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State-of-the-Art Report on Soil Cement

reported by ACI Committee 230

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Soil cement is a densely compacted mixture of portland cement, soil/aggregate, and water. Used primarily as a base material for pavements, soil cement is also being used for slope protection, low-permeability liners, foundation stabilization, and other applications This report contains information on applications, material properties, mix 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 emphasis on current practice regarding design, testing, and construction

Keywords: aggregates, base courses, central mixing plant, compacting; construction; fine aggregates, foundations, linings, mixing, mix proportioning, moisture content, pavements, portland cements, properties, slope protection, soil cement, soils, soil stabilization, soil tests, stabilization, tests; vibration

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1-INTRODUCTION

1.1-Scope

This state-of-the-art report contains information on applications, materials, properties, mix proportioning, design, construction, and quality-control inspection and

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testing procedures for soil cement. The intent of this report is to provide basic information on soil-cement technology with emphasis on current practice regarding mix proportioning, properties, testing, and construction.

This report does not provide information on fluid or plastic soil cement, which has a mortarlike consistency at time of mixing and placing Information on this type of material is provided by ACI Committee 229 on Controlled Low-Strength Material (CLSM). Roller-compacted concrete (RCC), which is a type of no-slump concrete compacted by vibratory roller, is not covered in this report. ACI Committee 207 on Mass Concrete has a report available on roller-compacted concrete.

1.2-Definitions

Soil cement-ACI 116R 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 admixtures including pozzolans, 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.

Cement content-Cement content is normally expressed in percentage on a weight or volume basis. The cement content by weight is based on the oven-dry weight of soil according to the formula

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

The required cement content by weight can be converted to the equivalent cement content by bulk volume, based on a 94-lb U.S bag of cement, which has a loose volume of approximately 1 ft^3. using the following formula'

$$C_v = \frac{D - \left[\dfrac{D}{1 + C_w/100}\right]}{94} \times 100$$

where

C_v = cement content, percent by bulk volume of compacted soil cement
D = oven-dry density of soil-cement in lb/ft^3
C_w = cement content, percent by weight of oven-dry soil

The criteria used to determine adequate cement factors for soil-cement construction were developed as a percentage of cement by volume in terms of a 94-lb U.S. bag of cement. The cement content by volume in terms of other bag weights, such as an 80-lb Canadian bag, can be determined by substituting 80 for 94 in the denominator of the preceding formula.

2-APPLICATIONS

2.1 -General

The primary use of soil cement is as a base material underlaying bituminous and concrete pavements. Other uses include slope protection for dams and embankments; liners for channels, reservoirs, and lagoons; and mass soil-cement placements for dikes and foundation stabilization.

2.2-Pavements

Since 1915, when a street in Sarasota, Fla. 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 100,000 miles of equivalent 24 ft wide pavement using soil cement have been constructed to date. Soil cement is used mainly as a base for road, street, and airport paving. When used with a flexible pavement, a hot-mix bituminous wearing surface is normally placed on the soil-cement base. Under concrete pavements, soil cement is used as a base to prevent pumping of fine-grained subgrade soils under wet conditions and heavy truck traffic. Furthermore, a soil-cement base provides a uniform, strong support for the pavement, which will not consolidate under traffic and will provide increased load transfer at pavement joints. It also serves as a firm, stable working platform for construction equipment during concrete placement.

Failed flexible pavements have been recycled with cement, resulting in a new soil-cement base (Fig. 2.1). Recycling increases the strength of the base without removing the old existing base and subbase materials and replacing them with large quantities of expensive new 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, on the other hand, the bituminous surface retains most of its original flexibility, it is normally removed rather than incorporated into the mixture.

The thickness of a soil-cement base depends on various factors, including: (1) subgrade strength, (2) pavement design period, (3) traffic and loading conditions, including volume and distribution of axle weights, and (4) thicknesss of concrete or bituminous wearing surface. The Portland Cement Association (PCA),[2,3] the American Association of State Highway and Transportation Officials (AASHTO),[4] and the U.S. Army Corps of Engineers (USACE),[5,6] have established methods for determining design thickness for soil-cement bases. Most in-service soil-cement bases are 6 in. thick. This thickness has proved satisfactory for service conditions associated with secondary roads, residential streets, and light-traffic air fields. A few 4 and 5 in. thick bases have given good service under favorable conditions of light traffic and strong subgrade support. Many miles of 7 and 8 in. thick soil-cement bases are providing good performance in primary and high-traffic secondary pavements. Although soil-cement bases more than

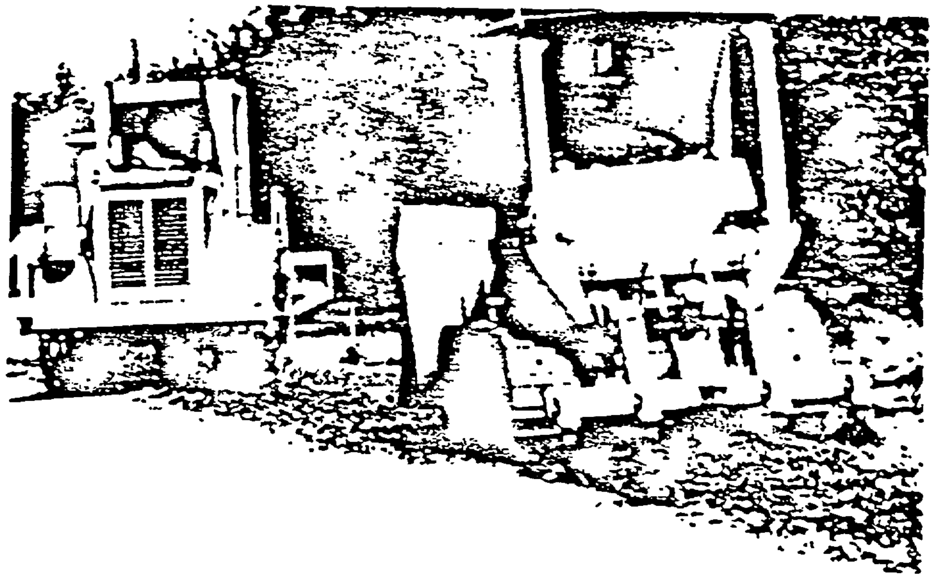

Fig 2.1-Old bituminous mat being scarified and pulverized for incorporation in soil-cement mix

9 in thick are not common. a few airports and heavy industrial pavement project[3] have been built with multilayered thicknesses up to 32 in

Since 1975, soil-cement base courses incorporating local soils with portland cement and fly ash have been constructed in 17 states[7] Specification guidelines and a contractor's guide for constructing such base courses are available from the Electric Power Research Institute.[8]

2.3-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 U.S Rock riprap of satisfactory quality for upstream slope protection was not locally available for many of these projects High costs for transporting riprap from distant quarries to these sites threatened the economic feasibility of some projects 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 in 1951. A test-section location along the southeast shore of Bonny Reservoir in eastern Colorado was selected because of severe natural service conditions created by waves, ice, and more than 100 freeze-thaw 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, Nebraska, and later at Cheney Dam, Kansas. Soil cement was bid at less than 50 percent 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 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.[9] The original test section at Bonny Reservoir has required very little maintenance and still exists today, almost 40 years later (Fig 2.2).

Since 1961, more than 300 major soil-cement slope protection projects have been built in the U.S. and Canada In addition to upstream facing of dams, soil cement has provided slope protection for channels, spillways, coastal shorelines, highway and railroad embankments, and embankments for inland reservoirs.

