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STRENGTH CHARACTERISTICS OF CALICHE SOILS
OF THE TUCSON AREA

by
James Lewis Post

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF CIVIL ENGINEERING
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For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
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THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my
direction by James Lewis Post
entitled STRENGTH CHARACTERISTICS OF CALICHE SOILS
OF THE TUCSON AREA
be accepted as fulfilling the dissertation requirement of the
degree of Doctor of Philosophy

RL Sloane
Dissertation Director

14 June 1966
Date

After inspection of the dissertation, the following members
of the Final Examination Committee concur in its approval and
recommend its acceptance:*

<u>RL Sloane</u>	<u>14 June 1966</u>
<u>Thomas Cannody</u>	<u>14 June 1966</u>
<u>E.M. Jorgensen</u>	<u>14 June 1966</u>
<u>A. F. Pacy</u>	<u>6/20/66</u>
<u>J. B. Forester</u>	<u>7/6/66</u>

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TABLE OF CONTENTS

	Page
LIST OF ILLUSTRATIONS	vii
LIST OF TABLES	x
ABSTRACT	xi
 CHAPTER	
1 INTRODUCTION	1
General	1
Statement of the Problem	1
Review of the Literature	2
2 ORIGIN AND NATURE OF CALICHE	3
Physiography of the Tucson Basin	3
Caliche Formation	4
Source of Samples	6
Carbonate Content Determination	7
Mechanical Analysis	7
Calcite Crystal Orientation	9
X-Ray Diffraction Equipment	11
Soil Mineral Determination	11
Apparent Specific Gravity and Water Solubility	13
3 UNCONFINED COMPRESSIVE STRENGTH OF CALCISOLS	16
Compressive Strength of Indurated Caliche	16
Soil Compaction Tests	17
Strength Testing Procedure	18
Compressive Strength of Remolded Soil Samples	19
4 ANALYSIS AND DISCUSSION OF SOIL STRENGTH	22
Characteristics of Fragmented Calcisols	22
Characteristics of Indurated Caliche	24
Comparison of Remolded and Indurated Calcisols	26
5 PORTLAND CEMENT TREATMENT	28
Soil-Cement Preparation Procedure	28
Effect of Relative Humidity on Curing	29

TABLE OF CONTENTS—Continued.

CHAPTER		Page
	Compressive Strength Testing Procedure	31
	Compressive Strength of Soil	32
	Compressive Strength of Cement-Stabilized Soil	33
	Effect of Calcite on Soil-Cement Mixtures	36
6	X-RAY ANALYSIS OF CEMENT-STABILIZED SOIL	39
	Preparation of Soil Specimens	39
	X-Ray Diffraction Procedure	40
	X-Ray Diffraction Analyses	40
7	DISCUSSION OF CALCISOL-PORTLAND CEMENT SYSTEMS	50
	Variable Strength Characteristics	50
	An investigation of Soil Minerals	52
	Effective amounts of Portland Cement	55
8	CONCLUSIONS	59
	General	59
	Recommendations for Further Research	61
APPENDICES		
A	GRAIN-SIZE DISTRIBUTION CURVES	63
B	COMPACTION CURVES AND AIR-DRY STRENGTHS VERSUS REMOLDING MOISTURE CONTENTS	67
C	AGE-DENSITY RELATIONSHIPS	79
D	COMPRESSIVE STRENGTHS OF REMOLDED CALCISOLS VERSUS MOISTURE CONTENTS	84
E	COMPRESSIVE STRENGTH CHANGES OF COMPACTED SOIL- CEMENT MIXTURES WITH AGE	90
F	CLAY MINERAL BASAL REFLECTIONS IN X-RAY DIFFRACTION TRACES OF CALCISOL	101
	LIST OF REFERENCES	104

LIST OF ILLUSTRATIONS

Figure		Page
1	Air-Dry Compressive Strength of Remolded Calcisols Versus Clay-Size Content	22
2	Compressive Strength of Indurated Caliche Versus Clay Content	24
3	Effect of Relative Humidity on Curing of Compacted Soil-Cement Mixtures	30
4	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample No. 2	35
5	Effect of Calcium Carbonate on Strength of Compacted Soil-Cement Mixtures	37
6	X-Ray Diffraction Traces of Portland Cement Reaction Products in Soil-Cement Mixtures	47
7	Calcium Hydroxide Lines in X-Ray Diffraction Traces of Soil-Cement Mixtures	48
8	Grain-Size Distribution Curves, Samples 1, 2, and 4 . . .	63
9	Grain-Size Distribution Curves, Samples 3, 5, and 6 . . .	64
10	Grain-Size Distribution Curves, Samples 7, 8, and 12 . .	65
11	Grain-Size Distribution Curves, Samples 9, 10, and 11 . .	66
12	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 1	67
13	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 2	68
14	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 3	69
15	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 4	70
16	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 5	71

LIST OF ILLUSTRATIONS--Continued

Figure		Page
17	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 6	72
18	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 7	73
19	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 8	74
20	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 9	75
21	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 10	76
22	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 11	77
23	Compaction Curve and Air-Dry Compressive Strength Versus Remolding Water Content, Sample 12	78
24	Compressive Strength of Remolded Calcisols Versus Moisture Content, Samples 1 and 2	84
25	Compressive Strength of Remolded Calcisols Versus Moisture Content, Samples 3 and 4	85
26	Compressive Strength of Remolded Calcisols Versus Moisture Content, Samples 5 and 6	86
27	Compressive Strength of Remolded Calcisols Versus Moisture Content, Samples 7 and 8	87
28	Compressive Strength of Remolded Calcisols Versus Moisture Content, Samples 9 and 10	88
29	Compressive Strength of Remolded Calcisols Versus Moisture Content, Samples 11 and 12	89
30	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 1	90
31	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 3	91

LIST OF ILLUSTRATIONS—Continued

Figure		Page
32	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 4	92
33	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 5	93
34	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 6	94
35	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 7	95
36	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 8	96
37	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 9	97
38	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 10	98
39	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 11	99
40	Compressive Strength Change of Compacted Soil-Cement Mixtures with Age, Sample 12	100
41	Clay Mineral Basal Reflections in X-Ray Diffraction Traces of Calcisols, Cement Content - None and 2.5% . .	101
42	Clay Mineral Basal Reflections in X-Ray Diffraction Traces of Calcisols, Cement Content - 5.0% and 7.5% . .	102
43	Clay Mineral Basal Reflections in X-Ray Diffraction Traces of Calcisols, Cement Content - 10.0% and 25.0% .	103

LIST OF TABLES

Table		Page
I	SOIL SAMPLE SITES	6
II	CARBONATE CONTENT	8
III	GRAIN-SIZE ANALYSES	10
IV	SOIL MINERAL COMPONENTS	13
V	APPARENT SPECIFIC GRAVITY AND SOLUBILITY	15
VI	COMPRESSIVE STRENGTH OF UNDISTURBED INDURATED CALICHE .	17
VII	OPTIMUM MOISTURE CONTENT AND MAXIMUM DRY DENSITY . . .	19
VIII	COMPRESSIVE STRENGTH OF REMOLDED CALCISOLS	21
IX	COMPRESSIVE STRENGTH OF SOIL-CEMENT MIXTURES	33
X	X-RAY DIFFRACTION ANALYSIS OF TUCSON FELDSPARS	42
XI	PHYLLITE-SOIL-CEMENT MIXTURES	53
XII	FELDSPAR-SOIL-CEMENT MIXTURES	54
XIII	AGE-DENSITY RELATIONSHIPS, NO CEMENT CONTENT	79
XIV	AGE-DENSITY RELATIONSHIPS, CEMENT CONTENT - 2.5% . . .	80
XV	AGE-DENSITY RELATIONSHIPS, CEMENT CONTENT - 5.0% . . .	81
XVI	AGE-DENSITY RELATIONSHIPS, CEMENT CONTENT - 7.5% . . .	82
XVII	AGE-DENSITY RELATIONSHIPS, CEMENT CONTENT - 10.0% . . .	83

ABSTRACT

The physical and chemical composition of caliche soils of the Tucson area were investigated in order to determine the compressive strength parameters of indurated and fragmented calcisols. The results of stabilization of fragmented calcisols with portland cement additive were determined.

The study consisted of measuring the compressive strength of undisturbed specimens of indurated caliche, determining the composition of the fragmented specimens, and measuring the strength of the remolded calcisols. The effect of admixtures of portland cement on the compressive strength of the remolded calcisols was measured and the soil-cement reaction products were investigated.

The identification of the soil minerals was accomplished by means of x-ray diffraction analysis. The calcisols were found to consist mainly of feldspar and randomly oriented microcrystalline calcite with lesser amounts of quartz and clay minerals.

The strength of the calcisols was found to be closely related to its clay content. The strongest indurated calcisols contained very small amounts of clay and the strongest remolded calcisols contained the largest amounts of clay. When the indurated caliche was fragmented it behaved as an inert granular material and with access to water the remolded calcisols were found to lose most of their bearing strength.

It was shown that a loss of compressive strength generally occurred in the remolded soil-cement mixtures after 28 days of curing.

The maximum compressive strength was determined to be primarily a function of the amount of portland cement added and of the combined feldspar-calcite content of the soil.

The feldspar suite of the Tucson basin was found to consist mainly of anorthoclase with lesser amounts of orthoclase and albite. Tests conducted on the feldspar suggest that the weak soil-cement bonding strengths are due to the feldspars and the strength losses which occur are the result of the chemical interaction of the calcite and alkali feldspars with the portland cement in an aqueous environment.

Portland cement was found to be an unsuitable additive for the effective stabilization of fragmented calcisols. Small amounts of cement prevented a quick condition in saturated fragmented calcisols and also prevented swelling. Much larger amounts of cement were found to be necessary for enduring stabilization of calcisols.

CHAPTER 1

INTRODUCTION

General

The soils of the Tucson area are predominantly calcisols. These soils lose strength and become unstable when they are fragmented. The addition of moisture to fragmented calcisols causes an almost complete loss of bearing strength and, when the wet soil is not subject to rapid moisture loss, the soil will tend to remain unstable for some time.

Statement of the Problem

An economical method of chemical stabilization is required which will improve the strength characteristics of these soils. A physical and chemical investigation of these calcisols is a requisite to development of this method. The physical investigation must include the mechanical analysis, packing order, moisture content, and strength characteristics of the calcisols, and the chemical analysis must include the mineralogical composition and the amount of calcium carbonate in the soils.

Portland cement is chosen as a potentially economical chemical stabilization agent and the strength properties of remolded cement-stabilized calcisols are investigated. The changes with time in the chemical composition of the cement-stabilized calcisols are observed.

