THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Gilbert Cobb Staehle for the degree of Master of Science They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science.

Frederic Bass
Chairman

G. A. Maney

William F. Holman

Date June 1- 1922

10-20 5M

THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Examination

This is to certify that we the undersigned, as a committee of the Graduate School, have given Gilbert Cobb Staehle final oral examination for the degree of

Master of Science

We recommend that the degree of

Master of Science

be conferred upon the candidate.

Frederic Bass
Chairman

J A Maney

William F. Holman

Date June 1 - 1922

10-20 5M

AN ANALYTICAL AND EXPERIMENTAL STUDY

OF

REINFORCED CONCRETE COLUMNS.

A THESIS

Submitted to the Graduate Faculty

of the

U N I V E R S I T Y OF M I N N E S O T A

by

GILBERT COBB STAEHLE

In partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE IN ENGINEERING

J u n e

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A C K N O W L E D G M E N T

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Credit is due the following gentlemen for making possible these tests:

Professor Frederick Bass, Head of the Department of Civil Engineering for the service he rendered in securing the needed materials.

Mr. George A. Maney, Assistant Professor of Structural Engineering, who gave much thought to, and made valuable suggestions regarding the results to be sought, the means of obtaining these results, and whose efforts in obtaining the materials required are mainly responsible for the accomplishment thereof.

Mr. M. B. Lagaard, Assistant Professor of Structural Engineering, who also rendered assistance in obtaining the materials required, but gave most valuable aid in the selection of materials, the design of forms and instruments, and all of the operations in connection with making of the column specimens.

Mr. Lyle Dills, a graduate student in engineering, who rendered valuable service in the making of specimens, their curing, and in preparing for the actual testing.

I N T R O D U C T O R Y

The work was undertaken at the suggestion of Professor George A. Maney, after the writer had sought his advice in regard to research work in reinforced concrete design. It had been the intention of the writer to carry on theoretical work, more particularly applied to flexural problems, but the opportunities for profitable research in a study of the direct stresses in concrete columns with spiral reinforcing, as outlined by Professor Maney, proved so attractive that the study of flexural stresses was made subservient to the other, at least for such a period of time as would be required in obtaining the results sought after.

In line with the suggestions made by Professor Maney, it was decided to make a series of experiments on specimens of reinforced concrete columns of as small a size as practicable in order to allow a large number to be made; to make variables of the percentage of spiral reinforcement, longitudinal reinforcement, and richness of mix; and to make provision for both the ordinary method of progressively applied loading, and for constant loading over a more or less considerable period of time.

The unique feature of the tests would, of course, have been the inclusion of specimens under long time loading, and much valuable data was expected to be derived from this part of the program, but apparently insurmountable obstacles encountered in securing funds for the special apparatus required have postponed efforts in this direction. While the original number of specimens planned, which included four specimens of each variable for the continued loading, has been made in anticipa- of funds for apparatus being available later on, it is now believed desirable to use these specimens for other data which may be more or less akin to the data it was expected to obtain from the continued load tests, and leave to future developments the provision for tests of time loading.

It is earnestly hoped that the efforts put forth on this series and the resulting data will develop interest in further experiments of a more elaborate and far reaching nature, and including such phenomena as the effect of continuously applied loading, which is without doubt the most important question involved in the design of reinforced concrete columns and, moreover, a question which has been almost entirely overlooked, or possibly ignored, up to the present time.

H I S T O R I C A L

In the period from 1898 to 1902 were made the earliest experiments of a scientific nature on hooped concrete columns. These experiments were made by M. Armand Considere, at L'Ecole des Ponts et Chaussees, Paris, France. The results of these tests were abstracted in the ENGINEERING RECORD for December 20 and 27, 1902, and are translated from the publications of M. Considere by Leon S. Moisseiff, Assoc. Mem. Am. Soc. C. E., under the book title of EXPERIMENTAL RESEARCHES ON REINFORCED CONCRETE, by Armand Considere, and published by the McGraw Publishing Company, New York.

Variables introduced in these early tests by M. Considere were richness of mix, percentage of longitudinal reinforcement, and percentage of lateral reinforcement. Specimens were subjected to progressive loading and to repeated loadings and unloadings. Observations on the elastic behavior for both longitudinal and lateral deformations were made.

IN LE GENIE CIVIL for February 9 and 16, 1907, "Hooped Concrete and Its Applications", M. Considere published the results of subsequent tests of a more extensive character, in which were considered the effects of richness of mix, age, percentage of water, ramming, and irregularities in workmanship, as well as various kinds of spiral reinforcements.

These published data from the experiments of M. Considere and the conclusions drawn by him have been used as a basis for the formulae and designing practice set forth in most of our text-books and in the requirements of the building departments of many of our large cities, right up to the present time.

Experiments made for the firm of Wayss and Freytag by C. von Bach at the laboratory of the Royal Technical High School, Stuttgart, Germany, at various times, and published in this country in the translation of Dr. Emil Morsch's EISENBETONBAU by The Engineering News Publishing Company, New York, confirm the experiments of M. Considere. The experiments made by Bach were not, however, on nearly as extensive a scale as were those of M. Considere.

Notable tests in the United States on columns reinforced with spiral hooping are those by J. E. Howard, Esq., at the Watertown Arsenal, and published in TESTS OF METALS, 1906, by the United States War Department; by Professor A.N.Talbot, at the University of Illinois Experimental Station, in 1907, reported in Bulletin No. 20 of that institution; by Professor M. O. Withey, at the University of Wisconsin, reported in Bulletin No. 300, and later and more extensive tests made during the years 1909 and 1910, in Bulletin No. 466 of the University of Wisconsin; and by C. G. Wrentmore, Mem. Am. Soc. C. E. and Messrs. Hugh Brodie and C. O. Carey, at the University of Michigan, begun in 1908 and reported in the February, 1914, Proceedings of the American Society of Civil Engineers.*

Other tests have been made in this country, in Europe, and in Canada, but the number of specimens tested, the lack of data on elastic behavior, et cetera, make them of little value other than as confirming in a general way, the results of the better known experiments.

* See Transactions, American Society of Civil Engineers, Vol. LXXV111.

The published results and conclusions drawn from the principal American tests have had their effect upon design formulae and practice as given in some of the leading textbooks and notably in the recommendations of the "Joint Committees"* on concrete and reinforced concrete, which modify considerably the working stresses as in their opinions are justified for concrete columns reinforced with spiral hooping.

