M. W. TINDER
COMMISSIONER OF HIGHWAYS

COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

January 4, 1955

ADDRESS REPLY TO
MATERIALS RESEARCH LABORATORY
132 GRAHAM AVENUE
LEXINGTON 29, KENTUCKY

ATTENTION:

A. 1.2
B. 3.8
D. 1.7

Memo to: D. V. Terrell
Director of Research

Since the inception of dense-graded aggregate bases about three years ago, one of the principal features of interest with respect to the materials has been the binding quality of limestone dust. As you know, at least 5 percent of the total aggregate in the base must be finer than the No. 200 mesh sieve size, and the grading of the entire aggregate is such that logically the binding action of the dust has a very important influence on the stability of the base.

Probably the first real interest in determining differences in binding qualities of stone dust used for this purpose, arose in 1953 when projects in several parts of the state using different stones and different construction features were under way. One of these was the Phil - Pine Grove Road in Casey County* where there was no calcium chloride additive, and there were others elsewhere with and without the additive. Marked contrasts in cementation of the materials during the construction of the bases and prior to bituminous surfacing were observed.

In his report on the Phil - Pine Grove Road Project, Mr. E. G. Williams mentioned preliminary tests in the laboratory and emphasized the need for more laboratory investigation to differentiate stone compositions and gradings from the standpoint of binding qualities. As a result, an extensive laboratory program was outlined, and

* See Research Laboratory Report No. 1 on "A Water-Bound, Dense-Graded Aggregate Base" December, 1953.

one part of it was started early in 1954. The study was chosen by William E. Howard, a member of the first group of graduate scholarship employees, as a work project and as thesis material for credit. Most of the laboratory work in the first phase was completed prior to the transfer of Mr. Howard to the Division of Planning in June, and a report on results of that work was given orally by both men at the meeting of the Research Committee on December 21. The attached report is a written version of material discussed at that time.

While the results are not regarded as conclusive, several trends in the data could be highly significant. As a minimum they point to lines of additional investigation which should be highly profitable. Contrasts in the effects of moisture content and calcium chloride additive on several physical properties of four widely different types of stone dust are indicated.

The physical property of greatest interest, of course, is the so-called intrinsic strength or cohesion since that is the feature of strength that is solely dependent upon cementation of the specimens by the stone dust. However, the frictional resistance to shearing stresses, deformation at failure, and the relative amounts of cementation and friction represented in total shearing resistance are important. With regard to the interpretation of data in this report, a more significant picture of the relative contributions by cementation and friction to shearing strength might have been given if the measured shearing stress at failure in unconfined compression rather than the theoretical shearing stresses at three normal stresses had been used.

An extension of this project is now in the formative stages, and work on the preparation of materials for test should start about the last of this month. This additional investigation will have a more restricted scope but will provide much more information about the cementation characteristics of one particular stone dust. Upon the completion of that work, still further possibilities for study should be apparent.

Respectfully submitted,

L. E. Gregg

L. E. Gregg
Assistant Director of Research

LEG/jk
Copies to: Research Committee Members
Mack Galbreath (3)

Commonwealth of Kentucky
Department of Highways

AN INVESTIGATION

OF

THE BINDING PROPERTIES OF LIMESTONE DUST

by

William E. Howard
Assistant Manager of
Special Study Section
Division of Planning

and

Ellis G. Williams
Research Engineer

Highway Materials Research Laboratory
Lexington, Kentucky

December, 1954

INTRODUCTION

A proper quantity of dust particles of various sizes has long been recognized as important in the construction of stone bases and pavements. Screenings for waterbound macadam bases are required to contain not less than a specified amount of dust sizes, and dense-graded limestone bases have controlling limits for the dust fraction. It is generally assumed that these particles serve a dual purpose: (1) in filling void spaces created by larger particles, thus enhancing the gross structure of the aggregate, and (2) in acting as a binder material in the presence of water. Furthermore, it has been demonstrated that the addition of small amounts of certain chemicals may improve the strength characteristics of limestone dusts.

Former studies have been concerned primarily with the overall strength properties of aggregate mixtures containing dust, rather than with the properties of the dust itself. However, in cases where binding properties are of primary concern, a more fundamental approach would be to investigate the dust and fine aggregate fractions before studying the mixture as a whole.

The purpose of this project was to study the binding properties of several different limestone dusts. The stones selected showed considerable differences in composition, and undoubtedly the scope of these differences encompassed the majority of limestones in Kentucky. In addition, an attempt was made to detect variations (if any) in the response of these stones to the effects induced by admixtures of calcium chloride - directly or indirectly.

Since water sources throughout Kentucky may vary from a definitely acid to a definitely alkaline reaction, information concerning the effect of changes in the pH of mixing water was of interest. Accordingly, analyses were run on a single type of stone with three mixing waters - one neutral, one acidic, and one alkaline.

The evaluation of materials was based primarily on results obtained from triaxial compression tests; however, moisture relationships also contributed information.

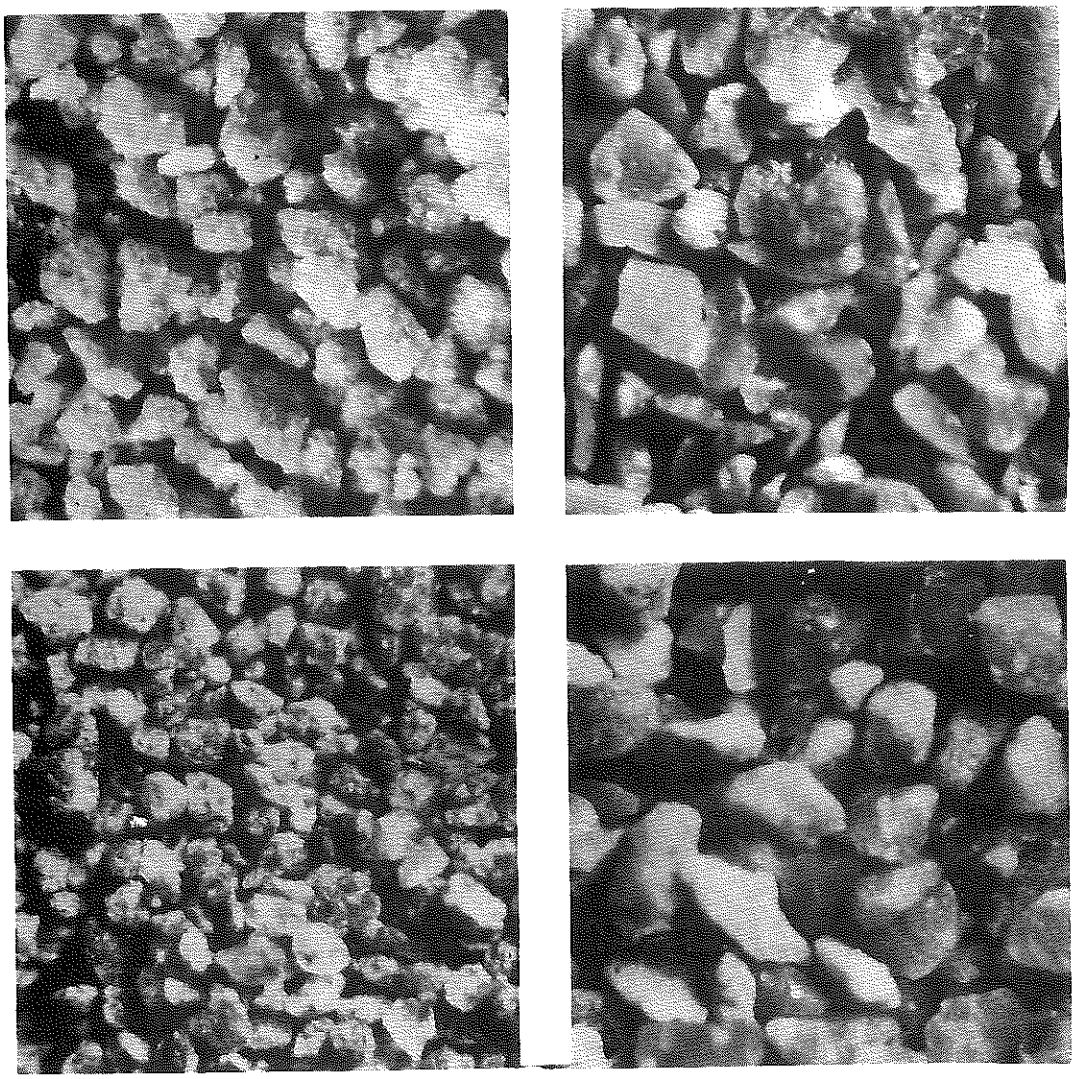


Fig. 1 - Photomicrographs of samples of the four limestones crushed and graded to the 40-80 sieve size (Magnification 30X).

At the upper left is stone A, having a high calcium carbonate relatively small and of reasonably uniform size. This stone had an extremely grainy texture.

At the upper right is stone B, which had an even greater calcium carbonate content (86.6 percent). Although the composition of this stone was essentially the same, its texture was smoother than that of stone A.

At the lower left is stone C, which had a significantly high silica content of 54.0 percent. The particle shape of this material was quite uniform, and the texture was decidedly grainy.

At the lower left is stone D, a material of high magnesium carbonate content (24.1 percent). Particle size of this stone was rather uniform, and its texture was slightly more grainy than stone B. Note the similarity in appearance of stones B and D.

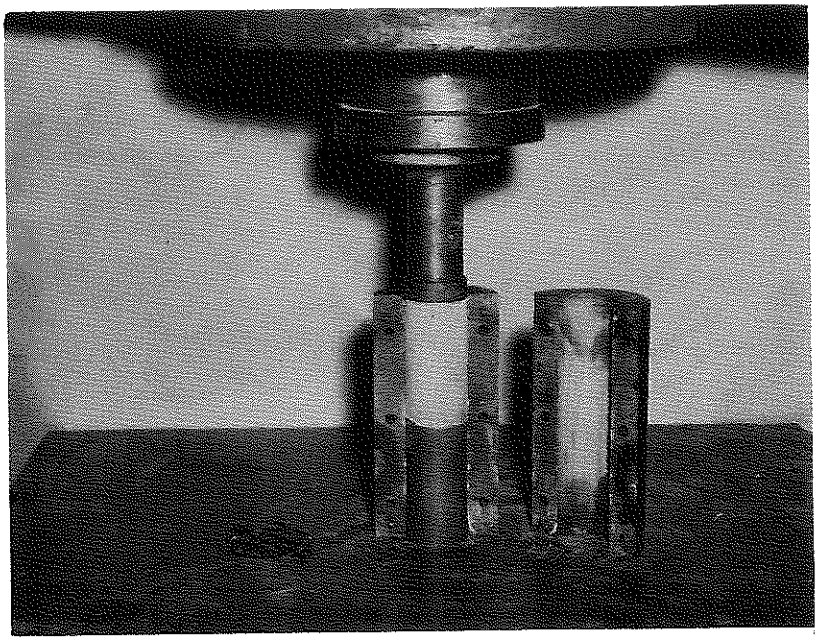


Fig. 2 - Split mold used in the preparation of specimens by double-plunger compression. All specimens were loaded to 800 psi.

to the preparation of test pieces, a number of trials were conducted to determine the minimum satisfactory loading. Specimens were compacted under unit loading of 200, 400, 600 and 800 psi. All except those prepared at the latter loading were very sensitive to handling and lacked uniformity in density; thus 800 psi was adopted as the standard compactive effort for these tests.

Both optimum moisture content and unit dry weight of each material were determined for the loading condition described above. Specimens, different from the standard test piece in that they had a height of approximately 2 in., were prepared at several moisture contents and optimum values were determined from the usual curves relating moisture content and unit dry weight.

Most samples were prepared with neutral water[2] alone or with neutral water plus calcium chloride. However, in two series of tests involving only one stone, the pH of the water was varied (in one case) by the addition of one ml. of a 10N sulphuric acid solution per 10 ml. of mixing water, and by a near-saturated solution of calcium carbonate in the other. Each of these represent an extreme value when compared to the mixing waters normally available, but the purpose of this exaggeration was to magnify differences in strength properties so that they might be more readily detected. There was no calcium chloride incorporated in any of the specimens containing acid and alkaline water.

Calcium chloride was used in pellet form and had a purity of 94 to 97 percent. The amount of one-half of one percent of the dry weight

[2] The term neutral water as used here refers to single-distilled water.

of stone dust was added to the mixing water of those specimens requiring this additive. It was realized that the ratio of aggregate surface area to calcium chloride content was far greater than that normally employed in dense-graded aggregate mixtures. However, no attempt was made to relate the surface areas involved or to increase the percentage of calcium chloride[3]. Furthermore, the differences in grading of the four dusts used would also result in differences in surface area. A fixed percentage of calcium chloride, somewhat in keeping with quantities normally used for base construction, was arbitrarily selected for use.

Curing

Compacted specimens were first weighed and then wrapped in very thin, transparent plastic membranes which sealed the sides of the cylinders but left the ends open. Curing was accomplished in the laboratory at room temperature by allowing the specimens to stand on end on heavy filter paper over a wire mesh (See Fig. 3). These conditions simulated (perhaps remotely) a portion of base course resting on the subgrade, being surrounded by additional base material, and having one surface exposed to the atmosphere.

Moisture content data applied to each specimen in its entirity; thus they represent an average, and do not show any adjustment for possible differentials within the specimens. However, it was recognized that during the following the curing period there could be variations in

[3] Inasmuch as the amount of calcium chloride per unit of aggregate surface in these mixes was extremely small in comparison with the amounts used for fully graded base mixes, there is no direct comparison between the two.

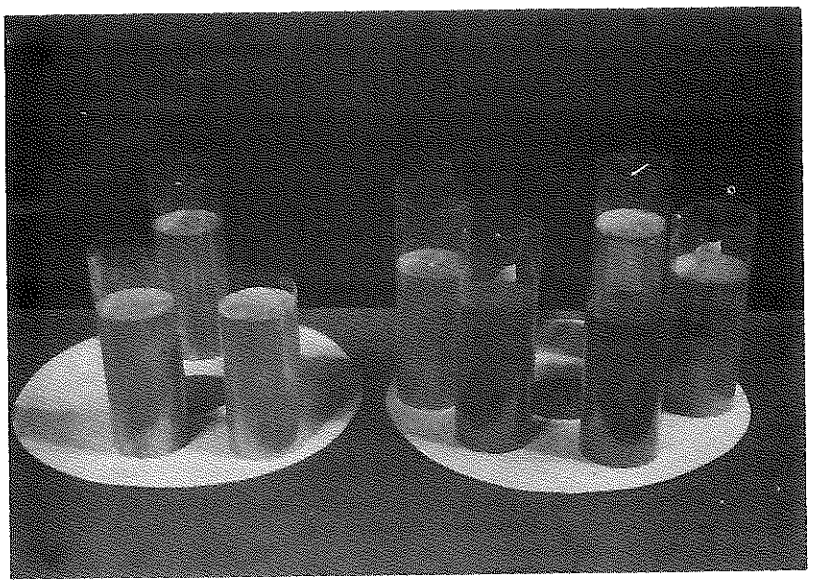


Fig. 3 - Appearance of specimens during the curing period. A plastic membrane surrounds the sides and both ends are open to the atmosphere. All specimens remained in this position throughtout the curing period.

moisture content within different parts of a sample. Such a condition could affect the result of the test, but a similar variation is usually present in a normal base course; hence, the results of this method are believed to be reasonably dependable.

Seven days was arbitrarily selected as a standard length of curing period for the compacted samples. One of the materials (Stone B) was selected for a study of the effect of curing time on triaxial compression test results and on moisture contents. Specimens in this series were cured for three days, seven days, and fourteen days.

Moisture contents were determined when the samples were first prepared and again when they were tested. The percentage loss of moisture was taken as a measure of the extent of curing. The effect of curing was based on any detectable change in strength properties which could be related to the length of curing period.

Triaxial Compression Testing

All strength relationships were determined by the triaxial compression test. In this method the specimens were failed by an axial compressive stress while being subjected to a uniform and constant lateral stress.

Test samples were encased in a thin rubber membrane (0.001-in. thickness) and tested in the triaxial pressure cell shown in Fig. 5. Axial load was applied through and read from a proving ring, while lateral pressure was provided by a compressed air system and measured on a Bourdon type gauge. A rate of deformation of 0.008 in. per minute was employed for all tests.

