil cement should be protected from freezing during the curing period. Insulation blankets, straw, or soil cover are commonly used.

CHAPTER 8—QUALITY-CONTROL TESTING AND INSPECTION

8.1—General

Quality control is essential to assure that the final product will be adequate for its intended use. Additionally, it should assure that the contractor has performed work in accordance with the plans and specifications. Field inspection of soil cement construction involves controlling the following factors:

1. Pulverization/gradation;
2. Cement content;
3. Moisture content;
4. Mixing uniformity;
5. Compaction;
6. Lift thickness and surface tolerance; and
7. Curing.

The Portland Cement Association and the USBR provide excellent information on quality-control inspection and testing of soil cement during construction (USBR 1988; DeGroot 1976; PCA 1987, 2001b).

8.2—Pulverization (mixed in place)

Most soils require minimum pulverization before processing starts. The heavier clay soils, however, require a considerable amount of preliminary work. The keys to pulverization of clayey soils are proper moisture control and proper equipment. Because clayey soils cannot be adequately pulverized in a central plant, their use is restricted to mixed-in-place construction. Most granular soils and aggregates and some recycled asphalt pavements treated with cement may not require prepulverization if it can be demonstrated that the pulverization equipment and techniques used achieve the necessary pulverization.

PCA specifications (1975b, 2001a) require that, at the completion of moist mixing, 80% of the soil cement mixture pass the No. 4 (4.75 mm) sieve and 100% pass the 1 in. (25.0 mm) sieve, exclusive of gravel or stone retained on these sieves. This is checked by doing a pulverization test, which consists of screening a representative sample of soil cement through a No. 4 (4.75 mm) sieve. Any gravel or stone retained on the sieve is picked out and discarded. The clay lumps retained and the pulverized soil passing the No. 4 (4.75 mm) sieve are weighed separately, and their dry weights determined. The degree of pulverization is calculated as follows (PCA 2001b)

$$\text{percent pulverization} = \frac{\begin{array}{c}\text{dry weight of soil cement mixture}\\ \text{passing No. 4 (4.75 mm) sieve}\end{array}}{\begin{array}{c}\text{dry weight of total sample}\\ \text{exclusive of gravel retained}\\ \text{on No. 4 (4.75 mm) sieve}\end{array}} \times 100$$

Note that for practical purposes, wet weights of materials are often used instead of the corrected dry weights. The wet-weight measurements are reasonably accurate, and permit immediate adjustments in pulverization and mixing procedures if necessary.

Pulverization can be improved by:

- Slower forward speed of the mixing machine;
- Additional passes of the mixing machine;
- Replacing worn mixer teeth; and
- Prewetting and premixing the soil before processing begins.

Soil that contains excessive moisture will not mix readily with cement. The percentage of moisture in the soil at the time of cement application should be at or near optimum moisture content. Excess moisture may be reduced by additional pulverization and air drying, or in extreme cases, by the addition of lime or fly ash.

8.3—Cement content control

8.3.1 *Mixed in place*—Cement is normally placed using bulk cement spreaders. A check on the accuracy of the cement spread is necessary to ensure that the proper quantity is actually being applied. When bulk cement is being used, the check is made in two ways:

- *Spot check*—A sheet of canvas, usually 1 yd^2 (1 m^2) in area, is placed ahead of the cement spreader. After the spreader has passed the canvas, the cement is carefully picked up and weighed (Fig. 8.1). The spreader is then adjusted if necessary, and the procedure is repeated until the correct spread per yd^2 (m^2) is obtained. For slurry application, a metal pan can be placed to capture the liquid then weighed. The cement content can be determined by knowing the *w/c* of the slurry.
- *Overall check*—The distance or area is measured over which a truckload of cement of known weight is spread. This actual area is then compared with the theoretical area, which the known quantity of cement should have covered.

Generally, the spreader is first adjusted at the start of construction after checking the cement spread per yd^2 (m^2) with the canvas. Slight adjustments are then made after checking the distance over which each truckload is spread. It is important to keep a continuous check on cement-spreading operations.

On small jobs, bagged cement is sometimes used. The bags should be spaced at approximately equal transverse and longitudinal intervals that will ensure the proper percentage of cement. Positions can be spotted by flags or markers fastened to ropes at proper intervals to mark the transverse and longitudinal rows.

