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16. ABSTRACT

Since construction in the late 1940's, the Friant-Kern Canal has experienced cracking, sliding, and sloughing of the side slopes in areas of expansive clays in both the concrete-lined and earth-lined portions. In the early 1970's, Bureau of Reclamation designers decided to remove portions of the canal lining, flatten the slopes, and reline the canal using a compacted soil-lime mixture in an attempt to stabilize the slopes. The project added 4 percent (based on dry soil weight) granular quicklime to the soil. Laboratory tests on the compacted soil-lime mixture showed that (1) soil-lime was about 20 times stronger than the untreated clay, (2) the strength of the soil-lime increases with time, (3) the plasticity index of the natural soil was reduced from 40 to 10 or less after adding the lime, and (4) the compressive strength of the soil-lime was dependent on the compacted density.

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LIME STABILIZATION ON FRIANT-KERN CANAL

by
Amster K. Howard
John P. Bara

December 1976

Earth Sciences Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

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INTRODUCTION

The Friant-Kern Canal which is part of the Central Valley Project in California, extends from the Friant Dam on the San Joaquin River east of Fresno south to the Kern River near Bakersville. It is 245 km (152 mi) long and delivers water to more than 400 000 hectares (1 million acres) of irrigated farmland in Southern California. The normal operating capacity is 115 m^3/s (4000 ft^3/s) in the first 114 km (71 mi) and gradually decreases to 57 m^3/s (2000 ft^3/s) at the terminus. About one-third of the length of the canal, from mile 34 to mile 88, traverses an area of expansive clays (Porterville Formation). Of this 87 km (54 mi) of canal, 37 km (23 mi) are earth lined and the remainder is concrete lined. Failures have occurred in both the concrete-lined and earth-lined sections. The canal was constructed during 1945 through 1951, and after 3 years of operation, this portion of the canal began cracking, sliding, and sides of the canal began sloughing and has been a continuing problem since. Maintenance of the canal slopes has been an expensive, continual problem. In the early 1970's, the Bureau of Reclamation decided to remove portions of the canal lining, flatten the canal slopes, and reline the canal using a compacted soil-lime mixture in an attempt to stablize the slopes.

Two of the worst areas were selected for rehabilitation with lime-stabilized soil. One area, at about mile 60, was in an earth-lined section, and the other, mile 82, was in the concrete-lined section. The contract, under specifications No. DC-6970, included 2.7 km (8900 ft) of compacted soil-lime lining and 0.55 km (1820 ft) of concrete lining over lime-stabilized backfill.

The general repair procedure has been to convert the original 1-1/2 to 1 failed concrete linings, to earth sections treated with lime with 2 to 1 slopes (fig. 1) as the failures occur. The failed earth-lined sections had the slopes flattened to 2 to 1 with the toe of the embankment moved in toward the center of the canal. Riprap was dumped into those areas where large slides had occurred. These repairs, however, have also failed. The compacted soil-lime earth lining is 0.6 m (2 ft) thick for the roads on the top of both banks and for the canal bottom. The side slopes are 1.1 m (3.6 ft) thick normal to the slope. For the compacted lime-treated earth fill beneath the concrete lining, the side slopes were left at 1-1/2 to 1, resulting in a thickness of 1.4 m (4.4 ft) normal to the slope. The bottom and roads are 0.6 m (2 ft) thick.

APPLICATIONS

This is the largest lime-stabilization job by the Bureau to date, and it is the first time that lime has been used to rehabilitate unstable canal embankments. Consideration should be given to further use of lime to condition wet clays because lime acts as a drying agent and also permits trafficability and construction under adverse weather conditions. Field observations indicate that lime may be sufficiently erosion resistant to eliminate the need for a gravel beach belt.

Laboratory tests indicate that the mellow time should be held to a minimum because higher fill densities can be attained which make the compacted soils more erosion resistant. Of more significance, a reduced mellow time will permit the contractor to keep his placing operations closed up, which will make future lime-stabilization work more economical and more competitive with other construction methods.

CONCLUSIONS

Since construction in the late 1940's, the Friant-Kern Canal has experienced cracking, sliding, and sloughing of the side slopes in both the concrete-lined and earth-lined sections, in the areas that had been built on expansive clays. To stabilize the slopes, the Bureau decided to remove portions of the canal lining, flatten the canal slopes, and reline the canal using a compacted soil-lime mixture.

The Engineering and Research Center laboratories conducted tests to determine the appropriate amount of lime to be added and to evaluate the final product. The conclusions of these tests are as follows:

1. For stabilization of the expansive soils along the Friant-Kern Canal, studies indicated that 4 percent hydrated lime should be added

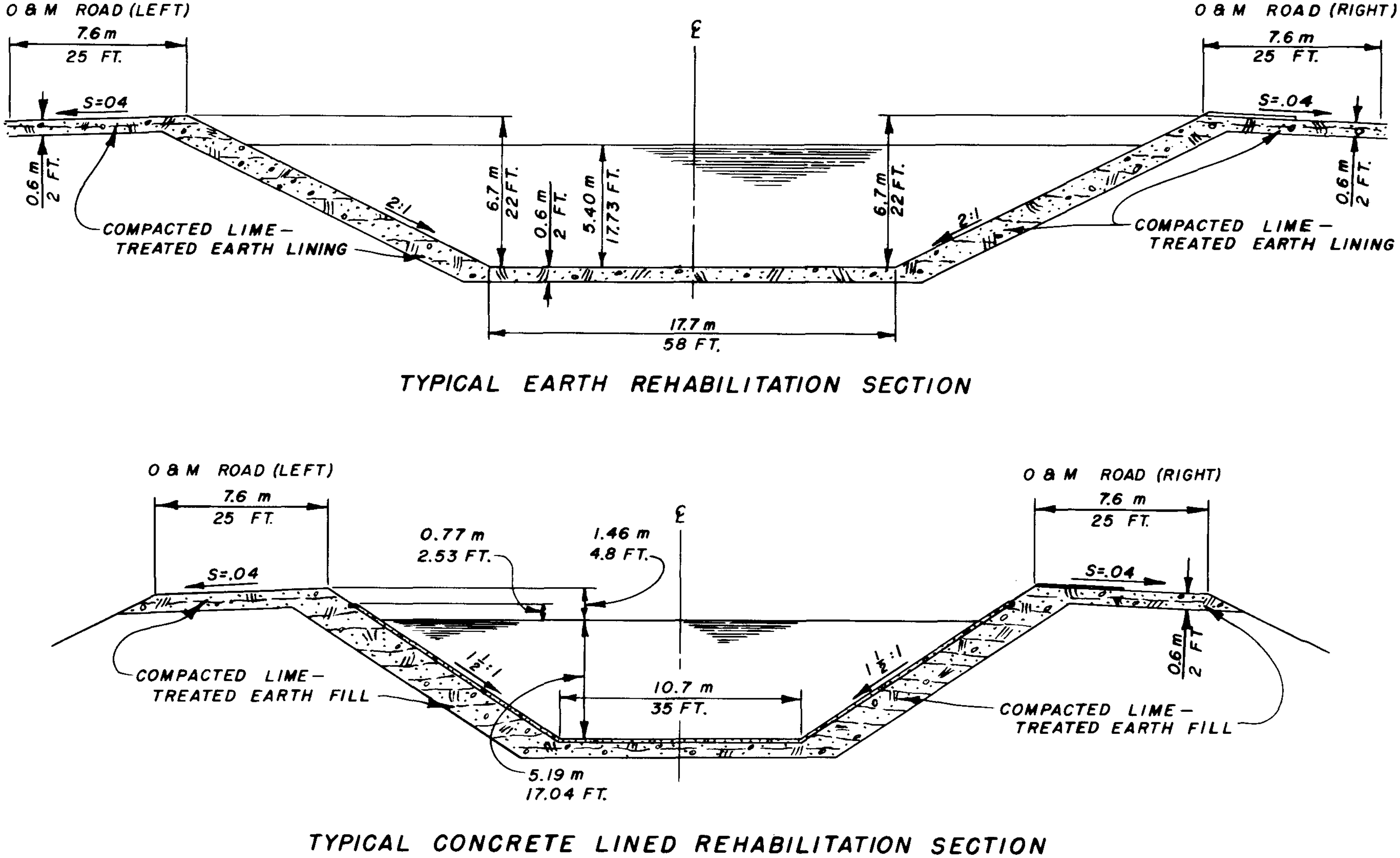

Figure 1.–Rehabilitated canal sections.

to the soil. The contractor elected to use granular quicklime, with 3.2 percent quicklime considered the equivalent of 4 percent hydrated lime. The amount of quicklime was increased to 4 percent due to difficulties in controlling the lime content during construction.

2. Samples of the compacted soil-lime had unconfined compressive strengths averaging about 20 times more than the unconfined compressive strength of the untreated soil.

3. The average unconfined compressive strength of the compacted soil-lime was about 2000 kPa (300 lb/in^2) 1 to 2 years after construction.

4. The strength of the compacted soil-lime increases with age.

5. The addition of lime reduced the PI (plasticity index) of the soil from about 40 to about 10.

6. The lime content of the soil-lime ranged from 0.5 to 4.2 percent. Even the low lime content showed a strength gain of eight times that of the untreated soil. However, some method of closer control of the lime content during construction would be beneficial to assure that the necessary amount of lime is being added uniformly throughout the embankment.

7. The compressive strength of the soil-lime was directly proportional to its compacted density.

8. After the lime and water has been mixed into the soil, compaction can begin as soon as the soil-lime is considered friable enough.

9. If possible, the soil should be compacted during the first 8 hours after mixing to obtain the maximum density, durability, and strength.

10. After a 24-hour mellow time, there is little difference in the density or strength of the soil-lime for longer mellowing times.

11. The durability of the soil-lime, based on wet-dry laboratory tests, is reduced with increased mellowing time.

12. The low air temperatures experienced on the Friant-Kern Rehabilitation Project during the winter construction period appeared to be beneficial for the construction operation rather than detrimental.

The following summary is based on test results of material from seven undisturbed soil-lime block samples from Friant-Kern Canal rehabilitation in 1973. Specimens for determining in-place density, unconfined compressive strengths, and wet-dry durability were obtained by coring the blocks with a 76-mm (3-in) diameter concrete core barrel. A summary of this test data is shown in table B-9.

1. The effective percent lime content (CaO content of treated soil minus CaO content of untreated soil) ranged from 2.3 percent to 4.2 percent.

2. The in-place dry density of the soil-lime ranged from 1170 kg/m^3 (73 lb/ft^3) to 1710 kg/m^3 (107 lb/ft^3). The natural moisture content of the soil-lime ranged from 21 to 44 percent.

3. The densities and moisture of the block samples correlated well with nearby field density tests results. Therefore, this laboratory data represents the as-built condition of the rehabilitated Friant-Kern Canal.

4. The unconfined compressive strengths for the material 6 months after placement ranged from 1130 kPa (164 lb/in^2) to 3300 kPa (478 lb/in^2). The strengths were directly proportional to the density of the specimens.

5. The wet-dry durability of the material was related to the density of the specimens, but apparently not to the lime content.

PROPERTIES OF SOILS FOR CANAL LININGS

Soil that is to be compacted and used as a canal lining must meet criteria for seepage, erosion, stability, and volume change. In general, canal linings are constructed of soils with a PI (plasticity index) of 10 to 25. Such soils would be classified, according to the Unified Classification System, as GC, SC, CL, GM, SM, ML, or combinations of these. Permeability tests and triaxial shear tests are used to evaluate the seepage potential and the soil strength for stability of the canal slopes. If the PI is 20 or below, soil workability is satisfactory and volume change is generally not a problem. The optimum moistures of these soils average about 14 to 20 percent and the shrinkage limit ranges from 10 to 20 percent. Thus, when the material is placed close to the optimum water content, it is also placed near its shrinkage limit. So, regardless of wetting and drying cycles, shrinkage and cracking is not severe, nor is it a significant problem.

The shrinkage limit is the water content of a soil below which a reduction in moisture will not cause a decrease in the volume of the soil mass. If the shrinkage limit is below the placement water content (generally close to optimum), then as the soil goes through wet and dry cycles due to water level fluctuations in the canal and dewatering operations, the soil can shrink and crack due to the decrease in moisture content from optimum to the shrinkage limit. If the shrinkage limit is close to optimum or above, then shrinkage and cracking are not as severe.

Clays of high plasticity, CH in the Unified Classification System, have optimum moisture around 25 percent and shrinkage limits from 5 to 15 percent. Therefore, CH soils would be liable to shrinkage and cracking and are not generally recommended for canal linings. In addition, CH soils can be highly expansive and as they become saturated, they swell and soften, resulting in lower strength and stability.

Expansive Soils

Expansive soils are those which 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, resulting 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 reports listed in appendix A refer to the original studies on the soil, subsequent investigations of slide areas, and a field trial of electrochemical treatment to stabilize the expansive soil.

The expansive potential of the soil may be increased when it is 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 remolded expansive soil will expand significantly more than an undisturbed sample of the same soil due to thixotropic hardening of the latter.

Several remedial measures have been tried by O&M (operation and maintenance) personnel, to control the deterioration of the Friant-Kern Canal. The slope of the canal sides was flattened from 1-1/2:1 to 2:1, but these slopes were also unstable. In the 1950's an electrochemical method was tried, but apparently did not increase the soil strength enough for stabilization nor was it economically feasible.

This report covers the current stabilization method of strengthening the embankments by mixing lime with the existing clay soils. The addition of lime to the soil changes it from a potentially highly plastic, expansive material to a potentially nonexpansive siltlike material. The criteria can be analyzed to predict the expansiveness of a particular soil (table 1) and soil samples from Friant-Kern (table 2) illustrate the expansive potential of the soil.

To illustrate the effect of adding lime to the soil on its expansive potential, data from tests on soil 51Y-51 with 3.2 percent granular quicklime (equivalent to 4 percent hydrated lime) are shown in table 3.

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 (plastic limit) increased, thus reducing the PI (plasticity index) of the soil (PI = LL - PL). (2) The finer clay-size particles agglomerate to

Table 1.—*Relation of soil index properties and probable volume changes for highly plastic soils* [1]

Data from index tests[2]			Estimation of probable expansion,[3] percent total volume change (dry to saturated condition)	Degree of expansion
Colloid content (percent minus 0.001 mm)	Plasticity index	Shrinkage limits, percent		
>28	>35	<11	>30	Very high
20-31	25-41	7-12	20-30	High
13-23	15-28	10-16	10-20	Medium
<15	<18	>15	<10	Low

[1]This table appears as table 3 in Earth Manual, Bureau of Reclamation, 2nd Edition, p. 212, 1974.
[2]All three index tests should be considered in estimating expansive properties.
[3]Based on a vertical loading of 6.9 kPa (1.0 lb/in^2) as for concrete canal lining. For higher loadings the amount of expansion is reduced, depending on the load and on the clay characteristics.