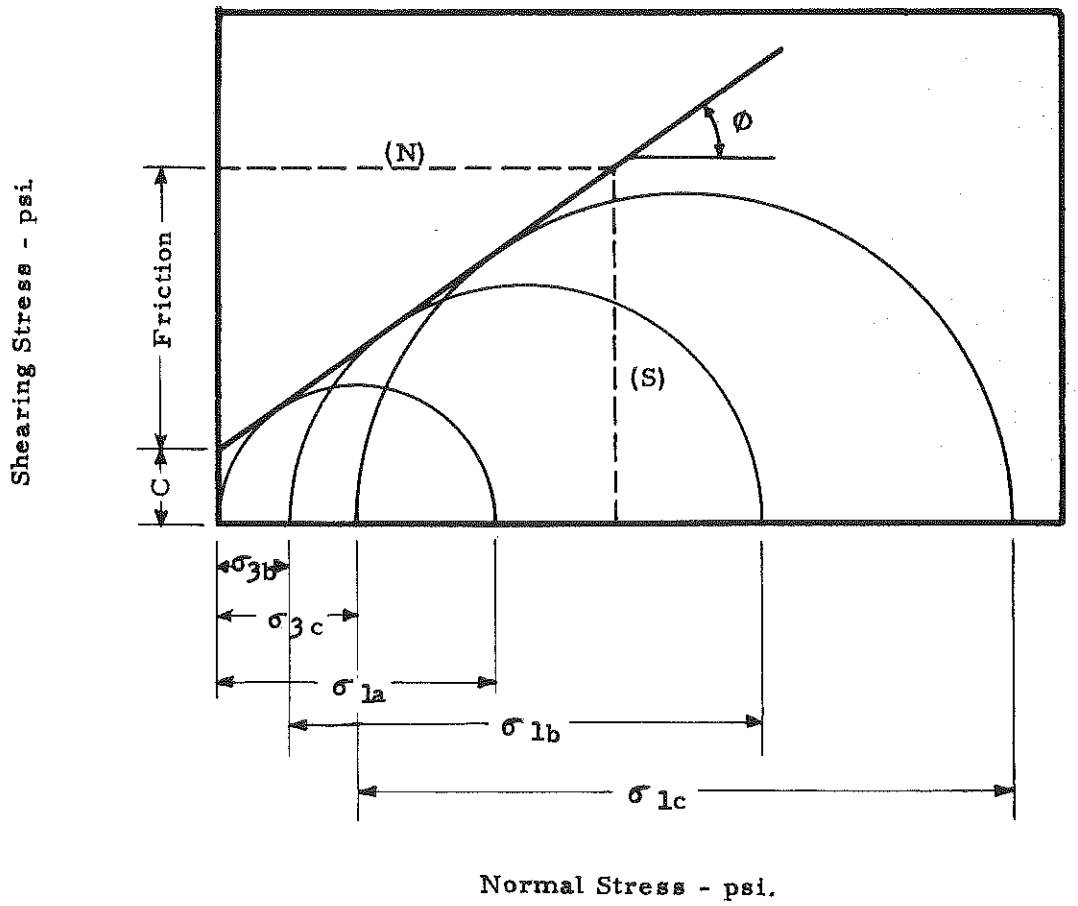


Fig. 4 - Mohr Diagram used for graphic determination of shearing strength. The three semi-circles have diameters equal to the net axial stress required to produce failure of a given material when subjected to three different lateral stresses (3_a, 3_b, 3_c). The semi-circles are removed from the origin a distance equal to the lateral stress imposed on the specimen.

The line tangent to the three semi-circles represents the envelope of failure conditions on the locus of all points representing the combined normal and shearing stresses on the plane of failure under any test condition. The angle of friction (Ø) is the angle between the tangent line and the horizontal. The intrinsic strength (C) is measured by the vertical distance from the point of origin to the intercept of the tangent line with the ordinate. Shearing stress (S) at any normal stress (N) may be read directly from the graph, or it may be computed from the formula: S = C+N ton Ø.

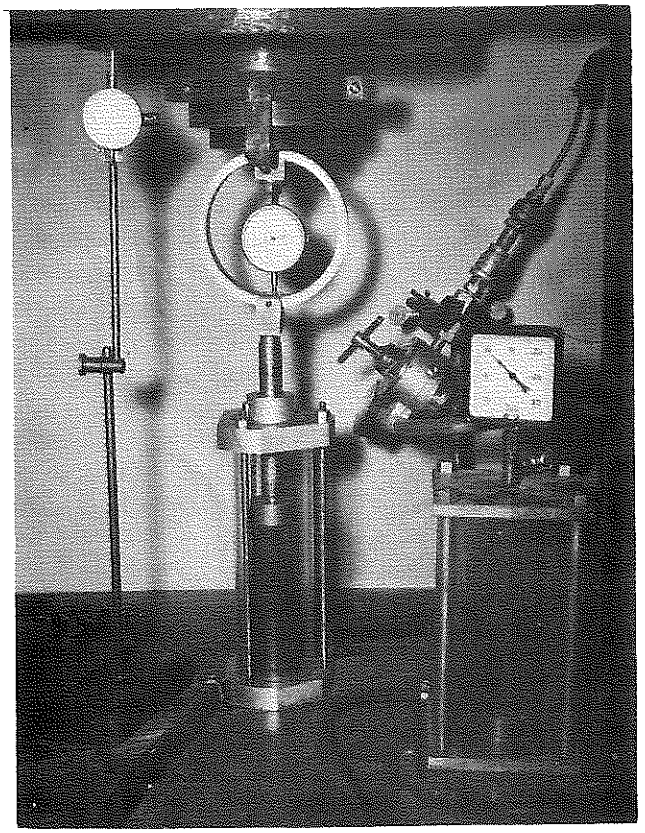


Fig. 5 - Triaxial compression cell used for determining strength properties of all test specimens. Vertical axial loads were applied by a Universal Testing Machine and were measured by the proving ring shown here. Lateral loads were imposed with compressed air, the control mechanism for which is shown at the right. Displacement of the specimen was measured by the extensiometer located at the left.

A complete test consisted of failing one or more samples at lateral pressures of 0, 10, and 20 psi. As a rule, at least one additional specimen was tested in each series to qualify previous data.

Triaxial compression test results expressed the following: (1) axial stress required to produce failure $(\sigma_1 - \sigma_3)$, (2) deformation (Δ), and (3) applied lateral stress (σ_3). Stress-strain curves were plotted to determine maximum axial stress as well as total deformation at failure of the specimen subjected to a given lateral stress. These axial and lateral stress data were then used to prepare a Mohr diagram for graphic analysis of strength properties (See Fig. 4). Total deformation was used only to indicate the relative deflection of a specimen when it was stressed to failure.

Strength analyses were made from a diagram showing normal stress data versus shearing stress data from tests on a single material at two or more lateral pressures. As noted in Fig. 4, this provides a graphic solution of the Coulomb equation:

$$S = C + N \tan \phi$$

where S = Shearing stress,

C = cohesion, or intrinsic strength,

N = normal stress,

and ϕ = angle of internal friction.

For a graphical solution, the vertical axial stress $(\sigma_1 - \sigma_3)$ is plotted as the diameter of a semi-circle whose center lies on the abscissa, and whose position with respect to the origin is determined by the lateral stress. The distance which the semi-circle is removed from the origin

is equal to the applied lateral stress (σ_3), or the center of the semi-circles is located a distance from the origin equal to $\sigma_3 + \frac{(\sigma_1 - \sigma_3)}{2}$. When the semi-circles representing stress conditions under different lateral loads have been plotted, a straight line (tangent or nearly tangent to all circles) is drawn. This line, the Mohr envelope, shows the limiting condition of all combined normal and shearing stresses which the material can withstand, and theoretically the line represents this relationship for failure of the material under any set of conditions.

Several fundamental properties of the material (as represented by the specimens) can be obtained from the Mohr envelope:

(1) The angle of internal friction (ϕ) - the angle between the envelope and the horizontal. The tangent of this angle is theoretically the coefficient of maximum grain-to-grain friction within the samples.

(2) The cohesion, or intrinsic strength (c) - the intercept made by the envelope and the ordinate.

(3) Shearing strength (S) - the shearing stress developed at failure when the material is subjected to a given normal stress.

Grouping of Tests

Tests were grouped into five series, but in the use of information it was sometimes desirable to apply data to more than one series of results. When it was necessary to establish comparisons, results were extracted and duplicated in other groups of data. An appropriate note in the text will inform the reader of any such transposition.

Series I was conducted to determine the effect of the length of curing time on strength properties and on moisture content. A single

stone (B) mixed with neutral water or neutral water plus calcium chloride, was used in this series. Triaxial compression tests were run on specimens cured for three days, seven days and fourteen days. Testing of two sets of samples (one set containing 0.5 percent calcium chloride) furnished data which showed comparative strength properties, or, the effect of curing. The extent of curing was determined by a comparison of the initial and final moisture contents of each sample. These data were then used to establish the effects of time and the presence of calcium chloride on the extent of curing.

Series II was a study of the comparative strength properties of the four limestones when mixed with neutral water. Stone B had already been tested under these conditions as a part of Series I and therefore was not retested.

With the exception that 0.5 percent calcium chloride was added to each specimen, Series III was similar to Series II in that the former compared the four stones when mixed with a neutral water plus calcium chloride. Again, data pertaining to stone B was transposed from Series I.

Series IV contrasted the effect of neutral water with the effect of acid water on the strength properties of a single stone dust (B). Curing was maintained at seven days.

Series V compared the strength properties of specimens of a single stone dust (B) when alkaline and neutral mixing waters were employed. Again, a seven-day curing period was used.

RESULTS

A total of 74 specimens of the various compositions were prepared and tested. Tabular data which follow present information concerning physical properties and strength characteristics of the compacted specimens. The first letter and subscript of each sample number in these tabulations designates the series (S_1 indicates Series I). In Series I the letter "W" indicates neutral mixing water was used in preparing the sample, while "C" indicates the addition of 0.5 percent calcium chloride to the mixing water. With both these letter designations, the subscript shows the number of days curing. In Series II through V, the capital letter following series designation identifies the stone used and corresponds to stone designations in Table 1. The letter subscripts in Series IV and V indicate the use of acid and alkaline mixing water respectively. For example, sample designation S_1W_7 indicates Series I (S_1), neutral mixing water (W) and seven days curing (subscript 7), while S_3A designates Series III (S_3) Stone A(A).

Moisture

Moisture data pertaining to all specimens are presented in Table 3, Lateral stress (0_3) at which each specimen was tested has been included as a possible means of determining the effect of moisture content upon other test values. Optimum moisture contents are included since they represent the quantity of mixing water added when specimens were prepared. These values were different for each of the four stones, but there was a very slight difference in the case of Stones A and B. The moisture content of each test specimen as determined immediately after it was prepared, designated as original moisture content, and again when it was tested

Table 3 - Summary of Moisture Data

Sample No. and Description	Lateral Stress (3)	Moisture Content-% Dry Wt. Test Specimen			Percent Loss of Moisture During Curing Period		
		Optimum	Original	When Tested	3 Days	7 Days	14 Days
			Series I				
S_1W_3	0	12.80	11.20	7.10	36.6		
Stone B	10	12.80	11.70	8.00	31.6		
Neutral	10	12.80	11.50	7.30	36.5		
Water	20	12.80	12.40	9.13	26.4		
Average			11.70	7.88	32.8		
S_1W_7	0	12.80	11.60	3.19		72.5	
Stone B	10	12.80	11.60	4.30		63.0	
Neutral	10	12.80	11.90	3.80		68.1	
Water	20	12.80	12.10	3.10		66.2	
Average			11.80	3.60		67.5	
S_1W_{14}	0	12.80	11.97	0.47			96.2
Stone B	10	12.80	11.74	0.46			96.1
Neutral	20	12.80	11.77	0.63			94.7
Water	20	12.80	12.20	0.63			94.8
Average			11.92	0.55			95.5
S_1C_3	0	12.80	11.95	7.34	37.3		
Stone B	10	12.80	12.30	8.26	32.8		
0.5%	10	12.80	11.31	7.50	33.7		
$CaCl_2$	20	12.80	12.10	7.90	34.7		
Average			11.92	7.75	34.6		
S_1C_7	0	12.80	11.50	5.17		55.1	
Stone B	0	12.80	11.60	5.70		50.8	
0.5%	10	12.80	12.00	5.83		51.3	
$CaCl_2$	20	12.80	11.80	5.76		51.2	
	20	12.80	12.00	5.78		51.8	
Average			11.78	5.67		52.0	
S_1C_{14}	0	12.80	11.72	2.77			76.3
Stone B	10	12.80	11.20	2.70			75.8
0.5%	20	12.80	11.69	3.83			67.2
$CaCl_2$	20	12.80	11.70	3.50			70.1
Average			11.58	3.20			72.4
			Series II				
S_2A	0	12.90	11.30	3.28		70.9	
Stone A	10	12.90	11.11	3.23		70.9	
Neutral	10	12.90	11.80	5.00		57.7	
Water	20	12.90	11.30	2.69		76.2	
	20	12.90	11.40	3.22		71.8	
Average			11.38	3.48		69.5	

supplied data on curing of the specimen. Moisture values for each group have been averaged to permit comparison on the basis of variations occurring within each group of specimens.

Series I contained two sets of comparable specimens cured for three, seven, and fourteen days. One set (designated as S_1W) was prepared with neutral mixing water and the second set (designated as S_1C) with mixing water containing 0.5 percent calcium chloride.

On the whole, better uniformity in moisture contents of samples within a given group was achieved when calcium chloride was added than when it was omitted. Because of the deliquescent nature of calcium chloride, this would be expected, as would the condition of greater percentages of moisture retained in the samples containing the admixture at any of the given ages. As shown by data plotted in Fig. 6, the extent of curing (or more specifically "drying") at 3 days was practically the same whether the specimens contained calcium chloride or not. But at later ages, the samples containing no admixture had dried to a much greater extent. At 14 days the samples without an admixture contained (on the average) less than 5 percent of their original moisture, whereas those containing calcium chloride had retained about 30 percent of their original moisture.

Taken at face value, these results imply that the concentration of calcium chloride may be influential on curing effects and, as noted later, other relationships. Perhaps the concentration at 3-days was too small to affect the rate of curing. At seven and fourteen days, the effect of the additive was prominent. Average concentration of calcium chloride in the

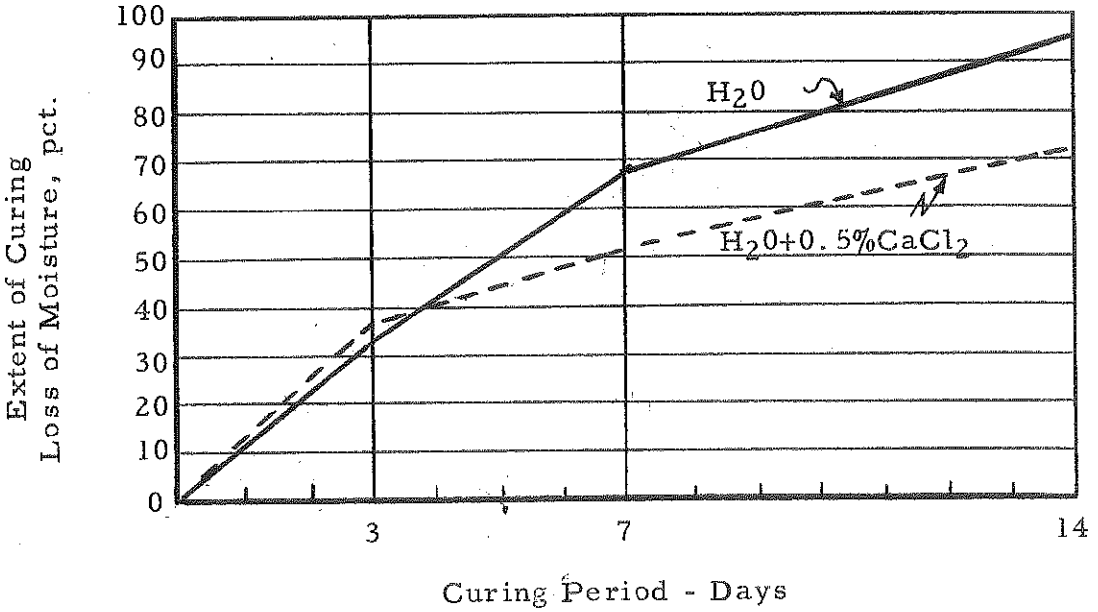


Fig. 6 - Relationship between extent of curing and curing time for stone B (Tested in Series I)

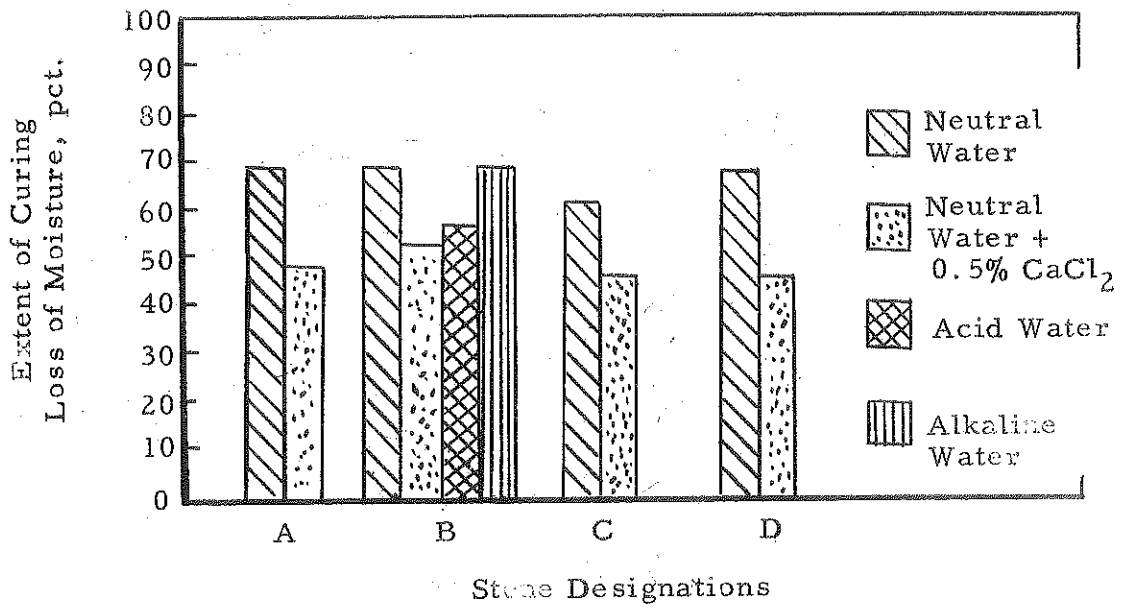


Fig. 7 - Average percentage moisture lost by groups of specimens at 7-day curing period.

water (based on a specimen originally containing 412 grams of stone dust, 52.7 grams of water and 2.06 grams of calcium chloride) at the various curing periods were as follows:

Curing Period (days)	Concentration of Calcium Chloride (percent-w/w)
0	3.9
3	5.8
7	8.1
14	13.9

These relationships and those plotted in Fig. 6, mean that, obstensibly at least, a concentration of calcium chloride less than six percent of the weight of water contained in the specimen had no effect upon the rate or extent of curing, but all concentrations of this value or greater resulted in a uniformly reduced rate of curing with regard to specimens containing only neutral mixing water.

