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The Bureau of Reclamation has constructed a great number and variety of hydraulic structures for water storage and conveyance throughout the western United States. A variety of construction techniques and materials have been used, but soil is the material utilized most often. Two types of clay soils have been encountered that cause special difficulties for some of these structures. The first is expansive clay and the second is dispersive clay. Lime treatment of both types of clays has been found to be an effective stabilization method.

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CONTENTS

	Page
Introduction	1
Canal stabilization	1
Expansive soils	2
Effect of lime on soil	3
Selection of lime content	4
Construction procedures on Friant-Kern Canal	5
Evaluation of lime stabilization	6
Utilizing dispersive clay in dam construction	7
Dispersive clays	9
Effect of lime on soil	11
Selection of lime content	11
Construction procedures for lime-treated dispersive clays	12
Evaluation of lime for stabilizing dispersive clay	13

INTRODUCTION

The Bureau of Reclamation has constructed a great number and variety of hydraulic structures for water storage and conveyance throughout the western United States. A variety of construction techniques and materials has been used, but soil is the material utilized most often. Two types of clay soils have been encountered that cause special difficulties for some of these structures; the first is expansive clay, and the second is dispersive clay. Lime treatment of both types of clays has been found to be an effective stabilization method.

CANAL STABILIZATION

The Friant-Kern Canal, constructed during 1945 through 1951, begins at Friant Dam, 25 miles northeast of Fresno, California, and follows the east side of the San Joaquin Valley for 152 miles to its southern terminus near Bakersfield. It delivers water to more than 1 million acres of irrigated farmland in southern California. The normal operating capacity of the canal is 4,000 ft^3/s in the first 71 miles and gradually decreases to 2,000 ft^3/s at the terminus. About 54 miles of the canal traverse an area of expansive clay (Porterville Formation). Of this 54 miles, 23 miles are earth lined and 21 are concrete lined. Failures have occurred in both the concrete-lined and earth-lined sections. After 3 years of operation, this portion of the canal began cracking, sliding, and sloughing and has been a continuing expensive maintenance problem.

In the early 1970's, the Bureau decided to rehabilitate two of the worst areas using soil-lime to stabilize the canal slopes. One area was in an earth-lined section and the other a concrete-lined section. The contract included 8,900 feet of compacted soil-lime lining and 1,820 feet of concrete lining over lime-stabilized compacted backfill. The compacted soil-lime earth lining was 2 feet thick for the roads on the top of both banks and for the canal bottom. The side slopes were 3.6 feet thick normal to the 2:1 slope. For the compacted soil-lime beneath the concrete lining, the side slopes were left at 1-1/2:1, resulting in a thickness of 4.4 feet normal to the slope. This was the largest lime-stabilization job by the Bureau at the time and was the first time lime was used to rehabilitate unstable canal sections.

EXPANSIVE SOILS

Expansive soils are those that exhibit significant volume change, expansion, and shrinkage, with changes in moisture content. For a canal lining, volume change can be a serious problem. Below the water level, the material expands due to water being absorbed into the soil. Lower densities and strengths result. Above the water surface, shrinkage occurs with cracks forming several feet deep and results in a loss of shear strength. As a result, canal slopes become unstable; and slides occur as in the case of Friant-Kern Canal. The expansive potential of the soil may be increased when used as a construction material. The density and moisture content of an expansive soil affect its volume change characteristics. In a dense soil resulting from compaction, more clay particles are packed into a unit volume than in a loose soil. When the moisture content increases, greater volume change will occur in the dense than in the loose soil condition. The structure of an expansive soil also affects the volume change potential. A compacted expansive soil will expand significantly more than an undisturbed sample of the same soil due to thixotropic hardening of the latter.

EFFECT OF LIME ON SOIL

Adding lime to soil has two major effects: (1) improving the soil workability and (2) increasing the soil strength.

The first effect is immediate and results from the following reactions of the lime with the soil: (1) an immediate reduction in plasticity where the LL (liquid limit) of the soil is decreased and the PL (plasticity limit) increased, thus reducing the PI (plasticity index) of the soil; (2) the finer clay-size particles agglomerate to form larger particles; (3) the large particles (clay clods) disintegrate to form smaller particles; and (4) a drying effect takes place due to the absorption of moisture for hydration of the lime, which reduces the moisture content of the soil. The result of these reactions is to make the material more workable and more friable or siltlike in texture. This eliminates the construction problems inherent in using a wet, sticky, heavy clay. Since the Friant-Kern Canal operates 10 months a year, speed of construction was an essential factor and the improved workability of the soil-lime an important benefit.