Table 2.—*Properties of soils from Friant-Kern Canal*

Index No.	Colloid content, (percent minus 0.001 mm)	PI (plasticity index)	SL (shrinkage limit)	Potential degree of expansion
3T-				
553		30	7	high
554		34	7	high
555		37	6	very high
556		36	7	very high
102	23	25	9	high
104	30	30	6	high
106	28	23	14	medium
130	35	50	12	very high
98	30	30	6	very high
98	30	30	6	very high
294		32	5	very high
299		50	7	very high
301	36	39	7	very high
302		38	7	very high
51Y-				
1	37	40	9	very high
2	55	41	7	very high
3	51	46	7	very high
5	41	37	8	very high
51	36	36	7	very high

Table 3.—*Effect of lime on Friant-Kern Canal soil*

Condition	Colloid content (percent minus 0.001 mm)	PI (plasticity index)	SL (shrinkage limit)	Potential degree of expansion
Untreated soil 51Y-51	36	36	7	Very high
With 3.2 percent lime, 0 hours after mixing		13	28	Low
72 hours after mixing		9	30	Low

form larger particles. (3) The large particles (clay clods) disintegrate to form smaller particles. (4) A drying effect takes place due to the absorbtion 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 is an essential factor and the improved workability of the soil-lime is 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, plasticity index 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. If a minimum strength material is needed, enough lime can be added to obtain that strength. Or enough lime can be added to increase the shrinkage limit to the placement moisture or higher to prevent excessive volume change through wetting and drying cycles.

In early 1970, block soil samples from the proposed construction sites on Friant-Kern Canal were tested to evaluate the percentage of lime required. The consistency limits and pH values of various lime percentages were determined (fig. 2) for two of the samples. Based on the pH values and the reduction in PI, 2 percent lime was sufficient. However, 4 percent lime was recommended to compensate for variations in field construction conditions and to increase the shrinkage limit to about optimum moisture (placement moisture) of the mixture. At this point, only hydrated lime was being considered and these tests were performed using hydrated lime.

Unconfined compressive strengths of the undisturbed clay ranged from 15 to 158 kPa (2.1 to 22.9 lb/in^2) and of the remolded clay from 72 to 123 kPa (10.5 to 17.8 lb/in^2). With 4 percent hydrated lime added and cured for 7 days, the strength was 1477 kPa (214.2 lb/in^2); another specimen soaked for an additional 7 days had a strength of 461 kPa (66.8 lb/in^2). Details of the 1970 tests are given in appendix B.

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

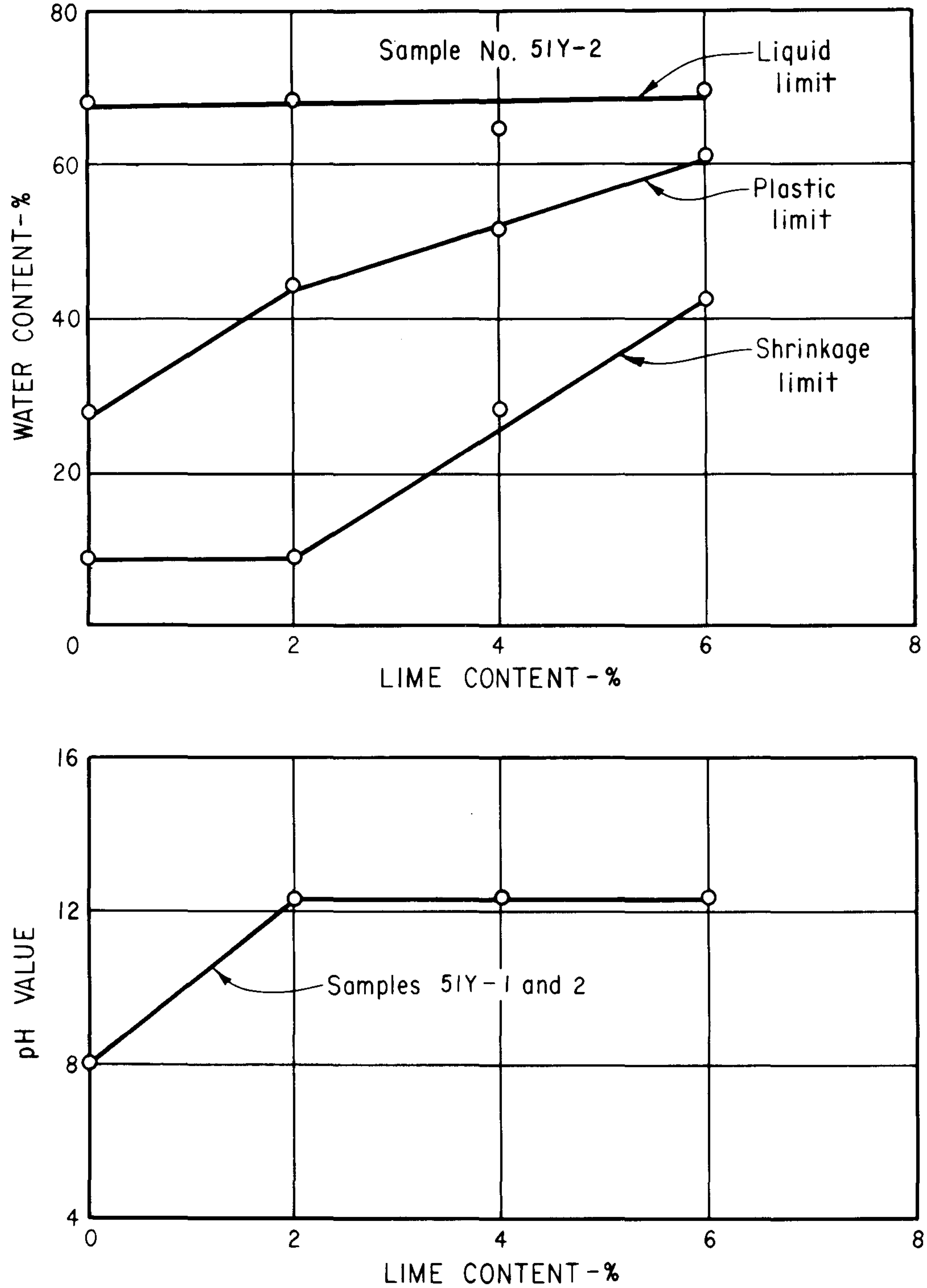

Figure 2.-Effects of varying amounts of hydrated lime on expansive clays.

the amount of quicklime was increased to 4 percent with the provision that extra quicklime be added where Government inspectors felt it necessary.

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 0.6 m (2 ft) 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 (fig. 3) 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 0.3-m (1-ft) 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 0.6-m (2-ft) 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 that was to be stabilized with lime and recompacted was removed by a benching operation. A series of long sloping benches or ramps were 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 and 0.3 m (1 ft) 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 benching operation is shown in figure 4. The material was spread on the canal bottom and 2 percent additional lime added as shown in figure 5. Then water was added to at least 2 percent over optimum moisture, then about 0.3-m (1-ft) depth of material was mixed with dozers and graders as shown in figure 6, with the rock being continually removed. After about 2 m (6.6 ft) 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 (fig. 7). A cable winch on a crane moved the roller up and down the slope.

The side slopes were constructed in three 0.4-m (1.2-ft) compacted lifts to give the specified 1.1-m (3.6-ft) compacted depth normal to the slope. The completed slope is shown in figure 8.

There are only 2 months, December and January, when the canal is unwatered and available for construction rehabilitation. The construction was started in the winter of 1972-73 and completed in the winter of 1973-74. There were 190 000 m^3 (250 000 yd^3) of soil-lime placed, under this contract.

UNDISTURBED BLOCK SAMPLES

Following the placement of the soil-lime, several undisturbed block samples were submitted to the Bureau Engineering and Research Center for testing. Of particular interest was the determination of the actual lime percentage in the mixture, the natural density and moisture, the strength, and the durability of the samples. Details of the testing are presented in appendices C and D.

Table 4 gives a summary of the test results on the block samples, along with results of tests on untreated soil, to provide a comparison. Some of the block samples were taken immediately after construction and some were taken a year later.

The effective lime content is the difference in the CaO (calcium oxide) content of the treated material and untreated material. Samples 51Y-43 through -49 were compared to untreated soil sample No. 51Y-51 which had a natural CaO content of 3.6 percent. Samples No. 51Y-54, -55, and -57 were also compared to the untreated soil sample No. 51Y-51. The CaO content corresponds approximately to the

Figure 3.–Rotary mixer mixing the soil, lime, and water. Photo P214-D-77913

Figure 4.–Long ramps cut down along the side slopes to canal bottom in benching operation. Photo P214-D-77911

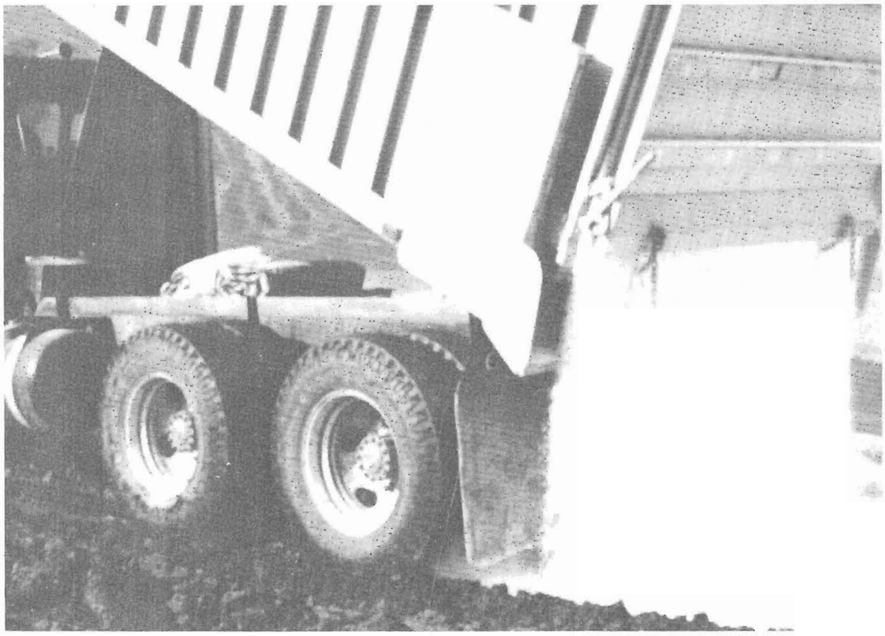

Figure 5.–Lime being spread on canal bottom prior to mixing. Photo P214-D-77912

Figure 6.–The contractor is using a road grader and a three-bottom, one-way, moldboard plow to process and mix lime into material for earth lining in the canal. Photo CN805-243-6874NA

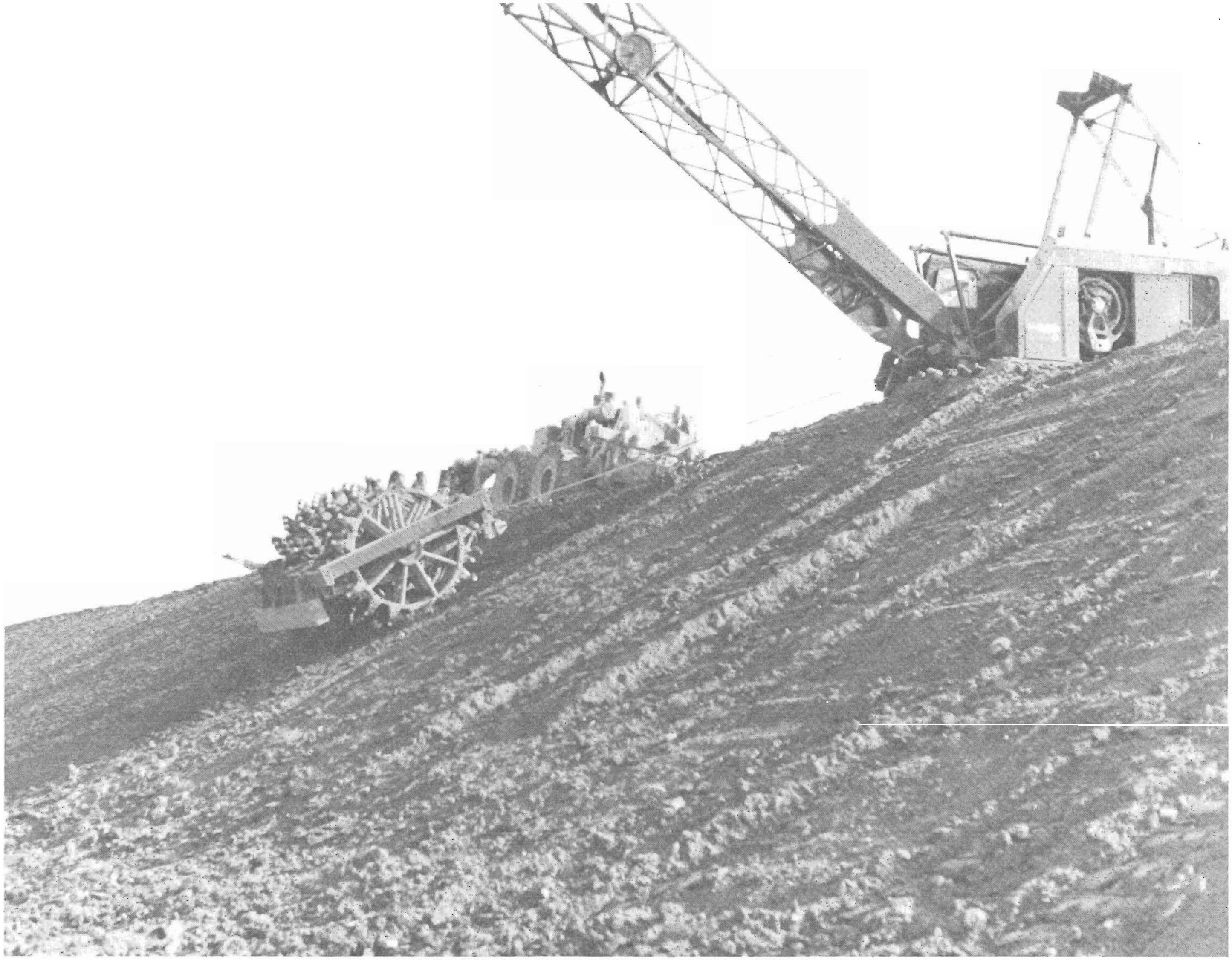

Figure 7.–A self-cleaning sheepsfoot roller in use to compact lime-treated material on the canal slope. Photo CN805-243-6980NA

Figure 8.–Completed canal slope of compacted soil-lime. Photo P214-D-77910

percent quicklime added as estimated by project personnel except for samples No. 51Y-55 and -57 which showed an added lime content of 1 percent or less. If some of the soil-lime is being placed at this low lime content, perhaps some determination of lime content during the construction should be implemented.