Altho the tests of Talbot and Withey have resulted in much valuable data and are to be commended as to their scope and the care with which they have been conducted, yet they are more or less inadequate from which to draw decisive conclusions in respect to certain outstanding features.

The tests by Talbot, made on full size specimens, do not include any specimens which have longitudinal reinforcing combined with spiral reinforcing.

The tests by Withey, by far the most elaborate and important of American tests, are more or less misleading, if not carefully analyzed, by reason of the longitudinal rods having practically

*See Transactions American Society of Civil Engineers, Vol. LXXX1 and LXXX11, and Proceedings of American Society of Civil Engineers for August, 1921.

direct bearing on the bearing plates when in the testing machine, altho of a few specimens this is true of only the top since the columns rested on and were integral with reinforced concrete footings.

The tests made at the University of Michigan by Messrs. Wrentmore, Brodie and Carey give data which is very complete up to unit loads of 700 or 800 pounds per square inch but give no data on elastic deformations beyond this point. Unlike the tests of Talbot and Withey these tests were on columns of a much smaller size, 4 inches in diameter by 27 inches long, which, however, are comparable to many of the specimens made by Considere and to the series made by the writer.

AIM OF TESTS - OBJECTS SOUGHT

During the period of 20 years which has elapsed since Considere published the results of his first experiments on hooped concrete columns, many tests have been made and considerable data on elastic behavior secured, but no really new ideas have been developed as to the behavior of hooped columns under load. Certainly the phenomena observed by Withey of the columns continuing to deform under a loading remaining constant in value should have pointed out the need for a special study of the relation of such phenomena to the carrying capacity of columns over a long period of time.

Experiments on the advancing deformation, or "flow", of concrete members other than columns, under continuously applied loading have been made by F. R. MacMillan, Mem. Am. Soc. C. E., while on the faculty of the University of Minnesota, and reported in Bulletin No. 3 of the University of Minnesota Studies in Engineering, and in various other publications to which Mr. MacMillan has made reference in a paper before the American Concrete Institute entitled "A Study of Column Test Data". Other experimenters also have made observations on this phenomena of "time yield", or"flow", whose published data is also referred to in the American Concrete Institute paper by Mr. MacMillan.*

Certainly a fruitful field for research is offered in obtaining reliable data as to the effect upon the life and continued load carrying capacity of concrete columns under continued loading in view of the results obtained by Mr.MacMillan. Whether or not, however, the data already obtained are sufficient to modify the designing practise now current is debatable. Certainly efforts have been made to bring into vogue designing practise which would ignore the effect of spiral reinforcing on concrete columns within the working loads and stresses, and requiring only a limited percentage as an additional factor of safety.

Withey, in his conclusions based upon the tests made by him at the University of Wisconsin, states: "Altho the yield point of a reinforced concrete column is practically independent of the percentage of spiral reinforcement, the ultimate strength and the toughness are directly affected by it. On account of the excessive deformations ac-

*See Transactions, American Concrete Institute, 1921.

companying loads beyond the yield point, on account of the probability that both yield point and ultimate strength are less in repeated or long time load tests than in the progressive load tests ordinarily made in the testing machine, and on account of the uncertainties which always surround the hypotheses adopted in designing, good practise demands that only a portion of the stress producing disintegration of the outside shell be used as a working stress; consequently, only enough lateral reinforcement is needed to prevent the longitudinal rods from bulging outward, and to provide an additional factor of safety against an overload by increasing the toughness and raising the ultimate strength somewhat above the yield point. From these tests one per cent of a closely spaced spiral of high carbon steel seems to be sufficient for this purpose."*

Talbot draws practically the same conclusions from the University of Illinois tests. While the observations and conclusions of Withey and Talbot have had their modifying effect upon the values of working stress commonly allowed for concrete columns having spiral reinforcement, and the recommendations

*University of Wisconsin Bulletin No. 466.

of the "Joint Committees" in particular have been very conservative in this respect, this conservatism is based almost entirely upon the observed fact that within the limit of the crushing strength of the concrete no noticeable effect upon the deformations of a column is secured from the use of spiral reinforcement.

Since still further modifications would be necessary if appreciable "flow" of concrete under continued loading occurs, it would seem that no more important problem is present in the field of reinforced concrete design than along this particular line.

Arguing from these premises, and, moreover, to satisfy themselves as to the suitability of the design formulae so far proposed, it was decided by Professor Maney and the writer to conduct the proposed series of tests with the particular purpose of obtaining more light upon the values which might justifiably be allowed for percentage of spiral reinforcement and to what extent its influence is modified or augmented by richness of mix, percentage of longitudinal reinforcement, repeated loadings, et cetera.

MATERIALS, AND EQUIPMENT.

The column molds, of which 32 were provided, were of 20 gauge galvanized sheet steel, cut from stock sheets and formed in the University tin shop. Each mold was in one piece 4 inches in diameter and 20 inches long after being formed, the longitudinal closure or joint being made by abutting flanges, secured by 1/4 inch stove bolts with nuts, spaced 5 inches centers. The 20 gauge sheet steel gave sufficient stiffness, when shaped to the 4-3/8 inch diameter and fastened with the stove bolts, to make unnecessary any clamps.

It was necessary, however, in setting up the molds ready for pouring, to brace them so as to prevent tipping. The method of doing this is described in a later paragraph.

The inside surfaces of all molds were first treated with bulk paraffin which remained even after removal of the first concrete. Subsequent oiling was, however, found to be desirable. After being used and removed, the molds were cleaned by scouring under a hot water faucet and then being vigorously rubbed with a piece of gunny sack cloth tied on to the end of a stick.

The aggregate selected was sand having a "fineness modulus"* of 2.84 and limestone crushed and sieved so as to be passed on a 1/2 inch and be retained on a 1/4 inch screen. The crushing of the limestone was done in the University Experimental Engineering Laboratory crusher from stone ranging in size from fine dust to large blocks, but principally of a size passing a 2 inch ring.

The sand was of particularly good quality taken from the stock of the Experimental Engineering Laboratory.

Cement was also taken from the stock of the Experimental Engineering Laboratory, being a standard brand and passing satisfactorily the usual test requirements.

The longitudinal reinforcement and 3/8" diameter spiral reinforcement used was ordinary mild or structural grade, purchased from the Illinois Steel Warehouse Company, a subsidiary of the United States Steel Corporation. Its properties as determined by physical test at the Experimental Engineering Laboratory are given in the accompanying table.

*See Bulletin 1, Structural Materials Research Laboratory, Lewis Institute, Chicago.