Review of the Literature

Most previous investigations of calcisols have been undertaken for agricultural or geological purposes. Extensive literature is available on the subject of the origin and formation of caliche soil horizons. A comprehensive bibliography has been presented by Cooley (1966). No systematic investigation of the engineering properties of caliche appears to have been made in order to develop realistic criteria for the prediction of behavior as a construction material.

Blake (1902) refers to the use of calcined caliche as a mortar which was used in the Tucson area before the advent of portland cement. Gibbings (1932) investigated the use of caliche as a portland cement additive. Caliche has been pulverized and used as road construction material in Texas and Oklahoma; however, it has been necessary to chemically stabilize the material when excess moisture is present (Texas Highway Department 1940), (Krupp 1956).

More recently it was found that certain caliche horizons of eastern New Mexico have a composition which is amenable to production of portland cement (Le Blanc 1957).

CHAPTER 2

ORIGIN AND NATURE OF CALICHE

Physiography of the Tucson Basin

Most of the soils of the Tucson area are underlain by calcareous soil horizons which are usually a few feet below the existing ground surface (Youngs 1931). These calcareous soil horizons may also be exposed at the ground surface or they may exist at a considerable depth. These deposits are commonly referred to as caliche.

In some areas the caliche soil horizons are many feet thick and in others only a few inches thick. The caliche varies from finely disseminated calcium carbonate in the soil to dense indurated material of considerable strength.

The Santa Cruz River, which drains the Tucson Basin, is bounded by a flood plain. The bottom land varies in width up to 1.5 miles and the soil has a weathering profile averaging 8 to 20 feet in thickness. The bottom land does not contain caliche horizons either in the soil or subsoil.

The bajadas between the surrounding mountains and the bottom lands are eroded into terraces. The terraces have been given names (Smith 1938). The upper terrace is the University terrace, the middle terrace is the Cemetery terrace, and the lower terrace along the bottom land is the Jaynes terrace.

The alluvium in the central part of the Tucson Basin, primarily the University terrace, is a cemented gravel to a depth of several feet

and is covered with a thin layer of surface soil. The aggregate material was derived mainly from the Santa Catalina and Rincon Mountains and consists of quartz, feldspar, and micas derived from granite. This material is cemented together by calcium carbonate which has been deposited on the soil particles and in the interstices.

The rolling irregular University bench occupies a lenticular area about 5 miles long and up to 3 miles wide. Pantano Creek, entering Tucson Basin from the east, may have migrated back and forth across the terrace and caused an accumulation of a particularly large amount of caliche there. The Pantano Creek watershed is probably the main source of calcium carbonate for the Tucson Basin. In the upper Pantano watershed there are extensive deposits of Paleozoic limestone and diverse calcareous Pleistocene lake-bed deposits.

The Cemetery bench is developed over more extensive areas than the University bench. It is 30 to 60 feet lower than the University terrace. The next lower Jaynes bench occurs on the sides of the Cemetery ridges.

Caliche Formation

The formation of caliche is brought about by the solution, transportation, and precipitation of calcium carbonate. The percentage of calcium carbonate in the soil varies widely. It usually occurs in irregular layers. It is often continuous over many acres and conforms roughly to the contour of the land. Caliche occurs only where there has been a supply of calcium carbonate in a solution of carbonated water, and where the drainage is not sufficient or rapid enough to remove the

water before evaporation occurs. Although the calcium carbonate is primarily derived from Paleozoic limestones, it may also be derived from igneous rocks, or from the soil.

Only about 8 parts per million of calcium carbonate is soluble in water at ambient temperatures; but in water saturated with carbon dioxide the solubility is increased to more than 800 parts per million (Breazeale and Smith 1930). The carbonic acid forms calcium bicarbonate. The precipitation of calcium carbonate from solution is caused by either the evaporation of water or by the loss of carbon dioxide from solution. A change in temperature or pressure may cause loss of carbon dioxide.

Caliche occurs at the lower edge of the surface moisture zone or the upper edge of the ground water zone. The deeper layers differ in character from those near the surface (Guild 1910). These usually consist of washed sand and gravel cemented with drusy scalenohedral crystals of calcite. As long as the caliche strata are permeable to water the strata will migrate downward in a soil as fast as erosion removes the upper soil surface. If aggradation occurs, a second stratum of caliche may form above the first.

The solubility of magnesium bicarbonate in ground water may run as high as 12,000 parts per million. This difference in the solubility of the bicarbonates is probably the reason that there is seldom more than one or two per cent of magnesium carbonate in caliche. Calcium sulfate is also very soluble and tends to remain in solution upon loss of carbon dioxide from solution.

Source of Samples

Bulk soil samples were acquired from eight sites, described in Table I below, which were considered to be representative of the three terraces of the Tucson Basin. A soil column was sampled in five sections at one site. When possible, blocks of indurated caliche were obtained from these sites for compressive strength tests.

TABLE I
SOIL SAMPLE SITES

Sample	Terrace	Site
1 - 5	University	Civil Engineering Building at East 2nd St. and Palm Rd. (Soil column)
6	University	Microbiology Building at East 5th St. and North Mountain Ave.
7	University	Services and Food-Handling Building at East 5th St. and North Park Ave.
8	University	Sears Store at East Broadway and South Wilmot Rd.
9	Cemetery	Ford Motor Company at East 22nd St. and South Wilmot Rd.
10	Jaynes	At intersection of West 22nd St. and Rubio Ave.
11	Cemetery	100 feet east of intersection of East 23rd St. and South 4th Ave.
12	Cemetery	At intersection of alley along South 4th Ave. about 250 feet north of freeway

The indurated blocks of caliche were prepared for compressive strength tests and the remainder of the bulk samples were reduced to

material passing a No. 20 U. S. Standard sieve. After the indurated blocks were tested for compressive strength they were reduced to minus No. 20 material. The soil samples were reduced in size by use of the jaw crushers and roller crushers in the comminution laboratory of the Department of Metallurgy of the University of Arizona. The samples were then put through a Braun pulverizer, thoroughly mixed, and stored for use.

Carbonate Content Determination

Portions of each samples were taken for determination of moisture content. The samples were oven-dried at 105° C for 24 hours, cooled in a desiccator, then weighed. The carbonate contents of the samples were determined, in duplicate, by Gravimetric Procedure given in the U. S. D. A. Handbook 60 (1954). A referee sample carbonate determination was made by the Department of Agricultural Soils and Chemistry of the University of Arizona which gave a good correlation with previously obtained results (36.1 per cent as compared to 35.5 per cent for Sample No. 2). Carbonate contents are given in Table II on the following page.

Mechanical Analysis

In order to determine the grain-size distribution of the soils, samples consisting of approximately 50 grams oven-dry weight were treated with 3N hydrochloric acid until the carbonates were dissolved. The solids were allowed to settle and the supernatant liquid was decanted. The residue was washed twice with distilled water and the supernatant liquid was again decanted. It was observed at this time that the calcium chloride had caused the clay-size material to flocculate.

TABLE II
CARBONATE CONTENT

Sample	Depth Beneath Surface, feet	Per Cent Calcium Carbonate		
		1st Trial	2nd Trial	Average
1	1 - 2	45.9	44.0	45.0
2	2 - 2.5	34.4	36.5	35.5
3	2.5 - 4	31.4	31.6	31.5
4	4 - 6	2.4	2.5	2.5
5	15 - 18	11.9	12.8	12.4
6	20 - 24	25.8	25.9	25.8
7	3 - 5	62.8	62.4	62.6
8	2 - 4	17.6	16.8	17.2
9	5 - 7	28.8	28.8	28.8
10	1 - 3	84.8	85.1	85.0
11	1 - 4	67.0	66.0	66.5
12	1 - 3	73.6	74.5	74.1

Hydrometer tests were conducted on the washed soils in an attempt to determine the grain-size distribution of the fines. Both sodium hexa-metaphosphate and sodium carboxymethyl cellulose were used in an attempt to deflocculate the soil fines. Neither was successful. One soil was treated with dilute acetic acid rather than hydrochloric acid. The acetic acid also caused flocculation. The acid treated soils were then washed on a No. 200 sieve and the retained material was oven-dried and weighed.

The grain-size distribution of each of the untreated soils was then determined. Approximately 50 grams oven-dry weight of each soil sample was treated with 200 ml of sodium hexa-metaphosphate stock solution (40 gm/l) in 200 ml of distilled water and allowed to temper for 24 hours. The hydrometer analysis of each soil sample was then performed.

A portion of the untreated soil Sample No. 2 was separated on a No. 200 sieve and the retained material discarded. The calcium carbonate content of the fines passing the No. 200 sieve was determined by gravimetric analysis to be 40.3 per cent by weight. The calcium carbonate content of the soil fines is not appreciably different from the calcium carbonate content of the whole soil sample. As a result, the amount of clay-size material in the soil fines from which the calcium carbonate is removed may be estimated. The procedure for determining the clay content of the soils is discussed in detail in Chapter 4. Grain-size analyses appear in Table III below.

The clay-size contents of soil Samples 4, 6, and 8 were determined directly by hydrometer analysis. The small amount of clay-size material which was present did not appear to flocculate. Grain Size Distribution Curves for each of the soil samples are given in Figures 8 through 11, Appendix A.

Calcite Crystal Orientation

A specimen of indurated caliche from Sample No. 2 was filed to form a level surface which was horizontal with respect to the in-place orientation of the specimen. The surface was treated with a dilute solution of hydrochloric acid, then washed with distilled water. The

TABLE III
GRAIN-SIZE ANALYSES

Soil Sample	Total Soil Sample			Without Calcium Carbonate		
	% Sand	% Silt	% Clay	%+No. 200	%-No. 200	% Clay (est.)
1	64.5	19.0	16.5	38.4	16.6	7.1
2	75.0	14.0	11.0	49.4	15.1	5.6
3	76.5	14.5	9.0	52.0	16.5	5.3
4	85.5	12.0	2.5	83.8	13.7	2.0
5	38.5	29.0	32.5	50.6	37.0	18.1
6	87.0	13.0	0.0	70.4	3.8	0.0
7	68.0	21.0	11.0	19.9	17.5	5.2
8	76.0	16.5	7.5	63.4	19.4	5.0
9	67.5	18.5	14.0	51.5	19.7	7.1
10	74.0	17.0	9.0	4.3	10.7	3.3
11	77.0	17.0	6.0	23.4	10.1	2.0
12	81.5	15.0	3.5	12.5	13.4	1.9

The filings were collected as the surface was cut. These filings were reduced in size to material passing the No. 200 sieve. An x-ray diffractometer trace was made of this material to determine the relative intensity of diffraction peaks for a randomly oriented powder specimen.