In Fig. 7 comparisons among specimens comprising the four different stones are made on the basis of percentage moisture lost at the age of seven days. As in the previous case, losses of moisture from the specimens containing no admixture were consistently higher than those from the samples containing calcium chloride. With regard to average results there were only minor variations in the curing conditions for comparable samples made with Stones A, B, and D, the specimens with no admixture having about 70 percent loss of moisture and those with the admixture averaging close to 50 percent loss. In the case of Stone C, the mean value of moisture loss from samples having no admixture, was abnormally low (only 60 percent) for which there is no obvious reason -

including the fact that specimens containing Stone C had relatively low densities or unit weights. It should be noted that variations among the moisture contents of individual samples in a given group were greater for Stone C than for any of the other aggregates.

Relationships established by tests on samples containing Stone B and made with acid and alkaline mixing water are obscured by the unusually large spread of data in one instance - S_4B_a, Table 3, (acid water). There is no obvious or logical reason why the rate of drying should be materially different when acid water instead of neutral or alkaline water is used.

Density

Measured physical properties and results of triaxial compression tests on each of the individual specimens are presented in Table 4. Each set of results corresponds to those bearing the same designation given for moisture content data in Table 3.

All the physical properties (except moisture content) are expressions of density. Bulk specific gravity applies to the compacted test sample while apparent gravity describes the dust particles themselves. Unit weight was included as a convenient and often-encountered expression of bulk gravity. Void ratio, which by definition relates the volume of voids to the volume of solids, was calculated from the expression:

$$e = \frac{Ga-Gb}{Gb}$$

where e = void ratio,
Ga = apparent specific gravity
and Gb = bulk specific gravity

Table 4 - Physical Properties of Test Specimens and Triaxial Compression Test Values

Sample No.	Specific Gravity Bulk	Specific Gravity Apparent	Unit Wt. lbs. per cu.ft.	Void Ratio	Moisture Content When Tested % Dry Wt.	Lateral Stress p.s.i.	Normal Stress p.s.i.	Deflection at Failure Inches
			Series I					
S_1W_3	2.00	2.73	124.8	0.37	7.10	0	61.0	0.108
	2.01	2.73	125.4	0.36	8.00	10	77.0	0.088
	2.00	2.73	124.8	0.37	7.30	10	92.5	0.066
	1.99	2.73	124.2	0.37	9.13	20	125.5	0.135
S_1W_7	2.03	2.73	126.7	0.35	3.19	0	93.0	0.078
	2.01	2.73	125.4	0.36	4.30	10	100.5	0.094
	2.00	2.73	128.8	0.37	3.80	10	131.0	0.105
	2.00	2.73	124.8	0.37	3.10	20	166.5	0.130
S_1W_{14}	1.98	2.73	123.6	0.38	0.47	0	42.0	0.030
	1.99	2.73	124.2	0.37	0.46	10	79.5	0.068
	1.94	2.73	121.1	0.41	0.63	20	101.0	0.062
	2.00	2.73	124.8	0.37	0.63	20	121.0	0.074
S_1C_3	2.02	2.73	126.1	0.35	7.34	0	69.5	0.100
	2.02	2.73	126.1	0.35	8.26	10	80.0	0.106
	1.98	2.73	123.6	0.38	7.50	10	84.0	0.072
	1.99	2.73	124.2	0.37	7.90	20	117.5	0.116
S_1C_7	1.98	2.73	123.6	0.38	5.17	0	79.0	0.096
	1.97	2.73	123.0	0.39	5.70	0	68.0	0.052
	1.99	2.73	124.2	0.37	5.83	10	90.5	0.086
	2.01	2.73	125.4	0.36	5.76	20	103.0	0.084
	2.00	2.73	124.8	0.37	5.78	20	140.0	0.092
S_1C_{14}	1.99	2.73	124.2	0.37	2.77	0	77.0	0.078
	1.98	2.73	126.6	0.38	2.70	10	110.0	0.060
	2.00	2.73	124.8	0.37	3.83	20	134.5	0.104
	2.00	2.73	124.8	0.37	3.50	20	145.0	0.104

Table 4 (Continued)

Sample No.	Specific Gravity Bulk	Specific Gravity Apparent	Unit Wt. lbs. per cu. ft.	Void Ratio	Moisture Content When Tested % Dry Wt.	Lateral Stress p.s.i.	Normal Stress p.s.i.	Deflection at Failure Inches
S_3B	1.98	2.73	126.3	0.38	5.17	0	79.0	0.096
	1.97	2.73	123.0	0.39	5.70	0	68.0	0.052
	1.99	2.73	124.2	0.37	5.83	10	90.5	0.086
	2.01	2.73	125.4	0.36	5.76	20	103.0	0.084
	2.00	2.73	124.8	0.37	5.87	20	140.0	0.092
S_3C	1.82	2.67	113.6	0.46	6.85	0	69.0	0.048
	1.83	2.67	114.2	0.46	8.73	10	94.5	0.098
	1.83	2.67	114.2	0.46	8.30	10	87.0	0.094
	1.81	2.67	112.9	0.48	6.40	10	114.0	0.078
	1.84	2.67	114.8	0.45	7.06	20	157.0	0.140
	1.82	2.67	113.6	0.46	6.50	20	150.0	0.124
S_3D	1.95	2.82	121.7	0.45	6.86	0	47.0	0.144
	1.92	2.82	119.8	0.47	5.80	0	51.0	0.080
	1.90	2.82	118.6	0.48	7.50	10	88.0	0.240
	1.93	2.82	120.4	0.46	7.09	10	85.0	0.168
	1.92	2.82	119.8	0.45	6.80	20	100.0	0.196
			Series IV					
S_4B	2.03	2.73	126.7	0.35	3.19	0	93.0	0.078
	2.01	2.73	125.4	0.36	4.30	10	100.5	0.096
	2.00	2.73	124.8	0.37	3.80	10	131.0	0.105
	2.00	2.73	124.8	0.37	3.10	20	166.5	0.130
S_4Ba	1.95	2.73	121.7	0.45	7.76	0	73.5	0.120
	1.95	2.73	121.7	0.45	5.30	10	113.5	0.124
	1.94	2.73	121.1	0.46	3.50	20	148.0	0.092

Table 4 (Continued)

Sample No.	Specific Gravity Bulk	Specific Gravity Apparent	Unit Wt. lbs. per cu. ft.	Void Ratio	Moisture Content When Tested % Dry Wt.	Lateral Stress p.s.i.	Normal Stress p.s.i.	Deflection at Failure Inches
		Series V						
S_5B	2.03	2.73	126.7	0.35	3.19	0	93.0	0.078
	2.01	2.73	125.4	0.36	4.30	10	100.5	0.096
	2.00	2.73	124.8	0.37	3.80	10	131.0	0.105
	2.00	2.73	124.8	0.37	3.10	20	166.5	0.130
S_5B_a	1.97	2.73	122.9	0.39	3.93	0	85.5	0.062
	1.98	2.73	123.6	0.38	4.12	10	125.5	0.128
	1.93	2.73	120.4	0.41	3.47	20	148.0	0.154

All the physical properties are of considerable significance since they define the condition of the material at the time it was tested in triaxial compression. Comparability of results within a given group, and among groups too, is dependent upon uniformity of physical properties of the specimens.

The general consistency in bulk specific gravity or unit weight of the specimens representing given combinations of materials implies uniformity of samples. Occassionally there were pronounced discrepancies, even for samples that were intended to be duplicates, but in almost every respect the unit weights and volumetric relationships were much more uniform than the moisture contents.

Significant differences in the samples containing different stones were evident. For example, the unit weights and void ratios of samples with Stone A and B were very much alike, as might be expected since both had high calcium carbonate contents and very similar gradations. On the other hand, Stone D (high magnesium carbonate), which also had about the same particle gradation, compacted to unit weights that were somewhat lower or to void ratios very much higher than those of which stones A and B were compacted. The much increased void in samples with Stone D indicates a resistance to compaction which is probably dependent on shape, or surface texture of the particles, and of course the unit weight also reflects the considerably greater apparent specific gravity of this stone. Stone C, which had a high silicon content, a much different gradation, and a lower apparent specific gravity than any of the other materials, had consistently the lowest unit weights, and void ratios approaching those of Stone D.

Strength Characteristics

The triaxial compression test data tabulated in Table 4 indicates rather broad variations among strength properties of the specimens. These contrast with the relative uniformity of physical properties just discussed. Theoretically the results should be practically the same where duplicate specimens and duplicate test conditions are involved. Actually, identical results can rarely be expected, and the range in acceptable variations is sometimes relatively large. This is so because of limitations in preparing samples and controlling test conditions, especially moisture content. Probably most of the variation that occurs in tests on materials such as these can be attributed to lack of uniformity in the specimens, despite the indicated similarity in physical properties previously discussed. In this respect, particle orientation and changes in density and moisture at different points within a sample are uncontrolable and are not necessarily reflected by any measured property of the separate test samples.

Triaxial compression test values - lateral stress, normal stress, and deflection at failure-are included in Table 4 to permit comparison of test values with respect to uniformity of test specimens. Lateral stress (σ_3) was, in each case, a preselected value. However, normal stress was a measured value dependent upon lateral applied stress and shearing strength of the specimen. It represents the net vertical stress ($\sigma_1 - \sigma_3$) measured at the point of failure as determined by plotting stress-deformation curves and selecting the peak value. These curves are included in

the Appendix. Deflection at failure was obtained from these same graphs and was the total deformation of the specimen at failure.

Fundamental strength characteristics calculated from triaxial test results are contained in Table 5. These values may be described as the strength properties of compacted stone dust. Data appearing in this table were derived from application of test values contained in Table 4 to the construction of Mohr Diagrams which are included in the Appendix.

Correlation of Physical Properties and Strength Relationships

Deformation. The measured deflection of specimens at failure, for which values are listed in the last column of Table 4, may be generally regarded as an indicator of brittleness. The smaller the deflection the greater the brittleness, all other things being equal.

An evaluation of trends in these relationships for specimens with and without calcium chloride in Series I is given in Fig. 8. The variable of curing is represented both by days of exposure prior to testing and also by variation in moisture content of the specimens, as given by the two bottom lines in the graph. Lateral pressures at which the specimens were tested are indicated by numbers alongside the plotted point for deflection at each of the three curing periods. The points and numbers apply only to the deflection curves (and not to the moisture curves), and the numbers have been placed on the side corresponding to the series designation noted for each curing interval at the bottom of the graph. Thus, numbers on the left of each vertical line apply to tests on specimens S_1 W_3 and therefore

Table 5 - Tri-axial Compression Test Properties

Sample No.	Moisture Content When Tested % Dry Wt.	Intrinsic Strength (C) psi.	Angle of Friction (Ø°)	Shearing Strength, psi at Normal Stresses (psi) of: 30	50	70
		Series I				
S_1W_3	7.88	17.0	37.8	40.3	55.8	71.3
S_1W_7	3.60	22.2	39.6	46.6	63.6	80.2
S_1W_{14}	0.55	11.0	41.0	37.1	54.5	71.9
S_1C_3	7.75	20.5	30.7	38.4	50.2	62.2
S_1C_7	5.67	18.5	34.8	39.4	53.3	67.2
S_1C_{14}	3.20	18.0	39.4	42.7	59.2	75.7
		Series II				
S_2A	3.48	23.5	38.7	47.5	63.6	79.7
S_2B	3.60	22.2	39.6	46.6	63.6	80.2
S_2C	5.29	19.5	43.0	47.5	66.2	84.8
S_2D	4.05	26.5	23.0	39.3	46.8	56.3
		Series III				
S_3A	5.64	14.0	41.7	40.7	58.6	76.3
S_3B	5.67	18.5	34.8	39.4	53.3	67.2
S_3C	7.31	18.5	40.5	41.1	61.3	78.3
S_3D	6.81	12.0	41.6	38.6	56.4	74.2
		Series IV				
S_4B	3.60	22.2	39.6	46.6	63.6	80.2
S_4B_a	5.51	18.0	40.0	43.2	60.1	76.8
		Series V				
S_5B	3.60	22.2	39.6	46.6	63.6	80.2
S_5B	3.84	20.0	39.0	44.3	60.6	76.7

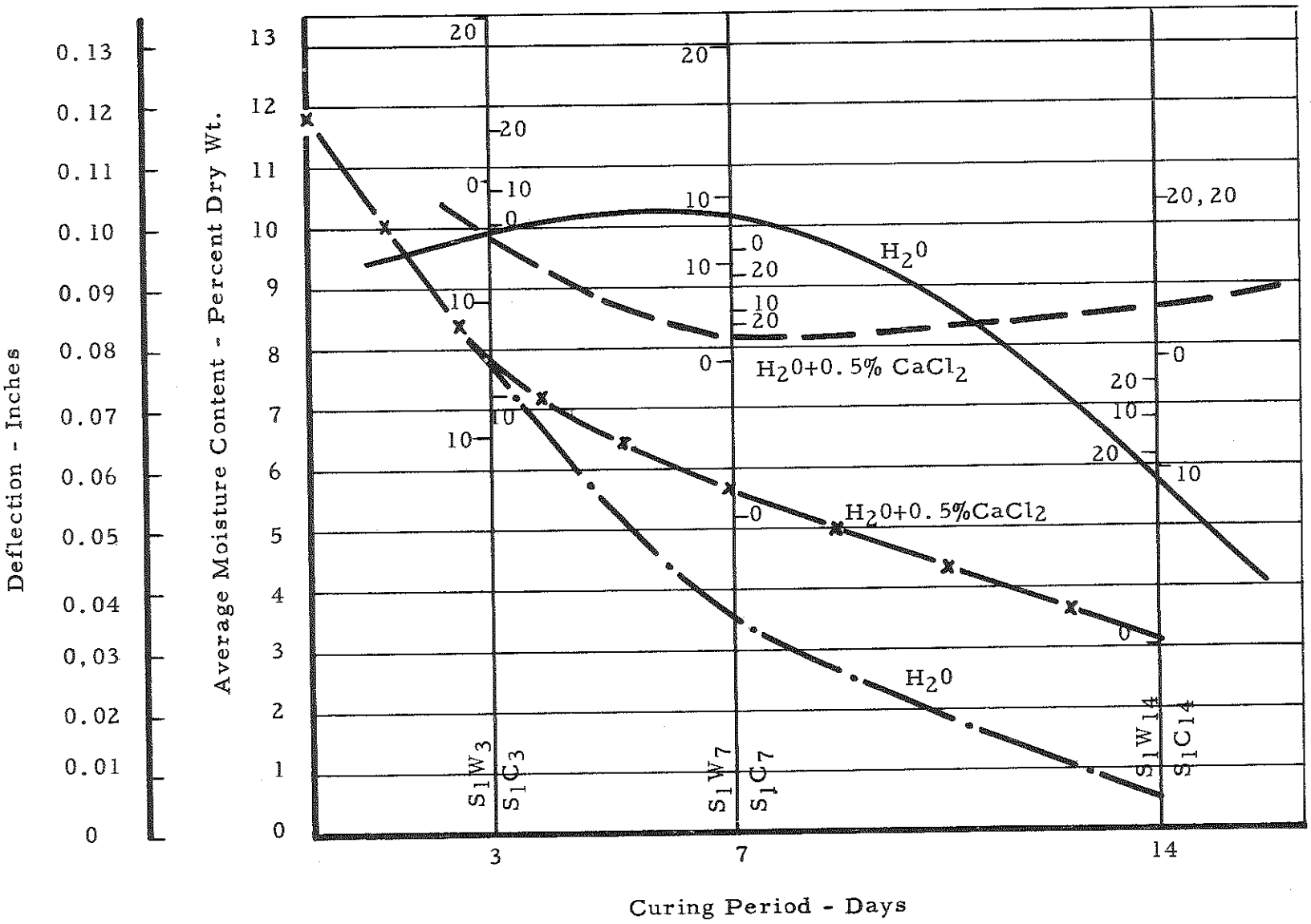


Fig. 8 - The effect of curing (samples with and without calcium chloride) on deflection of test specimens (the upper pair). Moisture-time curves (the lower pair) are included to permit a comparison of deflection-moisture content relationships.

define the position of the solid curve relating deflection and curing period for the specimens mixed with neutral water (H_2O) and no calcium chloride.