The 3/16" and 5/16" diameter wire for spiral reinforcement was cold drawn wire having a yield point and ultimate strength as shown in the accompanying table and deformation diagrams. It was purchased from the Illinois Steel Warehouse Company, and was delivered in the form of coils.

The spirals were made up in the machine shop of the Experimental Engineering Laboratory by turning on a lathe, the mandril having been first turned to such a diameter (found by experimenting) as would allow for the spring of the coil to give the desired core diameter. Two close extra turns were made at each end of the spiral coils to provide anchorage by bond. All spirals were given a pitch of .45 inch as nearly as possible. Such variation from the theoretical pitch as occurred could hardly affect the results to a very noticeable extent.

No spacing bars of any kind were used to maintain the pitch of the spirals, as the coils had in themselves after coming from the lathe sufficient stiffness to maintain this. The longitudinal rods were, of course, wired to the spirals, but this was to hold the longitudinal rods in position rather than to maintain the pitch of the spiral, as the rods could readily slip up and down after being wired.

TEST OF 5/16" ROUND LONGITUDINALS

Pieces Marked	Aver. Dia.	Area	Yield Point Lbs.Per Sq.In.	Ultimate Lbs.Per Sq.In.
1	.313	.0770	40,450	55,750
2	.318	.0792	41,300	57,700
3	.318	.0794	43,450	54,800
4	.315	.0779	42,000	58,450
5	.315	.0779	42,000	58,800
6	.317	.0788	41,700	58,230
7	.316	.0786	41,570	56,900
8	.316	.0785	41,500	57,100

14

TEST OF 1/4" SPIRAL WIRE

Pieces Marked	Aver. Dia.	Area	Yield Point Lbs.Per Sq.In.	Ultimate Lbs.Per Sq.In.
1	.243	.0464	89,500	90,200

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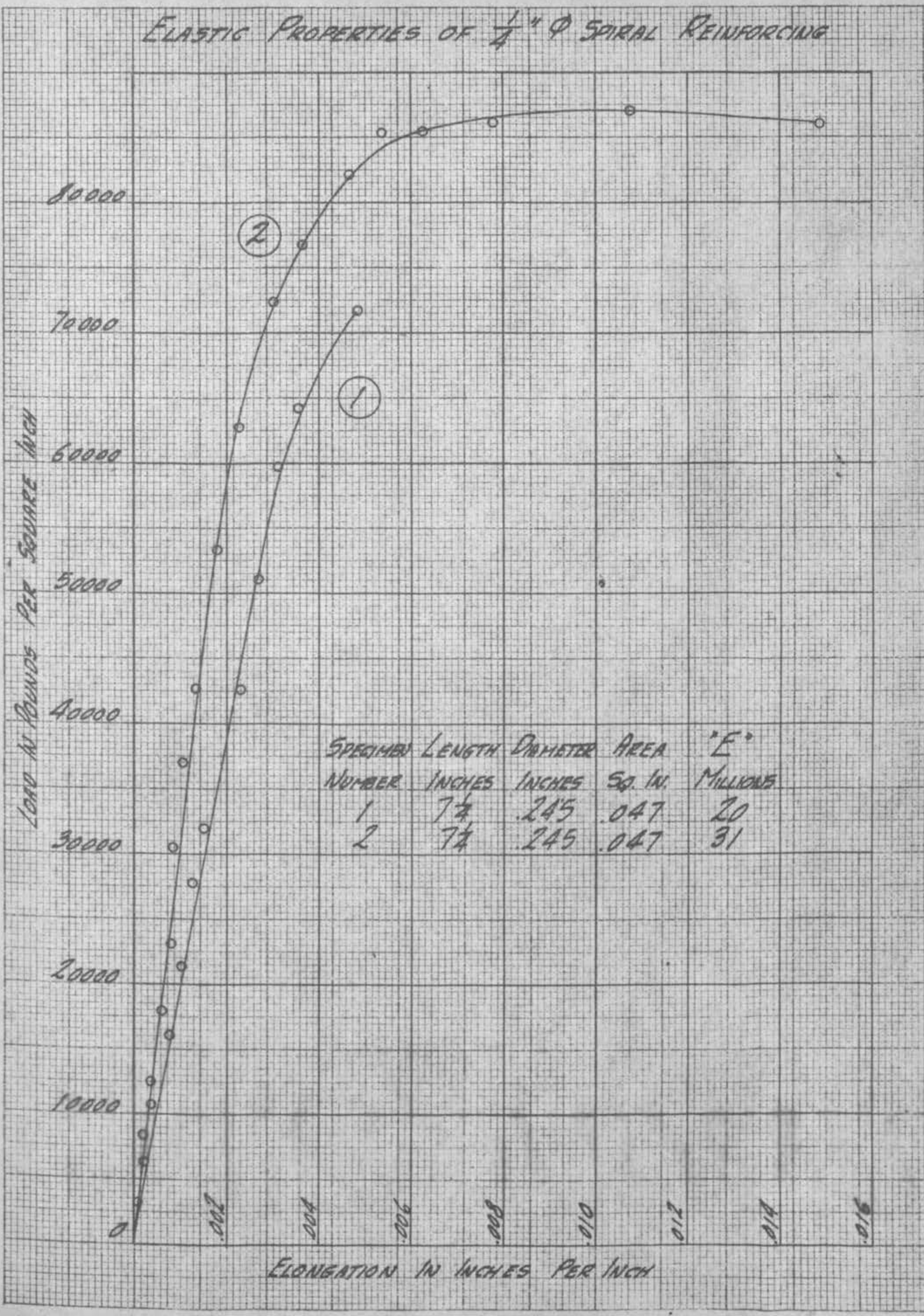
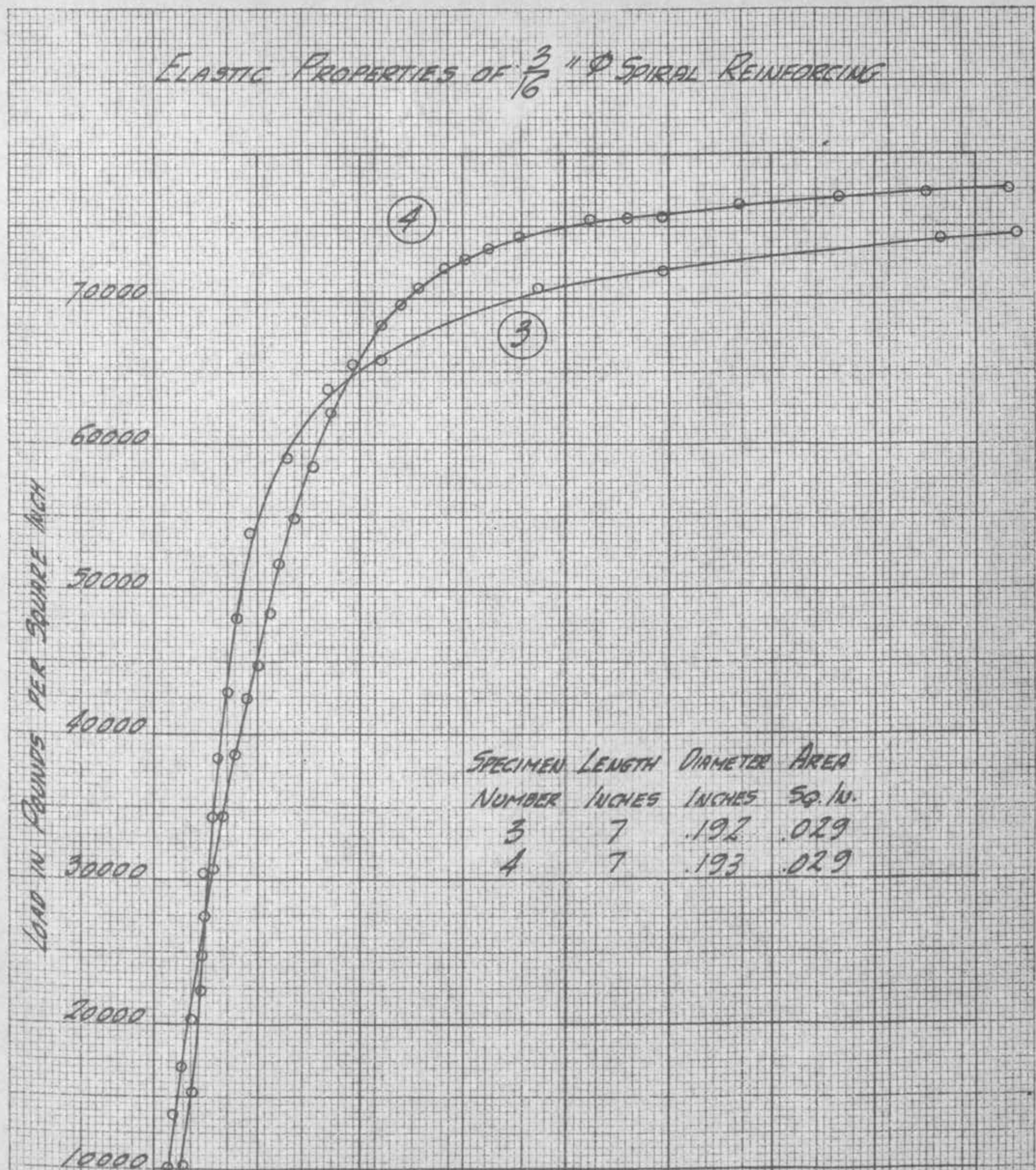