The indurated sample was cut to fit in the x-ray diffractometer specimen holder. An x-ray diffractometer trace was made of the horizontal surface of the sample. There appeared to be little or no preferred crystal orientation of the calcite in this caliche sample. The diffraction peak intensities of the two traces were nearly identical.

Further investigation of more than 60 x-ray diffractometer traces of caliche powder specimens indicated that there was essentially a random orientation of the calcite crystal morphology in caliche soils of the Tucson area. Only the lower caliche soil horizons, which contain visible scalenohedrons of calcite, show preferred orientation in powder diffractometer specimens, probably because of the cleavage characteristics of calcite.

X-ray Diffraction Equipment

A General Electric XRD-5 diffractometer, modified in 1964 to include linear amplification and pulse height discrimination, was used in this study. The diffractometer was equipped with a 1° beam slit, a medium resolution collimator slit, and a 0.1° detector slit. A 4° take-off angle was used. Nickel-filtered copper radiation, produced at 35kv and 23ma, was used. The detector tube was an SPG6 xenon-filled counter tube. The goniometer was driven at an angular velocity of two degrees 2 θ per minute.

During the preliminary mineralogical investigation of the soil samples a count rate of 500 CPS was used with a time constant of two seconds. A count rate of 200 CPS with a time constant of four seconds was used for later investigations of soil-cement reaction products. The advantages of using a lower count rate are discussed in Chapter 6.

Soil Mineral Determination

A concentration of clay-size minerals occurs in a soil horizon typified by Sample No. 5. The soil horizon appears to be a lacustrine

deposit. Possibly because of its origin the soil does not appear to be a calcisol even though the calcium carbonate content is about 12 per cent by weight. The clay content is estimated to be about 18 per cent of the total sample, as shown in Table III.

The principal non-clay minerals are quartz, calcite, and feldspar. These minerals were identified by visual observation and confirmed by x-ray diffraction analysis. Some trace minerals were observed. Magnetite was identified during the wet-sieve soil separation and organic matter was observed during the acid treatment.

An air elutriation process was used to secure a quantity of unaltered clay-size material from the soil sample. The resulting material was predominantly clay-size with some silt sizes included.

The procedure used for clay mineral determination was that of Warshaw and Roy (1961). Five different samples were prepared for x-ray diffractometer analysis. These were: random orientation, oriented slide, "glycolated" slide, oriented slide heated at 325°C for 24 hours, and oriented slide heated at 550°C for 24 hours.

Duplicate slides of the 325°C and 550°C heat-treated specimens were used to allow for breakage or apparatus malfunction. Two oriented slides heat-treated for 8 hours at 550°C were also used to determine the effect of time on crystal interlayer change. Little change was observed after the 8-hour period.

Because of the inclusion of some silt-sizes in the clay-size material, cementation of minerals, and the various mixed-layer clay combinations, only a rough estimate of the amount of different minerals present could be made. The larger size minerals were observed when the

soil samples were being reduced to material passing the No. 20 sieve. Estimated percentages of soil minerals are given in Table IV below.

TABLE IV
SOIL MINERAL COMPONENTS

Mineral Present	Estimated Per Cent	
	Total	Clay-size
Feldspar	45	5
Quartz	20	5
Calcite	12	15
Muscovite	7	25
Illite	5	15
Smectite	5	15
Chlorite	3	10
Trace Minerals	<u>3</u> 100	<u>10</u> 100

Apparent Specific Gravity and Water Solubility

The apparent specific gravity of the indurated caliche samples was determined by using the Archimedes principle. Each specimen was weighed while dry; then the buoyant weight was determined. The surface-dried specimens were reweighed. The apparent specific gravity was taken as the dry weight divided by the surface-dry weight less the buoyant weight.

The apparent specific gravity of the indurated caliche of the Tucson area appears to be about 25 per cent greater than the caliche of the Rio Grande basin which was tested by Gile (1961).

Portions of each soil sample were tested in duplicate for water solubility. About 15 grams of material passing a No. 20 sieve was put in a filter and 300 ml of boiling water was filtered through the soil. The oven-dry weight of the soil was determined before and after filtration.

The water-soluble mineral content was found to be very small, indicating that the water-soluble components were leached out as the soil horizons were formed. This finding agrees with that of Breazeale and Smith (1930). This also indicates that little weathering occurs in the upper caliche soil horizons after deposition, the indurated caliche horizons having a very low permeability, as shown by Shreve and Mallory (1933). The soil horizons below the upper indurated caliche horizon usually have a moisture content of less than 5 per cent of oven-dry weight, and may contain less than 1 per cent. Apparent specific gravities and water solubilities of the samples are listed in Table V on the following page.

TABLE V
APPARENT SPECIFIC GRAVITY AND SOLUBILITY

Sample	Apparent Specific Gravity (gm/cc)			Water Solubility (%)		
	1st	2nd	Average	1st	2nd	Average
1	1.79	1.85	1.82	0.30	0.38	0.34
2	2.13	1.97	2.05	0.45	0.41	0.43
3	1.77	1.65	1.71	0.34	0.25	0.30
4	--	--	--	0.26	0.22	0.24
5	--	--	--	0.42	0.31	0.37
6	2.34	2.30	2.32	0.17	0.14	0.16
7	--	--	--	0.34	0.28	0.31
8	1.86	1.90	1.88	0.23	0.22	0.23
9	--	--	--	0.35	0.32	0.34
10	2.30	2.01	2.11	0.58	0.54	0.56
11	2.43	2.24	2.34	0.34	0.32	0.33
12	2.37	2.36	2.37	0.32	0.27	0.30

CHAPTER 3

UNCONFINED COMPRESSIVE STRENGTH OF CALCISOLS

Compressive Strength of Indurated Caliche

Blocks of indurated caliche were cut to various sizes by means of a water-cooled masonry saw. The shape of the cut specimen was determined in each case by the shape of the sample. The specimen height was always between one to two times the maximum specimen cut width, and varied from about three to ten inches. The blocks were stratified and tended to break along horizontal layers.

The compressive strength of the cut specimens of indurated caliche was determined using a strain rate of approximately 0.05 inches per minute. The larger specimens were tested in a Tinius Olsen universal testing machine of 200,000 pound capacity, and the smaller specimens were tested in a Soiltest Model AP-350 Versa-Tester of 60,000 pound capacity.

The cut specimens which were tested in a normal position always failed in the lower part of the specimen, the upper part being more heavily indurated and stronger. The failures were evidenced by tension cracks appearing at the surface of the specimens.

Lateral strength tests were conducted on some of the specimens. Usually, only the ends of the specimens were cut for these tests. The lateral strength of the indurated caliche was found to be much greater than the normal strength, commonly more than twice the maximum normal

strength for the 24 specimens tested. Results of the compressive strength tests are summarized in Table VI below.

TABLE VI
COMPRESSIVE STRENGTH OF UNDISTURBED INDURATED CALICHE

Sample	Normal		Lateral	
	No. of Tests	Unit Stress (psi)	No. of Tests	Unit Stress (psi)
2	4	385 - 395	3	1960 - 2890
6	-	-	2	1230 - 1745
7	3	135 - 210	-	-
8	1	1120	1	2700
10	3	470 - 700	1	805
11	-	-	1	3300
12	3	1610 - 3360	1	5060

Soil Compaction Tests

Compaction tests were conducted on each of the soil samples to determine the optimum moisture content and maximum dry density of the different soils at a particular compactive effort. A Harvard miniature compaction device was used, rather than the standard compaction mold, so that more tests could be conducted in less time with a very large reduction in the amount of soil and storage space required (Wilson 1950).

A 25-pound spring was used in the kneading compactor. The compaction mold was filled in five lifts with 25 tamps per lift. This compactive energy gave soil densities comparable to the Standard compaction test, ASTM Designation: D 698 - 57 T. Soil Sample No. 5 was used

to determine the comparison between compaction methods because the soil originally contained less than 10 per cent of material retained on the No. 20 sieve.

Tap water was mixed with each soil charge and the soil-water mixture was allowed to temper until the soil assumed a uniform color. Calcium carbonate is hydrophilic (Graf 1955); therefore, the tempering period was ordinarily less than 10 minutes. Each compaction test was run in duplicate. A soil moisture determination was made from each residual soil-water mixture. The compacted soil cylinders were stored to air dry. Compaction curves were drawn and the optimum moisture content and maximum dry density of each soil sample was determined. Moisture-density data are given in Table VII on the following page. Compaction curves are given in Figures 12 through 23, Appendix B.

Strength Testing Procedure

The compressive strength of one of the duplicate soil cylinders was determined after 7 days drying time and the other after 14 days.

A Soiltest Model U-160, portable, hand-operated, unconfined compression apparatus was used to determine the compressive strength of the soil cylinders. The strain rate was held to about 0.05 inches per minute. The air-dry soil cylinders tended to exhibit brittle failure at a small amount of strain. The cross-sectional area of the soil cylinders was taken as the compaction cylinder area for purposes of stress computation.

The moisture content of the soil cylinders was determined after the specimens were stressed to failure. The moisture content of the

TABLE VII
OPTIMUM MOISTURE CONTENT AND MAXIMUM DRY DENSITY

Sample	Moisture Content (%)			Dry Density (pcf)
	After Pulverizing	Air Dry	Optimum	
1	1.1	0.9	19.2	102.0
2	2.6	1.6	30.0	86.5
3	2.0	1.3	26.0	91.0
4	0.6	0.6	18.3	102.0
5	1.8	1.6	18.5	107.0
6	0.3	0.2	15.5	108.5
7	1.7	0.9	21.2	101.0
8	2.2	1.5	30.0	87.5
9	1.2	1.2	23.5	97.5
10	0.7	0.5	13.8	112.5
11	0.7	0.6	18.5	102.5
12	0.7	0.5	17.5	107.0

specimens had almost returned to air-dry soil-moisture equilibrium after 14 days, the soil specimens with low clay content losing moisture most rapidly.

Compressive Strength of Remolded Soil Samples

The compressive strength of remolded air-dried calcisols appeared to be dependent primarily upon the amount of clay present in the soil. The pulverized calcite tended to act as an inert granular component. There was no apparent strength increase with time when moisture loss was

prevented. Soil samples exposed to high humidity conditions showed no gain in strength after a period of 90 days. The compressive strength of the soil appears to be dependent primarily on the soil moisture content and soil density and not on time. The presence of carbon dioxide in solution in the water will cause cementation of the calcite component according to Breazeale and Smith (1930). The carbon dioxide content of the molding water and of the high humidity storage room was insufficient for this effect to become apparent.

The moisture content versus compressive strength data were plotted for each soil sample. The maximum compressive strength of the remolded soil samples were determined after seven and fourteen days. The compacted soil samples were air-dried in the laboratory at average ambient room temperature.