Obviously just the general trends are implied by the graphs, considering the broad distribution of points. The intent is not to establish definite relationships.

The line representing samples with neutral water indicated that approximately the same deflection of specimens of this description may be expected at three and seven days. Therefore, moisture content at these intervals had little effect on maximum deflections. At fourteen days, however, the effect of reduced moisture content was quite noticeable. Specimens had entered a range of brittleness where slight deflections produced failure. The trend line representing specimens containing calcium chloride showed little difference in the deflection required to produce failure at 3, 7, or 14 days. It is highly doubtful that there is any significance in these differences. Changes in deformation which changes in lateral pressure were not consistent, and the differences in deformation at various ages were not great enough to define more than a very general trend at best.

It should be noted in Table 4 (Series II and III) that deflections (at 7 days curing) or specimens made with Stones A, C, and D increased when calcium chloride was added to the mixing water - a reversal of the effect observed with Stone B. Also, the use of both acid and alkaline waters resulted in slightly increased deflection values. These

observations led to the conclusion that the trends indicated in Fig. 8, did not represent a general relationship and applied only to the particular stone involved.

Intrinsic Strength. The effect of moisture content on the intrinsic strength of specimens made of Stone B is shown in Fig. 9. Results from specimens containing neutral mixing water indicated that maximum intrinsic strength was reached at an optium moisture value. Changes from the optium (especially decreases), resulted in diminishing intrinsic strengths which amounted to as much as 50 percent of the maximum value, if the single point reliably controls the trend in strength-moisture relations throughout this broad range. When calcium chloride was included in the mix, the above tendency was not observed. Decreases in intrinsic strength occurred, with reductions of moisture; however, these differences were small particularly in the range of moisture contents less than 6 percent.

In Fig. 10 a graphical comparison of the intrinsic strengths of samples containing the four stones (at 7 days curing) is made, and the effect of the presence of calcium chloride on such strengths is portrayed. Although all specimens sustained losses in intrinsic strength when calcium chloride was included in the mixing water, they differed considerably with regard to the degree to which they were affected.

Samples with Stones A and B (high calcium carbonate contents) possessed approximately equal intrinsic strengths when mixed with neutral water. With calcium chloride added, both groups showed appreciable decreases, those with Stone A being most severely affected.

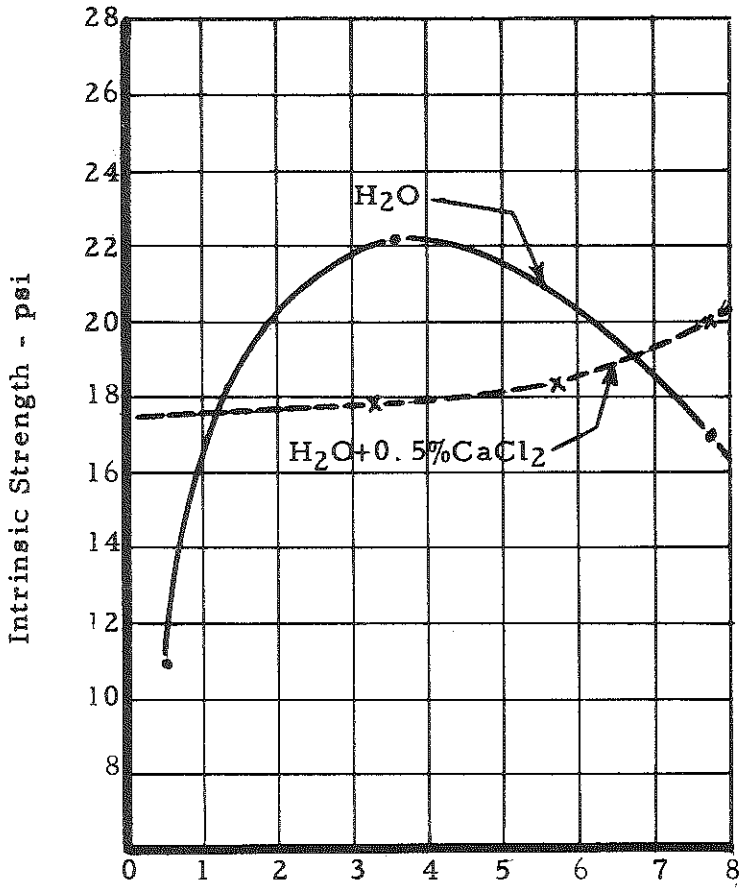


Fig. 9 - Relationship of intrinsic strength to moisture content for stone B (test specimens with and without calcium chloride).

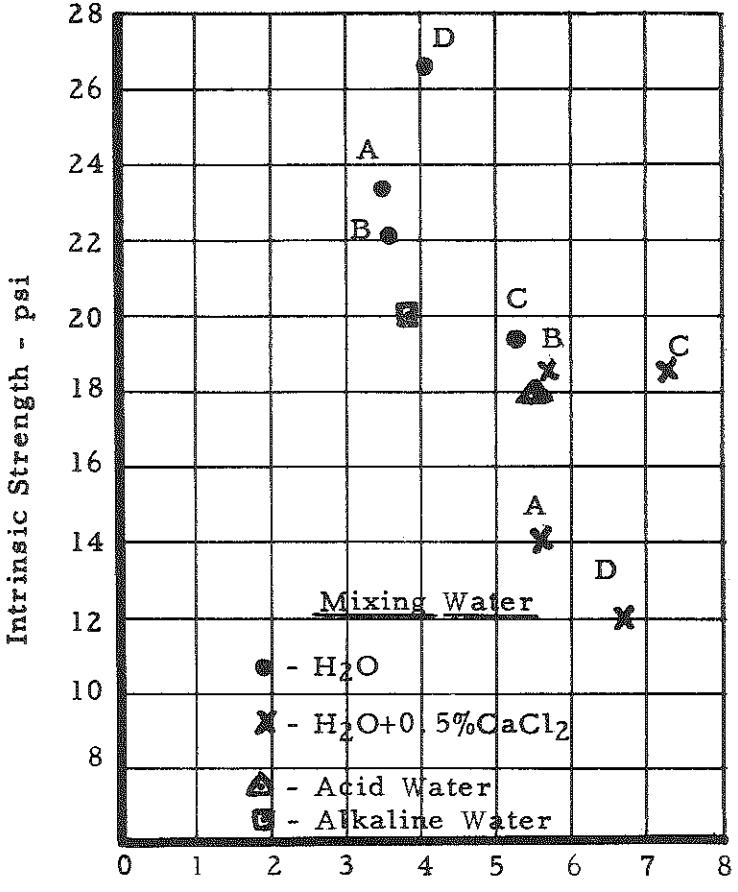


Fig. 10 - Comparison of intrinsic strengths and moisture contents of the four limestones (after seven days curing).

Samples with Stone C (high silicon content) were ostensibly affected very little by the addition of calcium chloride, while specimens with Stone D suffered the greatest loss and in all respects exhibited the most extreme intrinsic strengths.

Angle of Friction. Fig. 11 shows the relationship between angle of friction and moisture content for samples made of Stone B. The angle of friction for those specimens containing neutral mixing water varied only slightly with changes in moisture content, whereas specimens containing calcium chloride apparently were very sensitive to changes in moisture content. For the latter, high moisture contents produced relatively low angles of friction, but there were rapid increase in this angle with decreases in moisture.

Both the curves in Fig. 11 show near-linear relationships between moisture content and angle of friction. These curves intersect at a moisture content of 3 percent and an angle of friction of approximately 40 degrees. At moisture contents greater than 3 percent specimens prepared with neutral water had a definite superiority with regard to angle of friction.

Viewed from the standpoint of concentration of calcium chloride in the water remaining at various intervals of curing of specimens containing Stone B, the results indicated the angle of internal friction increased with increasing percentages of calcium chloride. In effect, within the range represented the concentration of calcium chloride increased from 4 per cent to approximately 14 per cent of the weight of water. At that point (see Fig. 11) the angle of internal friction equaled

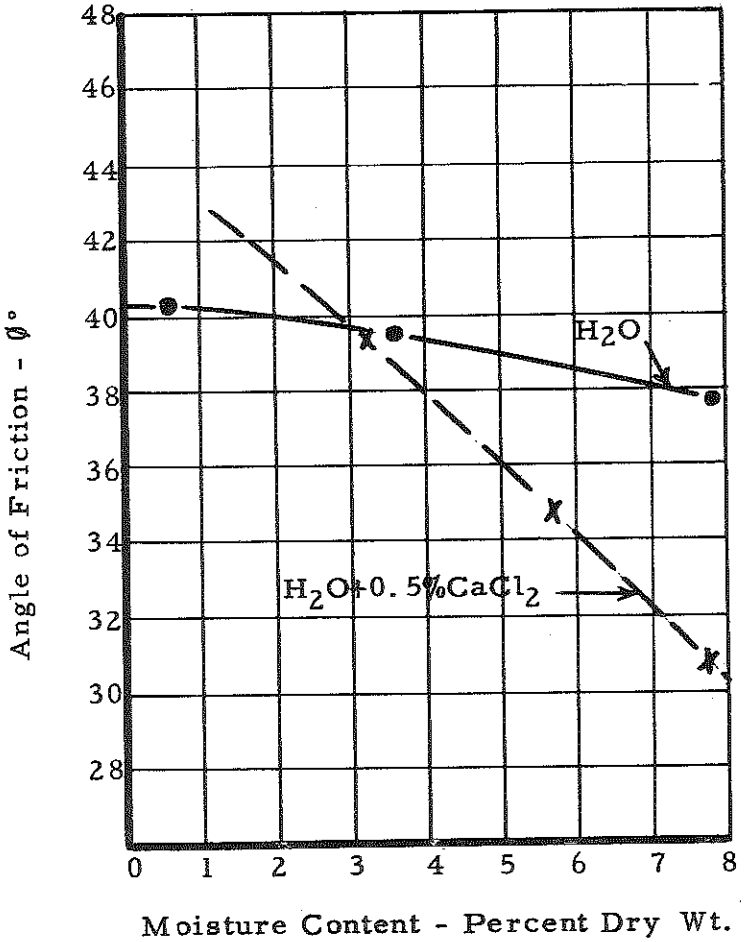


Fig. 11 - Relationship of angle of friction to moisture content for stone B (test specimens with and without calcium chloride).

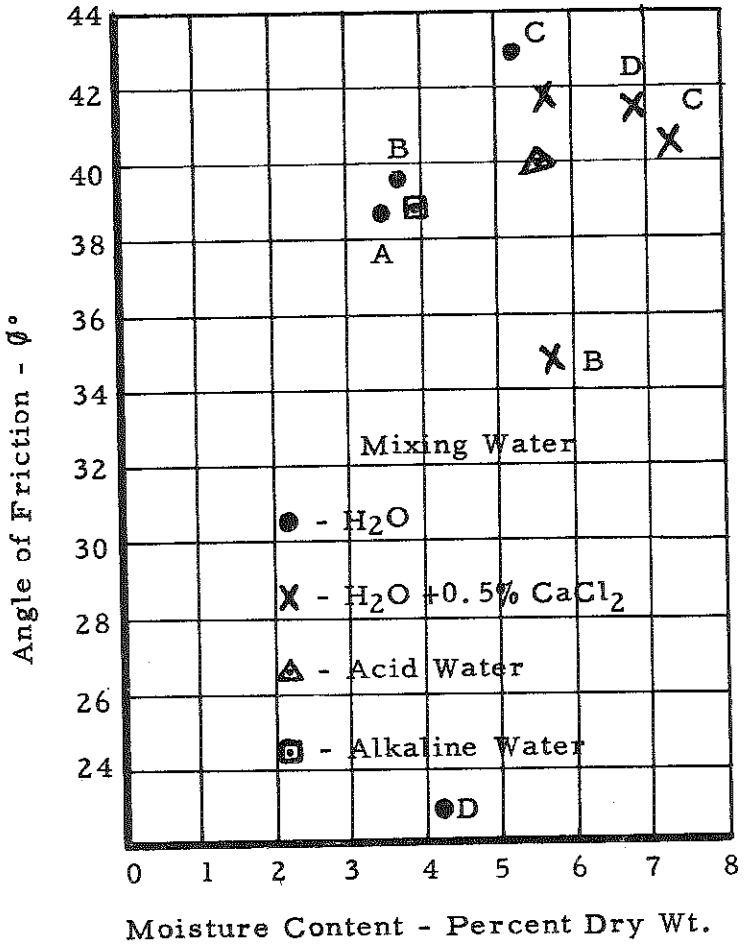


Fig. 12 - Comparison of angles of friction and moisture contents of the four limestones at three normal stresses (test specimens with and without calcium chloride).

the value achieved with neutral mixing water - there being comparable moisture contents in the specimens of both types. Because of the limited data and other circumstances of modified gradation, this is not meant to imply a definite relationship that would exist in dense-graded aggregate bases made with Stone B and different kinds of mixing water.

A comparison of the angles of friction of samples containing the stones after a 7-day curing period is given in Fig. 12. The frictional angle for each material is presented with respect to the average moisture content at which the specimens were tested.

The addition of calcium chloride produced widely varying results. Samples of Stone A and B (both high calcium carbonate) had nearly identical values when neutral water was used, but showed opposite responses to calcium chloride. The decrease which occurred with Stone B has already been discussed. Stone A, a material similar to Stone B (See Table 1 and 2), showed a marked increase in angle of friction when calcium chloride was added. Note also that moisture contents of these two stones (with and without calcium chloride) were almost identical and densities (See Table 4) as indicated by void ratios showed little variation. No particular significance is attached to these contrasts in relationships under these circumstances, although in general the results for Stone B would be considered the more significant in view of the greater number and variety of tests with that material.

Stone C showed a decrease in angle of friction when calcium chloride was added. However, the change was relatively slight, and

in both cases the indicated angle of friction was above 40°. A similar angle of friction was obtained for specimens of Stone D containing calcium chloride, whereas the angle of friction for specimens of the same material without calcium chloride was hardly half that value.

The data plotted in Fig. 12 indicated neither acid nor alkaline mixing water with Stone B had a significant effect on frictional resistance of the compacted specimens. It may be of interest that specimens containing acid water had an appreciably higher moisture content than samples prepared with neutral water, however, frictional resistance did not differ with each type of sample.

Sheering Strength. - Data in the Appendix plotted as Mohr Diagrams representing groups of samples of like composition were analyzed for the relationships between shearing strength at three normal stresses and the corresponding moisture contents of the specimens (See Table 5, also). The shearing strengths were taken from the envelope curve at points corresponding to 30, 50, and 70 p.s.i. normal stress, these being regarded as the maximum resistances the materials would have against shearing forces at some point in each sample where the combined shearing and normal stresses were as indicated.