For slopes exposed to moderate to severe wave action (effective fetch greater than 1000 ft) or debris-carrying, rapid-flowing water, the soil cement is usually placed in successive horizontal layers 6 to 9 ft wide by 6 to 9 in thick, adjacent to the slope. This is referred to as "stairstep slope protection" (Fig 2.3). For less severe applications, like those associated with small reservoirs, ditches, and lagoons, the slope protection may consist of a 6 to 9 in thick layer of soil cement placed parallel to the slope face. This method is often referred to as "plating" (Fig 2.4)

The largest soil-cement project worldwide involved 1.2 million yd^3 of soil-cement slope protection for a

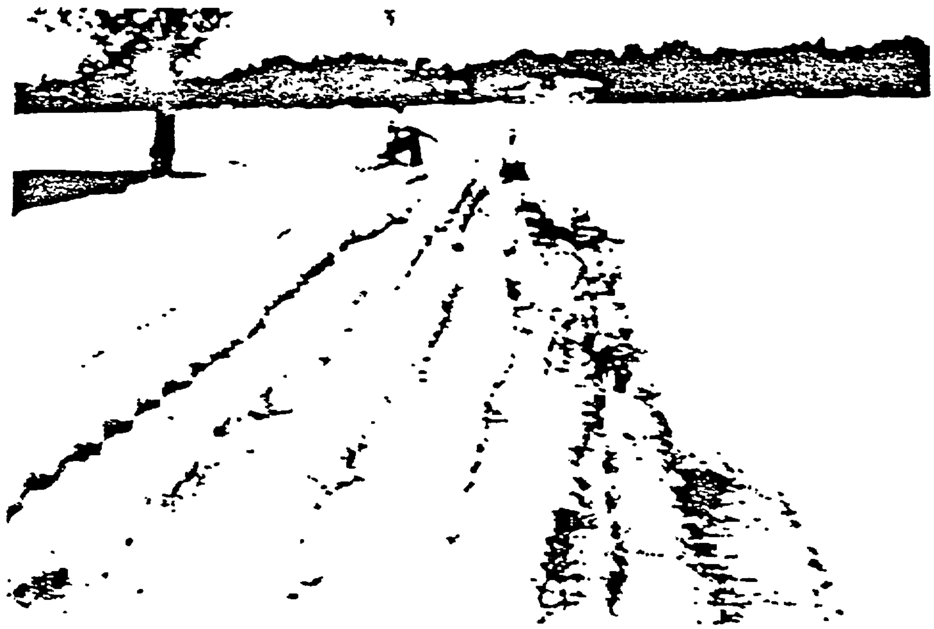

Fig. 2.2-Soil-cement test section at Bonny Reservoir, Colo., after 34 years

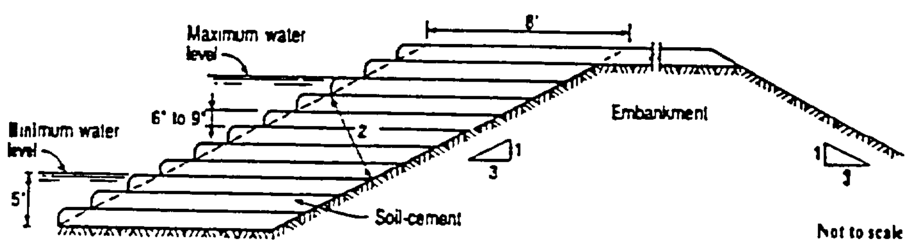

Fig 2.3-Soil-cement slope protection showing layered design

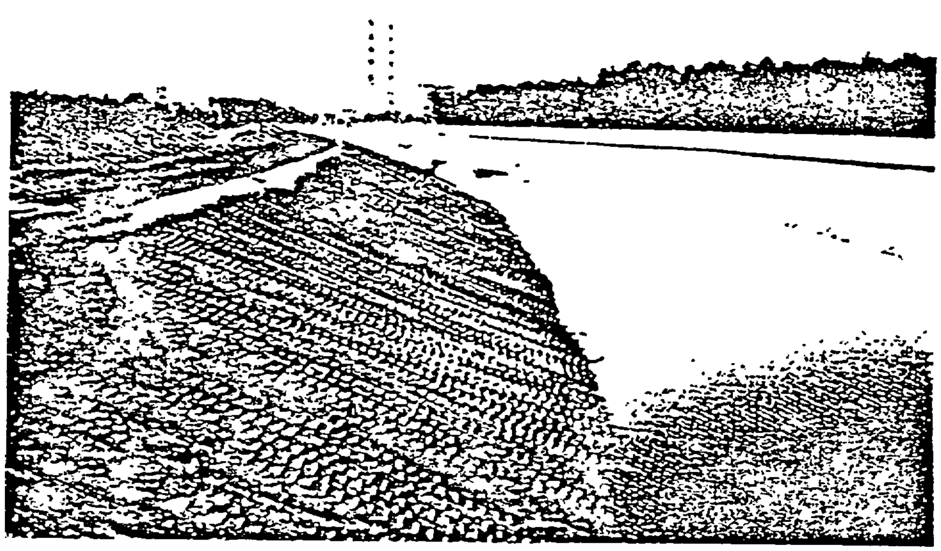

Fig 2.4-Soil-cement slope plating for cooling water flume at Florida power plant

7000-acre cooling-water reservoir at the South Texas Nuclear Power Plant near Houston. Completed in 1979, the 39 to 52 ft high embankment was designed to contain a 15 ft high wave action that would be created by hurricane winds of up to 155 mph. In addition to the 13 miles of exterior embankment, nearly 7 miles of interior dikes, averaging 27 ft in height, guide the recirculating cooling water in the reservoir. To appreciate the size of this project, if each 6.75 ft wide by 9 in. thick lift were placed end-to-end rather than in stairstep fashion up the embankment, the total distance covered would be over 1200 miles.

Soil cement has been successfully used as slope protection for channels and streambanks exposed to lateral flows. In Tucson, Arizona, for example, occasional flooding can cause erosion along the normally dry river beds. From 1983 to 1988, over 50 soil-cement slope protection projects were constructed in this area. A typical section consists of 7 to 9 ft wide horizontal layers placed in stairstep fashion along 2:1 (horizontal to vertical) embankment slopes. To prevent scouring and subsequent undermining of the soil cement, the first layer or two is often placed up to 8 ft below the existing dry river bottom, and the ends extend approximately 50 ft into the embankment. The exposed slope facing is generally trimmed smooth during construction for appearance. To withstand the abrasive force of stormwater flows of 25,000 to 45,000 ft^3/sec at velocities up to 20 ft/sec, the soil cement is designed for a minimum 7-day compressive strength of 750 psi. In addition, the cement content is increased by two percentage points to allow for field variations.[10]

More detailed design information on soil-cement slope protection can be found in References 11 through 13.

2.4-Liners

Soil cement has served as a low-permeability lining material for over 30 years During the mid-1950s, a number of 1 to 2 acre farm reservoirs in southern California were lined with 4 to 6 in. thick soil cement. One of the largest soil-cement-lined projects 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 reservoir bottom has a 6 in. thick soil-cement lining, and the sand embankments forming the reservoir are faced with 2 ft 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.[14] 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, it became less permeable 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 2½ 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 prior to final design decision.

Mix proportions for liner applications have been tested in which fly ash replaces soil in the soil-cement mixture. The fly ash-cement mixture contains 3 to 6 percent portland cement and 2 to 3 percent lime. Permeabilities significantly less than 1×10^{-7} cm/sec have been measured for such fly ash-lime-cement mixtures, along with unconfined compressive strengths before and after vacuum saturation, which indicate good freeze-thaw durability.[15] A similar evaluation has been made for liners incorporating fly ash, cement, and bentonite.[16]

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, N.Y. (Fig. 2.5). The section consisted of a 30 and 40 mil high-density polyethylene (HDPE) membrane placed between two 6-in. layers of soil cement. 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 ¾-in. aggregate scattered beneath the membrane.[17]

2.5-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 thick layer of medium-dense, liquifiable 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 percent cement content by dry weight, cohesion increased significantly, and it was possible to obtain a material with enough strength to prevent liquefaction.[18]

Soil cement was used in lieu of a pile or caisson foundation for a 38-story office building completed in 1980 in Tampa, Fla. 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