The soil samples with low clay content gained their maximum strength after seven days. The soil samples with a relatively high clay content, such as Sample No. 1, incurred some strength increase between seven and fourteen days. Results are given in Table VIII on the following page.

TABLE VIII
COMPRESSIVE STRENGTH OF REMOLDED CALCISOLS

Sample	<u>Maximum Compressive Strength (psi)</u>		<u>Moisture Content (%)</u>	
	7-Day	14-Day	7-Day	14-Day
1	255	300	1.4	1.1
2	170	170	3.4	-
3	200	200	-	2.6
4	65	65	-	0.8
5	560	565	2.4	2.4
6	35	35	0.2	-
7	260	285	1.5	1.5
8	95	100	2.9	2.6
9	210	240	2.1	1.8
10	105	105	0.8	0.5
11	85	95	0.9	0.8
12	95	-	0.8	-

CHAPTER IV

ANALYSIS AND DISCUSSION OF SOIL STRENGTH

Characteristics of Fragmented Calcisols

The air-dry strength of the remolded soil samples is directly related to the clay-size content of the soil. The relationship between the compressive strength of the soil and the amount of the clay-size material in the soil is shown in Figure 1, page 23. This relationship is similar to that obtained by Mielenz and King (1955) where the compressive strength of synthetic soils was determined for mixtures of sand and clay. The fragmented caliche appears to act in the same capacity as sand in the remolded soil.

A portion of Sample No. 2, which passed a No. 200 sieve, was compacted and allowed to air-dry for seven days. The maximum compressive strength of 172 lbs/sq. in. was close to the compressive strength for the whole sample. The compressive strength did not appear to be dependent on the total fines but only on the clay content.

Two assumptions were necessary to determine the amount of clay-size materials in the soil samples, excluding the calcite: the calcite content of any grain-size portion of the soil is nearly the same, and the slope of the grain-size distribution curve between the 74 micron and the 4 micron size is nearly the same for the soil without the calcite as with it.

The first assumption has been shown to be essentially correct, and the second assumption would follow from this. The complete

Figure 1. Air-Dry Compressive Strength of Remolded Calcisols versus Clay-Size Content.

grain-size analysis was determined for the whole soil samples, and the portion of each soil sample which passed the No. 200 sieve was found. The clay content of the soils was then computed. The computed clay content of the soils was also plotted on Figure 1.

The maximum compressive strength of the remolded soil samples was found to be for those soils compacted at optimum moisture-density, or compacted at one to two per cent less than the optimum moisture. The compressive strength of the soil samples with low clay content varied little with density, whereas the soil samples with higher clay content were quite sensitive with respect to density.

Characteristics of Indurated Caliche

An average curve was drawn in Figure 1 to fit the data for the clay content of the soil samples. Adjusted clay-content values were taken from this curve and plotted against the compressive strength of the indurated caliche test specimens, Figure 2, page 25.

The unconfined compressive strength of the indurated caliche which was tested is directly related to the clay content. Apparently the clay interferes with the crystalline growth of the calcite structure. The bonding between clay and calcite is poor. Clayey material tends to concentrate in the voids in the caliche. This material is usually washed out during the formation of the caliche and often concentrates in a lower horizon, such as the one represented by Sample No. 5, or is carried from the area during sediment deposition by the sudden high-intensity floods which are common in the Southwest.

Figure 2. Compressive Strength of Indurated Caliche versus Clay Content.

The specimens of indurated caliche having the greater apparent specific gravity tend to have the greatest normal compressive strength. However, because of the stratification of the caliche, thin dense layers having a high lateral compressive strength were found. The indurated caliche with the greatest strength tends to have a clay content of less than four per cent.

There does not seem to be any relationship between the amount of water soluble material in the caliche and the compressive strength of the caliche. This may be because of the low content which is present (see Table V, page 15). It has been shown by Shreve (1930) that an indurated layer of caliche may act as a semi-permeable membrane. The water soluble material tends to be drawn to the surface by evaporation where it can be carried away by rain runoff, or be leached out and concentrated in a lower horizon (Shreve and Mallory 1933).

Comparison of Remolded and Indurated Calcisols

There appears to be an inverse correlation between the compressive strength of remolded and indurated caliche. The strength of the calcisols is related to the amount of clay materials in the soils.

The remolded calcisols containing the larger amounts of clay material have greater compressive strength and the indurated calcisols containing smaller amounts of clay material have the greater strength.

There can be no direct correlation between the amount of compressive strength to be found in either case because the causes of strength are different. The clay tends to act as a binding agent in remolded calcisols. When the remolded soil is saturated it loses its

compressive strength. The clay tends to interrupt the formation of calcite crystalline intergrowth in indurated calcisols. When the indurated soil is saturated, it tends to retain most of its strength, as has been shown by Gile (1961). The strength loss is related to the calcium carbonate content of the soil.

There is only a general relationship between the amount of calcium carbonate contained by calcisols and the compressive strength of the calcisols. In the remolded soils the fragmented calcite tends to act as part of the granular component, which exhibits no cohesive properties. In the indurated soils the packing order and clay content of the soils overshadows the significance of the calcium carbonate content to the extent that one soil with a calcite content of 17.2 per cent, Sample No. 8, showed greater strength than another soil with a content of 85.0 per cent, Sample No. 10.

CHAPTER V

PORTLAND CEMENT TREATMENT

Soil-Cement Preparation Procedure

Type 1 portland cement, manufactured by the Arizona Portland Cement Company, was chosen as a chemical treatment agent because it was economical and readily available. According to information listed in Highway Research Board Bulletin 292 (1961), an admixture of seven per cent portland cement is sufficient to stabilize caliche. Thus, soil-cement mixtures of 2.5, 5.0, 7.5, and 10.0 per cent by weight of portland cement were chosen for investigation. Control samples which contained no cement were included in each series.

Portland cement passing the No. 200 sieve was mixed with the soil by means of a mixing cloth. The mixture was rolled until it was of uniform color. Tap water was added to the soil-cement mixture to bring it to the desired moisture content and mixed until it was of uniform color. The soil-cement mixtures were compacted immediately after mixing because of the rapid initial chemical reactions which take place.

The soil-cement mixtures were compacted using the Harvard miniature compaction apparatus (Wilson 1950), and using the same compaction procedure which was used for the untreated soils. The soil-cement mixtures were compacted at a compaction moisture content of optimum plus a moisture increase equal to 25 per cent of the added portland cement, as suggested by Taylor (1964). Several samples of neat portland cement

paste were compacted and it was found that the cement would hold about 22.5 per cent moisture at the compaction density used.

Soil-cement mixtures were made from the minus No. 20 fraction of each of the twelve soil samples. The compacted soil mixtures were allowed to cure in a high-humidity room at a temperature of about 70°F. The moisture in the curing room was supplied by a Walton Space Humidifier Model SF-5. Curing times of 1, 7, 14, 28, and 84 days were used. Soil-cement series were produced for each of these curing time periods. The soil-cement cylinders were made in duplicate when possible.

Effect of Relative Humidity on Curing

The relative humidity of the environmental control room was first adjusted to about 50 per cent. This was found to be inadequate for curing soil-cement mixtures, and the relative humidity was raised to about 90 per cent. In each case there was a fluctuation of about 10 per cent in the relative humidity. Because of the low initial relative humidity several soil series had to be discarded and replaced.

Figure 3, page 30, shows the effect of relative humidity on the compressive strength of soil-cement mixtures with a curing time of 28 days. At the lower relative humidity there was a greater strength with a cement content of less than 5.0 per cent. This was mainly due to the clay acting as a binding agent. There was less strength with a cement content of more than 5.0 per cent. This was probably so because there was insufficient moisture present for optimum hydration of the portland cement in the mixtures. The moisture content of the soil-cement

Figure 3. Effect of Relative Humidity on Curing of Compacted Soil-Cement Mixtures.

mixtures was found to be about 30 per cent for the 90 per cent relative humidity and about 5 per cent for the 60 per cent relative humidity.

The compacted soil-cement cylinders were stored on paper-lined shelves in the high humidity room. There was free drainage so that the only water in the specimens was that held by adsorption or that used to form hydration products. Not only portland cement hydration products were formed. It is believed that trace minerals, such as gypsum, silica gel, and even the calcite hydrate to some extent (Brooks, Clark, and Thurston 1950).

Compressive Strength Testing Procedure

The unconfined compressive strength testing apparatus has been described in Chapter 3. A strain rate of about 0.05 inches per minute was used for determining the compressive strength of the soil-cement cylinders. For these tests the amount of strain was recorded for the maximum compressive strength of each specimen. The lateral dimensions of the soil-cement cylinder was assumed to increase the same amount as the decrease in height. On this basis the adjusted area of the soil-cement cylinder was computed for maximum compressive strength. The adjusted unit compressive strength was then determined.

The compacted soil-cement cylinders were weighed before being stored in the curing room and weighed again when removed from the curing room for testing. After the specimens were tested to failure they were put in an oven at 105°C for 24 hours. In this way the moisture contents were determined. The soil-cement cylinder moisture contents and dry densities are tabulated in Tables XIII through XVII, Appendix C.

Compressive Strength of Soil

Compacted soil cylinders which contained no cement additive were included in each curing-time series of soil-cement mixtures. These soil samples were used to determine the relative moisture contents of the test series and to gain a comparison of strength increase with the various soil-cement mixtures at those moisture contents.

The compressive strength of the soil samples varied with moisture content to such an extent that no cementation strength increase with time could be ascertained, the humidity control of the environmental room not being sufficiently precise.

The moisture-strength relationships, Figures 24 through 29, Appendix D, show that when there is less than 20 per cent water content by weight there is a gain in the compressive strength of the compacted soil. This strength has been shown to be dependent upon the clay content for air-dried soil samples, see Figure 1. The gain in compressive strength as the compacted soil dries is probably due to the bonding of the clay fraction of the soil.

There is some evidence that the soils may have certain characteristic water adsorption coefficients. Some of the soil samples with high calcite contents, such as Sample No. 10, tended to adsorb a specific amount of water even though the relative humidity varied during the curing periods. Other soil samples which contained few fines, such as Sample No. 8, adsorbed sufficient water at a high relative humidity to collapse of their own weight.

The large variation in compressive strength with moisture content for the soil samples which were tested indicates that pulverized

calcisols which are exposed to water require a stabilizing agent if they are to be used for constructional purposes. The compressive strength of the soils which were tested varied widely with moisture content: Soil Sample No. 4, containing few fines, varied from 5 to 65 lbs/sq. in. and Sample No. 5, containing a large amount of fines, varied from 5 to 560 lbs/sq. in.