The second effect of adding lime to soil is a definite cementing action with the strength of the compacted soil-lime increasing with time. The lime reacts chemically with the available silica and some alumina in the soil to form calcium silicates and aluminates.

SELECTION OF LIME CONTENT

The percentage of lime added to a soil depends on whether the purpose is for modification (small percent to increase workability) or for stabilization (sufficient lime to provide strength). For stabilization, the lime percentage could be based on pH values, PI reduction, strength gain, or prevention of volumetric changes. When the pH of a soil-lime mixture reaches 12.4, sufficient lime has been added to react with all the soil. There is an optimum lime percentage past which adding more lime slightly reduces the PI of the mixture but cannot be economically justified.

Either hydrated lime or quicklime was allowed in the specifications, and the contractor elected to use quicklime. Since quicklime contains about 20 percent more available lime or CaO than hydrated lime, 3.2 percent quicklime was considered equivalent to 4.0 percent hydrated lime, and 3.2 percent quicklime was approved for use. However, after construction started, control of the lime content became difficult, so the amount of quicklime was increased to 4 percent with the provision that extra quicklime be added where Government inspectors felt it necessary.

The 4-percent lime reduced the PI of this particular clay from 47 to 12 and increased the shrinkage limit from 7 to 28. Improvement was also noted in increased compressive strength, about 20 times that of untreated soil.

CONSTRUCTION PROCEDURES ON FRIANT-KERN CANAL

The first stage of the soil-lime construction program was to rebuild the berm roads along the canal banks to provide a stable roadway of soil-lime so that rains would not halt operations. The road was to be 2 feet thick. First, the top half of the roadway material was excavated and stockpiled; the bottom half was then ripped, quicklime and water added, mixed, allowed to mellow, and then recompacted. A large quantity of rock was present, which was removed with a rock rake mounted on a dozer during the mixing operation. It was necessary, however, to add lime to the highly plastic clay soil before the rock could be removed. Without the addition of lime, the clay stuck to the rock and prevented rock rakes from picking it up. The contractor first tried rotary mixers for pulverizing and mixing; but the amount of rock present broke the mixer blades, so the soil-lime was mixed using bulldozers and road graders. The compaction of the lower 1-foot lift was done with a vibratory sheepsfoot roller. Then the material for the top lift was brought back, spread, 4 percent quicklime added, watered, mixed, allowed to mellow, and recompacted. The bottom of the canal was also stabilized to a 2-foot thickness and was constructed similar to the roadway.

Before reconstructing the canal side slopes, the rock riprap that had been dumped into slide areas had to be removed. Then all the material, which was to be stabilized with lime and recompacted, was removed by a benching operation. A series of long sloping benches or ramps was cut from the top of the bank down to the canal bottom with the cut extending far enough into the slope to remove the entire depth of required excavation material. Two percent quicklime was spread over the bench surface, 1 foot of material from the bench was mixed with the quicklime, and the lime-clay mixture was pushed into the canal bottom where the remaining oversize material was removed. The material was spread on the canal bottom and 2 percent additional lime added. Water was added to at least 2 percent over optimum moisture; then about 1-foot depth of material was mixed with dozers and graders, with the rock being continually removed. After about 6.6 feet of material had been mixed and cured for 24 hours, bulldozers started spreading the material on the slopes, which were then compacted with a self-cleaning sheepsfoot roller moving up and down the slope. A cable winch on a crane moved the roller up and down the slope. The side slopes were constructed in three 1.2-foot compacted lifts to give the specified 3.6-foot compacted depth normal to the slope.

EVALUATION OF LIME STABILIZATION

The first rehabilitation project was built in 1972-1973 and 1973-1974 and was completed in January 1974. It involved both earth-lined and concrete-lined sections. Laboratory tests were performed on undisturbed soil-lime block samples received in February 1973 and February 1974. Performance of the canal during the 1973 operating season and results of the laboratory tests showed the project to be highly successful, and a second project to be constructed in 1975-1976 and 1976-1977 was planned. In the second contract, only the canal banks were stabilized in two earth-lined sections, 1.0 and 1.5 miles in length. This time, 3.2 percent granular quicklime was specified. The project was completed in January 1977.