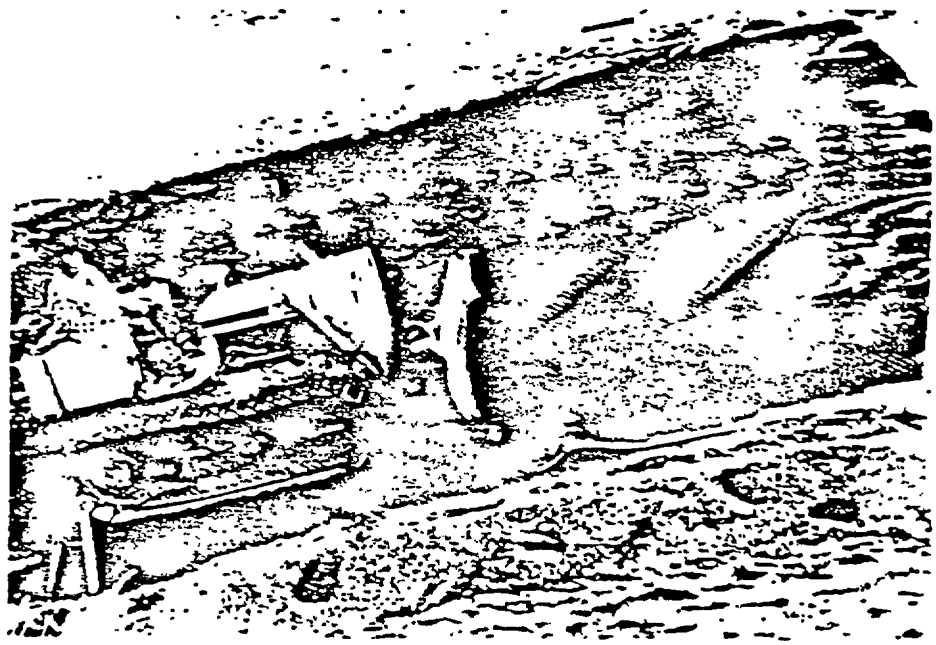

Fig 2 5-Spreading soil cement on membrane at 3:1 slope, Apalachin, N.Y.

limestone. The cavities within the limestone were filled with lean concrete to provide a uniform surface prior to soil-cement placement. The excavated fine sand was then mixed with cement and returned to the excavation in compacted layers. The 12 ft thick soil cement mat saved $400,000 as compared to 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.[19]

At the Cochiti Dam site in north-central New Mexico, a 35 ft deep pocket of low-strength clayey shale under a portion of the outlet works conduit was replaced with 57,650 yd^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, 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 wide spillway foundation mat at Richland Creek Dam near Ft Worth, Tex. About 10 ft of overburden above a solid rock strata was removed and replaced with 117,500 yd^3 of soil cement To satisfy the 28-day 1000 psi compressive strength criteria, 10 percent cement content was used. The substitution of soil cement for mass concrete saved approximately $7.9 million

2.6-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 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. 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 comparably equipped frame houses. A typical rammed-earth soil mix consists of 70 percent sand and 30 percent noncohesive fine-grained soil. Cement contents vary from 4 to 15 percent by weight with the average around 7 percent.[20]

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 utilize 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.

Recently, the Texas State Department of Highways and Public Transportation has specified on several projects that the fill behind retained earth-wall systems be cement-stabilized sand This was done primarily as a precautionary measure to prevent erosion from behind the wall and/or under the adjacent roadway.

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 slope protection, acts as an impervious core, and can be built

on relatively steep slopes due to its inherent shear strength properties. A monolithic soil-cement embankment was used to form the 1 100-acre cooling water reservoir for Barney M. Davis Power Plant near Corpus Christi, Tex. The reservoir consisted of 6.5 miles of circumferential embankment and 2.1 miles 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 utilizing the increased shear strength properties of the compacted cement-stabilized beach sand, the 8 to 22 ft high embankment was constructed at a relatively steep slope of 1.5H:1V.

Coal-handling and storage facilities have used soil cement in a variety of applications. The Sarpy Creek coal mine, near Hardin, Mont., utilized 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 must 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 long and 20 ft deep. The 15,500 yd^3 of soil cement were constructed in horizontal layers 22 ft wide at the bottom to 7 ft wide at the top. During construction, the outer soil-cement edges were trimmed to a finished side slope of 50 deg. 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 long by 36 ft high and has steep 55 deg side slopes. It was constructed entirely of soil cement with the interior zone of the berm containing 3 percent cement To minimize erosion to the exposed soil cement, the 3.3 ft thick exterior zone was stabilized with 6 percent cement

At the Louisa Power Plant near Muscatine, Iowa, only the exterior face of the coal-retaining berm was stabilized with soil cement. The 4 ft thick soil cement and interior uncemented sand fill were constructed together in 9 in. 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-deg angle against the edge during individual lift construction.

Several coal-pile storage yards have been constructed of soil cement. Ninety-five acres of coal storage yard were stabilized with 12 in of soil cement at the Independence Steam Electric Station near Newark, Ark., in 1983. The soil consisted of a processed, crushed limestone aggregate. The 12 in. thick layer was placed in two 6 in. 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 almost 100 percent coal recovery, a defined perimeter for its coal pile, reduced fire hazard, and all-weather access to the area for service and operating equipment.

3-MATERIALS

3.1-Soil

Almost all types of soils can be used for soil cement. Some exceptions include organic soils, highly plastic clays, and poorly reacting sandy soils. Tests including ASTM D 4318 are available to identify these problem materials.[21,22] Section 5.3 of this report, which focuses on special design considerations, discusses the subject of poorly reacting sandy soils in more detail. Granular soils are preferred. 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 percent fines passing a No. 200 sieve produce the most economical soil cement. However, some soils having higher fines content (material passing No 200 sieve) and low-plasticity have been successfully and economically stabilized. Soils containing more than 2 percent organic material are usually considered unacceptable for stabilization. Types of soil typically used include silty sand, processed crushed or uncrushed sand and gravel, and crushed stone.

Aggregate gradation requirements are not as restrictive as conventional concrete. Normally the maximum nominal size aggregate is limited to 2 in. with at least 55 percent passing the No. 4 sieve. For unsurfaced soil cement exposed to moderate erosive forces, such as slope-protection applications, studies by Nussbaum[23] have shown improved performance where the soil contains at least 20 percent coarse aggregate (granular material retained on a No. 4 sieve).

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. 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. 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 U.S. Bureau of Reclamation requires that clay balls greater than 1 in. be removed, and imposes a 10 percent limit on clay balls passing the 1-in. sieve.[11] The presence of fines is not always detrimental, however. 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 and help reduce the cement content.

3.2-Cement

For most applications, Type I or Type II portland cement conforming to ASTM C 150 is normally used.

Table 3.1 — 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 D 558), percent by weight	Typical cement contents for durability tests (ASTM D 559 and D 506), percent by weight
A-1-a	GW, GP, GM, SW, SP, SM	3-5	5	3-5-7
A-1-b	GM, GP, SM, SP	5-8	6	4-6-8
A-2	GM, GC, SM, SC	5-9	7	5-7-9
A-3	SP	7-11	9	7-9-11
A-4	CL, ML	7-12	10	8-10-12
A-5	ML, MH, CH	8-13	10	8-10-12
A-6	CL, CH	9-15	12	10-12-14
A-7	MH, CH	10-16	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-protect&

Cement requirements vary depending on desired properties and type of soils. Cement contents may range from as low as 4 to a high of 16 percent 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 3.1 are not mix-design recommendations The table provides initial estimates for the mix-proportioning procedures discussed in Chapter 5.

3.3-Admixtures

Pozzolans such as fly ash have been used where the advantages outweigh the disadvantages of storing and handling an extra material. Where pozzolans are used as a cementitious material, they should comply with ASTM C 618. The quantity of cement and pozzolan required should be determined through a laboratory testing program using the specific cement type, pozzolan, and soil to be used in the application

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 prior to mixing with cement. 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 investigation [24-29]

3.4-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 10 to 13 percent by weight of oven-dry soil cement.

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

4-PROPERTIES

4.1-General

The properties of soil cement are influenced by several factors, including (a) type and proportion of soil, cementitious materials, and water content, (b) compaction, (c) uniformity of mixing, (d) curing conditions, and (e) 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.

4.2-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 D 558) 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 A typical moisture-density curve is shown in Fig 4 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 However, the direction of this change 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, while the high specific gravity of the cement relative to the soil tends to produce a higher density. In general, Shen[30] showed that for a given cement content, the higher the density, the higher the compressive strength of cohesionless soil-cement mixtures.

Prolonged delays between the mixing of soil cement and compaction have an influence on both density and strength Studies by West[31] showed that a delay of more than 2 hr between mixing and compaction results in a significant decrease in both density and compressive strength. Felt[32] had similar findings but also showed that the effect of time delay was minimized, provided the mixture was intermittently mixed several times an hour, and the moisture content at the time 'of compaction was at or slightly above optimum.