The untreated material had an unconfined compressive strength of 110 kPa (16 lb/in²). The soil-lime material had strengths ranging from 870 kPa (126 lb/in²) to 3560 kPa (516 lb/in²), with an average of 2120 kPa (308 lb/in²). Even the soil-lime samples with low lime content (1.0 percent or less) had strengths over 8 times as great as the untreated material.

Samples No. 51Y-47 and -54 were taken from the same area, but a year apart. There is apparently some increase in strength with time, 2260 to 3560 kPa (328 to 516 lb/in²), for the in-place material.

All the soil-lime samples were nonplastic, whereas the untreated material had plasticity indices of 30 to 46. Some of the core specimens were subjected to three cycles of soaking and drying at a temperature of 38 °C (100 °F). As shown in table 4, some specimens did not survive the three wet-dry cycles, with the exceptions of specimens from the high-density, low-moisture samples. The specimens from blocks 44 and 49 had almost identical densities and moistures, and one crumbled during testing and one did not.

LABORATORY TEST RESULTS

The specifications for the Friant-Kern Canal Rehabilitation required a minimum of 2 days and a maximum of 7 days mellow time for the lime-treated earthfill. For this report, the following definitions are used:

- Mellow time.–The time period between the mixing of the lime with the soil and the compaction of the soil-lime mixture.
- Cure time.–The elapsed time since the final compaction of the soil-lime mixture.

After their initial experience with soil-lime construction in the winter of 1973-74, the field personnel asked the Denver office to investigate the effects of mellow time and temperature on the strength of the compacted soil-lime earthfill.

Effect of Mellow Time on Lime-soil Material

The Proctor moisture-density curves, soil consistency values, and the unconfined compressive strengths of a soil-lime mixture were determined for the following mellow times: 0 hour, 2 hours, 8 hours, 24 hours, 48 hours, and 72 hours. The soil used was from the jobsite at canal station 3122+40. The lime was a sample of the granular quicklime used on the project. The water was Denver tapwater. The soil was dried and screened and the material which passed a No. 4 screen (minus No. 4 material) was used for the mellow-time study. The properties of the untreated soil are shown in figure 9. The

Table 4.—*Laboratory test results, undisturbed block samples*

Sample No.[1] 51Y-	Station and location	Effective lime content, percent	Inplace condition			Unconfined compression					Wet-dry durability	Percent fines, (minus 200 screen)	Liquid limit	Plasticity index	Shrinkage limit
			Dry density,		Moisture,	Date percent	Date placed	Soaked samples	Strength,						
			kg/m³	(lb/ft³)					kPa	(lb/in²)					
43	3121+00 road	2.6	1710	(107)	21	11–72	12–72	yes	3300	(478)	good				
44	3173+00 road	4.2	1410	(88)	32	12–72	12–72	yes	1130	(164)	poor				
45	3187+00 road	3.6	1550	(97)	27	12–72	12–72	yes no	2430 1580	(353) (229)	good				
46	4338+08 slope	3.8	1170	(73)	44	1 –73	1 –73	—	—	—	poor				
47	3122+40 bottom	3.0	1490	(93)	29	12–72	1 –73	yes	2260	(328)	good	54		NP	
48	4331+25 bottom	2.9	1190	(74)	44	12–72	12–72	—	—	—	poor				
49	3140+00 slope	2.3	1460	(91)	30	1 –73	1 –73	yes no	1990 2250	(289) (326)	good				
51	3122+40		loose untreated soil									73	53	36	7
53	3122+40		loose untreated soil									65	51	30	10
54	3122+00 bottom	3.1	1510	(94)	30	12–72	1 –74	yes	3560	(516)		37		NP	
55	3187+00 slope	1.0	1460	(91)	31	12–72	1 –74	yes	870	(126)		48		NP	
56	3162+50	un-treated	1470	(92)	30		1 –74	no	110	(16)		89	70	46	7
57	3197+20	0.5	1590	(99)	26	12–73 or 1 –74	1 –74	yes	1860	(269)		50		NP	
58	3142+20		loose untreated soil									84	67	44	5

[1]Sample No. Example: 51Y (representative sample index number)
43 (representative sample number)

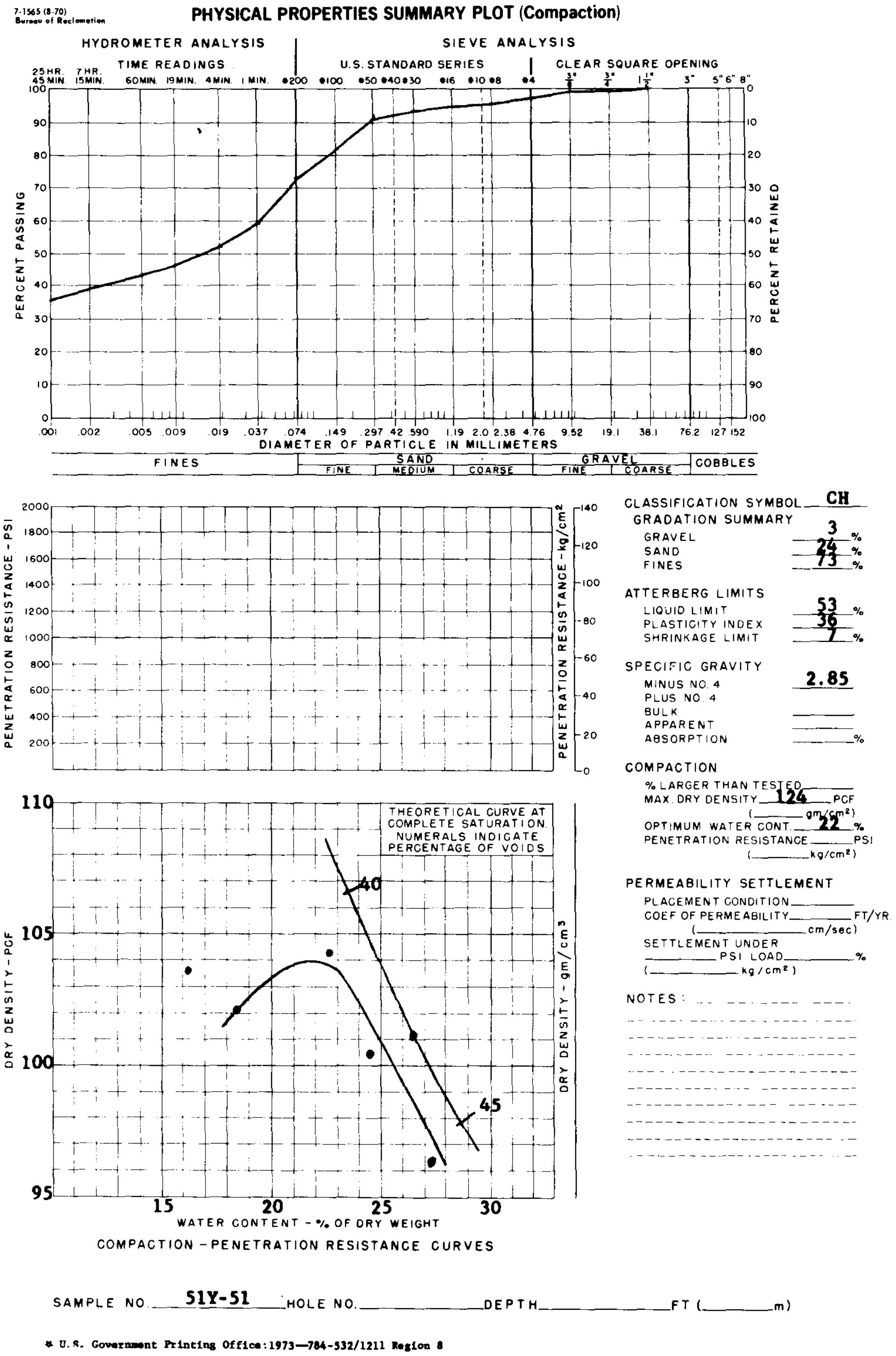

Figure 9.–Physical properties summary plot (compaction), sample No. 51Y-51.

lime, 3.2 percent by dry weight of the soil, was added to the dry soil, mixed, and enough water was added to bring the soil-lime mixture to a moisture content about five percent above optimum. Then at 0, 2, 8, 24, 48, and 72 hours after mixing, a sample of the soil-lime mixture was taken and Proctor moisture density curves and consistency limits were determined and cylinders prepared for unconfined compressive strength tests.

Effect of Mellow Time on Moisture-density Curves

The moisture-density curves for the untreated soil and the soil-lime for the various mellow times are shown on figure 10. The longer the soil-lime mixture mellowed, the lower the maximum density and the higher the optimum moisture. The largest difference in maximum density and optimum moisture occurred between the 2-hour and the 8-hour mellow time. After the 8-hour mellow-time, the change in maximum dry density and optimum were perceptible but insignificant.

Effect of Mellow Time on Strength

Immediately after the maximum density had been determined, three unconfined compressive strength specimens were prepared at 95 percent of the maximum density. The specimens were cured for 28 days in a sealed plastic bag and then broken in a compression testing machine. The averages of three specimens are plotted in figure 11 along with the maximum density for each of the mellow-time periods. The strengths of the cylinders are directly related to the density of the strength cylinders.

To see if the mellow time had a direct influence on the strength at 72 hours, mellow strength specimens were prepared at 95 percent of maximum density for the 2 hours rather than maximum density for the 72-hour test. The average strength was slightly higher than the 2 hours' strength specimens.

Effect of Mellow Time on Durability

Seven cylinders of the lime-treated soil were subjected to three cycles of soaking and two cycles of drying. The cylinders were compacted to 95 percent of Proctor maximum dry density for their particular mellow-time period. Six of the samples represented mellowing times of 0, 2, 8, 24, 48, and 72 hours. The seventh cylinder was prepared from material which had mellowed 72 hours, but was placed at 95 percent of the maximum dry density obtained for the 2-hour mellow time. The specimen density was equivalent to 102 percent of its respective Proctor maximum dry density. After the third soaking cycle, six of the samples had materially disintegrated. The other, the 72-hour cylinder placed at 95 percent of the 2-hour density, remained relatively intact. If the soil-lime construction material is placed at 95 percent of the maximum dry density for the respective mellowing time, the areas of the canal prism that are subject to wetting and drying action could suffer surface deterioration if not protected.

Effect of Mellow Time on Soil Consistency Values

The immediate effect of adding lime to a soil is to reduce the liquid limit and increase the plastic limit, thus reducing the plasticity of the soil (reduction in the plasticity index). Soil consistency tests (liquid limit, plastic limit, and shrinkage limit) were performed on the soil-lime mixture at the same time the Proctor moisture-density curves were being performed. Table 5 shows these values plus the plasticity index for the various mellow times along with the values for the untreated soil.

The 3.2 percent lime added to the soil reduced the PI of the soil about 70 percent. There was little difference in the LL, PL, PI, or the SL for the soil-lime mixture from 0- to 72-hour mellow time. The biggest change in the plasticity of the soil occurs within a few minutes of mixing. Letting the soil mellow for a certain time period has no advantage with respect to the plasticity of the soil-lime mixture.

The specifications call for 100 percent of the material to pass the 19-mm (3/4-in) screen and 60 percent to pass the No. 4 screen. In the laboratory tests the untreated soil was minus No. 4 material. After adding lime and water, 90 percent of the soil-lime mixture passed the No. 4 screen and 100 percent passed with slight hand pressure.

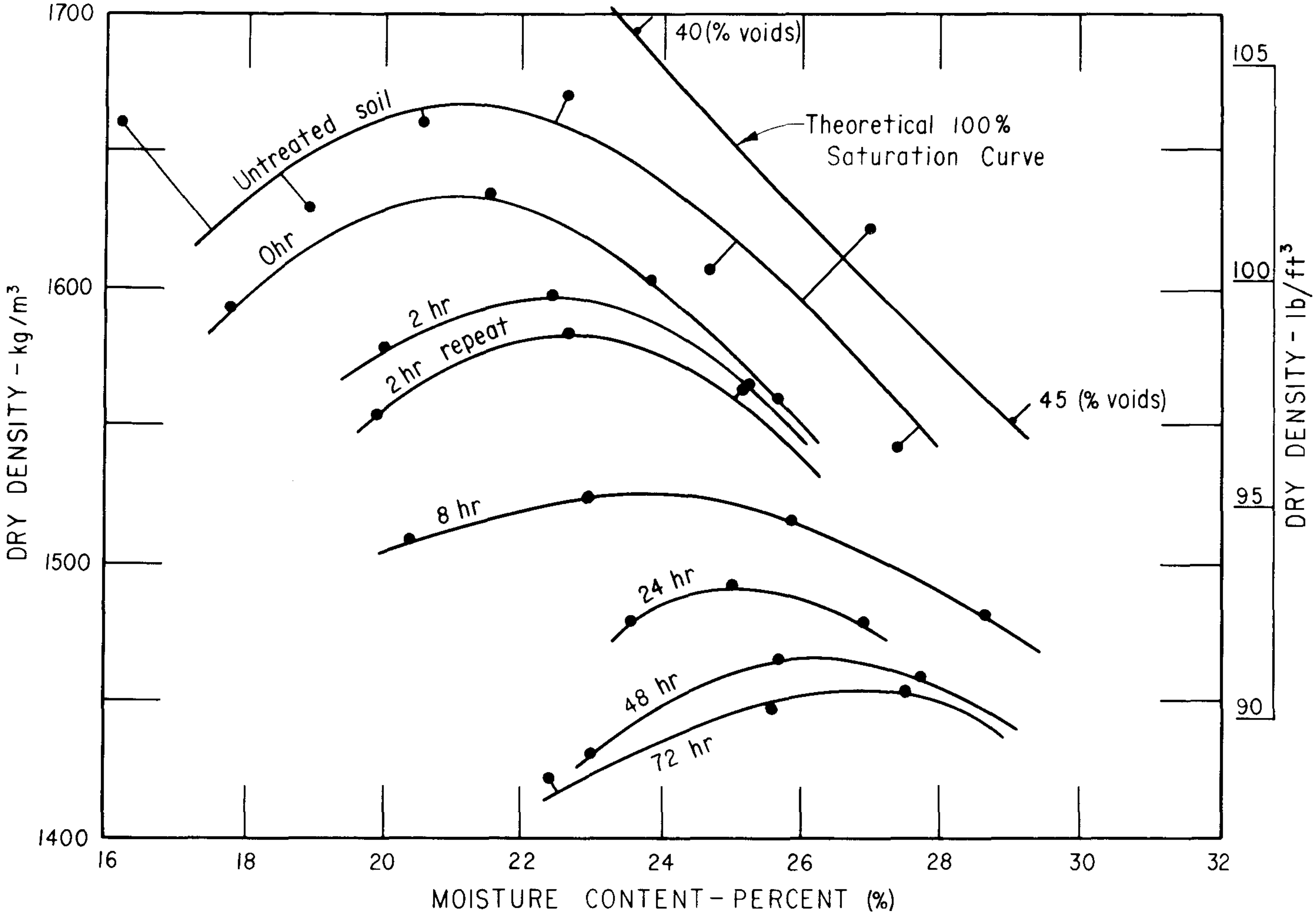

Figure 10.–Effect of mellow time on moisture-density curves of compacted soil-lime.