Encouraged by results of the first two projects, the Bureau has completed four more contracts using essentially the same design, construction, and evaluation techniques. The amount of lime specified varied according to laboratory test results to determine optimum use. Three of the four contracts were to rehabilitate operation and maintenance roads along the canal, and the fourth was to rehabilitate failed sections of concrete-lined canal. The fourth contract, 1983-1984, differed from previous jobs in that sloughed embankment had been previously removed by maintenance crews, and replacement material was obtained by mixing granular quicklime with clay in adjacent borrow areas and was hauled to the worksite.

Each of the rehabilitation projects has performed very well; and no new slips, slides, or sloughs have occurred. Sheepsfoot compactor imprints left in the bottom of the canal during construction are still evident even on the first completed project. Overall, use of soil-lime for canal rehabilitation appears to be a viable, economic method of stabilization.

UTILIZING DISPERSIVE CLAY IN DAM CONSTRUCTION

McGee Creek Dam is located near Atoka in southeastern Oklahoma. The dam will have an embankment height of 150 feet, a crest length of 2,200 feet, and a reservoir capacity of 4.4 million cubic meters. Water from the reservoir is principally for municipal and industrial use. Construction of the dam and appurtenant structures was begun in 1982 and is scheduled to be completed in 1986.

Dispersive clays were identified in the foundations for the dam and dike and in the borrow areas utilized in construction of McGee Creek Dam. Several small embankment dams, previously built by other agencies in the same general area, were constructed of dispersive clays; and all experienced extensive damage or complete failure. As a result, special considerations were utilized in the design and construction of McGee Creek Dam, with special attention being given to lime-treatment of dispersive clays and use of sand filters.

From results of materials investigations and design studies, it was determined that dispersive clays were present in significant quantity throughout the borrow and foundation areas but that they were not associated with any particular stratum, elevation, or formation. Some of the defensive design measures incorporated to prevent dispersive clay erosion were (1) use of fine sand filters with silty sand transitions to prevent internal erosion in the dam or dike; (2) lime-treated soil to be used on the downstream slope of the dam, underneath the core of the dam, and in critical locations such as backfill around conduits.

Minimum required thicknesses of lime-treated soil were 27 inches (0.7 m) on the downstream slope or 3 feet (1.0 m) if placed in horizontal layers, and 3 feet (1.0 m) underneath the core of the dam and dike. Compacted lime-treated soil beneath the core was required for the full bottom width of the cutoff trenches or extended a distance upstream from the chimney equal to the reservoir head at the top of the conservation pool.

DISPERSIVE CLAYS

Dispersive clays are clays that will erode in slow-moving or even quiet water by individual colloidal clay particles going into suspension.

This erosion process deals with the physicochemical state of the clay fraction of a soil that causes individual clay particles to deflocculate (disperse) and repel each other in the presence of free water. This deflocculation process, possibly due to high dissolved sodium content in the pore water relative to total dissolved salts, is found in dispersive clays and is quite different than the erosion mechanism for silt or very fine sand. Unlike erosion in cohesionless soils, erosion in dispersive clay is not a result of seepage through the pores of a clay mass. A concentrated leakage channel (crack) must be present in order for erosion to initiate in dispersive clay. Erosion of the walls of the leakage channel then occurs along the entire length at the same time, and rapid catastrophic failure may result. This mechanism is totally different than that for piping where erosion begins at the discharge end of the leak and progresses upstream through the structure until it reaches the water source.

Although fairly common in nature, dispersive clays were not always recognized as erosive or problem soils until recent years. At one time, they were thought to be associated only with arid or semiarid terrain and in areas of alkaline soils. More recently, dispersive clays and the same erosion problems have been found to exist in humid climates in various parts of the world also. Major problems have been experienced with dispersive clays in water projects in other countries including Australia, South Africa, Thailand, the Middle East, and in many parts of the southern United States. Dispersive clays have been encountered in alluvial clays in the form of flood-plain deposits, slope wash, lakebed deposits, and loess deposits. In gently rolling or flat areas, there is frequently no evidence of dispersive clay on the surface due to a protective layer of silty sand or topsoil; therefore, absence of erosion patterns typical of dispersive clay does not necessarily indicate absence of dispersive clay. In southeastern Oklahoma, erosion failures that occurred were embankments constructed of soils in the form of in situ residual clay, slope wash, and alluvium.