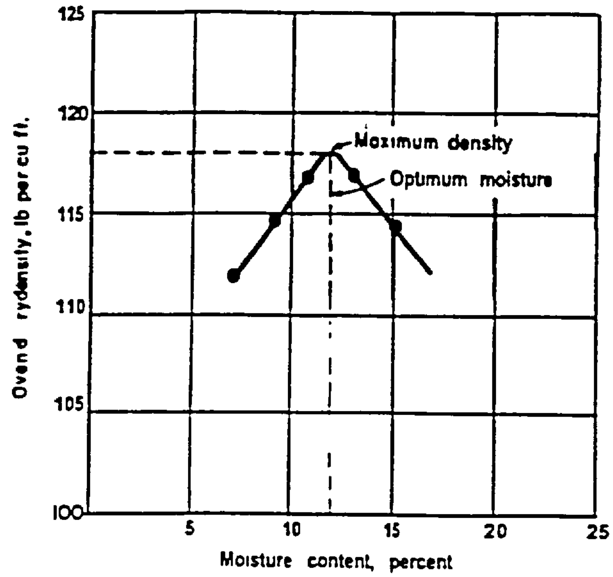

Fig 4 1- Typical moisture-density curve

Table 4.1 — Ranges of unconfined compressive strengths of soil-cement[33]

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	300-600	400-1000
Silty soils: AASHTO groups A-4 and A-5; Unified groups ML and CL	250-500	300-900
Clayey soils: AASHTO groups A-6 and A-7; Unified groups MH and CH	200-400	250-600

*Specimens moist-cured 7 or 28 days then soaked in water prior to strength testing

4.3-Compressive strength

Unconfined compressive strength f_c' is the most widely referenced property of soil cement and is usually measured according to ASTM D 1633. It indicates the degree of reaction of the soil-cement-water mixture and the rate of hardening. Compressive strength serves as a criterion for determining minimum cement requirements for proportioning soil cement. Because strength is directly 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 4.1. Soaking specimens prior to testing is recommended since most soil-cement structures may become permanently or intermittently saturated during their service life and exhibit lower strength under saturated conditions. These data 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 are representative for a majority of soils normally used in the United States in soil-cement construction Fig. 4.2 shows that a linear relationship can be used to approximate the relationship between compressive strength and cement content, for cement contents up to 15 percent and a curing period of 28 days.

Curing time influences strength gain differently depending on the type of soil. As shown in Fig. 4.3, the strength increase is greater for granular soil cement than for fine-grained soil cement.

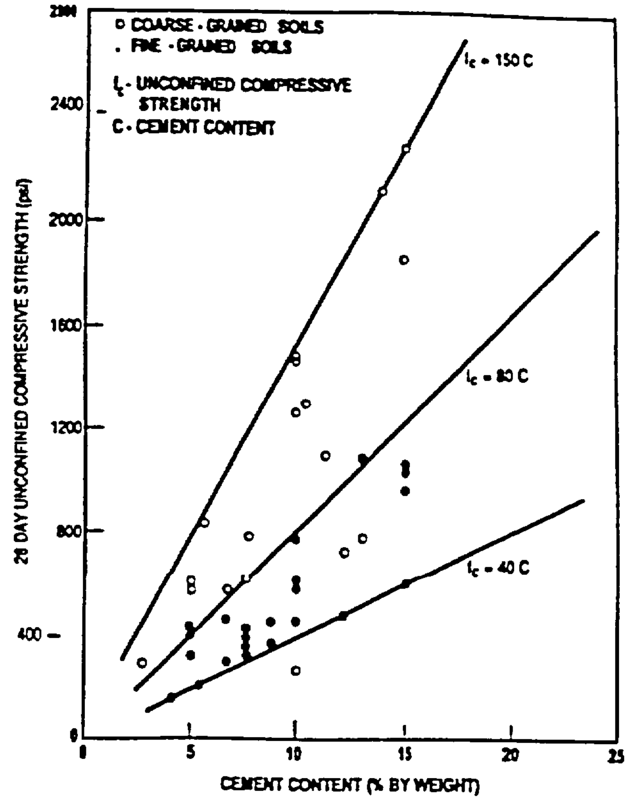

Fig 4.2-Relationship between cement content and unconfined compressive strength for soil-cement mixtures

4.4-Flexural (tensile) strength (modulus of rupture)

Flexural-beam tests (ASTM D 1635), direct-tension tests, and split-tension tests have all been used to evaluate flexural strength. Flexural strength is about one-fifth to one-third of the unconfined compressive strength. Data for some soils are shown in Fig. 4.4. The ratio of flexural to compressive strength is higher in low-strength mixtures (up to 1/3 f_c') than in high-strength mixtures (down to less than 1/5 f_c'). A good approximation for the flexural strength R is[34]

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

where

R = flexural strength, psi

f_c' = unconfined compressive strength, psi

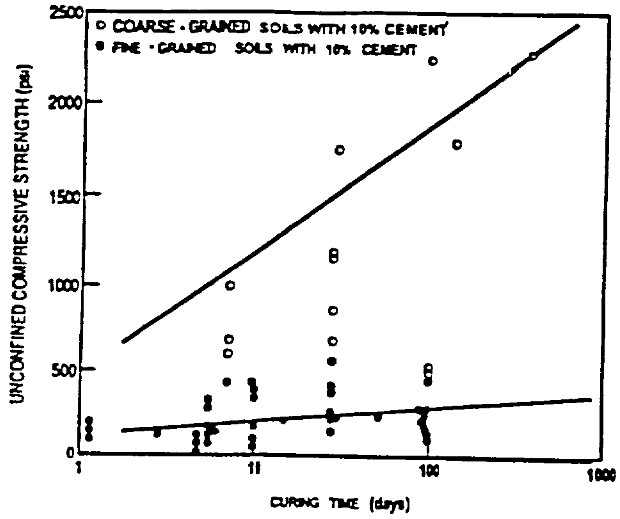

Fig 4.3-Effect of curing time on unconfined concrete compressive strength of some soil-cement mixture34

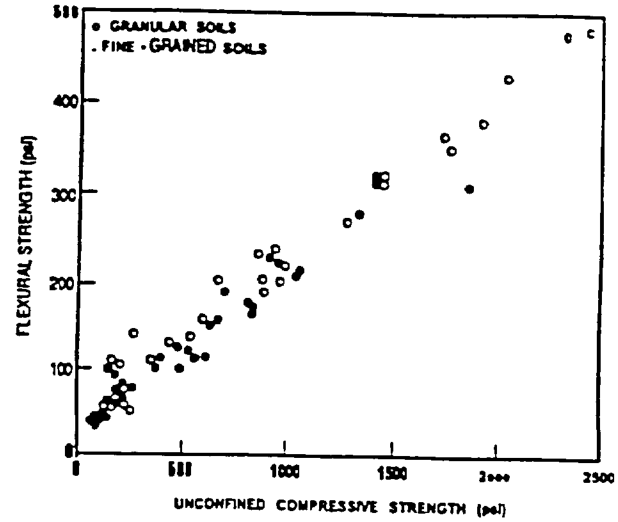

Fig 4.4-Relationship between unconfined compressive strength and flexural strength of soil-cement mixtures34

Table 4.2 — Permeability of cement-treated soils[17]

ASTM soil classification	Dry density, lb/ft³	Moisture content, percent	Cement content percent by weight	K coefficient of permeability ft per yr, 10^{-4} cm/sec	Gradation analysis, percent passing #4 (4.75 mm)	#10 (2.0 mm)	#40 (425 μm)	#200 (75 μm)	005 mm	0005 mm	Cement* required, by weight
Standard Ottawa sand	108 2 112 8 117 6	10 8 9 4 9.7	0 5 3 10 5	48,800 6900 76	(100 percent passing #20 (850 μm): 0 percent passing #30 (600 μm)						—
Graded Ottawa sand	103 2 104 7 107 4	13 7 13 6 12 3	0 5.4 10.5	16,300 470 21	100	100	28	2	—	—	—
Fine sand (SP)	101 c 100 9 103 6 105 3	12 2 13.2 12 3 12 0	0 3.2 6.5 9.5	750 560 190 21	100	100	91	7	1	—	11.5
Silty sand (SM)	100 8 99.9 104 0	14 9 14 7 15 1	0 3.2 6.4	5000 1400 60	100	100	96	13	12	2	8 0
Fine sand (SP)	100 1 105 8 109.3	16 0 14 8 13 5	0 6 12.2	360 20 1	99	99	96	6		61	—
Fine sand (SP)	101 0 106 7 108 2 108 8	13 8 13.3 13 4 13 4	3.1 6.3 --- 9.6	140 33 0.3 0.02	100	100	94	2		-	11.0
Fine sand (SP)	112.5 115.8	11 0 10 4	0 5.5	36 5	—	97	—	—	11	4	—
Fine sand (SP)	111 7 115 2	12 0 11 7	0 5 5	23 8	100	99	—	—	9	3	—
Silty sand (SM)	121.9 125.5	9.6 8 0	0 8.6	16 0 1	98	94	66	20	18	5	—
Silty sand (SM)	117.9 123 0	10 8 8 1	0 8 9	10 2	99	97	69	16	12	4	—
Silty sand (SM)	112 5 115 0	11 5 12.3	0 5 5	5 3	—	98	—	—	12	5	—
Silty sand (SM)	118 7 119 2	11 0 10 5	0 9.1	5 0.1	100	99	88	36	25	7	—
Silty sand (SM)	125 0	— 10.1	0 3 3 7.3	16 0 4 0.07	100	75	41	13	12	5	5.0