Compressive Strength of Cement-Stabilized Soil

There was a very close relationship between the cement content of the soil-cement mixtures and the compressive strength of those mixtures. This relationship was approximately linear for the amounts of portland cement which were used and appeared to be independent of the moisture content (see Figure 3). The relationship between the 28-day compressive strength of compacted soil-cement mixtures and cement content is shown, for Soil Sample No. 12, in Table IX below.

TABLE IX
COMPRESSIVE STRENGTH OF SOIL-CEMENT MIXTURES

Per Cent Cement	Strength in Lbs/sq. in.	Per Cent Cement	Strength in Lbs/sq. in.
none	collapsed	6.3	453
2.5	173	6.5	487
3.1	212	7.5	604
5.0	368	10.0	899

The compressive strength of the cement-stabilized soils increased during the 28-day curing period. After 28 days many of the

compacted soil-cement cylinders showed a loss in compressive strength, Sample No. 9 showing a loss after 14 days. In all cases the soil-cement mixtures which contained 2.5 per cent portland cement showed a compressive strength loss between 28 days and 84 days curing time. This loss varied from 14 to 65 per cent of the 28-day strength.

A typical example of the time-strength relationships of compacted soil-cement mixtures, Soil Sample No. 2, is shown in Figure 4, page 35. The remainder of the time-strength relationships are shown in Figures 30 through 40, Appendix E. Half of the soil samples which were tested showed a strength loss for all soil-cement mixtures between 28 and 84 days. These losses were as much as 41 per cent for the 5.0 per cent mixture, 31 per cent for the 7.5 per cent mixture, and 30 per cent for the 10.0 per cent mixture.

The 28-day compressive strengths of the soils varied from 364 lbs/sq. in. for Sample No. 8 to 1132 lbs/sq. in. for Sample No. 10. This strength does not appear to be dependent upon the clay content or the water-soluble components in the soil. It appears to depend primarily upon the grain-size of the soil; i.e., available surface area, and upon the predominant soil components.

The age-density relationships for the compacted soil and cement-stabilized soil cylinders, which are given in Tables XIII through XVII, pages 79-83, show that there is a definite relationship between the changes in compressive strength of the soil-cement samples between 28 and 84 days and the changes in the dry density of the samples. When the soil-cement mixtures consisted of 5.0 per cent or more portland

Figure 4. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

cement the compressive strength generally increased or remained constant when there was an increase in dry density.

Various soil and cement hydration products are formed and broken down as the chemical components tend toward an equilibrium state. The soil with no cement added also forms and loses hydration products over a period of time in the curing room environment, as shown in Table XIII, page 79.

The moisture content which the soil and soil-cement tends to hold in the high humidity room decreases with additional cement content. The addition of 2.5 per cent cement causes a 2 to 4 per cent decrease, and for each additional 2.5 per cent increment of cement added there is a further 0.5 per cent decrease in moisture content. The moisture content that soil-cement mixtures will hold appears to be independent of the curing time.

Effect of Calcite on Soil-Cement Mixtures

The soil samples which were tested exhibit a wide range of calcium carbonate contents, as shown by Figure 5, page 37. As previously indicated, the relationship between cement content and compressive strength of the soil-cement cylinders was approximately linear. The compressive strengths of the soil-cement mixtures which contained 10 per cent portland cement were plotted against the calcium carbonate contents of the soil samples in Figure 5. This set of curves is considered to be typical of the results of the other three soil-cement mixtures.

Figure 5. Effect of Calcium Carbonate Content on Strength of Compacted Soil-Cement Mixtures.

The soil samples which contain less than 50 per cent calcium carbonate do not appear to be much affected by the calcite component in the soil. When more than 50 per cent of the soil is calcite there is an increase in the compressive strength of the cement-stabilized soil. There is about a 50 per cent increase in the 1, 7, and 14 day compressive strength of the soil-cement specimens with an additional increment of 35 per cent calcium carbonate. There is nearly one hundred per cent increase in the 28 and 84 day compressive strengths in the same soils due to the 35 per cent increment.

CHAPTER VI

X-RAY ANALYSIS OF CEMENT-STABILIZED SOIL

Preparation of Soil Specimens

When the soil-cement mixtures from Sample No. 2 were prepared for the five different curing times, one additional soil-cement cylinder was compacted for each soil-cement mixture. These specimens were broken apart manually after the requisite curing times had elapsed.

Representative portions of the soil-cement cylinders were placed on paper towels until sufficiently dry for grinding. The soil-cement was reduced to minus No. 140 sieve size, using a mullite mortar and pestle.

The first x-ray diffraction traces were made from soil-cement samples which retained part of their moisture content. This was done to investigate the natural hydration products of the soil-cement mixtures. Some of the portland cement hydration products have different hydration states at different moisture contents, the calcium sulfoaluminates being one of these products (Copeland, et al., 1960). Then, all of the soil-cement mixtures which were prepared for x-ray diffraction analysis were put into a vacuum dessicator, the excess moisture in the specimens was removed, and the specimens were stored in sealed containers. This was done to prevent further hydration reactions.

X-ray Diffraction Procedure

The x-ray diffraction equipment described in Chapter 2 was used for producing x-ray diffraction traces of the soil-cement mixtures. The same apparatus components and settings were used, with the exception of the count rate and the time constant.

The first series of x-ray diffraction traces was made using the partially dried soil-cement samples. A count rate of 500 CPS was used with a time constant of two seconds. The traces were made from 3° to $65^{\circ} 2\theta$. Although the first order basal reflections of the hydrous layered silicates were adequate, there was insufficient detail recorded above $10^{\circ} 2\theta$.

The second series of x-ray diffraction traces was made using the vacuum-dried material. A count rate of 200 CPS was used with a time constant of four seconds. The traces were made from 10° to $50^{\circ} 2\theta$.

Randomly oriented powder specimens were used throughout this part of the investigation. Because of the cleavage habits of feldspar and the layered silicates true random orientation was not achieved. The room containing the x-ray diffraction equipment had a controlled temperature of about 70°F , but no attempt was made to halt the carbonation of the cement hydration products.

X-ray Diffraction Analyses

The soils of the Tucson area were previously found to consist predominantly of feldspars. The x-ray diffraction traces of the three feldspar samples, and 62 soil samples, were used to tabulate and identify the feldspar suite. The feldspar samples, even those passing a

No. 200 sieve, showed strong orientation when put in the specimen holder, so that it was not possible to determine precise diffraction peak intensities.

The diffraction pattern of the feldspars of the Tucson area was listed in detail in Table X, pages 42-45, for the diffraction angles of 13° to 42° 2θ . In addition, the diffraction pattern to 51° 2θ was observed and the last major peak at 50.65° 2θ was listed. There are more than 58 diffraction peaks in the first 51° 2θ angle and many of these peaks are doublets. This complex diffraction pattern comprises most of the soil x-ray traces so that minor soil components may be completely obscured.

The feldspar suite was tentatively identified by its peaks of major intensity between 27° and 29° 2θ . The major feldspar component was identified as anorthoclase by means of the x-ray data for the alkali-feldspar series as given by Donnay and Donnay (1952). This data is for high feldspars and gives slightly higher 'd' spacings than for low feldspars. It was found that many diffraction peaks were still unaccounted for. Orthoclase was identified initially by the 20.9° and 27.45° 2θ diffraction peaks, and albite by the 24.25° and 28.2° 2θ diffraction peaks.

The remainder of the x-ray diffraction peaks were compared and the feldspars were found to be composed of a three-phase solid-state solution of sodium and potassium aluminum silicate.

The feldspar suite appears to vary little throughout the east side of the Tucson basin watershed. The suite consists of about one-half anorthoclase and equal parts orthoclase and albite.

TABLE X

X-RAY DIFFRACTION ANALYSIS OF TUCSON FELDSPARS

Observed			Orthoclase KAlSi ₃ O ₈			Anorthoclase Na ₇₁ K ₂₉ AlSi ₃ O ₈			Albite NaAlSi ₃ O ₈			Tent. Indices Ortho. Alb.	
2θ°	d(Å)	Avg. I/I ₁	2θ°	d(Å)	I/I ₁	2θ°	d(Å)	I/I ₁	2θ°	d(Å)	I/I ₁	hkl	
13.35	6.65	-1	13.31	6.65	1	-	-	-	-	-	-	110	
13.6	6.51	2	13.56	6.51	1	-	-	-	-	-	-	020	
13.8	6.41	2	-	-	-	13.70	6.47	9	13.78	6.42	5	020	
15.05	5.89	-1	15.10	5.86	2	15.23	5.81	1	15.18	5.83	1	11 $\bar{1}$	
15.3	5.79	-1	-	-	-	15.39	5.75	1	15.69	5.64	1	1 $\bar{1}$ $\bar{1}$	
20.9	4.23	3	20.95	4.24	8	-	-	-	-	-	-	20 $\bar{1}$	
22.0	4.04	2	-	-	-	21.72	4.09	10	21.98	4.04	10	20 $\bar{1}$	
22.5	3.96	1	22.53	3.94	3	-	-	-	-	-	-	111	
22.9	3.87	-1	22.95	3.87	1	22.87	3.88	4	22.87	3.88	7	200	1 $\bar{1}$ 1
23.6	3.78	3	23.48	3.79	10	23.71	3.75	10	23.70	3.75	10	130	1 $\bar{3}$ 0
23.95	3.71	2	-	-	-	23.98	3.72	8	-	-	-	130	
24.25	3.67	2	-	-	-	-	-	-	24.45	3.64	8	130	
24.6	3.62	-1	24.57	3.62	4	-	-	-	-	-	-	1 $\bar{3}$ $\bar{1}$	
24.75	3.59	-1	-	-	-	24.63	3.61	1	-	-	-	1 $\bar{3}$ $\bar{1}$	