The relationships between shearing strength and moisture content for specimens with Stone B are shown in Fig. 13. Length of curing period in days is indicated on the graph by numbers in order to permit comparison of shearing strengths after equal periods of exposure. Because of the fact that the envelope were in all cases

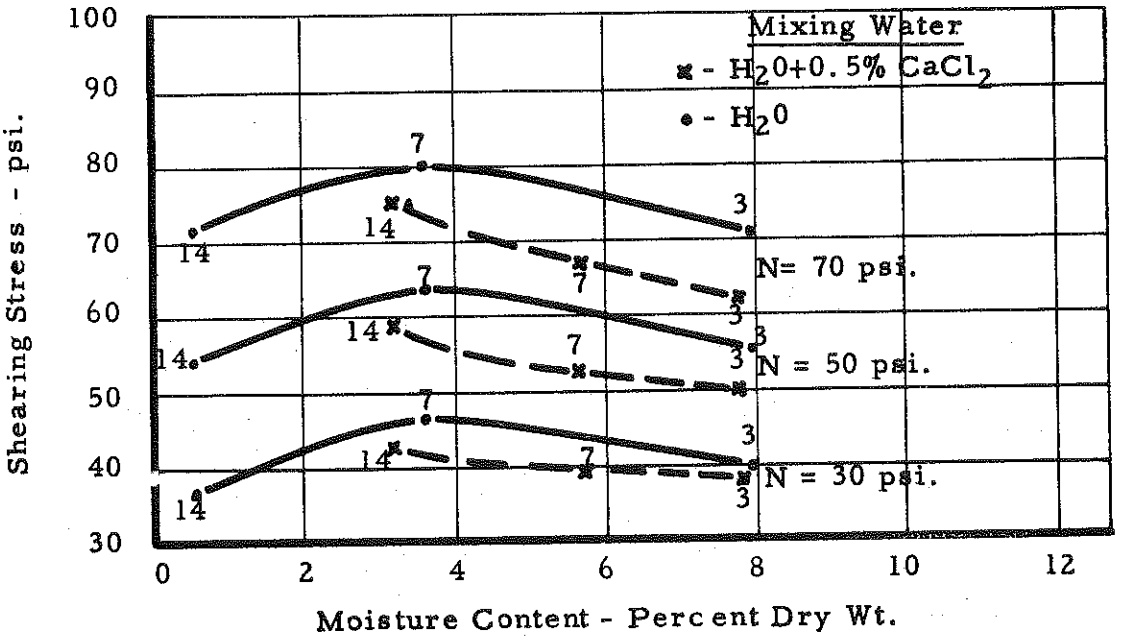


Fig. 13 - Relationship of shearing stress to moisture content for stone B at three normal stresses (test specimens with and without calcium chloride).

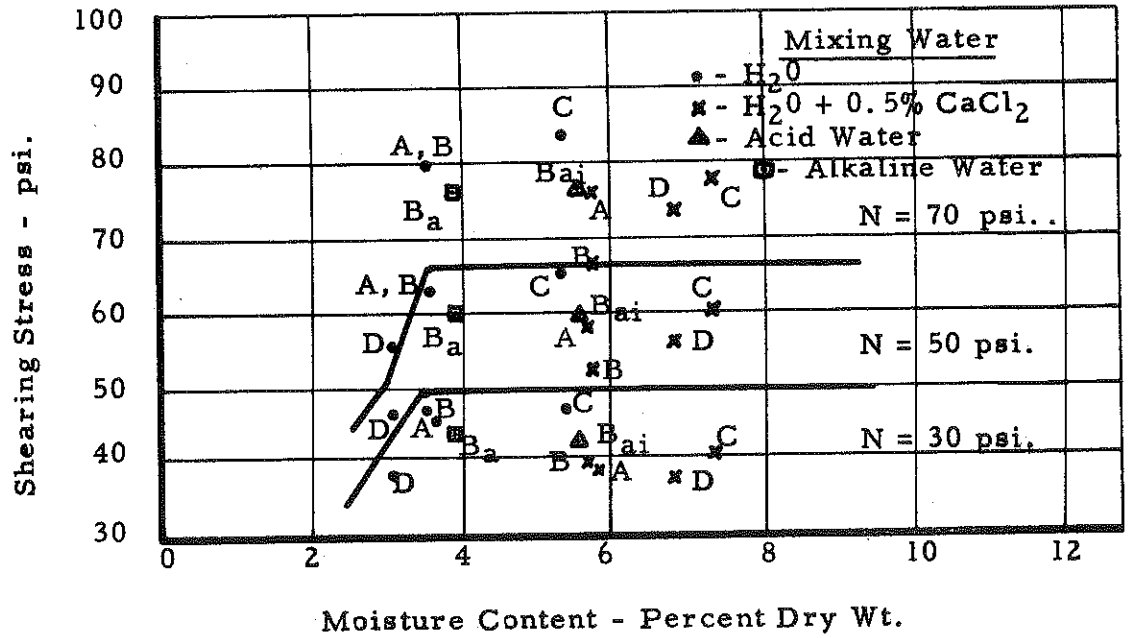


Fig. 14 - Comparison of shearing strengths and moisture contents of the four limestones after seven days curing (test specimens with and without calcium chloride).

drawn as straight lines, uniform patterns of results at the three different normal stresses were inevitable.

Mixtures prepared with neutral water possessed greater shearing resistance at 3 and 7 days but less at 14 days than did the samples containing calcium chloride. A definite optimum moisture content at which the greatest shearing resistance occurred was indicated for specimens prepared with neutral water. Changes from this optimum value resulted in a reduction of resistance to shearing forces and decreases were more pronounced at lower than at higher moisture contents. This condition was caused more by a loss of intrinsic strength at low moisture contents than by decrease in the angle of friction. Specimens containing calcium chloride exhibited a slight but steady increase in shearing strength with decreases in moisture content. Presumably this trend would continue at moisture contents lower than those measured in this study. Further, shearing stresses of these samples demonstrated less sensitivity to moisture content than did specimens prepared with neutral water.

A decrease in shearing resistance of specimens containing calcium chloride with respect to those prepared with neutral mixing water occurred as the normal stress increased. This point reflects the relatively low frictional resistance and high cohesion of specimens containing calcium chloride at high moisture contents. Only the 14-day specimens retained the same relative position on the graph and in this case the angle of friction was essentially equal to that acheived with neutral water.

Fig. 14 shows the relationships between moisture content and shearing strength at failure for specimens of the four stones at the three arbitrarily selected normal stresses. All specimens were tested after 7 days curing.

When mixing with neutral water Stones A and B (high calcium carbonate) and Stone C (high silicon) developed equal or almost equal shearing resistances at normal stresses of 30 and 50 p.s.i., but at 70 p.s.i. Stone C had a slightly higher value reflecting its greater angle of friction. Stone D, which had very low angle of friction and high intrinsic strength, developed appreciably lower shearing resistance even at low normal stresses. As these stresses increased, increases in shearing strength of the magnitude observed with other stones did not occur ostensibly indicating this to be an inferior material when prepared with neutral water.

Pronounced effects were achieved by adding calcium chloride to the mixing waters. Samples with Stones A, B, and C suffered losses of shearing strength. Changes in Stones A and C were approximately equal while the loss occuring with Stone B was appreciably greater at high normal stresses. Stone D showed a contrasting response, the shearing resistance being increased rather than decreased. This stone was the only one which, with the addition of calcium chloride, had an increase in angle of friction at this curing period. Its values were essentially equal to those of the other three stones with calcium chloride added but were still less than the values achieved by the other stones mixed with neutral water.

SUMMARY OF OBSERVATIONS AND CONCLUSIONS

This study has established differences in the individual response of several limestone dusts when mixed with neutral water and water containing 0.5 percent calcium chloride. A single stone dust was tested after curing periods of three, seven, and fourteen days (with and without calcium chloride) in an attempt to establish a pattern of performance by which the other three stones might be judged. In some respects, at least, this attempt was unsuccessful in that the control stone when cured for a seven day period often exhibited characteristics materially different from the other dusts. However, many findings appear to be significant and these are enumerated as follows:

1. The method of curing did not insure uniform moisture contents of all specimens when tested. Moisture contents were, however, sufficiently uniform to produce satisfactory results in every instance except one.

2. Specimens with and without calcium chloride sustained equal losses of moisture at three days of curing. After longer periods, those specimens containing calcium chloride retained a higher percentage of moisture and the data indicated that the effectiveness of calcium chloride as a moisture retaining agent is dependent upon its concentration in the mixing water.

3. Three of the limestones showed little variation in moisture lost at seven days curing when neutral mixing water was used. The fourth, Stone C, which had a high silicon content, lost appreciably less

moisture during this period. Approximately equal moisture losses for all stones occurred when the calcium chloride was added.

4. Intrinsic strength was highly sensitive to moisture content when neutral mixing water was used and a definite optimum moisture content with respect to this value was indicated. Large reductions in intrinsic strength resulted where moisture contents varied from this optimum. The inclusion of calcium chloride in mixing water resulted in reasonably uniform intrinsic strengths which were affected only by high moisture contents or possibly by concentration of calcium chloride in the mixing water.

5. Specimens of the four stones containing neutral water, when cured for 7 days, developed different intrinsic strengths. Stones A and B (high calcium carbonate) had very similar values. Stone D (high magnesium carbonate) had an appreciably higher value than Stones A and B while Stone C (high silicon) had an appreciably lower value. All these values were reduced when calcium chloride was added. Stone A was affected, in this manner, more than Stone B, although their chemical and physical characteristics (other than particle shape and texture) were very similar. Stone D showed the greatest sensitivity to calcium chloride and Stone C the least.

6. The angle of friction showed little variation with moisture content when neutral water was used but was highly sensitive when calcium chloride was added to the mixing water. When calcium chloride was present in the quantity used in this study, serious

reduction of the angle of friction occurred at moisture contents above 3 percent. It was presumed that lower moisture contents would result in higher frictional resistance, but the data did not extend far enough to definitely establish this point. Data did indicate that the concentration of calcium chloride in the water, as well as moisture content, has an important effect on angle of friction, since concentrations of less than 6 percent by weight of water appeared to produce reductions in frictional resistance.

7. Calcium chloride did not affect Stone A in the same manner that it did Stone B. At 7 days curing, the angle of friction of these stones was essentially equal when neutral water was used. When calcium chloride was added, Stone B (composed of smooth particles) exhibited a loss of friction while Stone A (having chunky, grainy particles) gained an equal amount. Stone C possessed the highest frictional resistance of all stones measured, when neutral water was used, but the angle of internal friction decreased slightly when calcium chloride was added. Stone D had an exceptionally low angle of friction when neutral water was used, but this value became the highest of the four stones when the mixing water contained calcium chloride.

In essence, these results imply that the addition of calcium chloride does not have the same effect on all limestones tested and that the effect, as measured in this study, may be either beneficial or detrimental depending upon the individual material. The stones containing large amounts of magesium carbonate was most benefited by calcium chloride addition. High calcium carbonate stones responded

both ways apparently depending on particle shape and texture. Stone with high silicon content was only slightly affected by calcium chloride.

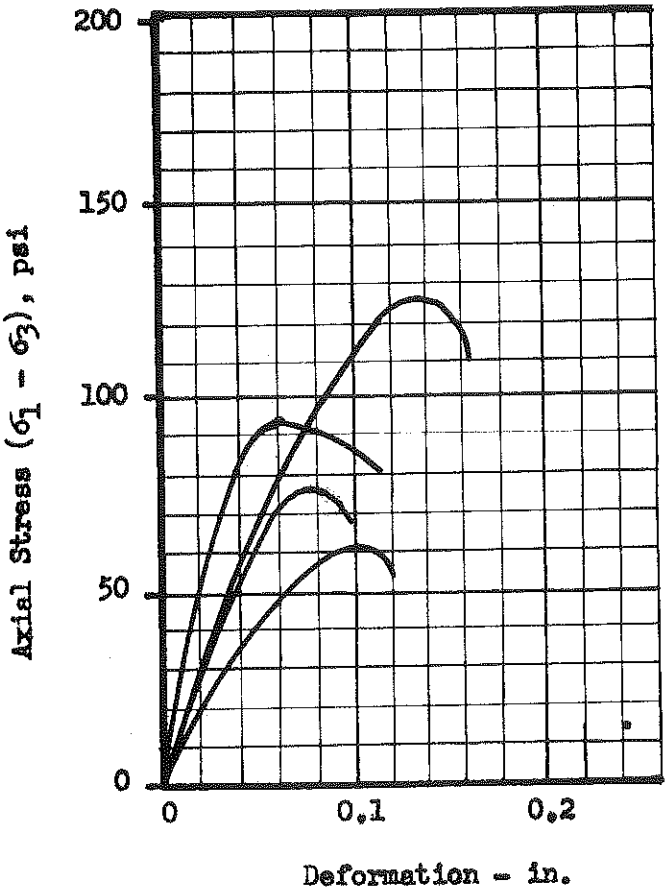
8. Shearing strengths of Stone B reached an optimum at approximately 3 percent moisture (7 days curing) when neutral water was used. Variations in this value reflected variations in intrinsic strength. Specimens containing calcium chloride showed an increase in shearing strength with decreases in moisture content, reflecting an improved angle of friction at lower moisture contents. Only at 14 days curing was the angle of friction greater when calcium chloride was included in the mixing water.

Stones A, B and C developed equal shearing resistance when combined with neutral mixing water. Stone D had a far smaller value; the difference being especially prominent at high normal stresses. When calcium chloride was added, all four stones had essentially equal shearing resistance at low normal stresses. As the normal stress increased Stone B decreased with respect to the others and showed the most unfavorable response to calcium chloride. Stone D showed a major improvement when calcium chloride was added to the mix.

9. Acid mixing water had an effect on Stone B which was similar similar to that of calcium chloride. It is believed, however, that the acidity normally encountered in mixing water would have no measurable effect.

10. Alkaline water also had a small but insignificant effect on Stone B. It is highly improbable that naturally occurring alkaline waters could have any effect.

APPENDIX



SAMPLE NO.

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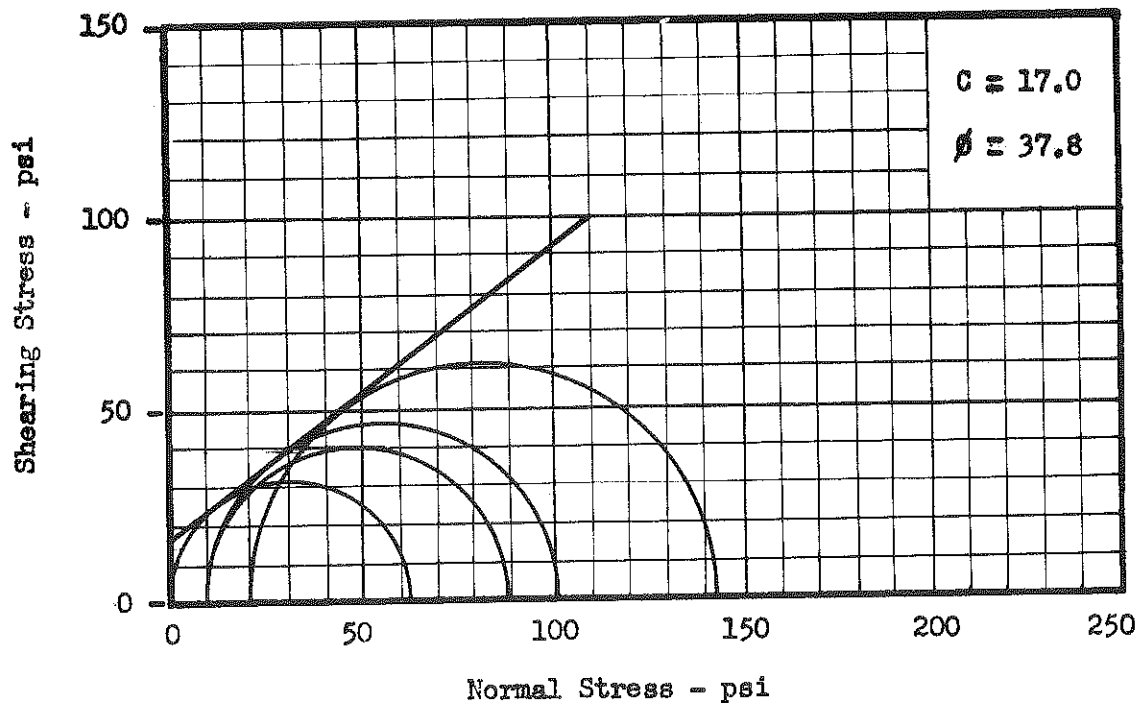