*Cement requirement based on ASTM Standard Freeze-Thaw and Wet-Dry Tests for soil-cement mixtures and PCA paving criteria

Values of 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[35] has shown that the split-tension test yields values that do not deviate by more than 13 percent from the direct tensile strength.

4.5-Permeability

Permeability of most soils is reduced by the addition of cement. Table 4.2 summarizes results from laboratory permeability tests conducted on a variety of soil types. A large-scale seepage test was performed by the U.S. Bureau of Reclamation on a section of layered stairstep soil cement facing at Lubbock Regulating Reservoir in Texas.[36] Results indicated a decrease in permeability with time, possibly due to shrinkage cracks in the soil-cement filling with sediment and the tendency for the cracks to self-heal. 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 which 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 perpendicluar to the lifts. Research by Nussbaum[23] has shown permeabilities for flow parallel to the compaction plane were 2 to 20 times larger than values for flow normal to the compaction plane.

4.6-Shrinkage

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. Fig 4.5 shows the results of field data on shrinkage cracking from five test locations in Australia [37] 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 (e.g., 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).[33] Methods suggested for reducing or minimizing shrinkage cracks include keeping the soil-cement surface moist beyond the normal curing periods and placing the soil cement at slightly below optimum moisture content.

4.7-Layer coefficients and structural numbers

Several different methods are currently being used for pavement design. In the AASHTO method for flexible pavement design, layer coefficient *a*, 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.

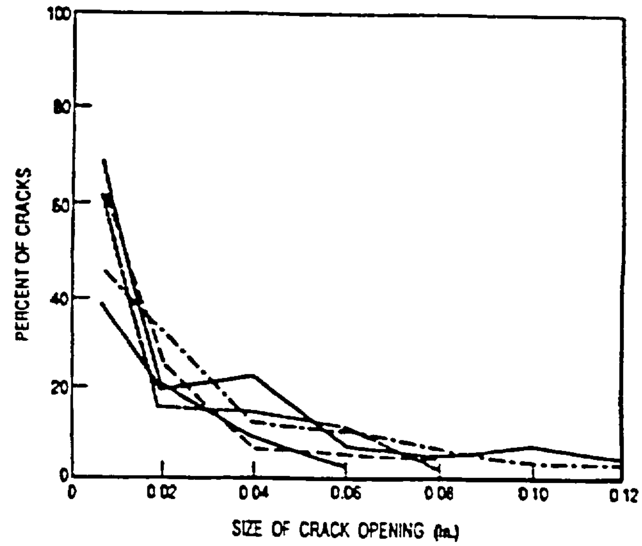

Fig. 4.5-Frequency distribution of various sizes of shrinkage cracks in soil cement[37]

Table 4.3 — Examples of AASHTO layer coefficients for soil cement used by various state DOTs

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

The following general equation for structural number reflects the relative impact of the layer coefficient and thickness[4]

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

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.

Table 5.1 — PCA criteria for soil-cement as indicated by wet-dry and freeze-thaw durability tests[1]

AASHTO soil group	Unified soil group	Maximum allowable weight loss, percent
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

*10 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 percent of the initial volume
2 Maximum water content during the test should be less than the quantity required to saturate the sample at the time of molding
3 Compressive strength should increase with age of specimen.
4 The cement content determined as adequate for pavement, using the PCA criteria above, will be adequate for soil-cement slope protection that is 5 ft or more below the minimum water elevation. For soil cement that is higher than that elevation, the cement content should be increased two percentage points.

The layer coefficients are actually the average of a set of multiple regression coefficients, which indicate the effect of the wearing course, the base course, and the subbase on the pavement's performance. Typical soil-cement layer coefficient a, values used by state departments of transportation are given in Table 4.3.

5-MIX PROPORTIONING

5.1-General

The principal structural requirements of a hardened soil-cement mixture are based on adequate strength and durability. For water resource applications such as liners, permeability may be the principal requirement. Table 3.1 indicates typical cement contents for pavement applications. Detailed test procedures for evaluating mix proportions are given in the Portland Cement Association Soil-Cement Laboratory Handbook[1] and by the following ASTM test standards:

ASTM D 558	Test for Moisture-Density Relations of Soil-Cement Mixtures
ASTM D 559	Wetting-and-Drying Tests of Compacted Soil-Cement Mixtures
ASTM D 560	Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures
ASTM D 1557	Moisture-Density Relations of Soils and Soil Aggregate Mixtures Using 10-lb Rammer and 18-in. Drop
ASTM D 1632	Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory
ASTM D 1633	Test for Compression Strength of Molded Soil-Cement Cylinders
ASTM D 2901	Test for Cement Content of Freshly Mixed Soil-Cement

5.2-Proportioning

Various criteria are used by different organizations to determine acceptable mix proportions. The Portland Cement Association (PCA) criteria are summarized in Table 5.1. Cement contents sufficient to prevent weight losses greater than the values indicated after 12 cycles of wetting-drying-brushing or freezing-thawing-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," TM 5-822-4[38] The durability and strength requirements for portland cement stabilization are given in Tables 5.2 and 5.3, respectively. 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. USACE frequently increases the cement content by 1 or 2 percent to account for field variations. For bank protection, USACE has an unnumbered draft Engineer Technical letter for interim guidance.[39]

The U.S. Bureau of Reclamation (USBR) design criteria for soil-cement slope protection on dams allow maximum losses during freeze-thaw and wet-dry dura-

Table 5.2 — USACE durability requirement[38]

Type of soil stabilized*	Maximum allowable weight loss after 12 wet-dry or freeze-thaw cycles, percent of initial specimen weight
Granular, *PI* < *10*	*11*
Granular, *PI* > *10*	
Silt	:
Clays	6

*Refer to MIL-STD-619B and MIL-STD-621A, U.S Army corps of Engineers

Table 5.3 — USACE minimum unconfined compressive strength criteria[38]

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

bility tests of 8 and 6 percent, 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 at 7 days and 875 psi 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.[11]

Pima County, Ariz., uses a considerable amount of soil cement for streambank slope protection. The county requires the soil cement to have a minimum 7-day compressive strength of 750 psi. The cement content is increased two percentage points for additional erosion resistance and to compensate for field variation. This results in a 7-day compressive strength of about 1000 psi. To facilitate quality-control testing during construction, the county has established an acceptance criterion based on a 1-day compressive strength test. For the local soils typically used, the 1-day strength is generally between 50 to 60 percent of the 7-day value.