ELASTIC PROPERTIES OF 1/4" Φ SPIRAL REINFORCING
LOAD IN POUNDS PER SQUARE INCH
80000
70000
60000
50000
40000
30000
20000
10000
0
.002
.004
.006
.008
.010
.012
.014
.016
ELONGATION IN INCHES PER INCH
2
1
SPECIMEN NUMBER | LENGTH INCHES | DIAMETER INCHES | AREA SQ. IN. | "E" MILLIONS
1 | 7 1/4 | .245 | .047 | 20
2 | 7 1/4 | .245 | .047 | 31


ELASTIC PROPERTIES OF 3/16 " Φ SPIRAL REINFORCING
4
3
70000
60000
50000
40000
30000
20000
10000
0
LOAD IN POUNDS PER SQUARE INCH
.002
.004
.006
.008
.010
.012
.014
.016
ELONGATION IN INCHES PER INCH
SPECIMEN NUMBER | LENGTH INCHES | DIAMETER INCHES | AREA SQ. IN.
3 | 7 | .192 | .029
4 | 7 | .193 | .029
MODULUS OF ELASTICITY - SPECIMENS 3 & 4 - 29,000,000.
"GANNNOTE" TRACING PAPER
K.E.&CO. N.Y.

MIXTURES EMPLOYED

AND

PROCEDURE IN MAKING AND CURING.

A considerable amount of time and effort was expended in experimenting to determine the proper proportions required for the crushing strength variables of plain concrete desired.

An attempt was made to obtain the desired strengths by Abrams' Method of Fineness Modulus and Water Ratio proportioning, and a large number of 6 inch by 12 inch cylinders were made based upon this method. The results however were disappointing in the extreme, and after several attempts had been made, this method was discarded entirely. Finally an arbitrary selection of proportions was made, the wetness of mix gauged by judgment and the desired range in crushing strengths obtained. The three different mixes determined upon were 1: 1: 2, 1: 1½: 3, and 1: 2: 4, by loose volume. The actual proportioning was done by weighing the materials on a Fairbanks scale, the unit weight of each material having first been determined for loose volume.

After pouring the first set of column specimens and removing the molds, it was found that considerable honeycombing existed, the spirals being exposed for the greater part of the length of the columns. These specimens were patched up with 1:1 cement mortar. As a result of this experience it was decided to change the proportioning of the aggregate so as to provide more sand and less stone. After this change in proportioning no honeycombing occurred except for small isolated portions on three or four specimens.

The mixes will be hereafter referred to as 1: 1: 2, 1: $1\frac{1}{2}$: 3, and 1: 2: 4 for convenience, disregarding the change in ratio of sand and stone. The exact proportions used for each batch of concrete are, however, given in tabulated form for reference.

A machine mixer was employed in making the concrete for the majority of 6 inch by 12 inch cylinders experimented with to obtain data on crushing strength of plain concrete, but this proved so cumbersome a method in view of the laboratory conditions that hand mixing was finally resorted to and used in making concrete for all column specimens as well as the 6 inch by 12 inch cylinders made from the same batches as the columns. The laboratory floor, when thoroly swept and wetted, made an excellent mixing floor, and it is believed a quality of concrete superior to that from machine mixing was obtained.

Slump tests were made of all batches measuring both the actual slump after removal of the slump mold, and also the "flow" or spread of the concrete after the slump flow table had been jigged 24 times subsequent to removal of slump mold.

The first two or three sets of columns made were of a rather stiff concrete but later ones were invariably of a mix wet enough to flow readily around the spiral and longitudinal reinforcement.