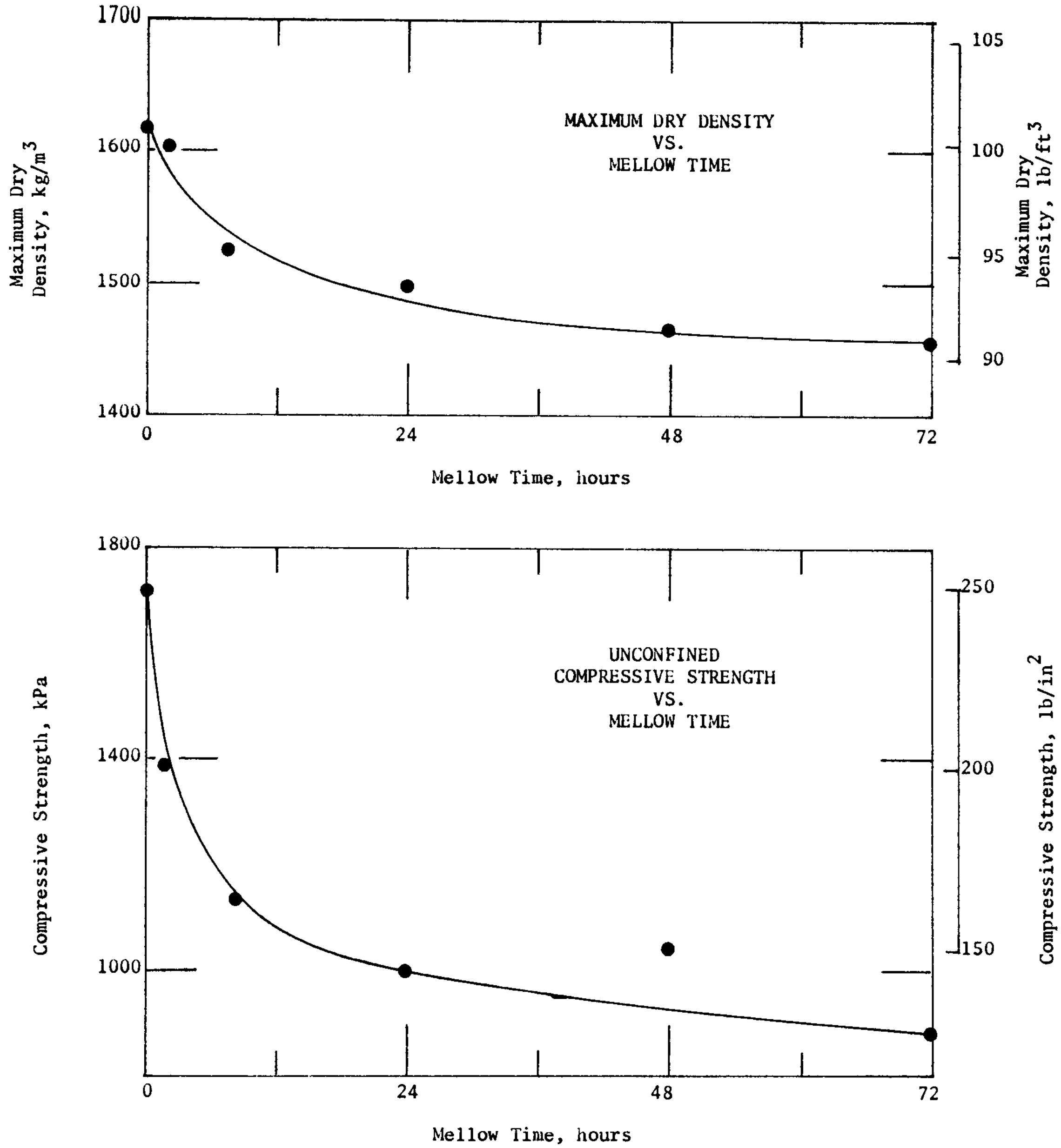

Figure 11.–Effect of mellow time on strength of soil-lime compacted to 95 percent of laboratory maximum dry density.

Effect of Temperature on Soil-lime

The soil and lime were cooled separately to a temperature of 2.2 °C (36 °F). Tapwater at a temperature of 25 °C (77 °F) was then mixed with soil and lime. The temperature of the mixture was about 27 °C (80 °F) immediately after mixing. The mixture was then placed in a cooler for 24 hours. The temperature of the material was 5.6 °C (42 °F) at the beginning of the moisture-density curve determination and the consistency tests.

Effect of Temperature on Moisture-density Curves

The compaction curve for the cool soil-lime mixture is compared with the curves for the room temperature mixture in figure 12. The maximum dry density was 64 kg/m³ (4 lb/ft³)

Table 5.—*Lime stabilization study, soil consistency values*

Condition	Liquid limit	Plastic limit	Plasticity index	Shrinkage limit
Untreated soil				
sample 1	56.1	19.9	36.2	—
sample 2	53.3	17.0	36.3	7.3
0 hrs mellow	47.7	34.8	12.9	28.3
2 hrs	42.8	31.4	11.4	30.9
8 hrs	40.4	33.2	7.2	31.6
24 hrs	41.8	31.1	10.7	30.9
48 hrs	42.6	32.3	10.3	30.0
72 hrs	40.9	31.9	9.0	30.4
Low temperature sample				
24 hrs	39.5	35.1	4.4	27.0

higher than the soil-lime mixture which had mellowed 24 hours at room temperature. The optimum moisture content was 2 percent less. The cooler temperature apparently retards the chemical processes. Thus, cooler temperatures during the placement of soil-lime earthwork would be an asset rather than a liability.

Effect of Temperature on Strength

The specimens for unconfined compressive strength tests were prepared immediately after the compaction tests. The test specimens were cured for 7 days at 0 °C (32 °F). Half of the specimens were then removed and cured at room temperature. The strength tests were performed at the end of 28 days.

Even though their density was higher, the strength of the cooled soil-lime was lower than the soil-lime placed at room temperature. The strengths of the specimens cured for 7 days at 0 °C (32 °F) and 21 days at room temperature were higher than the specimens cured at 0 °C for 28 days. With a longer curing period at warmer temperatures, the strength of soil-lime placed during cool weather should be equal to or greater than soil-lime placed at warm temperature.

Effect of Temperature on Soil Consistency Values

The consistency tests were performed at the same time as the compaction tests. The PI of the cool soil-lime was 4.4 compared to 10.7 for the soil-lime at room temperature for a 24-hour mellow time. The lower plasticity of the cool temperature material would be an advantage for the contractor during mixing and compaction operations.

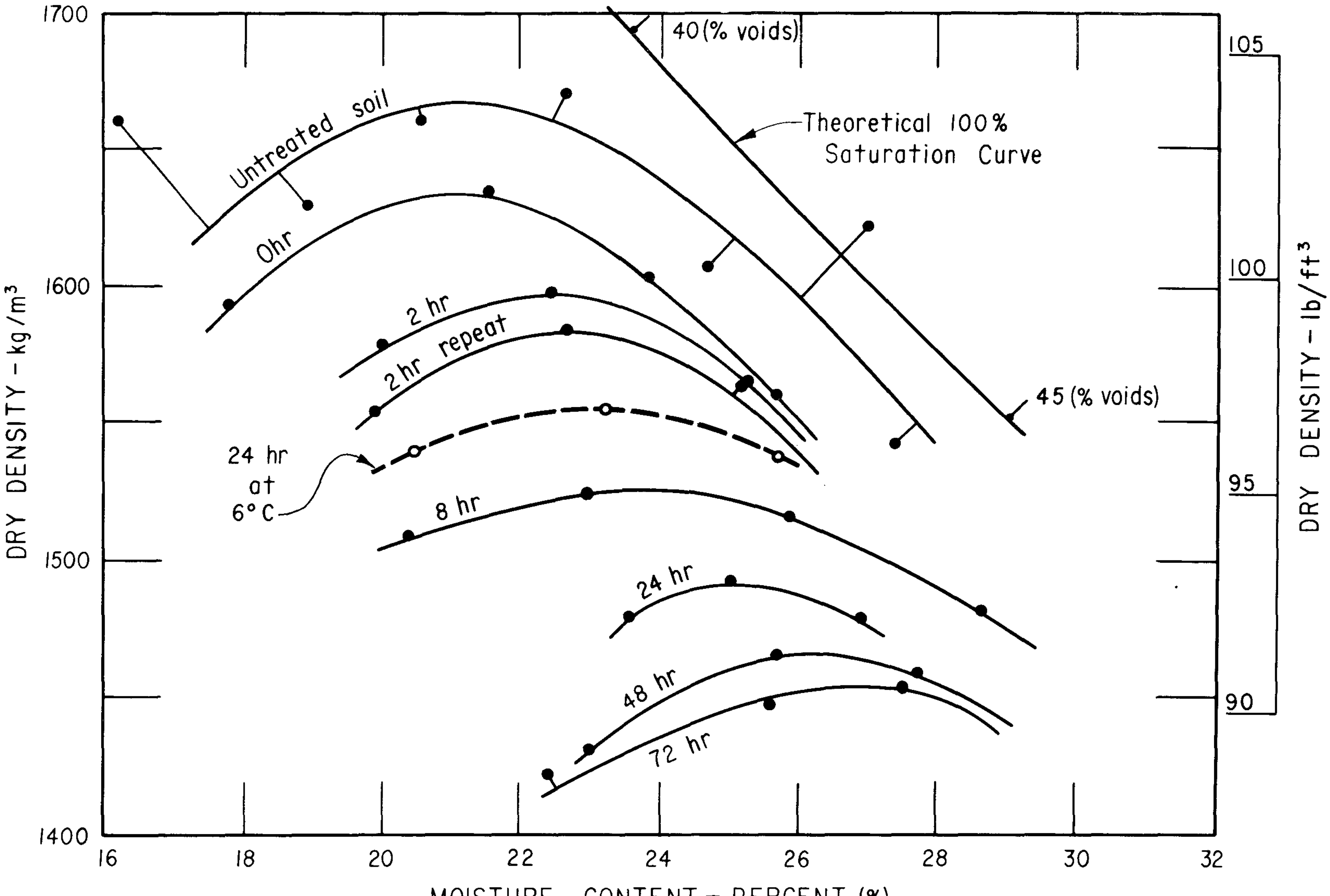

Figure 12.–Effect of temperature on moisture-density curve of compacted soil-lime.

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[11] "Earth Manual," second edition, p. 453-465, 1974.

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APPENDIX A

Selection of Lime Content; 1970 Tests

In January 1970, four undisturbed block samples were received from the Friant-Kern Canal for tests from which evaluation was made of the lime treatment. The original locations of the blocks and the laboratory identification numbers are as follows:

Sample, No. 51Y-	Location, mile-	Position on canal section	Elevation, m (ft)
1	79.92	right slope	125 (411)
2	79.92	right slope	126 (414)
3	79.85	left slope	126 (412)
5	79.94	right slope	126 (412)

A summary of the results of the consistency limits, gradation analysis, specific gravity, natural moisture and density, and unconfined compressive strength tests are shown on table A-1. In addition to this, unconfined compressive strength tests were run on air-dried, soaked, and remolded samples. To determine the percentage of lime required, 2, 4, and 6 percent hydrated lime was added and the pH and consistency limits determined for each mix. As a result of these tests, 4 percent hydrated lime was recommended.

Effect of Lime on Consistency Limits and pH Values

Different amounts of hydrated lime, 2, 4, and 6 percent were added to the clay and the consistency limits and pH of the mixture. These data are shown on table A-2, and for samples 51Y-1 and -2 are plotted and shown on figure 2 in the main text.

A 2-percent lime content appeared to be sufficient, based on the pH values and the reduction in PI. However 4 percent hydrated lime was required to increase the shrinkage limit to about optimum moisture (placement moisture) of the mixture. Quicklime was not used for these tests because only hydrated lime was being considered for the project. However 3.2 percent quicklime is considered equivalent to 4 percent hydrated lime.

Unconfined Compression Tests

Four unconfined compression tests were performed on each sample as follows:

(a) One at natural moisture and density

(b) One at natural density but soaked for 1 week

(c) One air-dried to approximate shrinkage limit then soaked for 1 week

(d) One remolded sample placed at natural density and moisture

In addition, material from sample No. 51Y-2 was mixed with 4 percent lime and five specimens were prepared and tested as follows:

(a) One with 7-day cure

(b) One soaked for 7 days

(c) One air-dried to approximate shrinkage limit, then soaked 7 days

(d) One with 28-day cure

(e) One cured for 7 days at 60 °C (140 °F)

The results are shown in table A-3. The strengths at natural density and moisture ranged from 28 to 158 kPa (4.0 to 22.9 lb/in^2) with an average of 61 kPa (8.8 lb/in^2). Soaking the samples for 1 week reduced the average strength to 22 kPa (3.2 lb/in^2) with a range of 15 to 30 kPa (2.1 to 4.4 lb/in^2).

Air drying the specimens gave a range of strengths from 14 to 32 kPa (2.0 to 4.6 lb/in^2) with an average of 20 kPa (2.9 lb/in^2). Remolding the samples increased the strength, with a range of 46 to 123 kPa (6.6 to 17.8 lb/in^2) for an average of 83 kPa (12.1 lb/in^2).