8.3.2 *Central mixing plant*—In a central mixing-plant operation, it is necessary to proportion the cement and soil before they enter the mixing chamber. When soil cement is mixed in a batch-type pug mill or rotary-drum mixing plant, the proper quantities of soil, cement, and water for each batch are weighed before being transferred to the mixer. These types of plants are calibrated simply by checking the accuracy of the weight scales.

For a continuous-flow mixing plant, two methods of plant calibration may be used.

- With the plant operating, soil is run through the plant for a given period of time and collected in a truck. During this same period, cement is diverted directly from the cement feeder into a truck or suitable container. Both the soil and cement are weighed, and

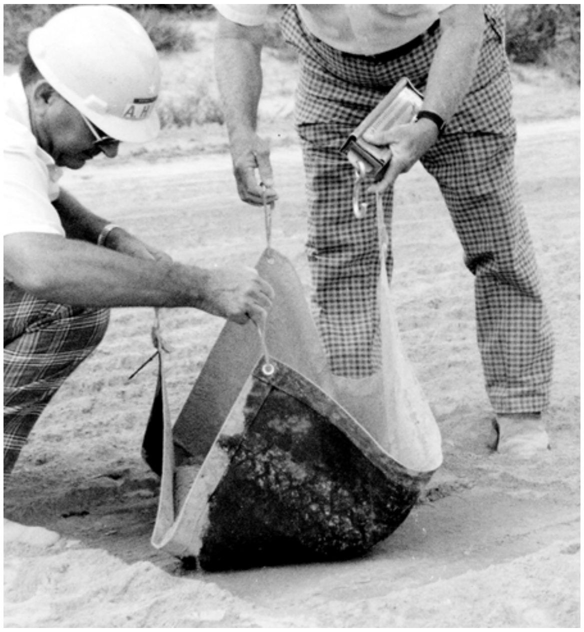

Fig. 8.1—Weighing cement collected on 1 yd^2 (0.8 m^2) of canvas to check on quantity of cement spread.

the cement feeder is adjusted until the correct amount of cement is discharged; and

- The plant is operated with only soil feeding onto the main conveyor belt. The soil on a selected length of conveyor belt is collected and its dry weight is determined. The plant is then operated with only cement feeding onto the main conveyor belt. The cement feeder is adjusted until the correct amount of cement is being discharged.

It may be necessary to calibrate the mixing plant at various operating speeds. Typically, plants are calibrated daily at the beginning of a project, and periodically thereafter, to assure that no change has occurred in the operation.

8.3.3 *Determining cement content of freshly mixed soil cement*—ASTM D5982 may be used to determine the cement content of freshly mixed soil cement. The test, which can be conducted in the field, provides results in approximately 15 minutes. It is reliable to within 1% of the actual cement.

8.4—Moisture content

Proper moisture content is necessary for adequate compaction and for hydration of the cement. The proper moisture content of the cement-treated soil is determined by the moisture-density test (ASTM D558 or D1557). This moisture content, known as optimum moisture, is used as a guide for field control during construction. The approximate percentage of water added to the soil is equal to the difference between the optimum moisture content and the moisture content of the soil. Additional moisture may be added to account for hydration of the dry cement and for evaporation that normally occurs during processing.

An estimate of the moisture content of a soil cement mixture can be made by observation and feel. A mixture near or at optimum moisture content is just moist enough to dampen the hands when it is squeezed in a tight cast.

Fig. 8.2—Soil cement at optimum moisture casts readily when squeezed in the hand and can be broken into two pieces without crumbling.

Mixtures above optimum will leave excess water on the hands, while mixtures below optimum will tend to crumble easily. If the mixture is near optimum moisture content, the cast can be broken into two pieces with little or no crumbling (Fig. 8.2). Checks of actual moisture content can be made daily using conventional or microwave-oven drying.

During compaction and finishing, the surface of the soil cement mixture may become dry, as evidenced by graying of the surface. When this occurs, very light fog spray applications of water are made to bring the moisture content back to optimum. Proper moisture content of the compacted soil cement is evidenced by a smooth, moist, tightly knit, compacted surface free of cracks and surface dusting.

8.5—Mixing uniformity

8.5.1 *Mixed in place*—A thorough mixture of pulverized soil, cement, and water is necessary to make high-quality soil cement. Where heavy clay soils are being treated, pulverization tests should be conducted before compaction as described in Section 8.2. The uniformity of all soil cement mixtures is checked by digging trenches or a series of holes at regular intervals for the full depth of treatment and then inspecting the color of the exposed material. When the mixture is of uniform color and texture from top to bottom, the mixture is satisfactory. A mixture that has a streaked appearance has not been mixed sufficiently.