TABLE X--Continued

Observed			Orthoclase KAlSi ₃ O ₈			Anorthoclase Na _{0.71} K _{0.29} AlSi ₃ O ₈			Albite NaAlSi ₃ O ₈			Tent. Indices Ortho. Alb.	
2θ°	d(Å)	Avg. I/I ₁	2θ°	d(Å)	I/I ₁	2θ°	d(Å)	I/I ₁	2θ°	d(Å)	I/I ₁	hkl	
25.2	3.53	-1	25.04	3.55	3	-	-	-	-	-	-	22 $\bar{1}$	
25.6	3.48	2	25.76	3.46	8	25.72	3.46	4	25.71	3.47	2	11 $\bar{2}$	
25.9	3.43	2	-	-	-	26.01	3.42	5	-	-	-	11 $\bar{2}$	
26.75	3.335	3	26.79	3.33	0	-	-	-	26.45	3.37	2	220	11 $\bar{2}$
27.0	3.300	2	27.13	3.28	9	-	-	-	-	-	-	20 $\bar{2}$	
27.45	3.245	9	27.35	3.26	6	-	-	-	-	-	-	040	
27.7	3.220	8	27.66	3.22	10	27.57	3.23	10	27.77	3.22	10	002	040
27.85	3.200	10	-	-	-	27.84	3.20	10	-	-	-	002	
28.2	3.165	3	-	-	-	-	-	-	28.06	3.18	10	002	
29.8	2.995	3	29.80	3.00	8	29.90	2.99	1	29.57	3.02	3	131	1 $\bar{3}$ 1
30.4	2.940	2	30.47	2.93	1	-	-	-	30.26	2.95	1	222	04 $\bar{1}$
30.75	2.905	2	30.75	2.90	2	30.64	2.91	3	-	-	-	041	131
30.9	2.890	1	30.92	2.89	1	-	-	-	-	-	-	022	
31.35	2.855	1	-	-	-	-	-	-	31.57	2.83	4	131	

TABLE X--Continued

Observed			Orthoclase			Anorthoclase			Albite			Tent. Indices Ortho. Alb. hkl
2 θ ^o	d($\text{\AA}$)	Avg. I/I ₁	2 θ ^o	d($\text{\AA}$)	I/I ₁	2 θ ^o	d($\text{\AA}$)	I/I ₁	2 θ ^o	d($\text{\AA}$)	I/I ₁	
31.6	2.830	1	-	-	-	-	-	-	-	-	-	
32.3	2.770	1	32.34	2.77	4	*32.45	2.76	2	-	-	-	13 $\bar{2}$
32.8	2.730	-1	-	-	-	-	-	-	-	-	-	
33.8	2.650	1	-	-	-	-	-	-	33.78	2.65	2	13 $\bar{2}$
34.4	2.610	1	34.36	2.61	4	-	-	-	-	-	-	31 $\bar{2}$
34.8	2.575	1	34.71	2.58	6	-	-	-	-	-	-	24 $\bar{1}$
35.1	2.550	2	-	-	-	35.35	2.54	7	-	-	-	31 $\bar{2}$
35.6	2.520	1	-	-	-	*35.54	2.52	1	35.63	2.52	4	11 $\bar{2}$
36.25	2.480	1	-	-	-	*36.67	2.45	2	-	-	-	310
37.1	2.420	1	-	-	-	*37.28	2.41	1	-	-	-	15 $\bar{1}$
37.65	2.385	1	-	-	-	-	-	-	-	-	-	
38.15	2.360	-1	-	-	-	-	-	-	-	-	-	
38.65	2.330	-1	-	-	-	*38.53	2.33	3	-	-	-	33 $\bar{1}$
41.00	2.200	-1	-	-	-	-	-	-	-	-	-	

TABLE X--Continued

Observed			Orthoclase KAlSi ₃ O ₈			Anorthoclase Na _{.71} K _{.29} AlSi ₃ O ₈			Albite NaAlSi ₃ O ₈		Tent. Indices Ortho. Alb.	
2 θ ^o	d(Å)	Avg. I/I ₁	2 θ ^o	d(Å)	I/I ₁	2 θ ^o	d(Å)	I/I ₁	2 θ ^o	d(Å)	I/I ₁	hkl
41.70	2.165	2	41.57	2.17	1	41.84	2.16	8	42.17	2.14	3	060
14 recorded reflections.												
50.65	1.800	3				*50.96	1.79	5				20 $\bar{4}$

*Data for Na_{.61}K_{.39}AlSi₃O₈. All ref. data from Donnay and Donnay (1952).

There are two other major components of the soils besides feldspar; namely, quartz and calcite. The quartz is represented by 8 diffraction peaks and the calcite by 9 peaks in the first $51^{\circ} 2\theta$. The clay mineral suite is represented primarily by basal reflections which occur from 6° through $9^{\circ} 2\theta$, and by the 040 reflections from 19° to $20^{\circ} 2\theta$.

Amid this complex diffraction pattern, which consists of more than 75 diffraction peaks, there are only four 'windows' where portland cement reaction products may be observed. These 'windows' are shown in Figure 6, page 47.

Two constituents of hydrated portland cement are visible in the diffraction trace of the 10 and 25 per cent soil-cement mixtures which were cured for one day, Figure 6. These constituents are tricalcium silicate (C_3S) and calcium hydroxide. There is insufficient tricalcium silicate at lesser cement admixtures, or for more than one day curing time, to appear on the other diffraction traces. Figures 6 and 7, pages 47 and 48, show that crystalline calcium hydroxide appears in the one-day 10 and 25 per cent mixtures, then persists in the 10 per cent cement mixtures through the 28-day curing period. The calcium hydroxide diffraction peak is missing in the 10 per cent cement mixture at the 84-day time period indicating that the calcium hydroxide has been used up in forming other compounds. This takes place at a time when a strength loss occurs in the soil-cement mixtures.

X-ray diffraction traces were made of hydrated portland cement specimens. These diffraction patterns were identified with the aid of the x-ray data given by Taylor (1964). Using this information, the cement components were identified in the soil-cement mixtures.

Figure 6. X-Ray Diffraction Traces of Portland Cement Reaction Products in Soil-Cement Mixtures.

Figure 7. Calcium Hydroxide Lines in X-Ray Diffraction traces of Soil-Cement Mixtures.

The portland cement attacked the clay minerals in the soil samples within the first day, as shown in Figures 41, 42, and 43, Appendix F. The intensity of the basal diffraction peaks is reduced by the additional increments of portland cement. The peaks were not further reduced by a longer curing time. The feldspars were also attacked by the portland cement. Some of the major diffraction peaks being reduced in intensity by as much as 80 per cent.

The pH of the soil samples varied between 8.4 and 8.8, which indicated that there might be some calcium hydroxide present in the soils. Samples No. 4 and No. 5 appeared to contain some crystalline calcium hydroxide. Soil Sample No. 5 is from a soil horizon of mineral concentration, and the diffraction pattern shows not only the presence of calcium hydroxide but shows a characteristically strong $4.98 \text{ \AA}$ diffraction peak, which indicates the presence of limonite. A high trace background intensity also indicates the presence of iron in the soil. The x-ray radiation from the copper target of the x-ray tube causes secondary, or fluorescent, radiation in the iron minerals.

Ettringite, tobermorite, and hydrogarnet may show diffraction peaks in the 5° to 20° 2θ range but the basal spacing reflections of the layered silicates tend to obscure diffraction peaks in this range. It is not possible to verify the existence of these minerals in the soil-cement mixtures.

CHAPTER VII

DISCUSSION OF CALCISOL-PORTLAND CEMENT SYSTEMS

Variable Strength Characteristics

The majority of the calcisol samples which were tested came under the PRA soil classification of A-2. Comparable studies of the compressive strength of compacted soil-cement, which were conducted by Catton (1962), indicated that for 10 per cent cement additive the 28-day strengths may be expected to vary from about 1400 to 1800 lbs/sq. in., and may be expected to increase by about 10 per cent by 84 days curing time. It is apparent from the data in Appendix E that the soils of the Tucson area are not so amenable to cement treatment.

The soil-cement mixtures which were tested gave 28-day compressive strengths which varied from 364 to 1132 lbs/sq. in. for 10 per cent cement admixtures. There appear to be four main parameters which determine the compressive strength of the compacted soil-cement mixtures. These include grain-size, clay content, calcite content, and feldspar content, or some combination of these. That part of the soil which is not clay or calcium carbonate is predominantly feldspar.

It has been shown, Figure 5, page 37, that the soil samples with a high calcium carbonate content, e.g., Sample No. 10, give high compressive strengths in soil-cement mixtures. When there are no fines in the soil and the calcium carbonate is macrocrystalline, e.g., Sample No. 6, a strong soil-cement is possible.

The clay content of the soil-cement mixtures does not affect the compressive strength to the extent of the other soil components. Its effect is immediate but not lasting with these soils; e.g., Sample No. 5, the soil-cement mixture losing strength after 28 days curing time. The 18 per cent clay content of Sample No. 5 gave a compressive strength to the compacted soil-cement mixture about 20 per cent higher than the upper members of the same soil column.

The calcium carbonate and feldspar appear to act in combination and to determine the compressive strength of the soil-cement mixtures. These two minerals are the predominant soil constituents. When the two minerals appear together in amounts of about 30 to 45 per cent calcium carbonate and 45 to 65 per cent feldspar, the compressive strength of the soil ranges from 450 to 575 lbs/sq. in. for 10 per cent cement, at age 28 days. When the calcite content is increased and the feldspar content is decreased the compressive strength becomes greater. When the feldspar component becomes predominant in the soil the soil-cement strength becomes less; e.g., Sample No. 8 with a 28-day compressive strength of 364 lbs/sq. in.

The compressive strength losses which occur in the soil-cement mixtures are believed to be due to the chemical interaction of the calcite and feldspar and portland cement in a moist environment. The compacted soil-cement mixtures which showed the greatest compressive strength losses after 28 days curing time were those which consisted predominantly of calcite and feldspar. The greatest strength losses occurred when the soil consisted of 60 to 80 per cent feldspar, 15 to 35 per cent calcite, and a clay content of less than 7 per cent.

It has been shown (Bogue 1955) that with some feldspars and alkali-bearing rocks, a reaction with calcium hydroxide will release alkali hydroxides which are then available for reaction with opaline silica in the aggregate. The alkali hydroxides react with silica to form alkali silicates, predominantly sodium silicate gel. The gel is not capable of diffusing through the hardened cement paste. The alkali silicate formed on the surface of an aggregate particle tends to draw solution from the cement paste and eventually disrupts the structure of the paste.

It was shown in Chapter 6 that there was free calcium hydroxide available in the soil-cement mixtures for at least 28 days curing time. All of the soils contain some residual calcium hydroxide with an in situ pH of about 8.6. Soils which are in the process of weathering also normally contain other silicate decomposition products, including silica gel and opaline silica. This silica is soluble in water to about 140 parts per million and is not affected by the calcium ion concentration (Krauskopf 1956).

All of the chemical components are available for alkali-aggregate decomposition reactions to occur. It is believed that this is the cause of the weak bonding and loss of strength of the soil-cement mixtures. A decomposition of the hydraulic cement compounds is believed to occur with subsequent formation of non-cementitious products.