The PCA Soil-Cement Laboratory Handbook[1] 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

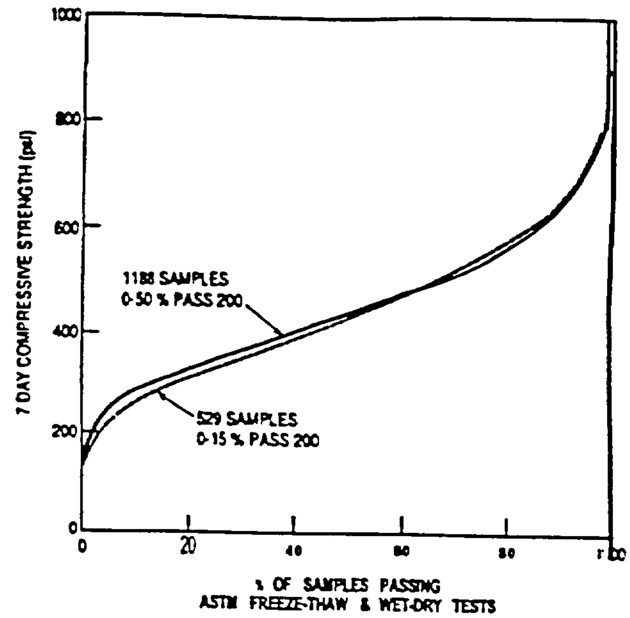

Fig 5.1-Relationship between compressive strength and durability of soil cement based on Portland Cement Association durability criteria[1]

5.3-Special considerations

5.3.1 *Strength versus durability*-In many soil-cement applications, both strength and durability requirements must be met to achieve satisfactory service life. ASTM D 559 and D 560 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. Fig. 5.1 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 would be adequate for all soils, but this strength would be higher than needed for most soils and would result in a conservative and more costly design. The determination of a suitable design compressive strength is simplified when materials within a narrow range of gradations and/or soil types are used. As a result, some agencies have determined and used successfully, for a particular type of material, a compressive strength requirement generally based on results of the wet-dry and freeze-thaw tests.

5.3.2 *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. in diameter and 4.584 in. in height with a height-to-diameter *(h/d)* ratio of 1.15. This differs from conventional concrete molds, which use *h/d* of 2.00. The *h/d* of 2.00 provides a more accurate measure of compressive strength from a technical viewpoint, since 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 C 42, an approximate correction can be made for specimens with *h/d* of 2.00 by multiplying the compressive strength value by a factor of 1.10.

5.3.3 *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[21] showed that organic material of an acidic nature usually had an adverse effect on soil cement. The study showed that organic content and pH do not in themselves constitute an indication of a poorly reacting sand. However, a sandy soil with an organic content greater than 2 percent or having a pH lower than 5.3, in all probability, will not react normally with cement. These soils require special studies prior to use in soil cement.

5.3.4 *Sulfate resistance*-As with conventional concrete, sulfates will generally attack soil cement. Studies by Cordon and Sherwood[40,41] 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. The 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.

6-CONSTRUCTION

6.1-General

In the construction of soil cement, the objective is to obtain a thoroughly mixed, adequately compacted, and cured material. Several references are available[8,13,42-44] that discuss soil-cement construction methods for various applications. Specifications on soil-cement construction are also readily available.[45-47]

Soil cement should not be mixed or placed when the soil or subgrade is frozen or when the air temperature is below 45 F. However, a common practice is to proceed with construction when the air temperature is at least 40 F 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. Soil-cement construction typically requires the addition of water equivalent to 1 to 1 ½ in. of rain; therefore, a light rainfall should not delay construction However, a heavy rainfall that occurs after most of the water has been added 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 usually will not harm it.

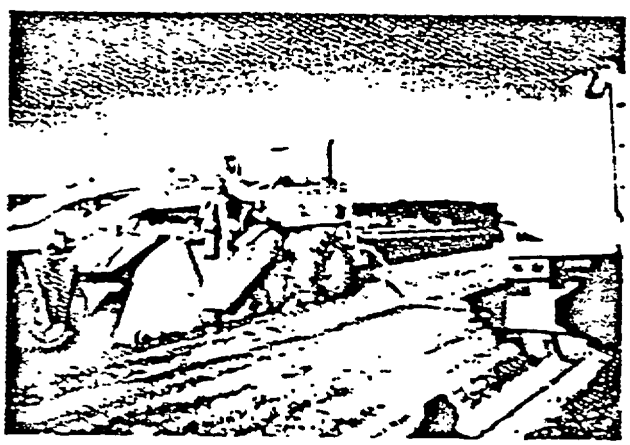

Fig 6 1 Transverse single-shaft mixer processing soil cement in place; multiple passes are required

6.2-Materials handling and mixing

Soil cement is either mixed in place or mixed in a central mixing plant. The typical types of mixing equipment are:

1. In-place traveling mixers
   a. Transverse single-shaft mixer
   b. Windrow-type pugmill
2. Central mixing plant
   a Continuous-flow-type pugmill
   b. Batch-type pugmill
   c. Rotary-drum mixer

6.2.1 *Mixed in place*-Mixing operations with subgrade materials are performed with transverse single-shaft-type mixers (Fig. 6.1 and 6.2). Mixing with borrow materials may be performed with single-shaft or windrow-type pugmill mixers (Fig. 6.3). Almost all types of soil, from granular to fine-grained, can be adequately pulverized and mixed with transverse single-shaft mixers. Windrow-type pugmills are generally limited to nonplastic to slightly plastic granular soils.

6.2.1.1 *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. should be removed. For single-shaft mixers, the soil is shaped to the approximate final lines and grades prior to mixing. Proper moisture content aids in pulverization For granular soils, mixing at less than 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.

Fig 6.2-Mixing chamber of a transverse single-shaft mixer

Fig. 6.3- Windrow-type traveling pugmill mixing soil cement from windrows of soil material

6.2.1.2 *Cement application*-Cement is generally distributed in bulk using a mechanical spreader (two examples of which are shown in Fig. 6.4 and 6.5) or, for small projects, by hand-placing individual cement bags. 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 must be operated at uniform speed with a relatively constant level of cement in the hopper. The spreader must 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. Forward speed must be slow and even. Sometimes a motor grader or loader pulls the truck to maintain this slow, even, forward speed. Although pipe cement-spreaders attached to cement-transport trucks have been used in some areas with mixed results, mechanical spreaders are generally preferred. The amount of cement required is specified as a percentage by weight of oven-dry soil, or in lb of cement per ft^3 of compacted soil cement. Table 6.1 can be used to determine quantities of cement per yd^2 of soil-cement placement

6.2.1.3 *Pulverization and* mixing-Single-shaft mixers are typically utilized 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 that obtained in the laboratory This reduced efficiency is sometimes compensated for by increasing the cement content by 1 or 2 percentage points from that determined in the laboratory testing program.

Windrow-type traveling mixing machines will pulverize friable soils. Nonfriable soils, however, may need preliminary pulverizing for proper mixing. This is usually done before the soil is placed in windrows for processing. The prepared soil is bladed into windrows and a "proportioning" device is pulled along to provide a uniform cross section. When borrow materials are used, a windrow spreader can be used to proportion the material. Nonuniform windrows cause variations in cement content, moisture content, and thickness. The number and size of windrows needed depend on the width and depth of treatment and on the capacity of the mixing machine.

Cement is spread on top of a partially flattened or slightly trenched prepared windrow. A mixing machine then picks up the soil and cement and dry-mixes them with the first few paddles in the mixing drum At that point, water is added through spray nozzles and the re-

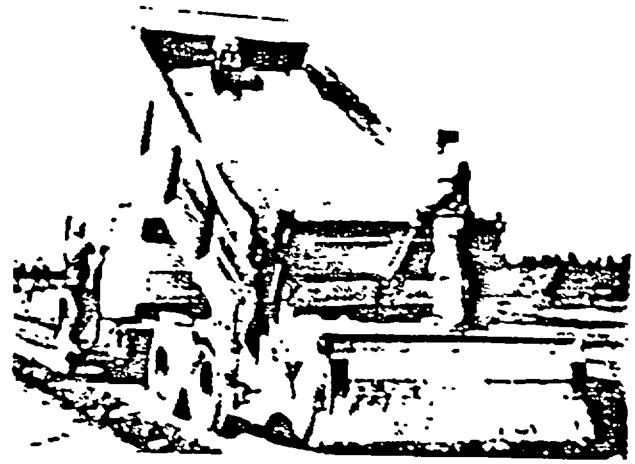

Fig. 6.4-Mechanical cement spreader attached to dump truck

Fig 6.5-Mechanical cement spreader attached to bulk cement transport truck

Table 6.1 — Cement spread requirement[51]

Cement content, lb/ft^3 of compacted soil cement	Cement spread, $lb/yd^2/in.$ of thickness of compacted soil cement
4.5	3.38
5.0	3.75
5.5	4.13
6.0	4.50
6.5	4.88
7.0	5.25
7.5	5.63
8.0	6.0
8.5	6.38
9.0	6.75
9.5	7.13
10.0	7.50
10.5	7.88
11.0	8.25
11.5	8.63
12.0	9.0
12.5	9.38
13.0	9.75
13.5	10.13
14.0	10.50
14.5	10.88
15.0	11.25
15.5	11.63
16.0	12.0