Adding 4 percent lime to the soil increased the strength (based on the remolded specimen) from 83 to 1480 kPa (12 to 214 lb/in^2) (7-day cure)

Table A-1.—*Summary of physical properties test results* (in-place density) *samples No. 51Y-1 through 4*

PROJECT Central Valley FEATURE Friant-Kern Canal SHEET 1 OF 1

IDENTIFICATION				PARTICLE-SIZE FRACTIONS IN PERCENT						CONSISTENCY LIMITS			SPECIFIC GRAVITY				INPLACE DENSITY			
				FINES										PLUS NO. 4						
SAMPLE NUMBER 51Y-	Station Elevation	Location	CLASSIFICATION SYMBOL	SMALLER THAN 0.005 mm	0.005 TO 0.074 mm	SAND NO. 200 (0.074 mm) TO NO. 4 (4.76 mm)	GRAVEL NO. 4 (4.76 mm) TO 3 IN. (76.2 mm)	COBBLES 3 IN. (76.2 mm) TO 5 IN. (127 mm)	OVERSIZE LARGER THAN 5 IN. (127 mm)	LIQUID LIMIT - %	PLASTICITY INDEX - %	SHRINKAGE LIMIT - %	MINUS NO. 4	BULK	APPARENT	ABSORPTION - %	DRY DENSITY kg/m³	Dry Density lb/ft³	Moisture Content – %	
1	mile 79.92 411	right slope	CH	65	30	5	-			66	40	9	2.75				1357	84.7	33.7	
2	mile 79.92 414	right slope	CH	66	29	5	-			68	41	7	2.75				1294	80.8	32.9	
3	mile 79.85 412	left slope	CH	63	29	8	-			70	46	7	2.73				1259	78.6	38.7	
4	mile 79.94 412	right slope	CH	52	27	21	-			57	37	8	2.74				1443	90.1	30.2	

TABLE ____ SHEET ____ OF ____

Table A-2.—*Characteristics of treated samples.*

Sample No., 51Y-	Lime added, %	Liquid limit	Plasticity index	Shrinkage limit	pH value
1	0				8.2
	2				11.9
	4				12.4
	6				12.6
2	0	68	41	7	8.6
	2	68	23	9	11.9
	4	65	13	28	12.4
	6	70	9	43	12.6
3	0	70	46	7	8.5
	2	73	26	13	11.8
	4	65	17	35	12.4
	6	69	16	42	12.7
5	0				8.9
	2				12.2
	4				12.4
	6				12.5

and 1740 kPa (252 lb/in^2) (28-day cure). Soaking the soil-lime specimen for a week resulted in a strength of 460 kPa (67 lb/in^2) and air drying for a week resulted in a strength of 124 kPa (18 lb/in^2).

Table A-3 also shows the natural density and moisture of samples cut from the undisturbed blocks and measured by the suspension in air and water method, or Designation E-10, "Earth Manual," (see Bibliography).

Table A-3.—*Unconfined compressive strength of soil and soil-lime samples*

Sample no., 51Y-	Specimen no.	Initial specimen data: As prepared: Dry density, kg/m³	(lb/ft³)	Moisture content, percent	Degree of saturation, percent	Wetted: Dry density, kg/m³	(lb/ft³)	Moisture content, percent	Degree of saturation, percent	Unconfined compression: Axial strain, percent	Strength, kPa	(lb/in²)	Treatment
1	1	1340	(83.7)	33.6	88					0.6	28	(4.1)	Natural moisture
	2	1355	(84.6)	33.4	89	1362	(85.0)	36.1	97	1.3	20	(2.9)	Soaked 1 week
	3	1373	(85.7)	34.0	—	1363	(85.1)	35.9	97	3.9	17	(2.5)	Air-dried, then soaked 1 wk.
	4	1333	(83.2)	33.3	86					4.9	92	(13.4)	Remolded
2	1	1374	(79.5)	33.7	80					1.4	30	(4.3)	Natural moisture
	2	1317	(82.2)	32.5	82	1314	(82.0)	37.0	93	1.6	14	(2.1)	Soaked 1 week
	3	1291	(80.6)	32.5	—	1261	(78.7)	40.3	94	4.8	14	(2.0)	Air-dried, then soaked 1 wk.
	4	1296	(80.9)	32.3	79					4.1	72	(10.5)	Remolded
3	1	1250	(78.0)	39.2	90					3.5	28	(4.0)	Natural moisture
	2	1251	(78.1)	39.3	91	1266	(79.0)	41.2	98	2.0	22	(3.2)	Soaked 1 week
	3	1278	(79.8)	37.7	—	1274	(79.5)	40.4	97	4.8	17	(2.5)	Air-dried, then soaked 1 wk.
	4	1269	(79.2)	37.5	89					5.7	46	(6.6)	Remolded
5	1	1456	(90.9)	29.3	91					2.0	158	(22.9)	Natural moisture
	2	1413	(88.2)	31.2	90	1383	(86.3)	35.1	98	1.5	30	(4.4)	Soaked 1 week
	3	1459	(91.9)	30.1	—	1466	(91.5)	31.0	98	2.4	32	(4.6)	Air-dried, then soaked 1 wk.
	4	1469	(91.7)	28.1	89					5.6	123	(17.8)	Remolded
[1]2	1	1418	(88.5)	27.9	—					0.5	1477	(214.2)	Humidity[2]
	2	1410	(88.0)	28.8	84	1360	(84.9)	33.4	90	1.3	461	(66.8)	Humidity,[2] soaked[3]
	3	1415	(88.3)	28.5	—	1362	(82.5)	35.6	91	3.6	122	(17.7)	Humidity,[2] air-dried, soaked[3]
	4	1402	(87.5)	29.1	—					0.5	1740	(252.4)	28 days, 100% rel. humidity
	5	1403	(87.6)	29.4	—					0.5	2826	(409.8)	Sealed 7 days at 140° F

[1]With four percent hydrated lime added.
[2]Seven days in 100 percent relative humidity
[3]Then one week soaked in water

Table A-4.—*Summary of unconfined compression test results*

PROJECT Central Valley FEATURE Friant-Kern Canal SHEET 1 OF 1

IDENTIFICATION			CLASSIFICATION SYMBOL	SPECIFIC GRAVITY	SPECIMEN NUMBER	INITIAL SPECIMEN DATA						TEST VALUES AT FAILURE, MAX ($\sigma_1 - \sigma_3$)			UNCONFINED COMPRESS. STRENGTH - psi (kg/cm²)	COHESION - psi (kg/cm²) (IF APPLICABLE)	
						AS PREPARED			WETTED								
SAMPLE NUMBER 51Y	Station Elevation	Location				DRY DENSITY - pcf (gm/cm³)	MOISTURE CONTENT - %	DEGREE OF SATURATION - %	DRY DENSITY - pcf (kg/cm²)	MOISTURE CONTENT - %	DEGREE OF SATURATION - %	EFF. LATERAL PRESSURE - psi (kg/cm²)	VOLUME CHANGE - %	AXIAL STRAIN - %			
1	mile 79.92	right	CH	2.75	1	83.7	33.6	88						0.6	4.1	Nat. moist.	
	411	slope			2	84.6	33.4	89	85.0	36.1	97			1.3	2.9	Soaked 1 week	
					3	85.7	34.0		85.1	35.9	97	Air-Dried, then		3.9	2.5	Soaked 1 week	
					4	83.2	33.3	86						4.9	13.4	Remolded	
2	mile 79.92	right	CH	2.75	1	79.5	33.7	80						1.4	4.3	Nat. moist.	
	414	slope			2	82.2	32.5	82	82.0	37.0	93			1.6	2.1	Soaked 1 week	
					3	80.6	32.5		78.7	40.3	94	Air-Dried, then		4.8	2.0	Soaked 1 week	
					4	80.9	32.3	79						4.1	10.5	Remolded	
3	mile 79.85	left	CH	2.73	1	78.0	39.2	90						3.5	4.0	Nat. moist.	
	412	slope			2	78.1	39.3	91	79.0	41.2	98			2.0	3.2	Soaked 1 week	
					3	79.8	37.7		79.5	40.4	97	Air-Dried, then		4.8	2.5	Soaked 1 week	
					4	79.2	37.5	89						5.7	6.6	Remolded	
5	mile 79.94	right	CH	2.74	1	90.9	29.3	91						2.0	22.9	Nat. moist.	
	412	slope			2	88.2	31.2	90	86.3	35.1	98			1.5	4.4	Soaked 1 week	
					3	91.1	30.1		91.5	31.0	98	Air-Dried, then		2.4	4.6	Soaked 1 week	
					4	91.7	28.1	89						5.6	17.8	Remolded	
2	with 4% hydrated lime				1	88.5	27.9					7 days 100% R.H.		0.5	214.2		
	added				2	88.0	28.8	84	84.9	33.4	90	7 days 100% R.H.		1.3	66.8	Soaked 7 more days	
					3	88.3	28.5		82.5	35.6	91	7 days 100% R.H.		3.6	17.7	Air-Dried soaked	
					4	87.5	29.1					28 days 100% R.H.		0.5	252.4		
					5	87.6	29.4					7 days at 140° F sealed		0.5	409.8		

APPENDIX B

Undisturbed Block Samples–1973

Seven undisturbed soil-lime block samples were received in February 1973 from the Friant-Kern Canal rehabilitation construction site. Table B-1 gives the original locations and laboratory identification numbers.

The following tests were performed on the samples: density, moisture content, unconfined compression, percent lime content, wet-dry durability, and permeability.

The specimens for testing were obtained by coring the undisturbed blocks with a 76-mm (3-in) diameter concrete core barrel. A summary of the results are shown in table B-2.

Percent Lime Content

Material from each block and from sacks of untreated soil submitted with the blocks, were tested for percent CaO (table B-3) by the Applied Sciences Branch of the Division of General Research.

In-place Density and Moisture Content

Four specimens from each block were obtained by coring; the diameters and lengths were measured, and the specimens weighted to determine the in-place wet densities. One specimen from each block had the moisture determined after the specimen was tested in unconfined compression. Another moisture sample was taken from the excess material from each block. In addition, an initial moisture

Table B-1.—Soil-lime block samples No. 43 through 49—1973

Sample No., 51Y-	Station	Location on canal section	Elevation, m (ft)	Lime added,[1] percent
43	3121+00	road 28 m (93 ft) right[2] of centerline	1324 (434.5)	3.3
44	3173+00	road 26 m (85 ft) right	132.6 (435.0)	5.0
45	3187+00	road 27 m (88 ft) right	132.3 (434.0)	4.0
46	4338+08	slope 12 m (40 ft) right	126.8 (416.0)	4.0
47	3122+40	bottom 6 m (19 ft) right	126.3 (414.5)	unknown
48	4331+25	bottom 3 m (10 ft) left	122.2 (401.0)	4.0
49	3140+00	slope 12 m (38 ft) right	126.5 (415.0)	4.0

[1]As estimated by project personnel.
[2]Right—facing downstream

Table B-2.—*Summary of physical properties test results (in-place density) samples No. 41Y-43 through 51*

PROJECT Central Valley FEATURE Friant-Kern Canal Rehabilitation SHEET 1 OF 1

IDENTIFICATION				PARTICLE-SIZE FRACTIONS IN PERCENT						CONSISTENCY LIMITS			SPECIFIC GRAVITY				INPLACE DENSITY			
				FINES										PLUS NO. 4						
SAMPLE NUMBER 51Y-	Station Elevation	Location	CLASSIFICATION SYMBOL	SMALLER THAN 0.005 mm	0.005 TO 0.074 mm	SAND NO. 200 (0.074 mm) TO NO. 4 (4.76 mm)	GRAVEL NO. 4 (4.76 mm) TO 3 IN. (76.2 mm)	COBBLES 3 IN. (76.2 mm) TO 5 IN. (127 mm)	OVERSIZE LARGER THAN 5 IN. (127 mm)	LIQUID LIMIT - %	PLASTICITY INDEX - %	SHRINKAGE LIMIT - %	Specific Gravity MINUS NO. 4	Added Lime Content - %	Unconfined compressive Strength k Pa	Unconfined compressive Strength lb/in2	DRY DENSITY kg/m3	Dry Density lb/ft3	Moisture Content - %	
43	3121+00 434.5	road 28m (93')Rt												2.6	3296	478	1714	107	21	
44	3173+00 435.0	road 26m (85')Rt												4.2	1131	164	1410	88	32	
45	3187+00 434.0	road 27m (88') Rt												3.6	2434	353	1554	97	27	
46	4338+08 416.0	slope 12m (40')Rt												3.8			1169	73	44	
47	3122+40 414.5	bottom 6m (19')Rt		21	33	46	-	mech. disp.			N.P.		2.82	3.0	2262	328	1490	93	29	
48	4331+25 401.0	bottom 3m (10') left												2.9			1185	74	44	
49	3140+00 415.0	slope 12m (38') right												2.3	1993	289	1458	91	30	
51	3122+40	untreated																		

Table B-3.—*Percent lime content samples No. 43 through 49 and 51*

Sample No. 51Y-	Lime added[1] during construction, %	Laboratory test total CaO, %	Effective percent lime (treated minus untreated), %
43	3.3	6.2	2.6
44	5.0	7.8	4.2
45	4.0	7.2	3.6
46	4.0	7.4	3.8
47	unknown	6.6	3.0
48	4.0	6.5	2.9
49	4.0	5.9	2.3
51	untreated	3.6	—

[1] As estimated by project personnel.

content was back-calculated from data obtained on specimens tested in unconfined compression after soaking for 7 days. The moistures and densities for individual specimens and the average for each block is shown in table B-5, and summary of those data in table B-4.

Table B-6 shows the densities and moisture contents of the undisturbed blocks compared to nearby fill densities and moistures reported by the project. The block densities and moistures correlate very well to the field in-place densities and moistures.

Unconfined Compression Tests

Two core specimens from each block were tested in unconfined compression. One specimen was tested at the natural moisture, and one specimen was soaked for 7 days before testing. The strengths appear to be related to the length of the sample and the density, but apparently have no correlation with moisture or lime content. The specimens were divided into two groups according to their length, 152 mm (6 in) and 114 to 140 mm (4.5 to 5.5 in). Table B-7 shows the two groups along with their strengths, density, and moisture. Figure B-1 shows the strengths of the specimens versus their density, illustrating the correlation between strength and density. The unconfined compression tests were conducted about 6 months after construction.