An Investigation of Soil Minerals

Three soil minerals were investigated in order to test the hypothesis concerning the disruption of soil-cement bonding. Bulk

samples of feldspar and phyllite were obtained from the eastern side of the Tucson Basin. The soil from Sample No. 10 was used because it contained 85 per cent calcite with only about 3 per cent clay. The feldspar and phyllite were investigated by x-ray diffraction analysis. It was found that the feldspar sample contained the same suite of feldspars as the soil samples and consisted of about 90 per cent feldspar and 10 per cent quartz. The phyllite sample was estimated to contain about 85 per cent muscovite mica, 5 per cent quartz, and 10 per cent chlorite.

The phyllite was reduced to minus No. 200 size to simulate the mica component of the soil samples. The phyllite was then put in three soil-cement mixtures. The results are shown in Table XI below.

TABLE XI
PHYLLITE-SOIL-CEMENT MIXTURES

Soil Sample	Per Cent Cement	Per Cent Phyllite	Age in Days	Strength in Lbs/sq. in.
No. 2	10.0	5.0	28	481
No. 2	10.0	none	28	452
No. 10	10.0	10.0	7	653
No. 10	10.0	none	7	661
Feldspar	10.0	10.0	7	494
Feldspar	10.0	none	7	355

The amounts of phyllite which were used did not affect the compacted soil-cement mixtures appreciably within 28 days. The feldspar, however, acquired a strength gain of nearly 40 per cent.

The phyllite may have acted as a soil filler, increasing the soil-cement density and, thus, increasing the compressive strength. It is known that calcium hydroxide reacts with clay minerals to form calcium silicate hydrates (Eades and Grim 1960). Some of these calcium silicate reaction products (pozzolans) have been identified by Sloane (1965). These calcium silicates are hydraulic cementing compounds.

The feldspar was reduced to material passing a No. 40 sieve. The feldspar was then mixed in three different ratios with Sample No. 10 and cured for 7 days. The results are shown in Table XII below.

TABLE XII
FELDSPAR-SOIL-CEMENT MIXTURES

Per Cent Soil	Per Cent Feldspar	Per Cent Cement	Strength in lbs/sq. in.
0	100	10.0	355
25	75	10.0	507
50	50	10.0	651
75	25	10.0	698
100	0	10.0	661

The soil of Sample No. 10 has a 7-day strength which is 86 per cent greater than the feldspar. It is known, however, that calcium carbonate does not work well as a soil binder because of its characteristic inertness and slow regrowth rate. This indicates that the poor bonding of the feldspar and cement reaction products is in part responsible for the variable strength characteristics of the compacted soil-cement

mixtures. The feldspar aggregate also exhibits low strength characteristics because of its perfect cleavage.

A 50 gram sample of the feldspar was mixed with 11.12 grams of calcium hydroxide in 300 ml of distilled water. The buffered mixture was well stirred once each day for seven days and stored at a temperature of about 75°F. Hydrochloric acid was then added to the mixture until the pH of the mixture was slightly above 7.0. The feldspar residue was put in a filter and 300 ml of boiling water was filtered through the feldspar. The oven-dry weight of the remaining solids was then determined. There was a loss of 0.152 per cent of the original dry weight of the feldspar over a seven day period.

The amount of dissolution of the feldspar, if considered a linear function with time, would give a loss per 100 grams of 0.6 grams per 28 days, and 1.8 grams per 84 days. This does not include the amount of water insoluble materials which may have been formed. The water soluble reaction products are primarily sodium hydroxide and potassium hydroxide, and the insoluble products include sodium and potassium silicates (Bogue 1955).

This chemical reaction is believed to be the main cause of strength loss by the compacted soil-cement mixtures which were tested.

Effective Amounts of Portland Cement

The lower horizon of indurated caliche, which is represented by Sample No. 6, appears to have been leached by fluctuations in the ground-water table (Guild 1910). As has been shown, it contains no fines and the calcium carbonate cementing agent consists of

macrocrystalline calcite. The addition of 5 per cent or more of portland cement is sufficient to insure a continued strength increase for at least 84 days.

The required cement content for the stabilization of the upper soil horizons appears to depend primarily upon the degree of weathering which has occurred and the concentration of weathering products.

The surface soil horizons and the sheets of indurated caliche which have been exposed by erosion, represented by Sample Nos. 1, 10, 11, and 12, require an addition of 10 per cent or more of portland cement in order to retain the maximum developed strength for at least 84 days.

The soil horizons which lie between the upper and lower indurated caliche horizons were nearly stabilized by the addition of 10 per cent portland cement. These horizons, represented by Sample Nos. 4 and 5, may be stabilized by the addition of 15 per cent portland cement.

The upper horizons of indurated caliche which have a soil cover are not stabilized by 10 per cent portland cement additive and may not be stabilized by less than 20 to 25 percent portland cement if there is a substantial amount of feldspar present. This soil horizon, represented by Sample Nos. 2, 3, 7, 8, and 9, shows a low compressive strength when mixed with small amounts of portland cement and compacted, as shown by Figures 4, and 30 through 40, pages 35 and 90-100. The maximum soil-cement strength is usually acquired within 28 days and sometimes sooner. A loss of strength then occurs which may vary from 20 to 30 per cent of the maximum strength, even for a 10 per cent soil-cement mixture.

The term, soil stabilization, as used in this study, refers to the process by which the physical properties of the fragmented calcisols may be improved to provide a foundation material which will furnish adequate support for loads transmitted to it.

An investigation which was conducted by Gibbings (1932) indicated that aggregate from the northeastern side of the Tucson Basin was reactive to portland cement. This aggregate, which was comparable to Soil Sample No. 4, showed a 28-day strength approximately proportional to the amount of portland cement used to a maximum limit of about 25 per cent cement having a compressive strength of nearly 3000 lbs/sq. in. For additions of 14.6 to 34.2 per cent cement there was little or no gain in compressive strength between 28 and 90 days curing time. This aggregate consisted largely of feldspar. Larger amounts of portland cement produce larger amounts of calcium hydroxide upon hydration to react with the feldspar aggregate.

The effective stabilization of calcisols in the Tucson Basin by means of portland cement may only be accomplished under certain conditions. The moisture content must be controlled so that there is adequate water present to develop the soil-cement hydration products during the early aging period but insufficient water available to permit the decomposition of these products after they are formed.

The addition of 2.5 per cent portland cement was found to be adequate to prevent slumping of fragmented calcisols when the soils are saturated with water.

It has been suggested (Bogue 1955) that cement aggregate reaction can be inhibited by the introduction of carbon dioxide into the

system in order to convert the active alkali hydroxides to carbonates. A large excess of calcium hydroxide may be successful in driving the soil-cement reactions to completion, but as has been shown, further addition of water to the system will also cause a continued lime-feldspar reaction.

A finely pulverized reactive silica or pozzolan might be successfully used to react with the calcium hydroxide and thus chemically stabilize the soil-cement reaction products.

The addition of clay to the soil-cement mixtures may cause a strength increase. This was indicated by Sample No. 5 and by the addition of phyllite to the feldspar sample.

CHAPTER VIII

CONCLUSIONS

General

1) The calcisols of the Tucson Basin consist mainly of varying proportions of feldspars and calcite with a lesser amount of quartz, clay minerals, and mica occurring in all grain sizes.

2) The compressive strength of indurated caliche of the Tucson Basin is dependant primarily upon its packing order and clay content, and to a lesser extent upon its calcium carbonate content. The indurated caliche contains a low clay content, the strongest specimens tested having a compressive strength of 1500 to 5000 lbs/sq. in. and a clay content of less than three per cent.

3) The compressive strength of fragmented calcisols which have been compacted is dependent primarily upon their dry density, clay content, and moisture content, and to a lesser extent upon their adsorption characteristics. The air-dry strength of remolded calcisols is directly related to the clay content, the strongest specimen tested having a compressive strength of about 550 lbs/sq. in. and a clay content of more than 18 per cent. With access to water the remolded calcisols rapidly lose nearly all of their compressive strength.

4) There is only a general relationship between the calcite content and the compressive strength of the indurated calcisols, the stronger soils consisting of calcite predominantly. When the calcite

is fragmented it acts as an inert granular material with no cohesive properties.

5) The maximum compressive strength of cement-stabilized calcisols generally occurs after 28 days curing time. The amount of strength which the soil-cement mixtures gain is dependent primarily upon the amount of portland cement added and upon the feldspar plus calcite content of the soils. It is dependent to a lesser extent on the clay content of the soil and the weathering of the soil horizon.

6) The strength of cement-stabilized soils is approximately a linear function of the amount of portland cement added. The rate of curing of these soil-cement mixtures is highly dependent upon the environmental humidity.

7) A strength loss occurs in the cement-stabilized calcisols of low cement content after a 28 day curing period. Soil samples from the unexposed horizons of indurated caliche showed large strength losses for all soil-cement ratios which were tested. The addition of 2.5 per cent portland cement will prevent slumping of the fragmented calcisols when saturated.

8) The compressive strength losses which occur in the soil-cement mixtures are believed to be due to the chemical interaction of the calcite, feldspar, and portland cement in an aqueous environment. The feldspar is shown to consist of a three-phase solid-state solution of alkali feldspars. The calcium hydroxide released by the hydration of portland cement in an alkali soil reacts with the alkali feldspars to destroy the hydraulic cement hydration products.

9) The lower horizons of the leached indurated caliche may be stabilized by the addition of less than 10 per cent portland cement, the weathered surface calcisol horizons by the addition of 10 per cent of cement, and the soil horizons between the indurated caliche horizons by the addition of 15 per cent of cement. The upper horizons of indurated caliche which have a soil cover are not amenable to stabilization with amounts of portland cement less than 20 to 25 per cent.

Recommendations for Further Research

The effect of longer curing times on the compressive strength of the soil-cement mixtures should be investigated. The effect of greater remolded soil density should also be considered for the soil series which was tested.

Soil-cement systems should be investigated in which pure mineral components of the soils are used. In particular, the reactions of binary systems containing feldspar, calcite, or phyllite and portland cement should be investigated. The result of all combinations of these soil components with portland cement should then be considered.

The solubility of the feldspars of the Tucson area in buffered calcic alkaline aqueous solutions should be determined and the reaction products should be identified. The effects of leaching the calcisols before adding portland cement should be considered.

Other stabilizing agents than portland cement should be investigated, such as asphalt. Calcium hydroxide, clays, or pozzolans might be effective separately or in combination with portland cement.

The generation of carbon dioxide in the curing of soil-cement mixtures should also be investigated. The carbon dioxide should not only counteract the reactive aggregate but also cause regrowth of the fragmented calcite.

APPENDIX A

GRAIN-SIZE DISTRIBUTION CURVES

Figure 8. Grain-Size Distribution Curves.

Figure 9. Grain-Size Distribution Curves

Figure 10. Grain-Size Distribution Curves.