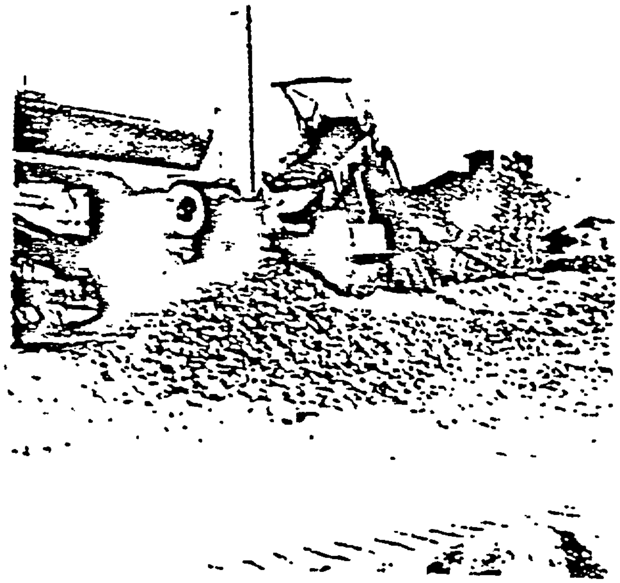

Fig 6 6- Vibrating screen removing oversized material from soil portion of mixture

maining paddles complete the mixing A strikeoff attached to the mixing machine spreads the mixed soil cement

6.2.2 *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 dificul to pulverize There are two basic types of central plant mixers-pugmill mixers, either continuous-flow or batch, and rotary-drum mixers Although batch pugmills and rotary-drum mixers have been used satisfactorily, the most common central plant mixing method is the continuous-flow pugmill mixer. Production rates with this type of mixer vary between 200 and 800 t/hr.

6.2.2.1 *Borrow material*-Soil borrow sources are usually located near the construction site. Natural deposits are generally variable to an extent and do not contain consistent, uniform materials throughout.

The U.S. Bureau of Reclamation recommends the following procedure for handling borrow material.[48] If the material in the borrow area varies with depth, full-face cuts should be made with the excavation machinery. This selective excavation insures 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 pugmill mixer. Removal of some oversize clay balls and other large particles can be done by screening through 1 to 1 ½-in. mesh (Fig. 6.6) In some cases, selective excavation may be necessary to avoid excessive clay lenses

6.2.2.2 *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 pugmill plant is shown in Fig 6.7. A typical plant consists of a soil bin or stockpile, 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 prior to loading (Fig. 6.8).

A pugmill mixing chamber consists of two parallel shafts equipped with paddles along each shaft (Fig.

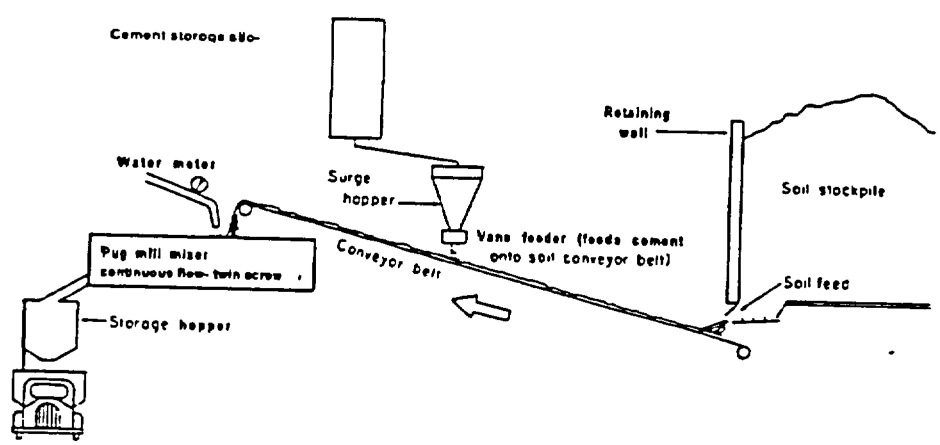

Fig 6 7-Diagram of continuous-flow central plant for mixing soil cement

6 9). 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, pugmill tilt, and paddle pitch are adjusted to optimize the amount of mixing in the pugmill. Thorough blending in the mixer is very important, and the length of mixing time is used to control this factor. Some specifications dictate the minimum blending time. Usually 30 sec is specified, although satisfactory blending has been achieved in shorter periods, depending on the efficiency of the mixer.

6.2.2.3 *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 min should elapse between the start of moist-mixing and the start of compaction. Haul time is usually limited to 30 min.

For multiple-layer stairstep 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 deg horizontal angle to the slope, normally 2 ft thick and spaced about 300 to 400 ft 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, since 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.

6.2.2.4 *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 prior to 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 Spreading may also be done with asphalt-type pavers Some pavers are equipped with one or more tamping bars, which provide initial compaction. Soil cement is usually placed in a layer 25 to 50 percent thicker than the final compacted thickness For example, a 8 to 9 in loosely placed layer will produce a compacted thickness of about 6 in. 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.

6.2.2.5 *Bonding successive layers*--Bonding successive layers of soil cement is an important requirement for applications 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 which have been effective in improving bond between layers include the following:[49,50]

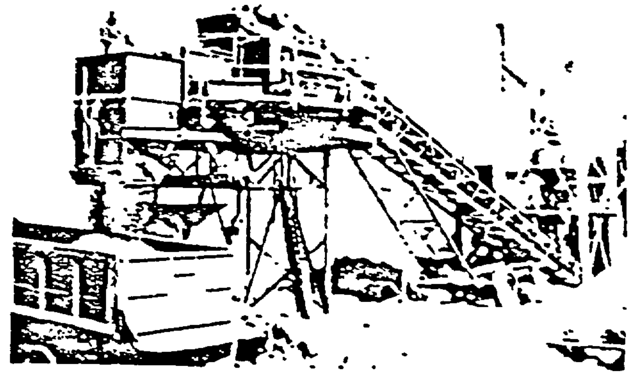

Fig. 6 8- Typical continuous-flow central mixing plant

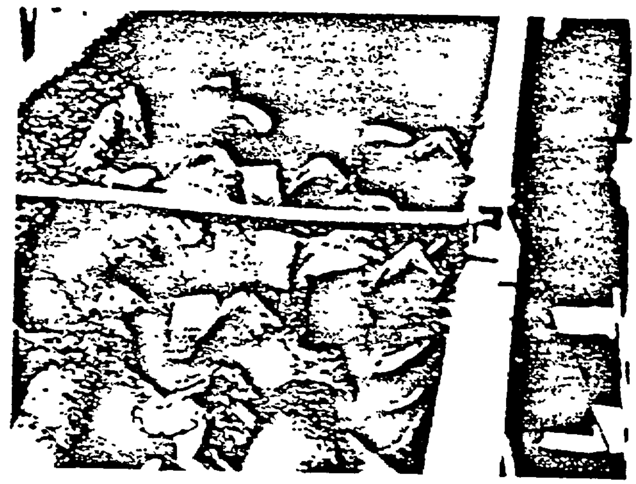

Fig 6.9-Mixing paddles of a twin-shaft, continuous flow central mixing plant

1. Minimizing time between placement of successive layers.
2. Use of either dry cement or cement slurry. The dry cement should be applied at about 1 lb/yd^2 to a moistened surface immediately prior to placement. The cement slurry mix should have a water-cement ratio of about 0.70 to 0.80.
3. After the soil cement has set, brushing the surface with a power broom to provide a roughened surface texture.
4. Use of chemical retarding agents.