Wet-dry Tests

The wet-dry durability tests were performed according to procedures established for soil-cement. The samples were soaked for 7 days, oven-dried at 71 °C (160 °F) for 42 hours, weighed and measured, soaked for 5 hours, weighed and measured; then back to the oven for 42 hours, and the process repeated. Three cycles of drying and wetting were completed. As shown in table B-8, some of the specimens did not survive the three cycles. With the exception of specimens from blocks 51Y-44 and -49, the high-density, low-moisture samples were more durable than the low-density, high-moisture specimens. The specimens from blocks 51Y-44 and -49 had almost identical densities and moistures, and the former crumbled during testing while the latter did not. The percent lime had no apparent effect on the differences in wet-dry durability since the lime content of 51Y-44 was twice that of 51Y-49.

Figure B-2 shows sample No. 51Y-45 after the second drying period as an example of a core that remained intact. Figures B-3, B-4, and B-5 show the progressive deterioration of sample No. 51Y-48 through two drying cycles. Figure B-6 shows the shrinkage cracks in the clay balls present in specimen 51Y-44.

It was apparent that the wet-dry durability test procedures used for soil-cement were too stringent for lime-clay soils. The drying cycle was too severe and did not represent actual field conditions.

Table B-4.—*In-place density and moisture content samples No. 43 through 49*

Sample No., 51Y-	Dry density, kg/m^3 (lb/ft^3)	Moisture content, %
43	1710 (107)	21
44	1410 (88)	32
45	1550 (97)	27
46	1170 (73)	44
47	1490 (93)	29
48	1460 (74)	44
49	1458 (91)	30

Table B-5.—*Density and moisture contents for undisturbed soil-lime block samples, samples No. 51Y-43 through 49—1973*

Sample no., 51Y-	Specimen no.	Wet density, kg/m³	(lb/ft³)	Moisture content, percent	Dry density, kg/m³	(lb/ft³)	Test method
43				21.5			
	1	2079	(129.8)				Direct moisture determination
	2	2030	(126.7)	21.2	1676	(104.6)	Density by measurement, direct moisture determination
	3	2076	(129.6)	19.9	1732	(108.1)	Density by measurement, moisture back calculated
	4	2075	(129.5)				
	AVERAGE	2075	(128.9)	20.9	1703	(106.30	Density by measurement
				$\frac{128.9}{1.209}$ =	1708	(106.6)	Dry density based on wet density
44				29.3			Direct moisture determination
	1	1825	(113.9)	36.2	1339	(83.6)	Density by measurement, direct moisture determination
	2	1877	(117.2)				Density by measurement, direct moisture determination
	3	1871	(116.8)	31.7	1421	(88.7)	Density by measurement, direct moisture determination
	4	1882	(117.5)				Density by measurement, direct moisture determination
	AVERAGE	1863	(116.3)	32.4	1379	(86.1)	Density by measurement
				$\frac{116.33}{1.324}$ =	1408	(87.9)	Dry density based on wet density
45				27.6			Direct moisture determination
	1	1998	(124.7)				Density by measurement
	2	1962	(122.5)				Density by measurement
	3	1946	(121.5)	27.6	1525	(95.2)	Density by measurement, moisture back calculated
	4	1983	(123.8)	27.2		(97.3)	Density by measurement, direct moisture determination
	AVERAGE	1972	(123.1)	27.4	1559	(96.3)	Density by measurement
				$\frac{123.14}{1.274}$ =	1545	(96.6)	Dry density based on wet density

Table B-5 Continued.—*Density and moisture contents for undisturbed soil-lime block samples, samples No. 51Y-43 through 49—1973*

Sample no., 51Y-	Specimen no.	Wet density, kg/m³	(lb/ft³)	Moisture content, percent		Dry density, kg/m³	(lb/ft³)	Test method
46				45.3				Direct moisture determination
				43.8				Direct moisture determination
	1	1664	(103.9)	45.0		1149	(71.7)	Density by measurement, moisture back calculated
	2	1717	(107.2)					Density by measurement
	3	1680	(104.9)					Density by measurement
	4	1690	(105.5)	41.8		1192	(74.4)	Density by measurement, direct moisture determination
	AVERAGE	1689	(105.4)	44.0		1169	(73.0)	Density by measurement
				$\frac{105.4}{1.440}$	=	1173	(73.2)	Dry density based on wet density
47				30.0				Direct moisture determination
	1	1894	(118.2)	29.2		1466	(91.5)	Density by measurement, direct moisture determination
	2	1969	(122.9)	28.1		1536	(95.9)	Density by measurement
	3	1962	(122.5)					Density by measurement
	4	1886	(117.7)					Density by measurement
	AVERAGE	1927	(120.3)	29.1		1501	(93.7)	Density by measurement
				$\frac{120.3}{1.291}$	=	1493	(93.2)	Dry density based on wet density
48				43.5				Direct moisture determination
				44.8				Direct moisture determination
	1	1719	(107.3)	45.0		1185	(74.0)	Density by measurement direct moisture determination
	2	1664	(103.9)					Density by measurement
	3	1685	(105.2)	41.8		1189	(74.2)	Density by measurement, direct moisture determination
	4	1689	(105.4)					Density by measurement
	AVERAGE	1690	(105.5)	43.8		1187	(74.1)	Density by measurement
				$\frac{105.5}{1.438}$	=	1176	(73.4)	Dry density based on wet density

Table B-5. Continued—*Density and moisture contents for undisturbed soil-lime block samples, samples No. 51Y-43 through 49—1973*

Sample no., 51Y-	Specimen no.	Wet density, kg/m³	(lb/ft³)	Moisture content, percent	Dry density, kg/m³	(lb/ft³)	Test method
49				30.6			Direct moisture determination
	1	1871	(116.8)				Density by measurement, moisture back calculated
	2	1895	(118.3)	30.0	1458	(91.0)	Density by measurement
	3	1908	(119.1)				Density by measurement
	4	1911	(119.3)	29.3	1479	(92.3)	Density by measurement, direct moisture determination
AVERAGE		1897	(118.4)	30.0	1469	(91.7)	Density by measurement
				$\frac{118.4}{1.300}$ =	1459	(91.1)	Dry density based on wet density

Table B-6.—*Location of block samples and in-place field densities samples No. 51Y-43 through 49—1973*

Sample No. 51Y-	Density test identification[1]	Station	Distance from centerline[2] m (ft)	Location in canal prism	Elevation m (ft)	Dry density, kg/m³ (lb/ft³)	Moisture content, percent
43		3121+00	28 r (93)	Road	132.4 (434.5)	1710 (107)	21
	11-22-A-1	3113+00	26 r (87)	Road	133 (435)	1750 (109)	16
	11-22-A-2	3116+00	26 r (86)	Road	133 (435)	1670 (104)	19
44		3173+00	26 r (85)	Road	133 (435)	1410 (88)	32
	12-7-A-2	3171+00	28 r (92)	Road	133 (435)	1360 (85)	35
45		3187+00	29 r (88)	Road	132 (434)	1550 (97)	27
	12-7-A-1	3192+50	26 r (86)	Road	133 (435)	1680 (105)	21
46		4338+08	12 r (40)	Slope	127 (416)	1170 (73)	44
	1-7-A-1	4337+05	11 r (35)	Slope	127 (416)	1220 (76)	39
	1-11-A-1	4338+75	11 r (35)	Slope	125 (415)	1220 (76)	45
47		3122+40	6 r (19)	Bottom	126 (415)	1490 (93)	29
	12-18-A-1	3120+00	1 r (3)	Bottom	125 (415)	1810 (113)	30
	12-23-A-4	3120+00	8 r (25)	Bottom	126 (415)	1710 (107)	20
48		4331+25	3 l (100)	Bottom	122 (401)	1190 (74)	44
	12-23-A-1	4331+60		Bottom	122 (401)	1280 (80)	42
49		3140+00	12 r (38)	Slope	126 (415)	1460 (91)	30

[1]Data obtained from Construction (L-29) Progress Reports.

[2]Distance as shown, (r) right or (l) left, from centerline

Table B-7.—*Unconfined strength of core from block samples No. 51Y-43 through 49—1973*

Sample No. 51Y-	Specimen No.	Soaked	Strength, kPa	Strength, (lb/in²)	Density, kg/m³	Density, (lb/ft³)	Moisture, percent	Comments	Plotted in figure B-1
			152 mm (6-in) specimens						
43	3	Yes	3300	(478)	1710	(106.6)	20.9		x
44	3	Yes	1130	(164)	1410	(87.9)	32.4		x
45	3	Yes	2430	(353)	1550	(96.6)	27.4		x
45	3	No	1580	(229)	1560	(97.1)	27.6	Clay inclusion	
47	1	Yes	2260	(328)	1500	(93.2)	29.1	Two pieces	x
49	2	Yes	1990	(289)	1460	(91.1)	30.0		x
49	4	No	2250	(326)	1460	(91.1)	30.0		x
			114- to 140-mm (4½ to 5½ in) specimens						
44	1	No	3090	(448)	1410	(87.9)	32.4		x
46	1	Yes	2560	(371)	1170	(73.2)	44.0		x
47	2	No	1700	(247)	1490	(93.2)	29.1	Poor sample	
48	1	Yes	2070	(301)	1180	(73.4)	43.8		x

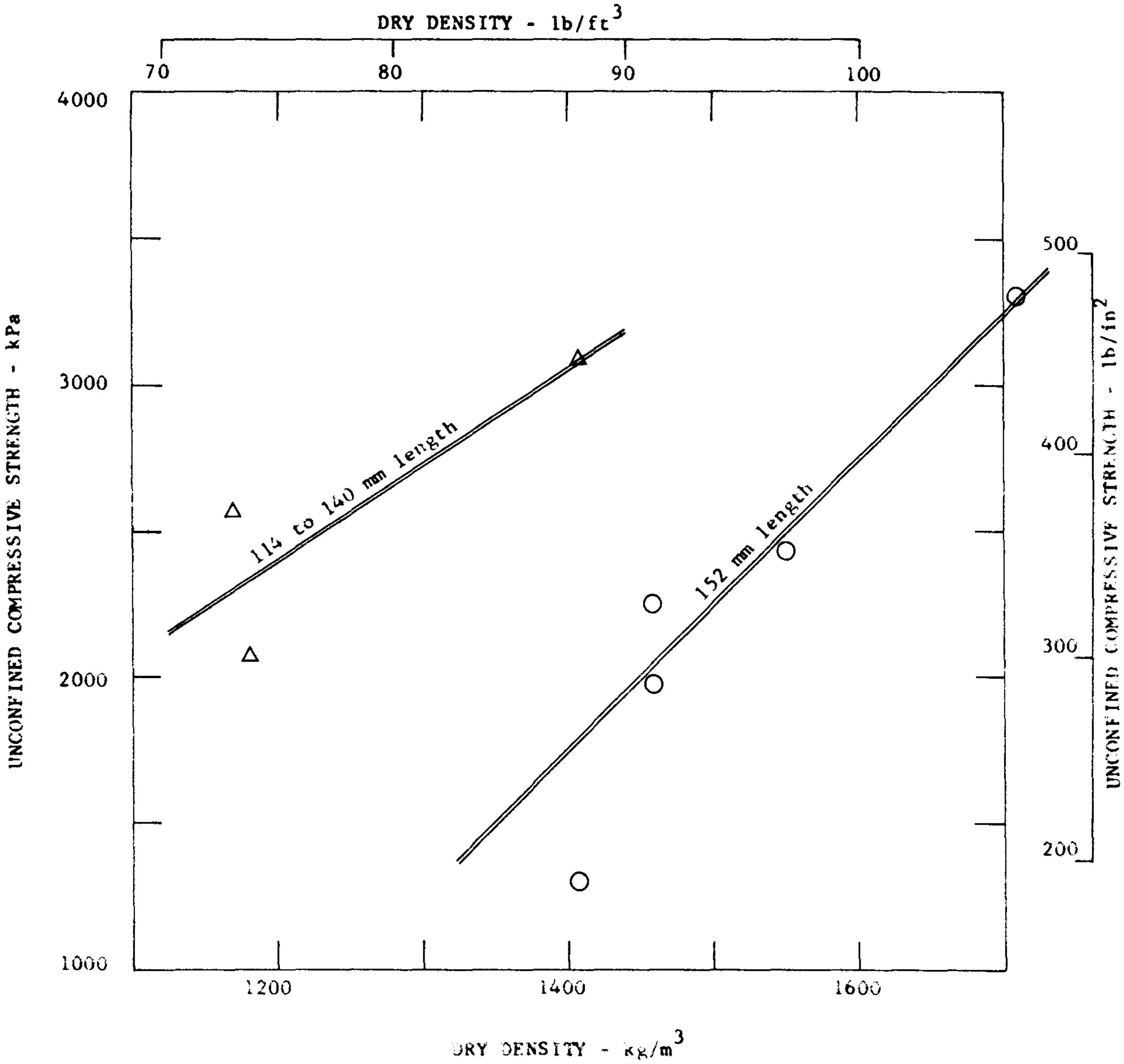

Figure B-1.–Compressive strength versus dry density relationships for soil-lime core specimens.