Previous to pouring concrete, the molds were set up on a large piece of slate as a platform, whose surface had been first thoroly cleaned and oiled. Nine or ten molds were set in a row, so that large planks resting at their ends on heavy iron mold supports could be used on either side to brace the column molds against tipping. The planks were wired or otherwise secured against displacement and the individual molds were separated at their bottoms and near their tops by bricks. Around the bottoms of the column molds sufficient sand was deposited to prevent leakage of cement.

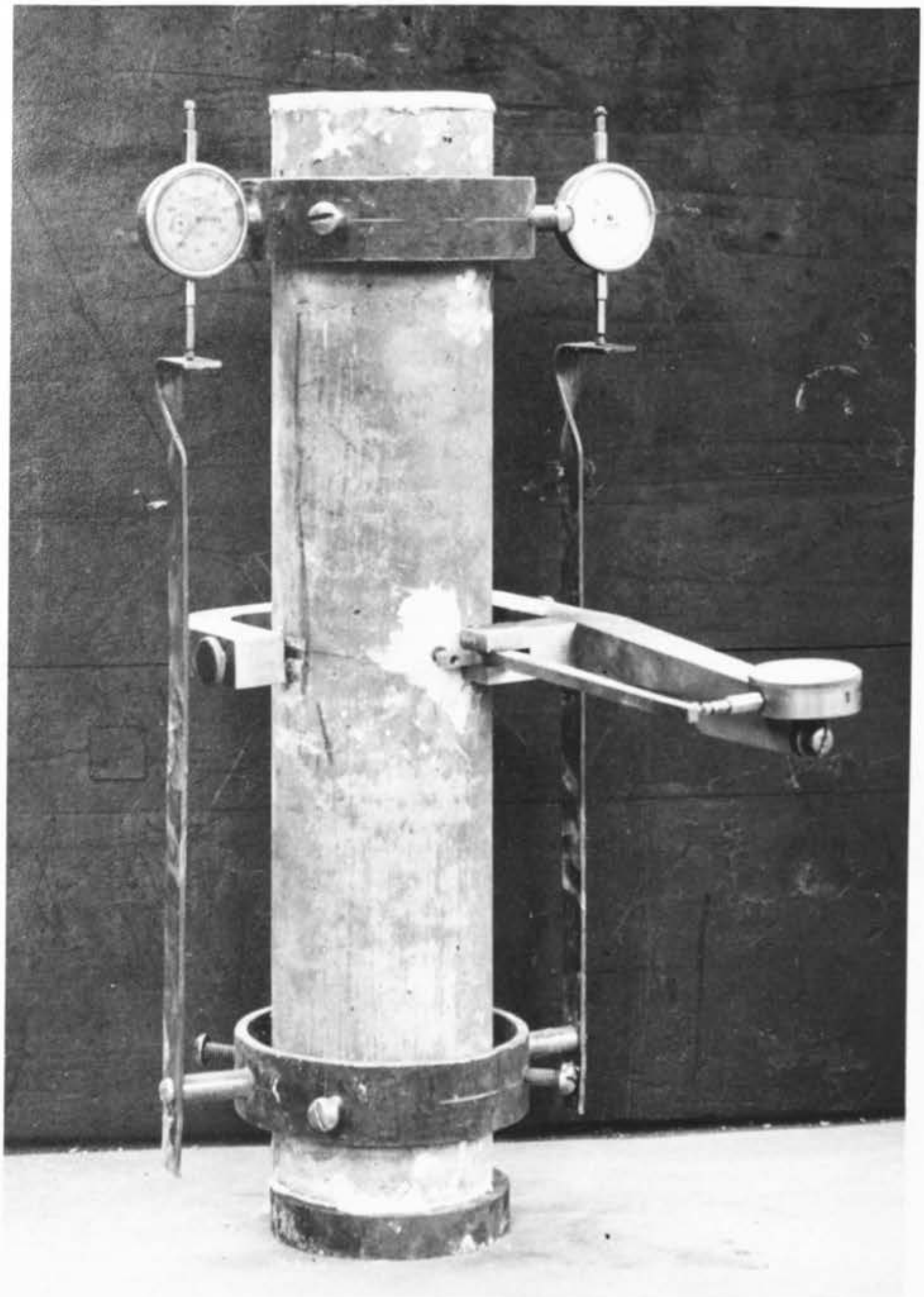
The pouring of each column was accompanied by vigorous hand tamping with 5/16 inch or 3/8 inch rods, two being used simultaneously. The concrete was deposited in sections, so that the tamping could be done to the best possible advantage. After a column mold was filled to the top an electric hammer was applied for several seconds so as to remove all air bubbles.

The molds for the first six sets of specimens were removed the day following pouring, and for the remaining two sets two or three days after pouring.

Curing for the first six sets of columns was done by covering a set of specimens with sacks which were wet down every two or three days; sand being placed on the floor surrounding the specimens also. The damp sacks were removed after from two weeks to 18 days of curing, and the specimens allowed to finish their curing in the rather dry air of the laboratory. The remaining two sets of columns, after being removed from their molds, were placed in a moist air curing room and allowed to remain there for 21 days, then removed to complete their curing in the dry laboratory air.

INSTRUMENTS AND APPARATUS FOR TESTING

The apparatus used for obtaining longitudinal deformations consisted of two cast-iron rings having four screws for securing the rings to the column specimens and two plugs diametrically opposite for receiving screws by which the standards or dials, as the case might be, were attached. The standards were made from flats of stock heavy enough to give the necessary stiffness, but flexible enough to permit adjusting to the varying conditions of the tests. The two standards were secured to the lower ring by the screws mentioned above. On the upper ring two Ames dials were attached by means of screws, their legs resting on the supports made by bending the ends of the standards 90 degrees. On the first two or three columns tested one dial was reversed from the position described above so that it was near the bottom of the specimen and the one on the opposite side near the top. It was necessary in most of the testing for the writer to take readings on both dials as well as run the testing machine, so that for convenience in reading both dials were faced to the front, which resulted in one of the dials being slightly off center. To take care of this latter