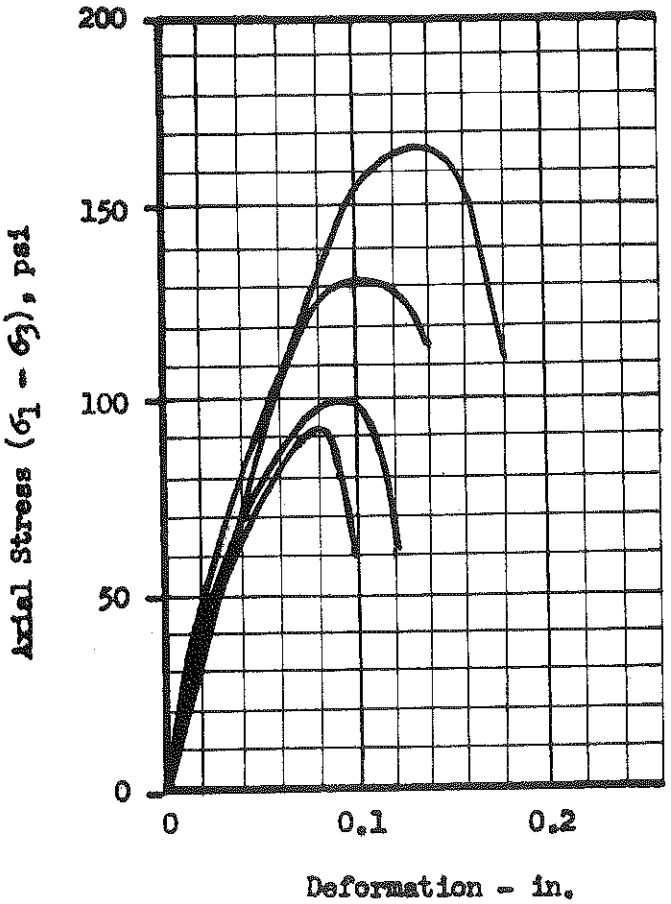

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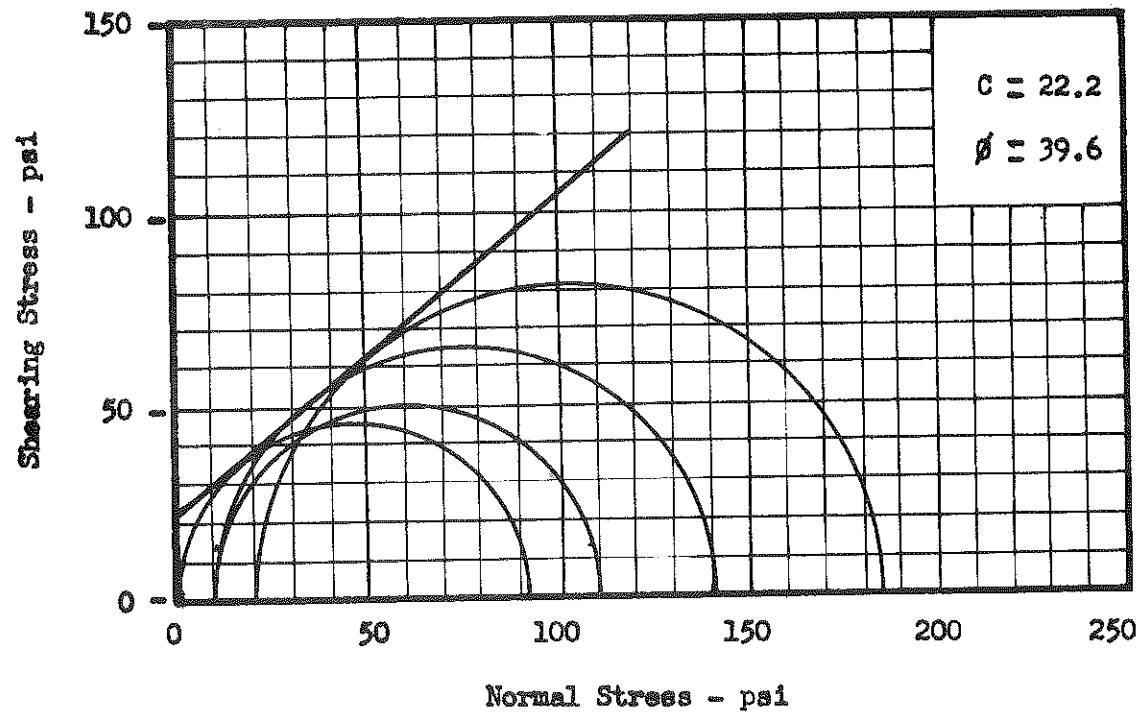
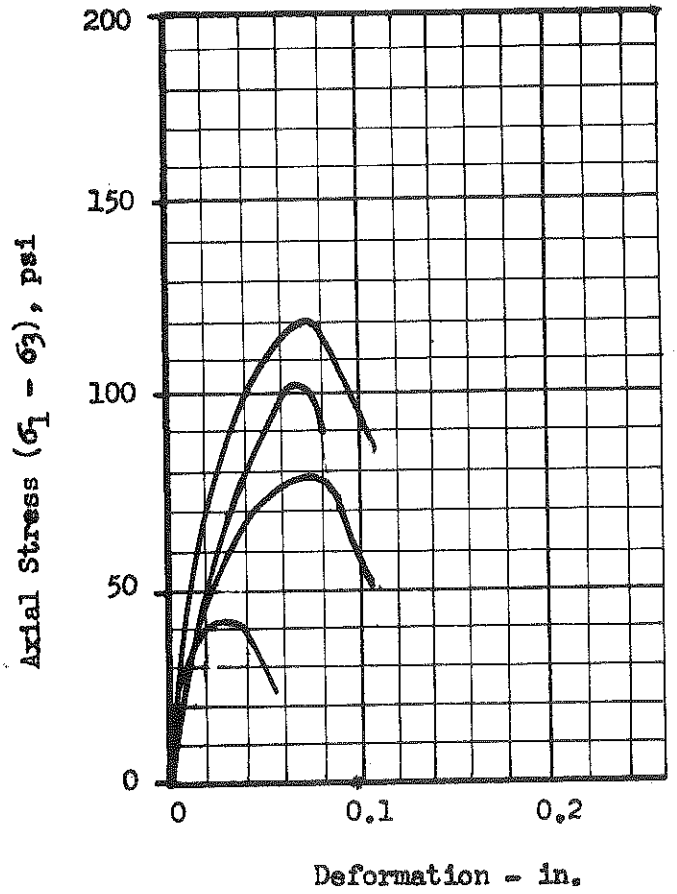
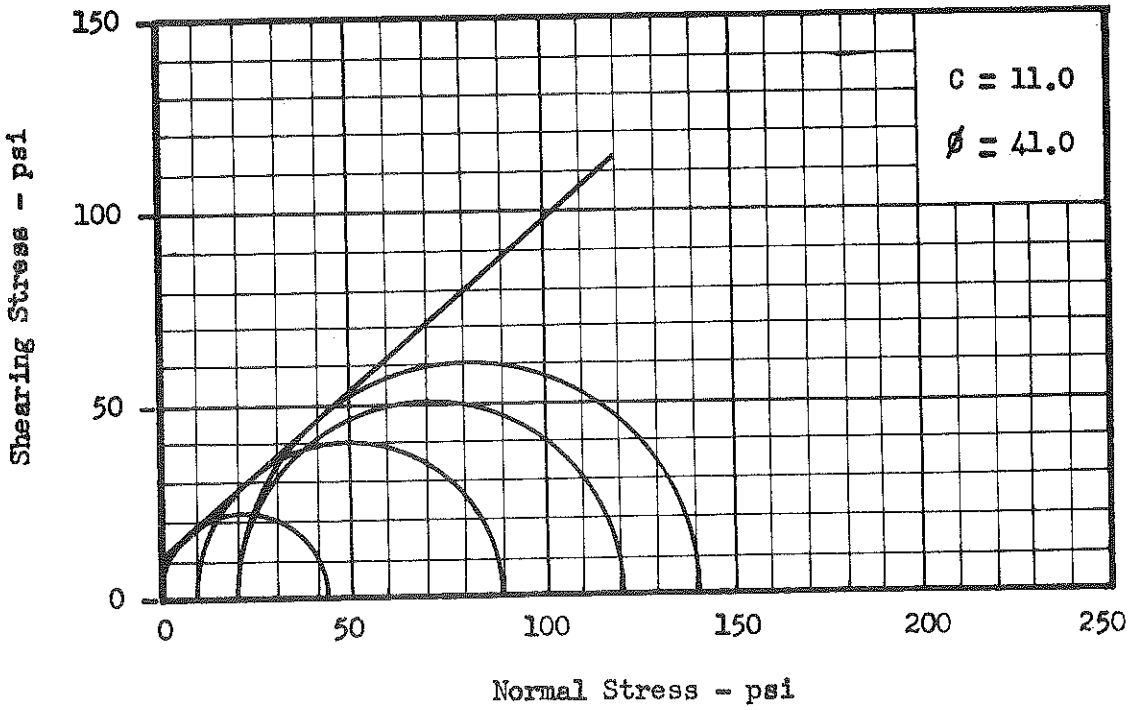
S_1W_7



SAMPLE NO.

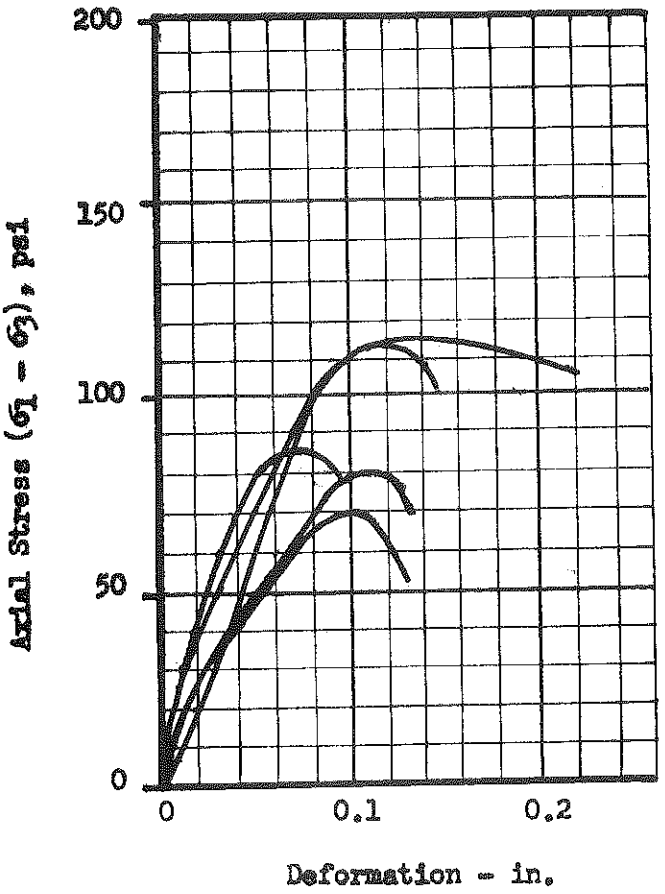
$S_1 W_{14}$

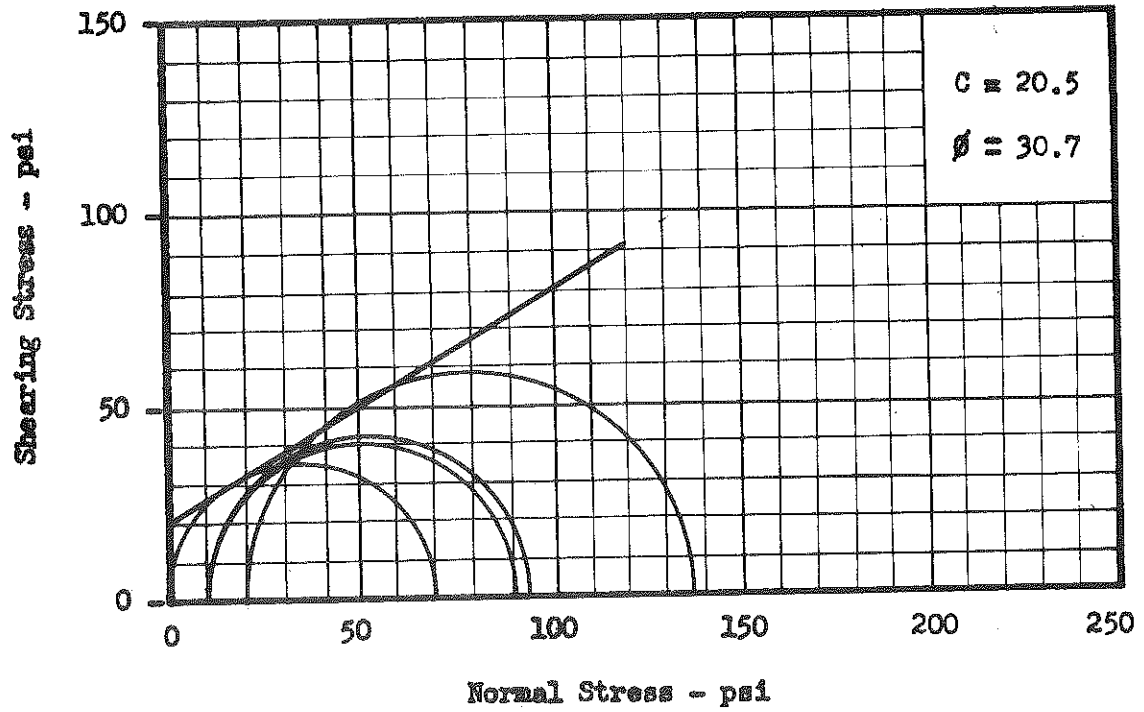




SAMPLE NO.

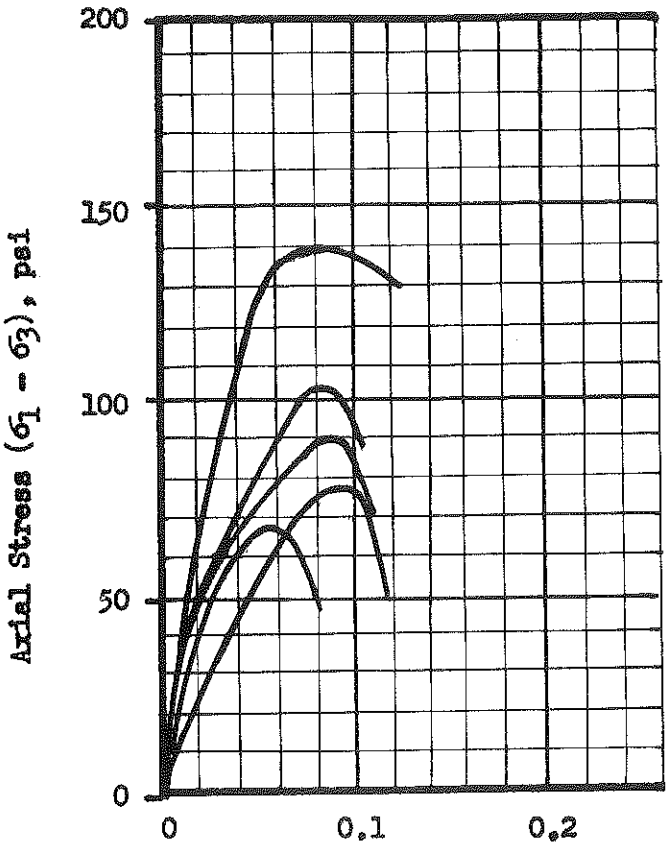
S_1C_3

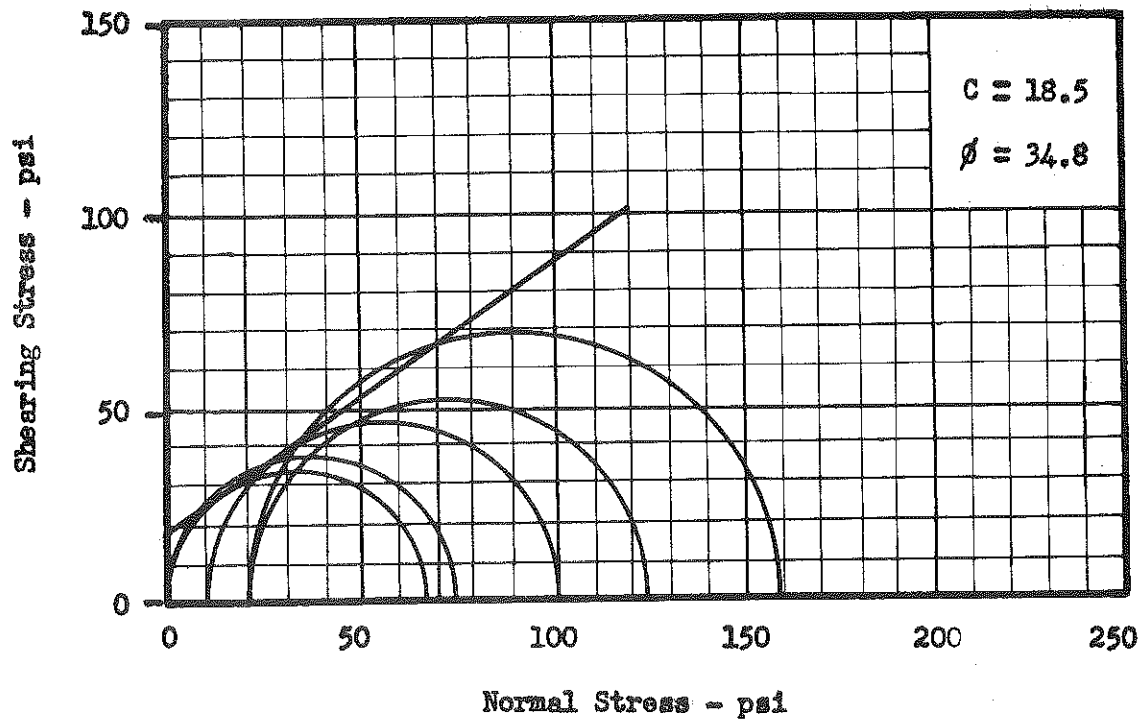




SAMPLE NO.