8.5.2 *Central mixing plant*—For central-plant-mixed soil cement, the uniformity is usually checked visually at the mixing plant. It can also be checked at the placement area in a manner similar to the method used for mixed-in-place construction. The mixing time necessary to achieve an intimate uniform mixture will depend on the soil gradation and mixing plant used. Usually 20 to 30 seconds of mixing are required.

8.6—Compaction

The soil cement mixture is compacted at or near optimum moisture content to some specified minimum percent of maximum density. Generally, the density requirements range from 95 to 100% of the maximum density of the cement-treated soil as determined by the moisture-density

Fig. 8.3—Checking soil cement density with a nuclear gauge.

test (ASTM D558 or D1557). The most common methods for determining in-place density are:

- Nuclear method (ASTM D2922 and D3017) (Fig. 8.3);
- Sand-cone method (ASTM D1556); and
- Balloon method (ASTM D2167).

In-place densities are determined daily at frequencies that vary widely, depending on the application. The tests are made immediately after rolling. Comparing in-place densities with the results of maximum density results from the field moisture-density test indicates any adjustments in compaction procedures that may be required to ensure compliance with job specifications.

8.7—Lift thickness and surface tolerance

8.7.1 *Lift thickness*—Compacted lift thickness is usually checked when performing field-density checks with the sand-cone or the balloon method, or by digging small holes in the fresh soil cement to determine the bottom of treatment if the nuclear density method is used. Depth can be determined using a 2% solution of phenolphthalein. The phenolphthalein solution can be squirted down the side of a freshly cut face of newly compacted soil cement. The soil cement will turn pinkish-red, while the untreated soil and subgrade material (unless it is calcium-rich soil) will retain its natural color. Thickness can also be checked by coring the hardened soil cement. This provides a small-diameter core for measuring thickness and for strength testing if required. Lift thickness is usually more critical for pavements than for embankment applications. For pavements, the USACE typically tests thickness with a 3 in. (75 mm) diameter core for every 500 yd^2 (420 m^2) of soil cement. Other agencies, such as Caltrans, require that thickness measurements be taken at intervals not to exceed 1000 ft (300 m).

8.7.2 *Surface tolerance*—Surface tolerances are usually specified for soil cement pavement applications. The USBR controls only the soil cement embankment crest road elevation to within 1/8 in. (3 mm) of design grade. To provide a reasonably smooth surface for pavement sections, smoothness is usually measured with a 10 or 12 ft (3 or 3.7 m) straightedge, or with surveying equipment. The USACE typically requires that deviations from the plane of a soil cement base course not exceed 3/8 in. (9 mm) in 12 ft (3.7 m) using a straightedge placed perpendicular to the centerline at about 50 ft (15 m) intervals. Most state DOTs limit the maximum departure from a 12 or 10 ft (3.7 or 3 m) straightedge to about 3/8 in. (9 mm). In addition, a departure from design grade of up to 5/8 in. (9 mm) is usually allowed.

CHAPTER 9—REFERENCES

9.1—Referenced standards and reports

The standards referred to in this document are listed below with their serial designation. The standards listed were the latest editions at the time this document was prepared. Because some of these standards are revised frequently, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest edition.

American Concrete Institute

207.5R Roller-Compacted Mass Concrete

325.10R Report on Roller-Compacted Concrete Pavements

ASTM International

C42 Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

C150 Specification for Portland Cement

C595 Specification for Blended Hydraulic Cements

C618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

C989 Specification for Slag Cement for Use in Concrete and Mortars

C1157 Performance Specification for Hydraulic Cement

D558 Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures

D559 Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures

D560 Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures

D1556 Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method

D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))

D1632 Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory

D1633 Test Methods for Compressive Strength of Molded Soil-Cement Cylinders

D1635 Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading

D2167 Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method

D2901 Test Method for Cement Content of Freshly Mixed Soil-Cement (withdrawn)

D2922 Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)

D3017 Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth) (withdrawn, replaced by D6953)

D5982 Test Method for Determining Cement Content of Fresh Soil-Cement (Heat of Neutralization Method)

These publications may be obtained from these organizations:

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
www.concrete.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

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Report on Soil Cement