Table B-8.—*Wet-dry durability tests, undisturbed soil-lime block samples No. 51Y-43 through 49—1973*

Sample no., 51Y-	Effective quick lime, percent	Specimen[1] w %	Specimen[1] γd kg/m³	Specimen[1] γd (lb/ft³)	Condition, (after three wet-dry cycles)
43	2.6	20.9	1710	(106.6)	good
44	4.2	32.4	1410	(87.8)	crumbled cycle 2
45	3.6	27.4	1550	(96.6)	good
46	3.8	44.0	1170	(73.2)	crumbled cycle 2
47	3.0	29.1	1490	(93.2)	good
48	2.9	43.8	1180	(73.4)	crumbled cycle 2
49	2.3	30.0	1460	(91.1)	good

w = moisture content (%)
γd = dry density (unit weight)

Figure B-2.–Soil-lime core (51Y-45 core No. 1, tag No. 220 wet-dry after second drying period) after two wet-dry cycles. Photo E-2327-22NA

Figure B-3.–Soil-lime core (51Y-48 core No. 4 tag No. 230 wet-dry, after soaking 1 day) after 7 soaking days. Photo E-2327-9NA

Figure B-4.–Soil-lime core (51Y-48 (4) tag No. 230) wet-dry after first drying period, after 7 soaking days and 42 hours drying (one wet-dry cycle). Photo E-2327-18NA

Figure B-6.–Soil-lime core (51Y-44 (2) tag No. 239) wet-dry, after first drying period, after one wet-dry cycle (see fig. B-4). Photo E-2327-13NA

Figure B-5.–Soil-lime core (51Y-48 (4) tag No. 230) wet-dry, after second drying period, after two wet-dry cycles (see fig. B-4). Photo E-2327-26

Table B-9.—*Summary of test results, undisturbed soil-lime block samples No. 51Y-43 through 49—1973*

Block No., 51Y-	Station	Location	Elevation, m	Elevation, (ft)	Added CaO content, percent	Dry density, kg/m³	Dry density, (lb/ft³)	Moisture content, percent	Unconfined compressive strength, kPa[1]	(lb/in²)	kPa[2]	(lb/in²)	Wet-dry durability
43	3121+00	Road	132.4	(434.5)	2.6	1710	(107)	21	3300	(478)			Good
44	3173+00	Road	132.6	(435.0)	4.2	1410	(88)	32	1130	(164)	3090	(448)	Poor
45	3187+00	Road	132.2	(434.0)	3.6	1550	(97)	27	2430	(353)			Good
									1580	(229)			
46	4338+08	Slope	126.8	(416.0)	3.8	1170	(73)	44			2560	(371)	Poor
47	3122+40	Bottom	126.3	(414.5)	3.0	1490	(93)	29	2260	(328)	1700	(247)	Good
48	4331+25	Bottom	122.2	(401.0)	2.9	1190	(74)	44			2080	(301)	Poor
49	3140+00	Slope	126.5	(415.0)	2.3	1460	(91)	30	1990	(289)			Good
									2250	(326)			

[1]76-mm by 152-mm (3-in by 6-in) specimens.

[2]76-mm by 114-mm to 140-mm (3-in by 4½-in to 5½-in) specimens.

APPENDIX C

Undisturbed Block Samples–1974

In February 1974, four undisturbed block samples were received from the Friant-Kern Canal Rehabilitation Project. The table below gives the original locations and laboratory identification numbers:

The following tests have been run on the samples and the results summarized in table C-2.

Consistency limits	Moisture content
Gradation analysis	Unconfined compression
Specific gravity	Percent lime content
Density	

Coring to Obtain Test Specimens

As shown in figure C-1, a portable drill rig was clamped to the front of a forklift and a 76-mm (3-in) diameter diamond bit core barrel was used to core the undisturbed soil-lime blocks to obtain samples for testing. The blocks were anchored with sandbags as shown in figure C-2. This was a quick and simple method compared to hand cutting specimens from the soil-lime blocks. In the poorer samples, recovery of intact core was difficult as shown in figure C-3. Obtaining a core with the necessary 2 to 1, length to diameter ratio, for unconfined compression testing was a problem. However, in the better samples, it was possible to get a core extending the depth of the block as shown in figure C-4. Block 51Y-54 is shown in figure C-5 after twenty-four 76- by 152-mm (3- by 6-in) samples had been cored from this block. Test specimens from the block with no lime were obtained by hand cutting and trimming.

Standard Properties

The untreated block sample was classified as CH, highly plastic clay, according to the Unified Classification System. The lime treated material would have been classified as either SM (silty sand) or ML (sandy silt), if it were treated as a soil; however, since it is a unique material, it will not be classified according to the normal soil classification procedures.

The physical properties are listed in table C-2. Two different methods, mechanical dispersion and air dispersion, were used in the gradation analysis of the soil-lime mixture and the results (table C-1) vary considerably, one from the other. The mechanical dispersion breaks down the particles more than does the air-dispersion

Table C-1.—*Soil-lime block samples No. 51Y-54 through 57—1974*

Sample No. 51Y-	Station	Location on canal section	Elevation m (ft)	Year placed	Lime added
54	3122+00	bottom 5 m (15 ft) right of centerline	126.5 (415.0)	1973	yes
55	3187+00	slope 12 m (38 ft) right of centerline	128.0 (420.0)	1973	yes
56	3162+50	34 m (110 ft) left of centerline	133.5 (438.0)	—	no
57	3197+20	slope 14 m (46 ft) left of centerline	128.9 (423.0)	1974	yes

Table C-2.—*Summary of physical properties test results* (in-place density) *samples No. 51Y-54 through 57—1974*

PROJECT Central Valley FEATURE Friant-Kern Canal Rehabilitation SHEET 1 OF 1

IDENTIFICATION				PARTICLE-SIZE FRACTIONS IN PERCENT						CONSISTENCY LIMITS			SPECIFIC GRAVITY				INPLACE DENSITY			
				FINES										PLUS NO. 4						
SAMPLE NUMBER 51Y	Station Elevation	Location	CLASSIFICATION SYMBOL	SMALLER THAN 0.005 mm	0.005 TO 0.074 mm	SAND NO. 200 (0.074 mm) TO NO. 4 (4.76 mm)	GRAVEL NO. 4 (4.76 mm) TO 3 IN. (76.2 mm)	COBBLES 3 IN. (76.2 mm) TO 5 IN. (127 mm)	OVERSIZE LARGER THAN 5 IN. (127 mm)	LIQUID LIMIT - %	PLASTICITY INDEX - %	SHRINKAGE LIMIT - %	Specific Gravity	Lime Content %	Unconfined Compressive Strength k Pa	Unconfined Compressive Strength lb/in2	DRY DENSITY kg/m3	Dry Density lb/ft3	Moisture Content - %	Construction Season
54	3122+00	bottom	5m	10	27	60	3	mech.	disp.		N.P.		2.81	3.1	3585	520	1506	94	30	1973
	415.0	(15') Rt		3	9	85	3	air	disp.											
55	3187+00	slope	12m	21	28	48	3	mech.	disp.		N.P.		2.82	1.0	1034	150	1458	91	31	1973
	420.0	(38') Rt		7	10	80	3	air	disp.											
56	3162+00	untreated	34m	66	23	11	0			71	46	8	2.84	0	110	16	1474	92	30	
	438.0	(110') left																		
57	3197+00	slope	14m	17	32	49	2	mech.	disp.		N.P.		2.82	0.5	1793	260	1586	99	26	1974
		(46') left		5	13	80	2	air	disp.											

TABLE ____ SHEET ____ OF ____

Figure C-1.–Undisturbed hand-cut block of soil-lime being cored to obtain samples for laboratory testing. Photo P-214-D-77905

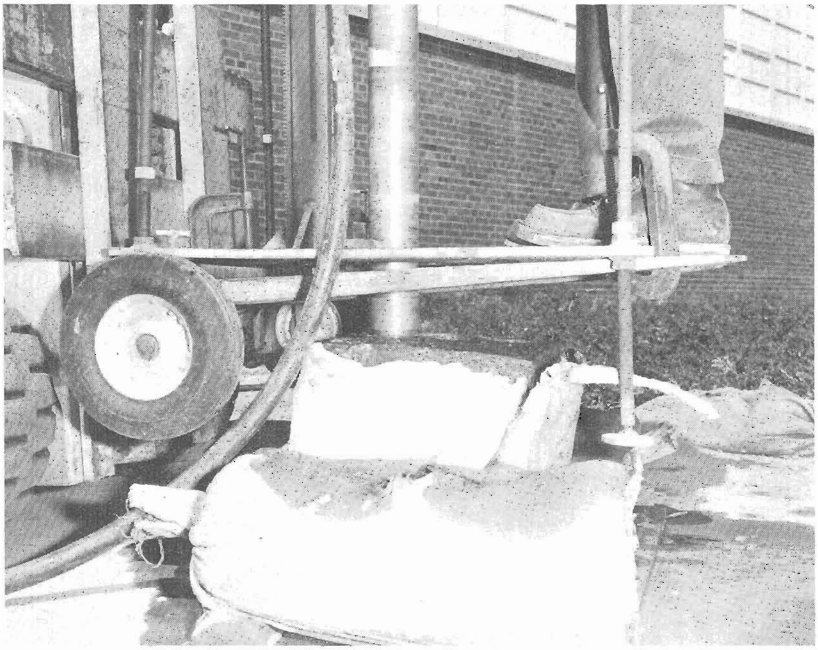

Figure C-2.–Soil-lime block anchored with sand bags for stability during drilling. Photo P-214-D-77906

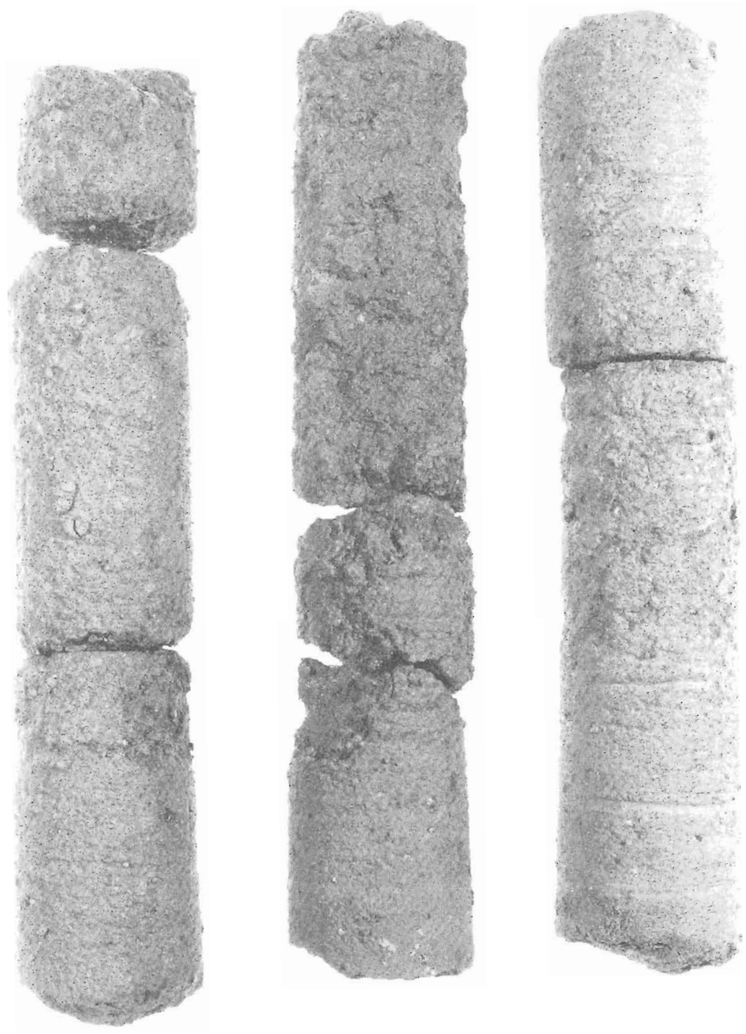

Figure C-3.–Core samples from hand-cut block 51Y-55, soil-lime. Photo P-214-D-77907

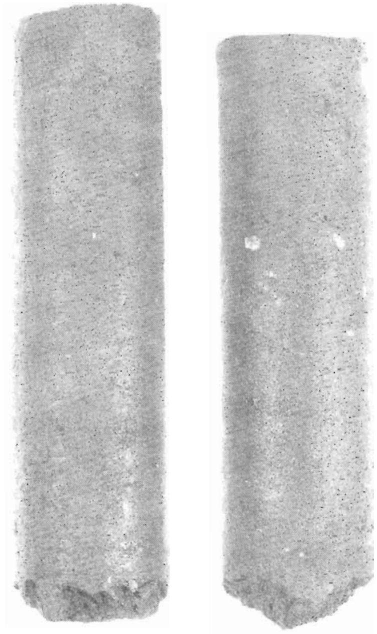

Figure C-4.–Core samples from hand-cut block 51Y-57, soil-lime. Photo P-214-D-77908

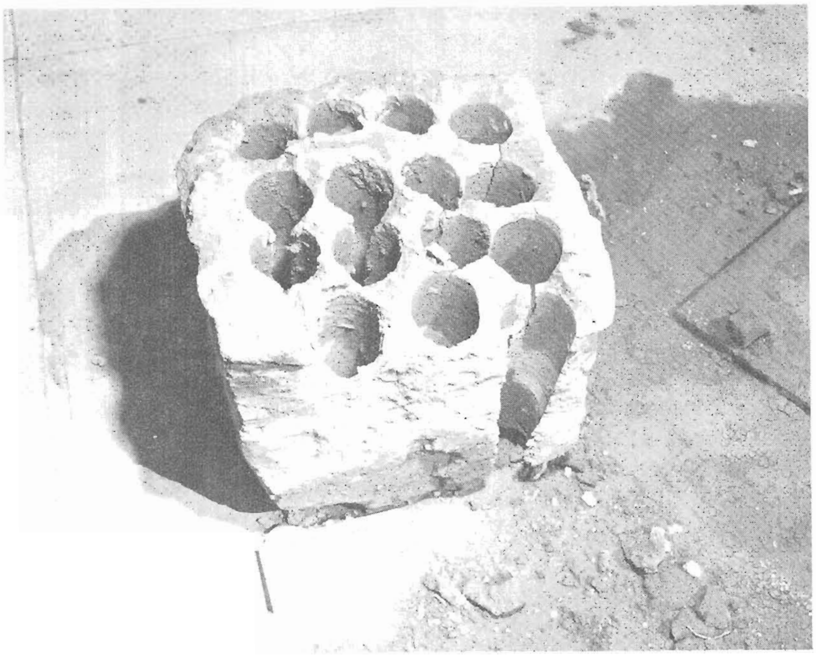

Figure C-5.–Soil-lime block 51Y-54 after completion of coring to obtain samples for laboratory testing. Photo P-214-D-77909 method, thus increasing the sand sizes about 50 percent and the percent of fines about 300 percent. Atterberg limits of the fine fraction of the material showed the fines to be nonplastic.

In-place Density and Moisture Content

The specimens obtained from coring were measured (9 diameters and 3 lengths, for each specimen) and weighed to determine the densities of the blocks. Some of the smaller pieces of core were used for moisture determinations only. In the cores which were soaked prior to testing in unconfined compression, the final moisture content was determined and the initial moisture content back-calculated. In addition, densities of some of the pieces were determined by the "suspension-in-air-and-water" method. Where both methods were used on the same sample, the suspension method density was generally 16 kg/m^3 (1 lb/ft^3) higher than the density by measurement. The moistures and densities for individual specimens and the average for each block is shown in tables C-3 through C-5.

The blocks were 254 mm (10 in) to 406 mm (16 in) deep, representing one compacted lift placement which was 400-mm (14-in) average depth on the job. Since a sheepsfoot roller was used which had shorter teeth than the compacted thickness, the specimens were divided into top and bottom categories to see if there were any differences in density or moisture. The density and moisture were uniform throughout blocks 51Y-54 and 51Y-57. Block 51Y-55 showed some difference but there were not enough samples to make a reliable determination. The center of block 51Y-54 was definitely less dense or stable than the top and bottom, and this was obvious during the coring operation.