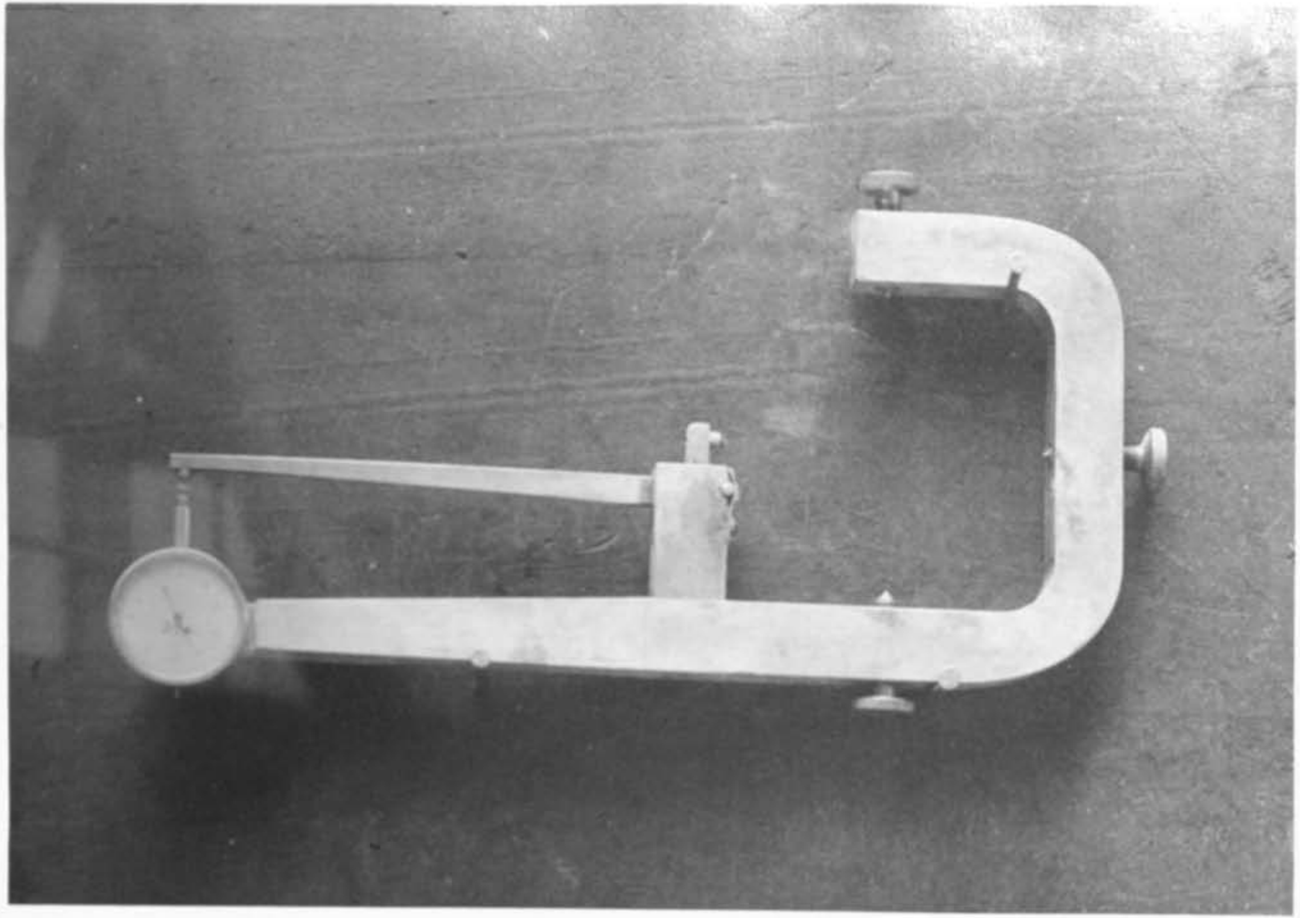
Instruments for obtaining longitudinal and lateral deformation measurements in place on column specimen.

condition the standard under the dial off center had to be bent slightly to give support to the dial leg.

The length of the standards and distance between rings when set on the column specimens was such as to give a gage length of 16 inches, as nearly as possible.

Trouble was experienced in testing the first two or three columns because of the shortening amounting to more than the total range of the dials, which necessitated a resetting of the dials. This difficulty was done away with by using dials having a greater range. Two sets of rings and two sets of standards were available, but only one set of the larger range dials was used since they could be readily transferred from one set of rings to the other.

The instrument used for obtaining lateral deformations was not available until after a number of specimens had been tested. It was made in the machine shop of the Experimental Engineering Laboratory and consists essentially of a metal frame equipped with a movable arm having contact at one end against a plug set in the column and at the other end with the leg of an Ames dial. It is pivoted near the end in contact with the column so as to



Instrument for obtaining lateral deformation measurements.

12-21-6M

give a ratio of 1 to 10 between lateral swelling of the column and the movement of the dial. The frame itself is adjusted and secured to the column specimen by three screws which have bearing on three sides of the column in holes drilled into the spiral wire. This is not an ideal instrument for the results desired, but it undoubtedly gives a fair measure of the values for lateral distortion. The preparation of a column specimen for the setting of this instrument took so much time that its use on more than a few of the specimens was not attempted.

The 200,000 pound Tinius Olsen testing machine was used for making all column tests except in one or two cases where repeated loadings of not more than 5000 pounds per square inch were being made, in which instances a 100,000 pound Tinius Olsen machine was used. The 6 inch by 12 inch cylinders were tested in either of these two machines, as happened to be most convenient.

Since the load carrying capacity of the columns exceeded the capacity of the 200,000 pounds Tinius Olsen machine in more than one case for specimens only 28 days old and reinforced with the intermediate percentage of spiral hooping, the need for a machine of much greater capacity is apparent. The machine of the Minneapolis Building Department, which has a capacity of 400,000 pounds, is the only other machine available nearby.

12-21-6M

DESCRIPTION OF COLUMNS

The reinforced columns, of which the total number made was seventy, were all 4 inches in diameter, out to out of spiral reinforcing, with a 3/16 inch cover of concrete over the spiral reinforcing, or a total of 4-3/8 inches over all, and were all 20 inches long.

The plain concrete column specimens, of which ten were made, were of the same overall dimensions as the reinforced columns.

Details of the mix used for the various sets, as well as of kind and percentage of longitudinal and spiral reinforcing, curing and age at which tested are given in the accompanying tables.

All specimens were capped with plaster of Paris at both ends previous to being tested. Since all longitudinal reinforcement had been cut to a length of 19½ inches no opportunity was offered for the ends of the rods to bear directly against the bearing plates of the testing machine and the plaster of Paris capping gave an additional insurance against this happening. The capping was not done as carefully as it should have been done, or as carefully as it would have been done if more time and assistance had been available. Many interesting phenomena was observed by reason of the end bearing due to poor capping being out of true, which will be described in more detail under other headings.