6.3-Compaction

Compaction begins as soon as possible and is generally completed within 2 hr of initial mixing. The detrimental effects of delayed compaction on density and strength have already been described in Section 4.2. No section is left unworked for longer than 30 min during

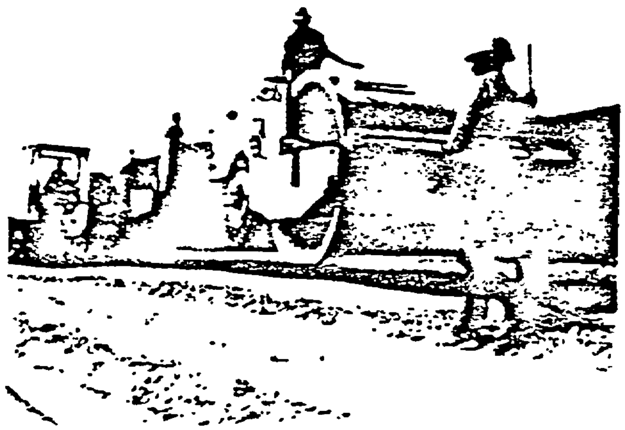

Fig 6 10-Compacting outer edge with rounded steel flange welded to steel-wheel roller

compaction operations The principles governing compaction of soil cement are the same as those for compacting the same soil without cement treatment. For maximum density, the soil-cement mixture should be compacted at or near optimum moisture content as determined by ASTM D 558 or D-1557. Most specifications require soil cement to be uniformly compacted to a minimum of between 95 and 98 percent 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 The sheepsfoot roller is often followed by a multiple-wheel, rubber-tired roller for finishing For granular soils, vibratory steel-wheeled 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 Greater thicknesses, particularly for granular soils, can be compacted with heavy equipment designed for thicker lifts Regardless of the lift thickness and compaction equipment used, the fundamental requirement is that the compacted layer achieve the specified minimum density throughout the lift

6.4-Finishing

As compaction nears completion, the surface of the soil cement is shaped to the design line, grade, and cross section Frequently, the surface may require lift scarification to remove imprints left by equipment or potential surface compaction planes * The scarification can be done with a weeder, nail drag, spring tooth, or spiketooth harrow. 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 stairstepped 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 6 10)

*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

6.5-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. This is normally done using the toe of a motor grader or dozer. Joints made in this way will be strong and will be 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 insure that joints are vertical and that material in the joint area is adequately mixed and thoroughly compacted. For such multiple-layer constructions as stairstepped embankments, joints are usually staggered to prevent long continuous joints through the structure.

6.6-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 the curing coat is not damaged.

Water-sprinkling and bituminous coating are two popular methods of curing Sprinkling the surface with water, together with light rolling to seal the surface, has proven successful. In bituminous curing, the soil cement is commonly sealed with an emulsified asphalt. The rate of application is dependent on the particular emulsion, but typically varies from 0.15 to 0.30 gal/yd^2. 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 which will be used to hold aquatic life.

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

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

7-QUALITY CONTROL TESTING AND INSPECTION

7.1-General

Quality control is essential to assure that the final product will be adequate for its intended use. Additionally, it must 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
7. Curing

References 48 and 51 provide excellent information on quality-control inspection and testing of soil cement during construction

7.2-Pulverization (mixed in place)

Most soils require minimum pulverization before processing starts. However, the heavier clay soils require a considerable amount of preliminary work. The keys to pulverization of clayey soils are proper moisture control and proper equipment. Since clayey soils cannot be adequately pulverized in a central plant, their use is restricted to mixed-in-place construction.

PCA specifications[45,46] require that, at the completion of moist mixing, 80 percent of the soil-cement mixture pass the No 4 sieve and 100 percent pass the 1-in 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 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 sieve are weighed separately and their dry weights determined. The degree of pulverization is calculated as follow[51]

$$\text{Percent pulverization} = \frac{\text{Dry weight of soil-cement mixture passing No. 4 sieve}}{\text{Dry weight of total sample exclusive of gravel retained on No. 4 sieve}} \times 100$$

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

Fig 7.1-Weighing cement collected on 1 yd² of canvas to check on quantity of cement spread

and permit immediate adjustments in pulverization and mixing procedures if necessary.

Pulverization can be improved by:

1. Slower forward speed of the mixing machine
2. Additional passes of the mixing machine
3. Replacing worn mixer teeth
4. Prewetting and premixing the soil before processing begins
5. Adding lime to highly plastic soils to reduce plasticity and improve workability.

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.

7.3-Cement-content control

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

1. *Spot check*-A sheet of canvas, usually 1 yd² in area, is placed ahead of the cement spreader. After the spreader has passed, the canvas with cement is carefully picked up and weighed (Fig. 7.1) The spreader is then adjusted if necessary and the procedure repeated until the correct spread per yd² is obtained.

2. *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 with the canvas. Then slight adjustments are 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 insure 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.

7.3.2 *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 pugmill 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

1. 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 the cement feeder is adjusted until the correct amount of cement is discharged.

2. 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

7.4-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 D 558 or D 1557). 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. About 2 percent 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. 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. 7.2). 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 mois-

Fig 7.2-Soil cement at optimum moisture casts readily when squeezed in the hand and can be broken into two pieces without crumbling

ture 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.

7.5-Mixing uniformity

7.5.1 *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 prior to compaction as described in Section 7.2. 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. Depth of mixing is usually checked at the same time as uniformity. Routine depth checks are made during mixing operations and following compaction to assure that the specified thickness is attained. Following compaction, a final check on mixing uniformity and depth can be made using a 2 percent 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.

7.5.2 *Central mix 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 sec of mixing are required

7.6-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 percent of the maximum density of the cement-treated soil as determined by the moisture-density test (ASTM D 558 or D 1557). The most common methods for determining in-place density are:

1. Nuclear method (ASTM D 2922 and D 3017)
2. Sand-cone method (ASTM D 1556)
3. Balloon method (ASTM D 2167)

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 insure compliance with job specifications.

7.7-Lift thickness and surface tolerance

7.7.1 *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. 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 U.S. Army Corps of Engineers typically tests thickness with a 3 in. diameter core for every 500 yd^2 of soil cement. Other agencies, such as Caltrans, require that thickness measurements be taken at intervals not to exceed 1000 linear ft.

7.7.2 *Surface tolerance*-Surface tolerances are usually not specified for soil-cement embankment applications, although lift elevation may be monitored with survey techniques. The U.S. Bureau of Reclamation controls only the soil-cement embankment crest road elevation to within 0.01 ft of design grade. To provide a reasonably smooth surface for pavement sections, smoothness is usually measured with a 10-ft or 12-ft straightedge, or with surveying equipment. The U.S. Army Corps of Engineers typically requires that deviations from the plane of a soil-cement base course not exceed ⅜ in. in 12 ft using a straightedge placed perpendicular to the centerline at about 50-ft intervals. Most state transportation departments limit the maximum departure from a 12-ft or 10-ft straightedge to about ¼ in. In addition, a departure from design grade of up to $^5/_8$ in. is usually allowed.

CONVERSION FACTORS

1 ft=0.305 m
1 in =25 4 mm
1 lb=1 454 kg
1 mile=1 61 km
1 psi=6.895 kPa
1lb/ft^3 = 16.02 kg/m^3
1lb/yd^3=0.5933 kg/m^3
1 ft/sec =30.5 cm/sec
1 acre=0 4047 ha

8-REFERENCES

8.1-Specified references

The standards referred to in this document are listed below with their serial designation The standards listed were the latest effort at the time this document was prepared. Since some of these standards are revised frequently, generally in minor detail only, 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-89 Roller Compacted Mass Concrete

ASTM

C 42-87	Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 150-89	Standard Specification for Portland Cement
C 595-86	Standard Specification for Blended Hydraulic Cements
C 618-89	Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
D 558-82	Standard Test Method for Moisture-Density Relations of Soil-Cement Mixtures
D 559-82	Standard Methods for Wetting-and-Drying Tests of Compacted Soil-Cement Mixtures
D 560-82	Standard Methods for Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures
D 1556-82	Standard Test Method for Density of Soil in Place by the Sand-Cone Method
D 1557-78	Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 1 O-lb (4.54-kg) Rammer and 18-in. (457-mm) Drop
D 1632-87	Standard Methods of Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory
D 1633-84	Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders
D 1635-87	Standard Test Method for Flexural Strength of Soil-Cement Cylinders
D 2167-84	Standard Test Method for Density and Unit Weight of Soil in-Place by the Rubber Balloon Method
D 2901-82	Standard Test Method for Cement Content of Freshly Mixed Soil-Cement
D 2922-81	Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)
D3017-78	Standard Test Method for Moisture Content of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)
D 4318-84	Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

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This report was submitted to letter ballot of the committee and approved in accordance with ACI balloting procedures