The densities and moistures are summarized (table C-6) with the densities adjusted for the 16-kg/m^3 (1-lb/ft^3) higher value determined from the "suspension-in-air-and-water" method over the density, determined from measurements of the specimens.

Percent Lime Content

Material from the top and bottom of each block sample was tested by the Bureau Water Treatment Section for percent CaO, and compared with the percent CaO in a sample of untreated soil. The effective lime content equals the difference between that of the untreated and treated soil. Sample 51Y-54 (table C-7) shows 2.7 to 3.5 percent, or the expected amount of effective lime. Block samples obtained a year ago showed effective lime contents of 2.3 to 3.8 percent, with the average 3.2 percent.

Sample No. 51Y-55 from the 1972-73 construction period, and sample No. 51Y-57 from the 1973-74 construction period showed 0.2 to 1.2 percent effective lime content. The low lime content of these two samples is of particular concern because they are from the canal side slopes where the greatest strength is needed. Some consideration should be given to establish a field determination of percent CaO content, so the quality of the product can be assured during construction.

Unconfined Compression Strength

Five 76- by 152-mm (3- by 6-in) cylindrical specimens from block 51Y-54 were tested in unconfined compression. The strengths ranged from 2350 kPa (341 lb/in^2) to 4830 kPa (700 lb/in^2) with an average of 3560 kPa (516 lb/in^2) (table C-8). Three 76- by 102-mm (3- by 4-in) specimens from this block had strengths that ranged from 3170 to 4210 kPa (460 to 610 lb/in^2) with an average of 3590 kPa (520 lb/in^2). There was one 76- by 152-mm (3- by 6-in) specimen tested from block 51Y-55 with a strength of 870 kPa (126 lb/in^2). Three 76- by 102-mm (3- by 4-in) specimens from this block had strengths that ranged from 700 to 1510 kPa (102 to 219 lb/in^2), with an average of 1150 kPa (166 lb/in^2). The strengths of five 76- by 152-mm (3- by 6-in) specimens from block 51Y-57 ranged from 1630 to 2040 kPa (236 to 296 lb/in^2), with an average of 1860 kPa (269 lb/in^2). Three 76- by 102-mm (3- by 4-in) specimens from this block had strengths that ranged from 1450 to 2060 kPa (210 to 298 lb/in^2) for an average of 1820 kPa (264 lb/in^2).

Five specimens were hand cut from the block of untreated soil, 51Y-56, and tested in unconfined compression. The strengths ranged from 100 to 120 kPa (14 to 18 lb/in^2), with an average of 110 kPa (16 lb/in^2).

Table C-3.—*Density and moisture content, undisturbed soil-lime block samples, sample No. 51Y-54*

Specimen No.	Wet density, kg/m³	Wet density, (lb/ft³)	Moisture content, percent	Dry density, kg/m³	Dry density, (lb/ft³)	Location in block
Moisture			[3]30.5			Top
Moisture			[3]30.8			Top
Moisture			[3]30.7			Top
1-A1	[1]1918	(119.7)	[3]30.1	1474	(92.0)	Top
	[2]1953	(121.9)	[3]30.1	1501	(93.7)	Top
1-B1	[1]1932	(120.6)	[4]30.3	1483	(92.6)	Top
1-C1	[1]1946	(121.5)				Top
1-D1	[1]1950	(121.7)	[4]30.3	1496	(93.4)	Top
2-A1	[1]1945	(121.4)	[4]29.7	1498	(93.5)	Top
2-B1	[1]1935	(120.8)				Top
2-C1	[1]1974	(123.2)	Top			
2-D1	[1]1977	(123.4)				Top
3-A1	[1]1934	(120.7)				Top
3-B1	[1]1945	(121.4)				Top
3-C1	[1]1940	(121.1)	[4]30.1	1491	(93.1)	Top
3-D1	[1]1938	(121.0)				
4-A1	[1]1932	(120.6)				Top
4-B1	[1]1951	(121.8)				Top
Average	[1]1945	(121.4)	30.3	1488	(92.9)	Top
			30.1	1501	(93.7)	
	Dry density based on average wet density and moisture = 1493 kg/m³ (93.2 lb/ft³)					
4-C1	[1]1980	(123.6)				Center
Moisture			[3]31.9			Bottom
Moisture			[3]30.0			Bottom
Moisture			[3]33.7			Bottom
1-A2	1890	(118.0)				Bottom
1-B2	[1]2007	(125.3)				Bottom
1-C2	[1]1910	(119.2)				Bottom
1-D2	[1]2043	(127.5)				Bottom
2-A2	[1]1985	(123.9)	[4]25.6	1580	(98.6)	Bottom
2-B2	[1]1908	(119.1)	[4]30.8	1459	(91.1)	Bottom
2-C2	1919	(119.8)				Bottom
2-D2	1908	(119.1)				Bottom
3-A2	1954	(122.0)				Bottom
3-B2	1928	(120.4)				Bottom
3-C2	1938	(121.0)	[4]31.4	1475	(92.)	Bottom
3-D2	1928	(120.4)				Bottom
4-B2	1917	(119.7)	[4]31.5	1458	(91.0)	Bottom
Average	1942	(121.2)	30.7	1493	(93.2)	
	Dry density based on average wet density and moisture = 1485 kg/m³ (92.7 lb/ft³)					

[1]Density determined from measurements.
[2]Density determined by suspension in air and water.
[3]Moisture content measured.
[4]Moisture content calculated.

Table C-4.—*Density and moisture content, undisturbed soil-lime block samples, sample No. 51Y-55*

Specimen No.	Wet density, kg/m³	Wet density, (lb/ft³)	Moisture content, percent	Dry density, kg/m³	Dry density, (lb/ft³)	Location in block
Moisture			[3]36.3			Top
Moisture			[3]33.4			Top
Moisture			[3]31.6			Top
Density	[2]1892	(118.1)	[3]30.9	1445	(90.2)	Top
1-B1	[1]1836	(114.6)				Top
2-A1	[1]1858	(116.0)	[4]31.1	1417	(88.5)	Top
2-C1	[1]1831	(114.3)	[4]33.9	1367	(85.3)	Top
3-A1	[1]1892	(118.1)	[4]29.4	1463	(91.3)	Top
3-C1	1815	(113.3)				Top
Average	[1]1847	(115.3)	32.4	1415	(88.4)	
			30.9	1445	(90.2)	
	Dry density based on average wet density and moisture content = 1395 kg/m³ (87.1 lb/ft³)					
2-A2	[1]1777	(110.9)				Center
2-B2	[1]1748	(109.1)				Center
Average	1762	(110.0)				
Moisture			[3]28.3			Bottom
Moisture			[3]29.0			Bottom
Moisture		(120.0)	[3]32.1			Bottom
1-B2	[1]1922	(120.0)				Bottom
2-B3	[1]1936	(120.8)	[3]28.9	1501	(93.7)	Bottom
			[3]28.9	1522	(95.0)	Bottom
2-C2	[1]1924	(120.1)				Bottom
3-A2	[1]1862	(116.2)	[4]31.0	1421	(88.7)	Bottom
3-B1	[1]1860	(116.1)				Bottom
Average	[1]1900	(118.6)	29.9	1461	(91.2)	
			28.9	1522	(95.0)	
	Dry density based on average wet density and moisture content = 1463 kg/m³ (91.3 lb/ft³)					

sample no. 51Y-56 (no lime)

Specimen No.		Moisture content, percent	Dry density, kg/m³	Dry density, (lb/ft³)	Location in block
1-B		[3]30.2	1480	(92.4)	Top
1-C		[3]29.5	1490	(93.0)	Top
2-A1		[3]29.6	1503	(93.8)	Top
2-A2		[3]29.6	1461	(91.2)	Bottom
2-C2		[3]31.1	1440	(89.9)	Bottom
Average		[3]30.0	1474	(92.0)	

[1]Density determined from measurements.
[2]Density determined by suspension in air and water.
[3]Moisture content measured.
[4]Moisture content calculated.

Table C-5.—*Density and moisture content, undisturbed soil-lime block samples, sample No. 51Y-57*

Specimen No.	Wet density, kg/m³ (lb/ft³)	Moisture content, percent	Dry density, kg/m³ (lb/ft³)	Location in block
Moisture		[3]24.8		Top
Moisture		[3]26.8		Top
Moisture		[3]26.0		Top
2-A1		[3]25.5	1557 (97.2)	Top
2-B1		[3]25.7	1559 (97.3)	Top
2-C1	[1]1970 (123.0)	[4]25.9	1565 (97.7)	Top
3-B1	[1]1977 (123.4)	[4]25.9	1572 (98.1)	Top
Average	[1]1974 (123.2)	25.8	1568 (97.9)	
			1557 (97.2)	
3-A1	[1]1975 (123.3)			Center
3-C1	[1]1966 (122.7)	[3]25.4	1567 (97.8)	Center
		[3]25.4	1576 (98.4)	Center
Average	[1]1971 (123.0)	25.4	1567 (97.8)	
			1576 (98.4)	
Moisture		[3]27.0		Bottom
Moisture		26.2		Bottom
Moisture		[3]30.5		Bottom
1-A1	[1]1967 (122.8)	[4]25.9	1562 (97.5)	Bottom
1-B1	[1]1956 (122.1)	[4]26.4	1548 (96.6)	Bottom
1-C1	[1]1969 (122.9)	[4]26.2	1560 (97.4)	Bottom
2-A2	[1]1967 (122.8)			Bottom
2-B2	[1]1970 (123.0)	[4]25.6	1568 (97.9)	Bottom
2-C2	[1]1967 (122.7)	[4]26.1	1559 (97.3)	Bottom
3-B2	[1]1972 (123.1)	[4]26.5	1559 (97.3)	Bottom
3-C2	[1]1954 (122.0)	[3]25.6	1556 (97.1)	Bottom
		[3]25.6	1567 (97.8)	
Average	[1]1966 (122.7)	26.6	1559 (97.3)	
	Dry density based on average wet density and moisture content = 1552 kg/m³ (96.9 lb/ft³)			

[1]Density determined from measurements.
[2]Density determined from suspension in air and water.
[3]Moisture content measured.
[4]Moisture content calculated.

Table C-6.—*Summary of dry densities and moisture content, samples No. 51Y-54 through 57*

Sample No., 51Y-	Dry density, kg/m³ (lb/ft³)	Moisture content, percent	Material
54	1510 (94)	30	soil-lime
55	1460 (91)	31	soil-lime
56	1470 (92)	30	soil
57	1590 (99)	26	soil-lime

Table C-7.—*Percent lime content*

Sample No. 51Y		CaO content* percent	Effective CaO content, percent
54	(bottom)	7.1	3.5
	(top)	6.3	2.7
55	(bottom)	4.3	0.7
	(center)	4.8	1.2
	(top)	4.7	1.1
57	(bottom)	4.4	0.8
	(top)	3.8	0.2
51	untreated	3.6	—

*Expressed as percentage of soil weight.

Table C-8.—*Strength relationship to percent lime content, samples No. 54 through 57*

Sample No. 51Y-	Strength,		Effective lime content, %	Sample Source
	kPa	(lb/in²)		
54	3590	(520)	3.1	Soil-lime from 1973
55	1030	(150)	1.0	Soil-lime from 1974
56	110	(16)	—	No lime
57	1790	(260)	0.5	Soil-lime from 1974

Block 51Y-54 was a companion sample to one submitted a year ago, 51Y-47, which was obtained right after construction, to compare the increase in strength over a year's curing period, which is shown to be (table C-9) over 50 percent.

The strength of samples from the 1972-73 construction period were dependent on the density of the sample. Those samples with comparable densities are listed (table C-10) along with the specimens from the 1973 through 1974 construction period.

The lower strengths of samples No. 51Y-55 and 51Y-57 are obviously due to their low lime content. However, even with as little as 0.5 to 1.0 percent effective lime, the strength of the material was at least eight times greater than the untreated soil.

Table C-9.—*Strength relationship to curing time, samples No. 51Y-47 and 54*

Sample No. 51Y-	Station	Location on canal section	Elevation	Curing time	Strength	
					kPa	(lb/in²)
47	3122+40	bottom 6 m (19 ft) right	414.5	1 month	2260	(328)
54	3122+00	bottom 5 m (15 ft) right	415.0	1 year	3590	(520) (or 58.85% increase)

Table C-10.—*Strength relationship to dry density, samples No. 51Y-44, 49, 55, 45, 47, 54, 43 and 57.*

Sample No. 51Y-	Effective CaO content, %	Dry density, kg/m³	(lb/ft³)	Strength kPa	(lb/in²)	Construction period, year 19-
44	4.2	1410	(88)	1130	(164)	72 thru 73
49 (2)	2.3	1460	(91)	1990	(289)	72 thru 73
49 (4)	2.3	1460	(91)	2250	(326)	72 thru 73
55	1.0	1460	(91)	1030	(150)	73 thru 74
45	3.6	1550	(97)	2430	(353)	72 thru 73
47	3.0	1490	(93)	2260	(328)	72 thru 73
54	3.1	1510	(94)	3590	(520)	73 thru 74
43	2.6	1710	(107)	3300	(478)	72 thru 73
57	0.5	1590	(99)	1790	(260)	73 thru 74

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ABSTRACT

Since construction in the late 1940's, the Friant-Kern Canal has experienced cracking, sliding, and sloughing of the side slopes in areas of expansive clays in both the concrete-lined and earth-lined portions. In the early 1970's, Bureau of Reclamation designers decided to remove portions of the canal lining, flatten the slopes, and reline the canal using a compacted soil-lime mixture in an attempt to stabilize the slopes. The project added 4 percent (based on dry soil weight) granular quicklime to the soil. Laboratory tests on the compacted soil-lime mixture showed that (1) soil-lime was about 20 times stronger than the untreated clay, (2) the strength of the soil-lime increases with time, (3) the plasticity index of the natural soil was reduced from 40 to 10 or less after adding the lime, and (4) the compressive strength of the soil-lime was dependent on the compacted density.

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DESCRIPTORS–/ compaction tests/ compressive strength/ *soil stabilization/ Atterberg limits/ soil mechanics/ soil properties/ *lime-soil mixtures/ slope stabilization/ Proctor curves/ in-place density/ soil tests/ laboratory tests/ *canal linings/ canal construction/ soil plasticity/ temperature/ *expansive clays/ clays/ *soils/
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