PROPERTIES OF REINFORCED CONCRETE COLUMNS

Columns Marked	Nominal Mix	Actual Mix	Slump in Inches	Flow in Inches	Days in Moist Curing
1 to 9 incl	1:1½:3	1:1½:3	4	24x24½	14
10 " 17 "	1:1½:3	1:2¼:2¼	4½	25x27	14
18 " 25 "	1:1 :2	1:1½:1½	6½	24½x24	14
27 " 34 "	1:2 :4	1:3 :3	5-3/4	25½x25	14
34 " 41 "	1:1½:3	1:2¼:2¼	8	28x28	18
42 & 49Y	1:1½:3	1:2¼:2¼	8	28x28	18
44 to 49 "	1:1½:3	1:2¼:2¼	8	28x28	18
50 " 57 "	1:1½:3	1:2¼:2¼	7½	28x28	21
58 " 65 "	1:1½:3	1:2¼:2¼	7½	28x28	21
70 " 71 "	1:1½:3	1:2¼:2¼	7½	28x28	21
80	1:1½:3	1:2¼:2¼	7½	28x28	21
81 " 82 "	1:1½:3	1:2¼:2¼	7½	28x28	21

PROPERTIES OF PLAIN CONCRETE SPECIMENS

Cylinders Marked	Size	Nominal Mix	Actual Mix	Slump in Inches	Flow in Inches	Days in Moist Curing
B1 and C1	4-3/8x20	1:1½:3	1:2¼:2¼	4½	25x27	14
D1 " E1	4-3/8x20	1:1:2	1:1½:1½	6½	24½x24	14
F1 " G1	4-3/8x20	1:2:4	1:3:3	5-3/4	25½x25	14
H1 " I1	4-3/8x20	1:1½:3	1:2¼:2¼	8	28x28	18
J1 " K1	4-3/8x20	1:1½:3	1:2¼:2¼	7-1/2	28x28	21
B2 " C2	6 x 12	1:1½:3	1:2¼:2¼	4½	25x27	14
D2 " E2	6 x 12	1:1:2	1:1½:1½	6½	24½x24	14
F2 " G2	6 x 12	1:2:4	1:3:3	5-3/4	25½x25	14
H2 " I2	6 x 12	1:1½:3	1:2¼:2¼	8	28x28	18
J2 " K2	6 x 12	1:1½:3	1:2¼:2¼	7½	28x28	21

CRUSHING STRENGTH OF 6" x 12"

PLAIN CONCRETE CYLINDERS

Cylinders Marked	Nominal Mix	Age In days	Crushing Strength
B 2	1:1½:3	32	2930
D 2	1:1 :2	28	3950
F	1:2 :4	28	1600

PROPERTIES OF REINFORCED CONCRETE COLUMNS

Columns Marked	Longitudinal Reinforcement (Number)	(Dia.)	(Per cent)	Spiral Reinforcement (Dia. wire)	(Pitch)	(Per cent)
1 to 9 incl.	4	5/16"	2.78	1/4"	.45"	11.6
10 " 17 "	6	5/16"	4.16	1/4"	.45"	11.6
18 " 25 "	4	5/16"	2.78	1/4"	.45"	11.6
27 " 34 "	4	5/16"	2.78	1/4"	.45"	11.6
34 " 41 "	6	3/16"	1.5	1/4"	.45"	11.6
42 & 49Y	6	3/8"	6.	1/4"	.45"	11.6
44 " 49 "	6	3/8"	6.	1/4"	.45"	11.6
50 " 57 "	4	5/16"	2.88	5/16"	.45"	17.3
58 " 65 "	4	5/16"	2.69	3/16"	.45"	6.42
70 " 71 "	4	5/16"	2.78	1/4"	.45"	11.6
80				3/16"	.45"	6.42
81 " 82 "				1/4"	.45"	11.6

TIME OF LOADING REINFORCED COLUMN SPECIMENS

Columns Marked	(Age at (First Loading (In Days	(Elapsed Time Between Start (Of Successive Loadings In (Hours And Minutes
1	28	
5	37	
10	28	
11	32	
18	28	
19	30	
27	31	
28	34	
30	35	00:19,00:17,00:19,00:40,00:31
12	50	24:05,23:50,21:17
20	46	20:40,22:00,25:10
13	53	00:11,00:20,00:23,00:32,00:25
21	53	14:30,04:15,04:40,13:57,05:23 03:50
14	55	
15	58	14:15,05:10,03:50,02:47,05:33 03:45
16	60	00:16,00:22,00:28,00:32
35	29	
40	28	
49	30	
49Y	32	
50	27	
51	28	
52	35	
58	27	
59	31	

BEHAVIOR UNDER TEST

A number of extremely interesting phenomena were observed in testing the various column specimens, and altho the same or similar characteristics have been observed by other experimenters, it is believed that the phenomena are well worth commenting upon.

It was noticed on a number of the specimens, particularly those loaded but once, or for the first of the repeated loadings, that the readings on longitudinal deformation showed very erratic results during the earlier stages of loading, but once the loading became advanced to say between 2000 and 3000 pounds per square inch, or thereabouts, the readings became extremely regular. This was undoubtedly due to either poor capping or to a softness or irregularity in the quality of the concrete at the tops and perhaps also at the bottoms of the specimens. A breaking down of the concrete in the tops of several columns was noticed particularly and in one or two cases, at the bottoms.

An inferior quality of concrete at the ends and particularly at the tops could easily be explained by the conditions of tamping. There is to be considered also the fact that the concrete at the two ends of the specimens would not have as effective lateral restraint exerted on it as would exist for the remaining length, since the two close extra turns of spiral wire could hardly be as effective as the portion of the spiral in the remainder of the column lengths.

Indeed, it is believed that these tests have emphasized very strongly the need of effective anchorage by bonding of the spiral at the ends of columns. On all but three of the columns tested, where actual failure occurred, the spiral wire broke in one or more places close to either the top or bottom of the specimen, or as happened in one case, at the top and bottom both.

In some cases two breaks in the spiral occurred simultaneously, in some one immediately following the other, and in a number the spiral broke at only one place. Of the several specimens in which the spiral did not break at either of the ends, some had breaks at or near mid-length of the specimens and some did not break the spiral, but distorted to such an extreme form of curve that they either slipped out of the testing machine, or bent the rod of the bearing block to such an extent as necessitated removal of the specimens from the testing machine. In such cases it was found that the concrete opened up on the tension side of the curvature and that the longitudinal rods were pulled away from the top of the column a very noticeable distance. Several cases of bond failure of the spiral were distinctly apparent under the higher loadings, which was, however, to have been expected.