Dispersive clays cannot be identified by the conventional index tests such as visual classification, gradation, or Atterberg limits. It has been observed that there can be large differences in erodibility of soils with identical visual appearance and index properties when samples were obtained only several feet apart. Laboratory tests most commonly used for identifying dispersive clays are the crumb test, the double hydrometer test, the pinhole test, and chemical analysis of the pore-water extract. None of the individual tests are totally reliable for identifying dispersive clays, so it is prudent to perform all four tests on each soil sample to evaluate overall dispersive potential.

EFFECT OF LIME ON SOIL

When lime is mixed with soil, the following four reactions take place: (1) cation exchange; (2) flocculation and agglomeration; (3) carbonation; and (4) pozzolanic reactions. The first two reactions contribute to the control of clay dispersion and clay modification in general. The third reaction, carbonation, has little positive effect and should be minimized in the construction process. The fourth reaction is believed associated with long-term strength gain.

SELECTION OF LIME CONTENT

The design lime content is generally defined as the minimum lime content required to make the soil nondispersive. In addition, it may be desirable to increase the shrinkage limit to near optimum moisture content in order to prevent cracking from drying when using lime-treated soil in surface layers. Soil modification for better workability is sometimes controlled by decreasing the PI to some acceptable level. This control has generally not been used for dispersive clays, however.

Dispersive clays are almost always made nondispersive by the addition of 1 to 4 percent lime. The design lime content is often, however, increased 0.5 to 1.0 percent for construction to account for construction losses, uneven distribution, incomplete mixing, etc. Sometimes a minimum value of 2 percent is specified for construction. Based on laboratory test results, the specifications for McGee Creek Dam required between 1.5 and 3.0 percent lime to be aded to the soil on a dry-mass basis.

CONSTRUCTION PROCEDURES FOR LIME-TREATED DISPERSIVE CLAYS

The following general procedures for handling, mixing, and placing lime-treated soil were outlined in the specifications and were those generally used by the contractor.

Soil to be lime treated was pulverized with a high-speed rotary mixer or disk harrow prior to applying lime, and the moisture content was brought to within 2 percentage points of optimum. Hydrated lime was uniformly spread by truck on the pulverized soil to result in between 1.5 to 3.0 percent lime by dry soil mass. The lime was mixed with the soil using a rotary mixer, and additional water was added as necessary to bring the mixture to within 2 percentage points of optimum. When mixing was completed, the soil-lime mixture was cured for at least 96 hours before placing. Either the exposed surface of the mixture was lightly rolled to prevent moisture loss or the mixed material was stockpiled and the surface sealed.

Each section of the foundation was carefully prepared coincident with final mixing and pulverization of the lime-treated earthfill. The soil-lime was mixed until 100 percent passed the 25-mm sieve and 60 percent passed the 4.75-mm sieve. Immediately after final mixing, the lime-treated earthfill was placed and compacted in horizontal lifts of no more than 150 mm after compaction. The lime-treated earthfill was compacted to no less than 95 percent of Proctor maximum dry density using a tamping roller followed by a pneumatic-tired roller. The top of each compacted lift was scarified or disked before the next lift was placed.

For high-quality earthwork construction control, the following were monitored: (1) pulverization, (2) lime content, (3) dispersivity, and (4) unit weight and moisture content. If embankment materials were placed on the compacted lime-treated earthfill within 36 hours, no special curing provisions were required. Otherwise, the exposed surface of the lime-treated earthfill was compacted with a pneumatic-tired roller to seal the surface; and it was sprinkled with water for 7 days or until embankment material was placed.

A number of undisturbed block samples were taken from the compacted soil-lime and sent to the laboratory for design verification testing.

EVALUATION OF LIME FOR STABILIZING DISPERSIVE CLAY

Dispersive clays were identified throughout the borrow and foundation areas for McGee Creek Dam and Dike. Addition of 1.5 to 3.0 percent hydrated lime by dry mass of soil rendered all the dispersive clays nondispersive and allowed their use in constructing the embankment-foundation contacts, as erosion-resistant material on the downstream slope of the embankments and for placement as specially compacted backfill in areas of high piping potential such as along conduits through the embankment. This was more economical than attempting to identify the randomly occurring dispersive clays and selectively wasting them. Materials were used directly from the borrow areas to construct the remainder of the dam and dike embankments. Specially designed filters were, however, incorporated into the embankments to guard against possible erosion of any dispersive clays present. A second benefit of using lime-treated soil was the improved workability of some of the highly plastic clays encountered.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-822A, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.