S_1C_7





SAMPLE NO.

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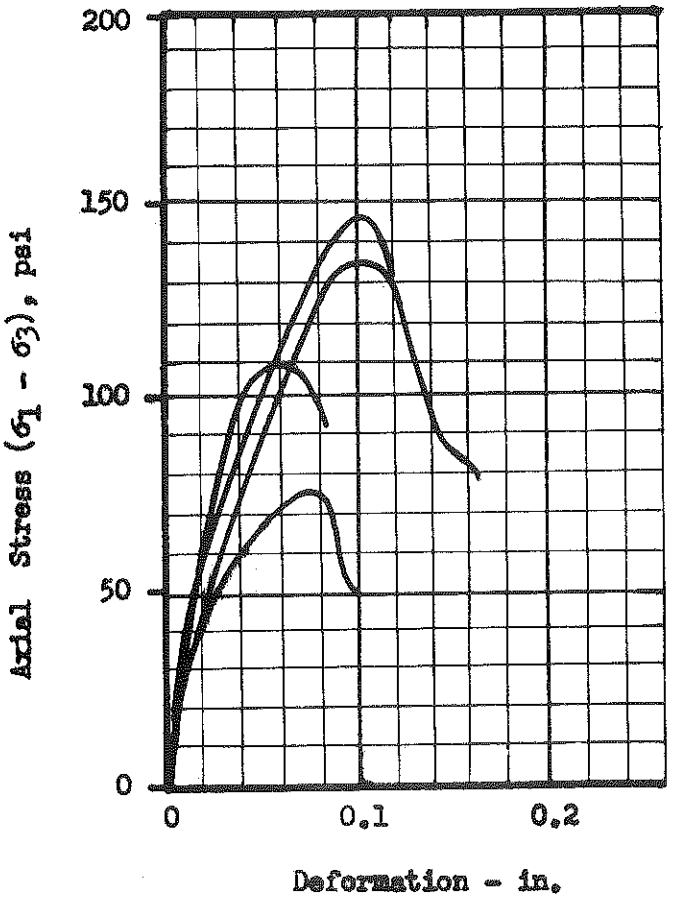

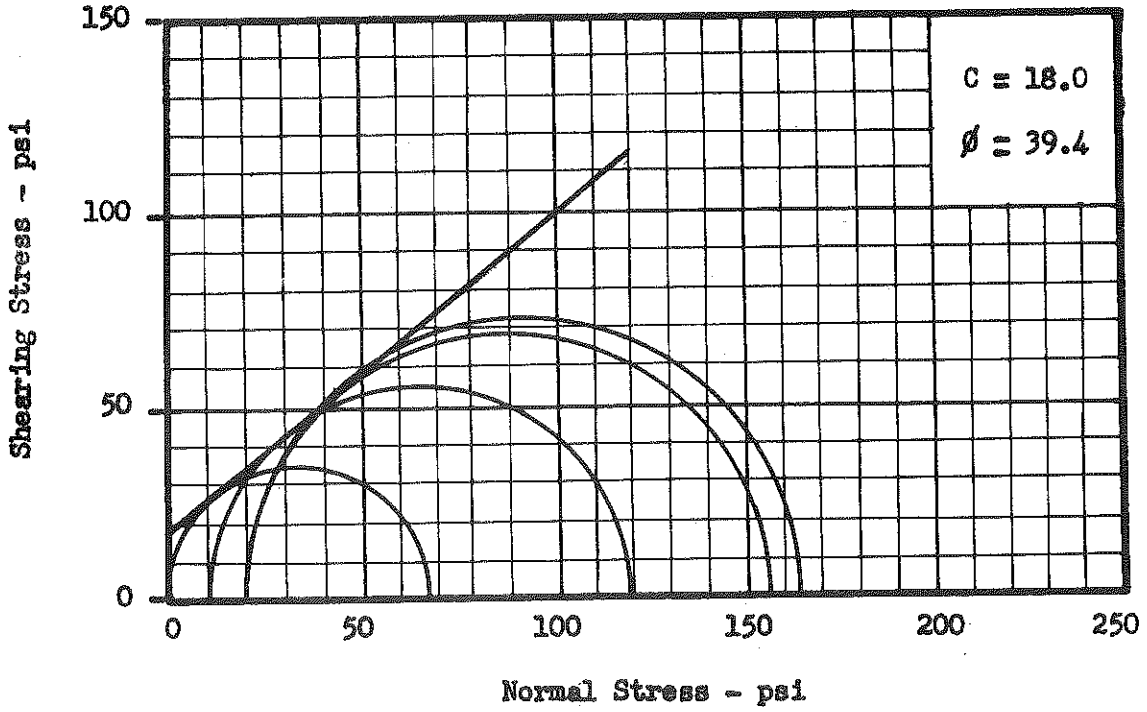

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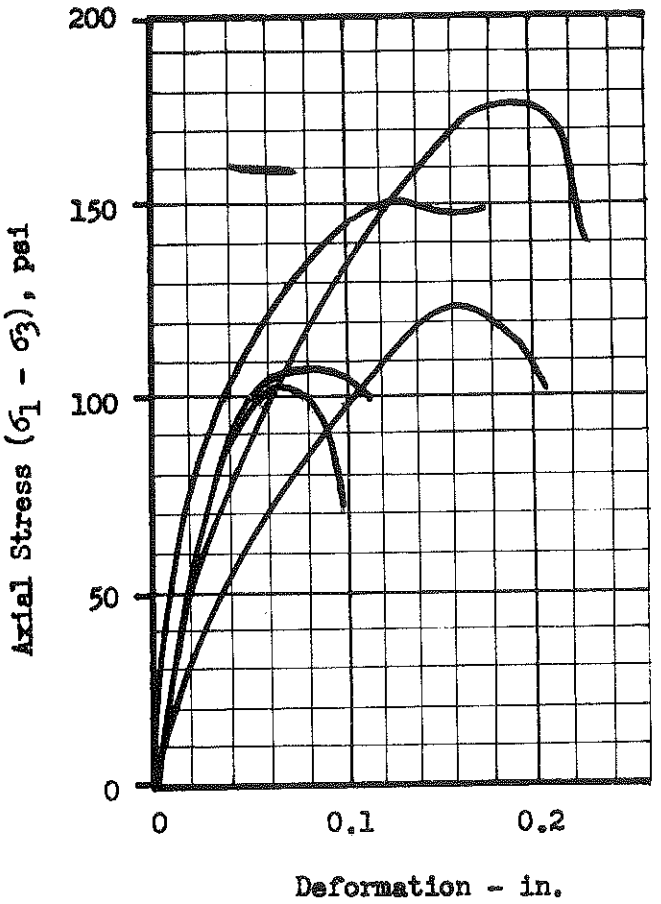
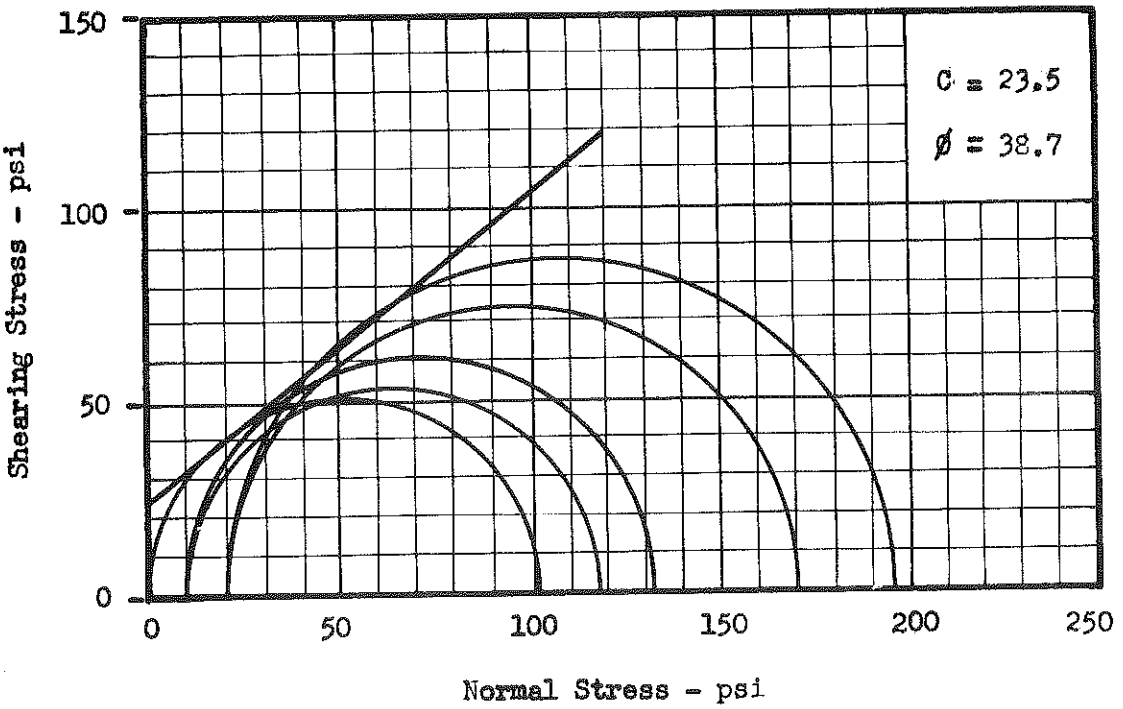
S_2A





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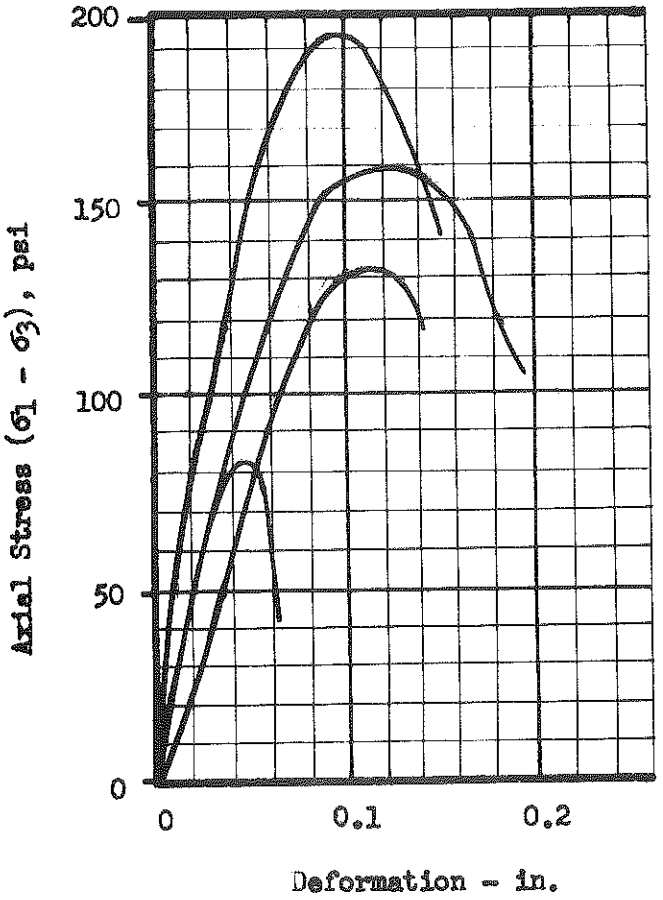