Figure 11. Grain-Size Distribution Curves

APPENDIX B

COMPACTION CURVES AND AIR-DRY COMPRESSIVE STRENGTHS VERSUS REMOLDING MOISTURE CONTENTS

Figure 12. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 13. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 14. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 15. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 16. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 17. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 18. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 19. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 20. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 21. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 22. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

Figure 23. Compaction Curve and Air-Dry Compressive Strength versus Remolding Moisture Content.

APPENDIX C
AGE-DENSITY RELATIONSHIPS

TABLE XIII
AGE-DENSITY RELATIONSHIPS
(No Cement Content)

Sample No.		1-Day	7-Day	14-Day	28-Day	84-Day
1	Moisture	25.6	23.7	27.7	28.4	17.3
	Density	97.2	97.1	96.8	97.0	102.9
2	Moisture	28.6	36.5	36.3	41.1	17.5
	Density	84.0	85.6	85.2	82.6	83.7
3	Moisture	29.1	35.7	31.1	34.6	21.2
	Density	90.7	87.5	89.3	89.3	87.3
4	Moisture	21.7	27.7	27.0	17.0	16.4
	Density	95.2	96.2	96.5	98.4	98.9
5	Moisture	19.2	29.4	26.5	27.5	22.8
	Density	102.4	103.6	103.2	104.7	105.6
6	Moisture	17.0	21.8	20.6	24.7	15.0
	Density	105.0	101.4	105.6	105.8	107.8
7	Moisture	23.0	27.8	27.5	31.6	27.8
	Density	96.3	97.4	97.3	97.3	96.4
8	Moisture	29.3	35.6	33.8	32.5	31.7
	Density	89.4	89.8	89.8	87.7	87.1
9	Moisture	24.4	-	30.9	5.4	30.0
	Density	94.3	-	96.1	92.8	91.7
10	Moisture	18.6	19.3	19.1	19.8	19.8
	Density	102.4	103.5	106.4	107.1	107.7
11	Moisture	21.8	23.7	24.4	25.7	22.6
	Density	99.2	100.9	100.2	98.9	99.4
12	Moisture	16.2	17.0	20.6	24.7	19.1
	Density	105.2	103.4	104.9	105.8	105.3

Note: Moisture content in per cent and dry density in lbs/cu. ft.

TABLE XIV
AGE-DENSITY RELATIONSHIPS
(Cement Content - 2.5 per cent)

Sample No.		1-Day	7-Day	14-Day	28-Day	84-Day
1	Moisture	23.4	19.6	26.0	26.5	19.1
	Density	95.3	95.4	94.6	95.8	100.6
2	Moisture	27.6	35.2	34.0	36.0	16.5
	Density	81.9	82.6	84.3	83.0	82.4
3	Moisture	26.9	31.5	27.7	30.2	26.1
	Density	89.6	85.9	88.1	89.0	87.8
4	Moisture	18.4	25.7	25.4	19.1	17.1
	Density	94.4	94.3	95.1	98.0	99.2
5	Moisture	20.3	23.7	24.4	24.8	23.9
	Density	100.6	100.2	100.1	99.6	100.8
6	Moisture	14.1	17.9	16.4	16.9	15.9
	Density	106.9	104.5	108.1	109.0	109.3
7	Moisture	22.2	25.4	24.8	25.3	27.0
	Density	93.8	95.7	95.3	94.5	94.3
8	Moisture	26.6	28.6	29.2	28.9	31.5
	Density	89.6	88.8	87.9	87.5	86.8
9	Moisture	23.7	23.2	26.3	5.0	32.3
	Density	95.0	96.3	94.7	91.2	88.0
10	Moisture	14.7	14.9	16.1	15.6	18.6
	Density	101.8	102.3	105.8	107.2	107.0
11	Moisture	20.0	20.4	20.2	21.2	23.2
	Density	98.6	100.2	100.3	98.9	98.4
12	Moisture	15.7	15.6	17.8	19.0	19.1
	Density	105.1	104.2	104.8	106.2	107.1

Note: Moisture content in per cent and dry density in lbs/cu. ft.

TABLE XV
AGE-DENSITY RELATIONSHIPS
(Cement Content - 5.0 per cent)

Sample No.		1-Day	7-Day	14-Day	28-Day	84-Day
1	Moisture	22.5	18.2	23.8	23.4	18.0
	Density	95.6	95.5	95.2	97.6	101.5
2	Moisture	27.2	32.8	33.0	34.3	16.1
	Density	82.5	83.8	84.3	83.7	83.1
3	Moisture	26.6	29.2	26.6	28.2	26.0
	Density	89.9	87.3	88.9	90.5	88.8
4	Moisture	17.9	21.7	22.3	20.1	20.1
	Density	95.2	95.2	97.1	99.7	102.1
5	Moisture	21.1	23.4	24.5	24.9	23.7
	Density	99.3	100.4	99.1	99.1	100.4
6	Moisture	13.5	16.9	15.9	15.7	13.2
	Density	109.7	106.9	109.8	111.1	112.9
7	Moisture	21.4	25.3	24.8	25.1	26.4
	Density	94.5	95.9	95.7	95.2	95.1
8	Moisture	26.3	27.7	27.9	26.9	29.8
	Density	89.7	90.0	89.3	88.8	88.6
9	Moisture	23.3	23.6	26.0	5.5	29.7
	Density	95.8	96.1	95.2	91.9	91.2
10	Moisture	14.0	14.3	17.3	15.1	15.0
	Density	102.8	102.9	104.6	108.4	109.3
11	Moisture	19.0	19.9	19.4	20.3	20.2
	Density	101.3	101.7	102.5	101.1	100.7
12	Moisture	15.5	16.1	17.1	18.0	17.3
	Density	106.8	106.2	107.2	108.3	108.5

Note: Moisture content in per cent and dry density in lbs/cu. ft.

TABLE XVI
AGE-DENSITY RELATIONSHIPS
(Cement Content - 7.5 per cent)

Sample No.		1-Day	7-Day	14-Day	28-Day	84-Day
1	Moisture	21.4	17.9	21.8	22.5	17.9
	Density	96.0	96.6	96.5	97.6	101.3
2	Moisture	26.5	32.3	31.3	32.6	18.3
	Density	82.8	83.6	85.7	85.6	85.1
3	Moisture	25.7	28.2	25.9	27.9	26.2
	Density	91.7	89.2	90.5	91.7	90.2
4	Moisture	17.7	22.0	22.0	18.4	18.9
	Density	95.9	96.1	97.6	102.1	103.5
5	Moisture	19.9	22.8	24.0	24.7	22.4
	Density	99.5	101.3	99.5	99.7	101.4
6	Moisture	13.4	15.4	15.1	14.5	12.3
	Density	111.9	110.6	112.1	113.3	114.7
7	Moisture	21.4	24.5	24.3	24.5	25.9
	Density	95.3	96.6	96.8	96.5	96.7
8	Moisture	25.9	27.0	27.3	25.8	28.9
	Density	91.1	91.1	91.6	90.7	89.7
9	Moisture	22.8	22.9	25.3	6.1	28.6
	Density	96.1	95.9	96.1	92.7	92.1
10	Moisture	14.3	14.6	17.1	13.7	14.2
	Density	103.3	103.9	105.5	109.0	110.4
11	Moisture	18.7	18.8	18.6	19.7	19.3
	Density	102.2	103.1	103.0	102.4	102.9
12	Moisture	15.4	15.5	16.6	17.5	15.7
	Density	108.7	105.9	108.2	109.0	110.0

Note: Moisture content in per cent and dry density in lbs/cu. ft.

TABLE XVII
AGE-DENSITY RELATIONSHIPS
(Cement Content - 10.0 per cent)

Sample No.		1-Day	7-Day	14-Day	28-Day	84-Day
1	Moisture	20.9	17.9	21.3	19.2	19.3
	Density	97.7	96.9	97.5	97.7	104.0
2	Moisture	26.1	31.2	30.2	31.3	19.6
	Density	83.7	85.8	86.7	86.3	86.5
3	Moisture	25.2	27.3	26.0	27.2	27.6
	Density	92.7	90.5	91.6	92.7	92.4
4	Moisture	17.6	22.0	21.0	18.6	17.6
	Density	96.8	97.0	98.8	103.3	105.1
5	Moisture	21.3	23.0	23.4	24.9	22.6
	Density	99.6	101.9	99.7	99.2	101.9
6	Moisture	13.1	15.3	13.9	14.3	11.9
	Density	113.4	111.6	115.2	114.0	116.4
7	Moisture	22.0	24.0	23.7	23.7	25.1
	Density	96.4	98.1	97.6	97.8	97.5
8	Moisture	25.5	26.3	26.4	24.8	27.8
	Density	92.1	92.9	92.1	92.6	91.4
9	Moisture	22.0	22.8	25.0	6.3	27.7
	Density	97.6	97.4	96.6	93.0	93.6
10	Moisture	13.9	15.2	15.8	13.4	13.9
	Density	104.0	104.7	104.2	111.0	111.4
11	Moisture	18.4	18.8	18.4	18.8	18.7
	Density	102.4	103.2	104.6	104.1	103.9
12	Moisture	15.1	16.0	15.7	16.4	15.2
	Density	109.0	107.3	110.3	111.0	110.7

Note: Moisture content in per cent and dry density in lbs/cu. ft.

APPENDIX D
COMPRESSIVE STRENGTHS OF REMOLDED CALCISOLS
VERSUS MOISTURE CONTENTS

Figure 24. Compressive Strength of Remolded Calcisol versus Moisture Content.

Figure 25. Compressive Strength of Remolded Calcisol versus Moisture Content.

Figure 26. Compressive Strength of Remolded Calcisol versus Moisture Content.

Figure 27. Compressive Strength of Remolded Calclisol versus Moisture Content.

Figure 28. Compressive Strength of Remolded Calcisol versus Moisture Content.

Figure 29. Compressive Strength of Remolded Calcisol versus Moisture Content.

APPENDIX E

COMPRESSIVE STRENGTH CHANGES OF COMPACTED
SOIL-CEMENT MIXTURES WITH AGE

Figure 30. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 31. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 32. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 33. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 34. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 35. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 36. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 37. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 38. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 39. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

Figure 40. Compressive Strength Change of Compacted Soil-Cement Mixtures with Age.

APPENDIX F
CLAY MINERAL BASAL REFLECTIONS IN X-RAY
DIFFRACTION TRACES OF CALCISOL

Figure 41. Clay Mineral Basal Reflections in X-Ray Diffraction Traces of Calcisol.

Figure 42. Clay Mineral Basal Reflections in X-Ray Diffraction Traces of Calcisol.

Figure 43. Clay Mineral Basal Reflections in X-Ray Diffraction Traces of Calcisol.

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