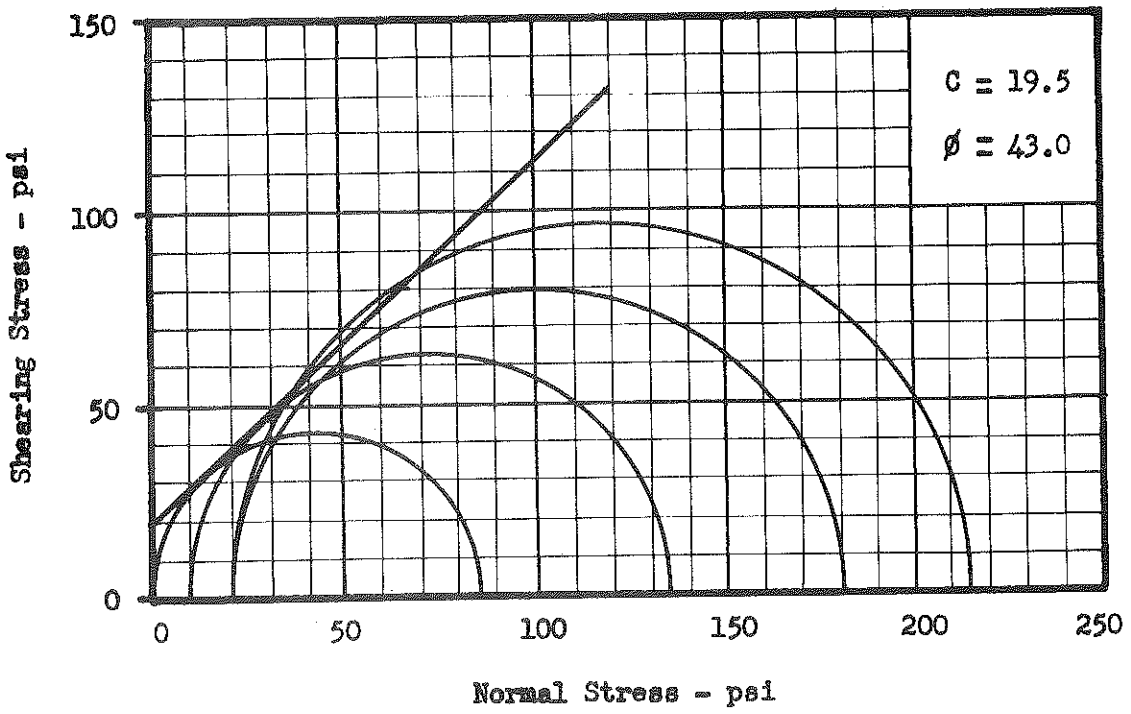

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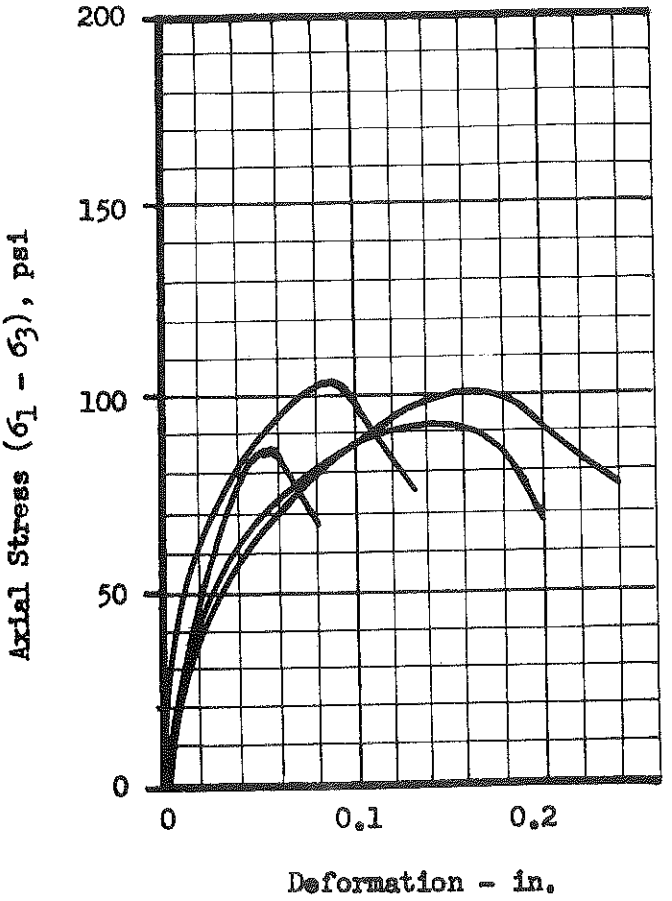
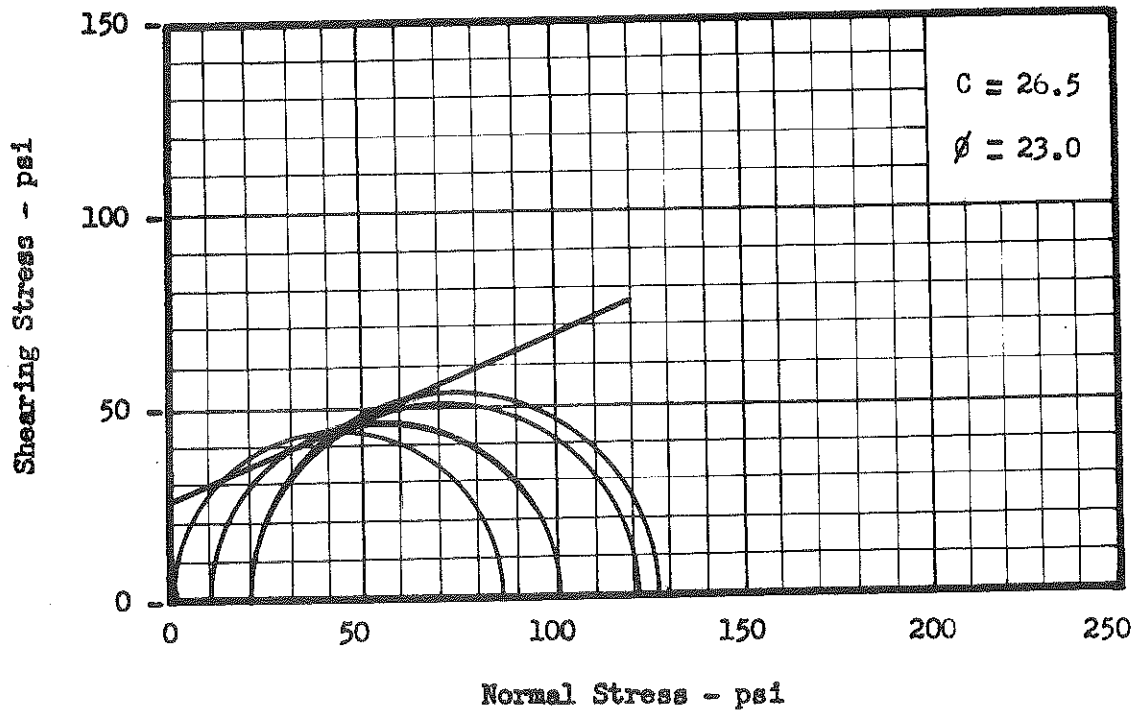
S_2D





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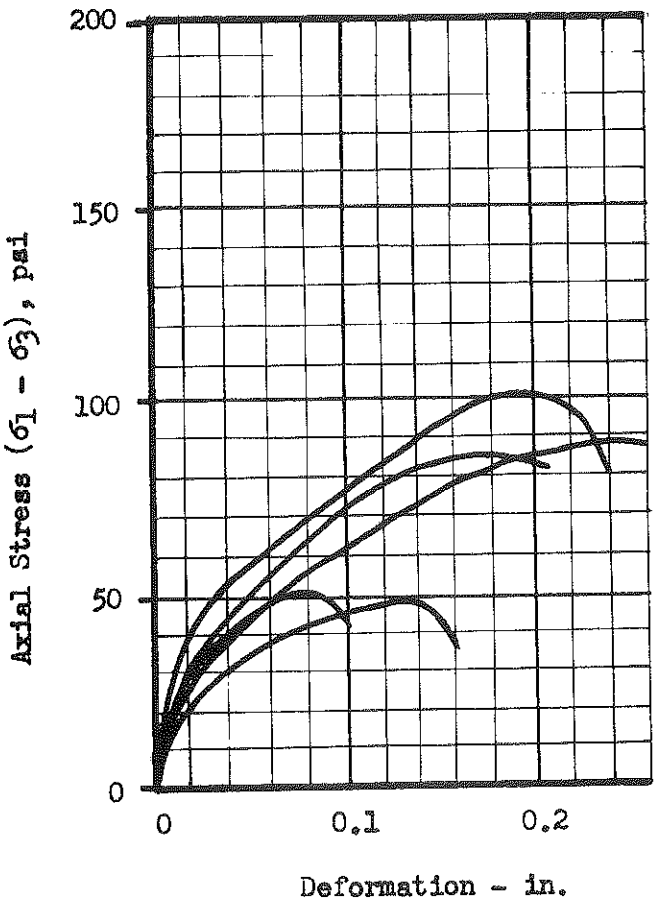
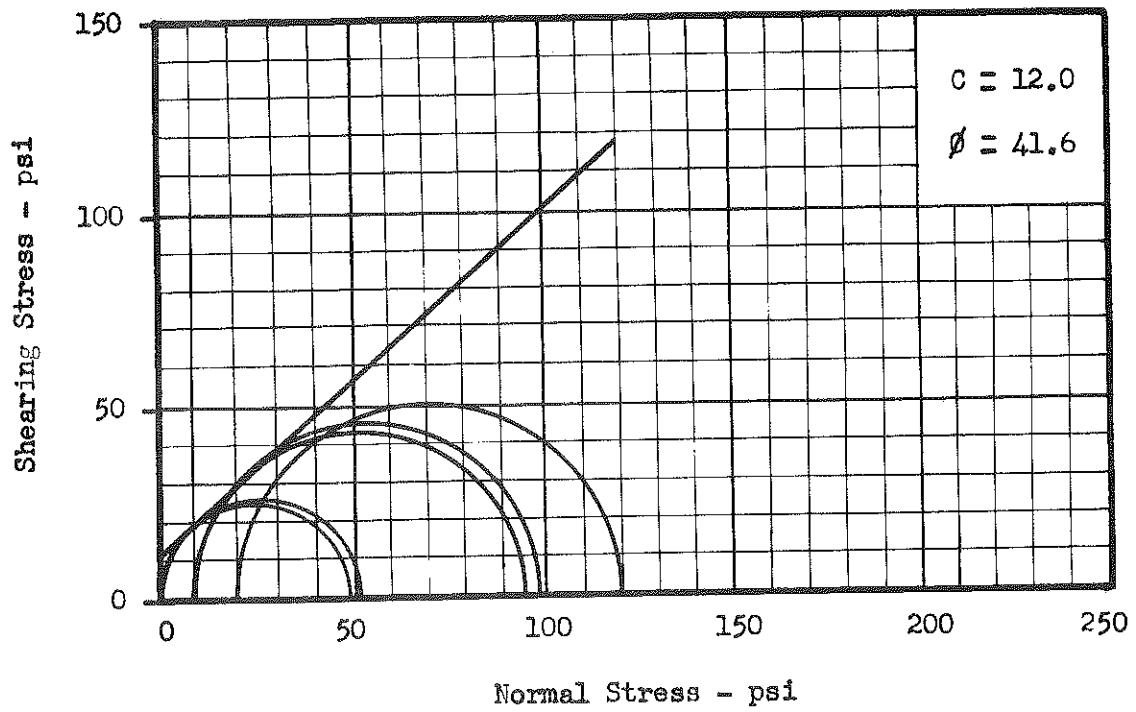
S_3D





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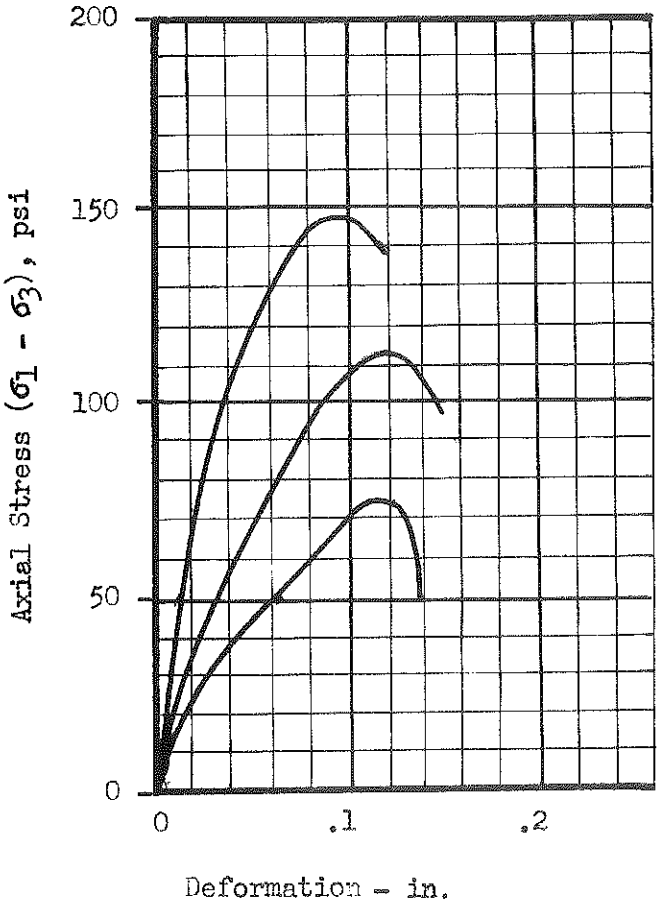
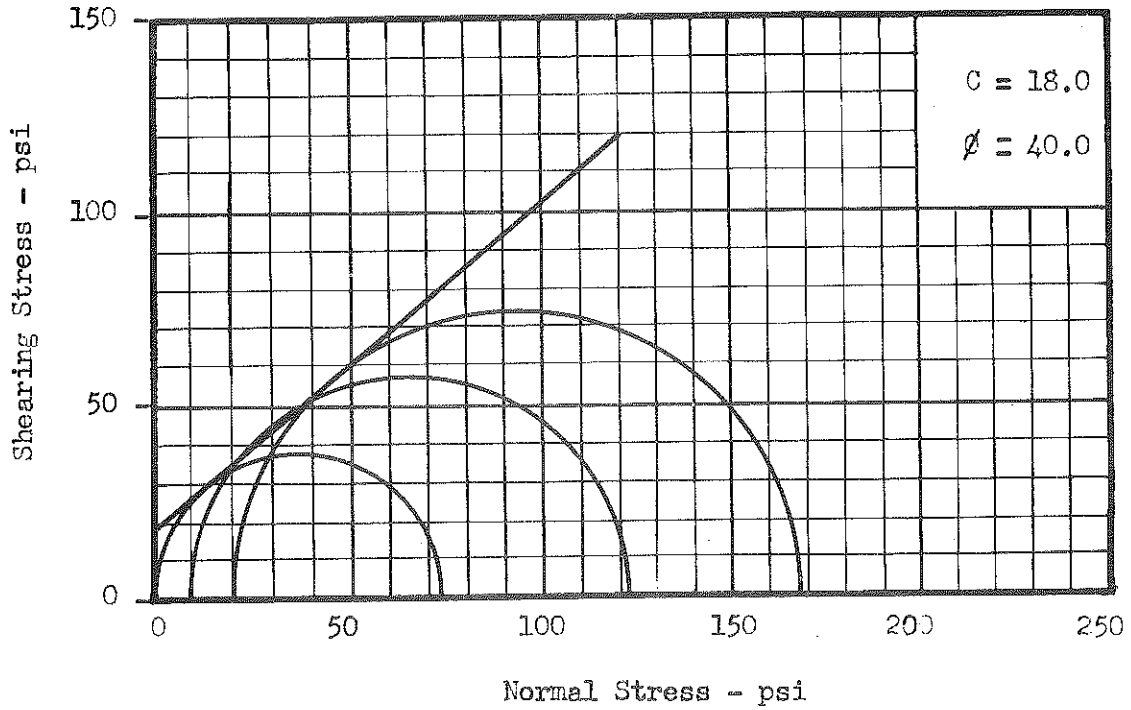
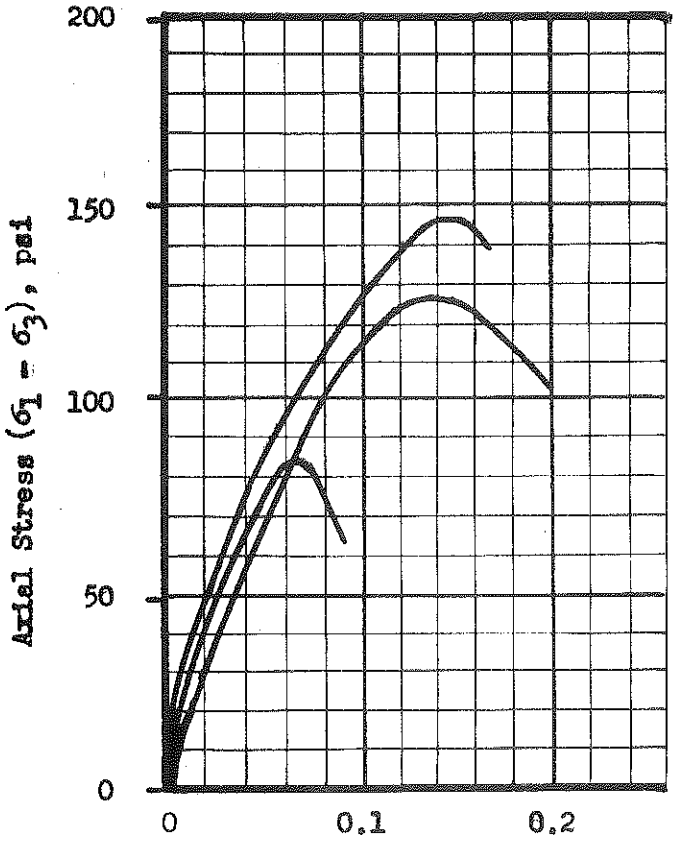
S_4B_a







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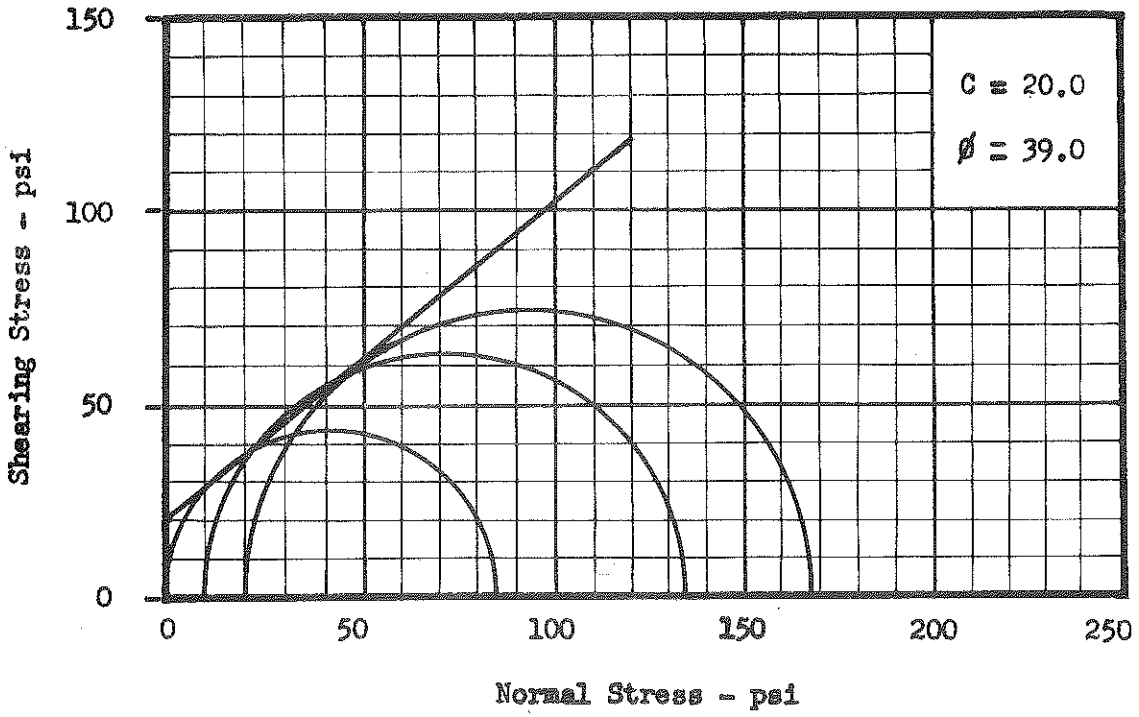
S_5B_a