On two or three specimens, during the period immediately preceding the spalling of the surface concrete, it was noticed that the outer shell seemed to have been entirely separated from the core inside the spiral hooping, a hollow sound being emitted under light blows of a metal rod.

On all specimens tested to destruction at one progressive loading, a more or less considerable lateral deflection appeared shortly before the ultimate strength had been attained. In some cases this deflection took the general form of a letter "S", and in others a simple bowing. For the specimens subjected to repeated loadings, however, no appreciable curvature could be observed, the specimens remaining quite straight until actual failure occurred by breaking of the spiral wire, or by the specimens refusing to take additional load.

One particularly interesting phenomenon, which was also observed by Considere, and to which he attaches considerable importance, was the ability of the hooped columns to hold their ultimate loading for a considerable period, the while deforming quite rapidly. This phenomenon was almost a source of irritation in the writer's tests since it delayed the work considerably. While the column continued to support its ultimate load, the dials could be observed to rotate rapidly, and the column itself undergo great distress, and assuming the most exaggerated form of curvature in some instances.

While Considere refers at length to the phenomenon just recounted he does not make any particular reference to the fact that, even under the lesser loadings, hooped columns continue to deform longitudinally while the loading is kept constant. Withey makes particular reference to this phenomenon and in fact took observations on the advancing yield over periods of from thirty minutes to four hours. Messrs. Wrentmore, Brodie and Carey state in their account of the tests made at the University of Michigan that, "The beam was never held up by the column, but always dropped showing progressive deformation." Of the University of Minnesota tests made by the writer it cannot be said that the beam was never held up by the column, however. In fact in several instances under loadings of perhaps three, four or five thousand pounds per square inch not only did the beam hold up but a slight recovery was shown by the dials. In general tho, particularly after the loading had exceeded the ultimate strength of the plain concrete and the longitudinal reinforcing, the progressive deformation under constant loading was quite marked and near the ultimate strength of the specimens, the dial hands fairly raced.

The above phenomena are, however, considerably modified, if not entirely eliminated, after several repeated loadings on a column. The effect of repeated loadings is without question, to pack the concrete particles into a very dense mass and give greatly increased stiffness and toughness.

Another phenomenon observed, which, however, is easily explained by poor capping of the

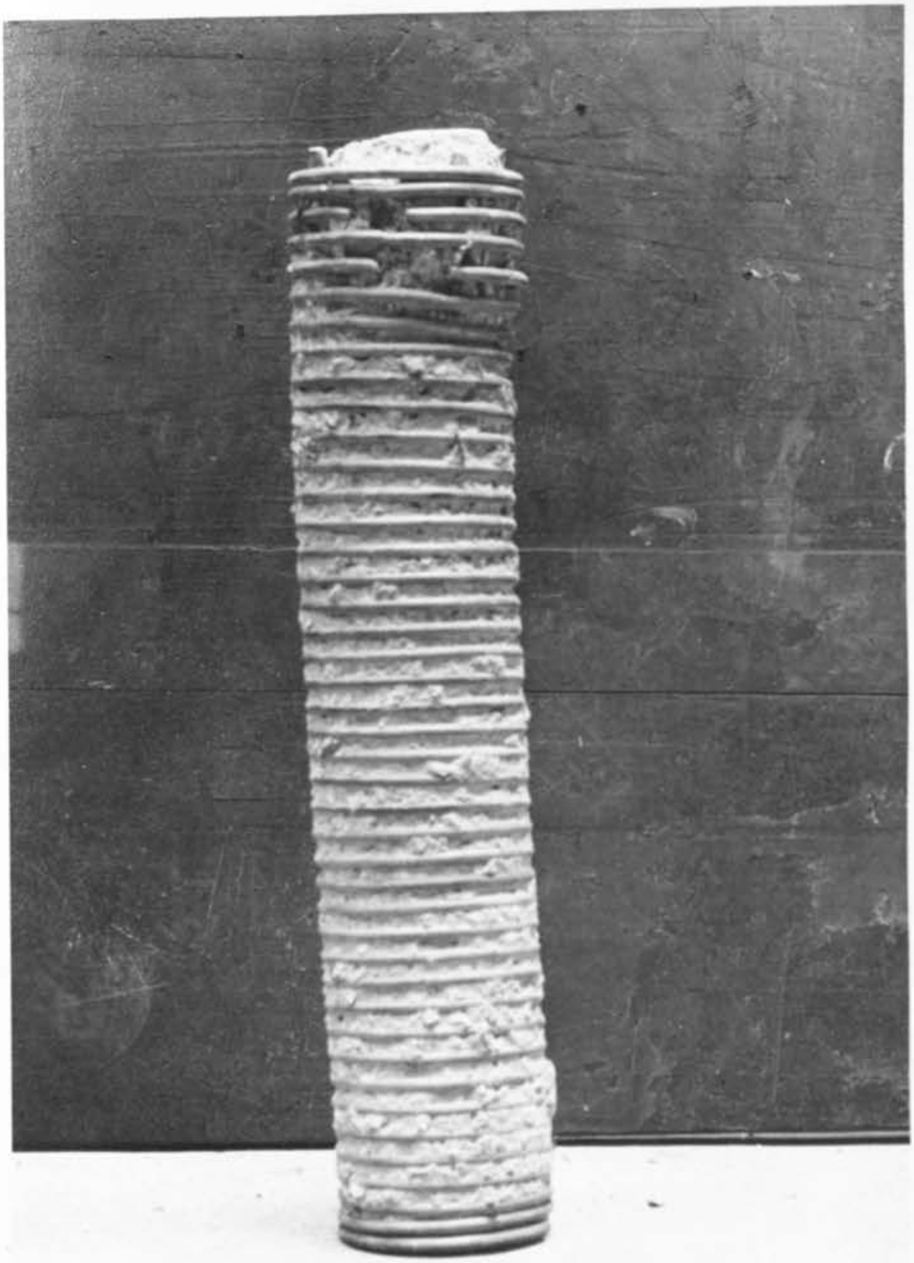
From left to right - columns 15, 12, 14, 10, 11, 5.

From left to right - columns 35, 50, 71, 18, 19, 16.

From left to right - columns 28, 30, 20, 27, 49, 49Y.

From left to right - columns 51, 58, 40, 59, 52, 13.

From left to right - columns K2, B2, F2, 1, 21, 2.



Column 5.

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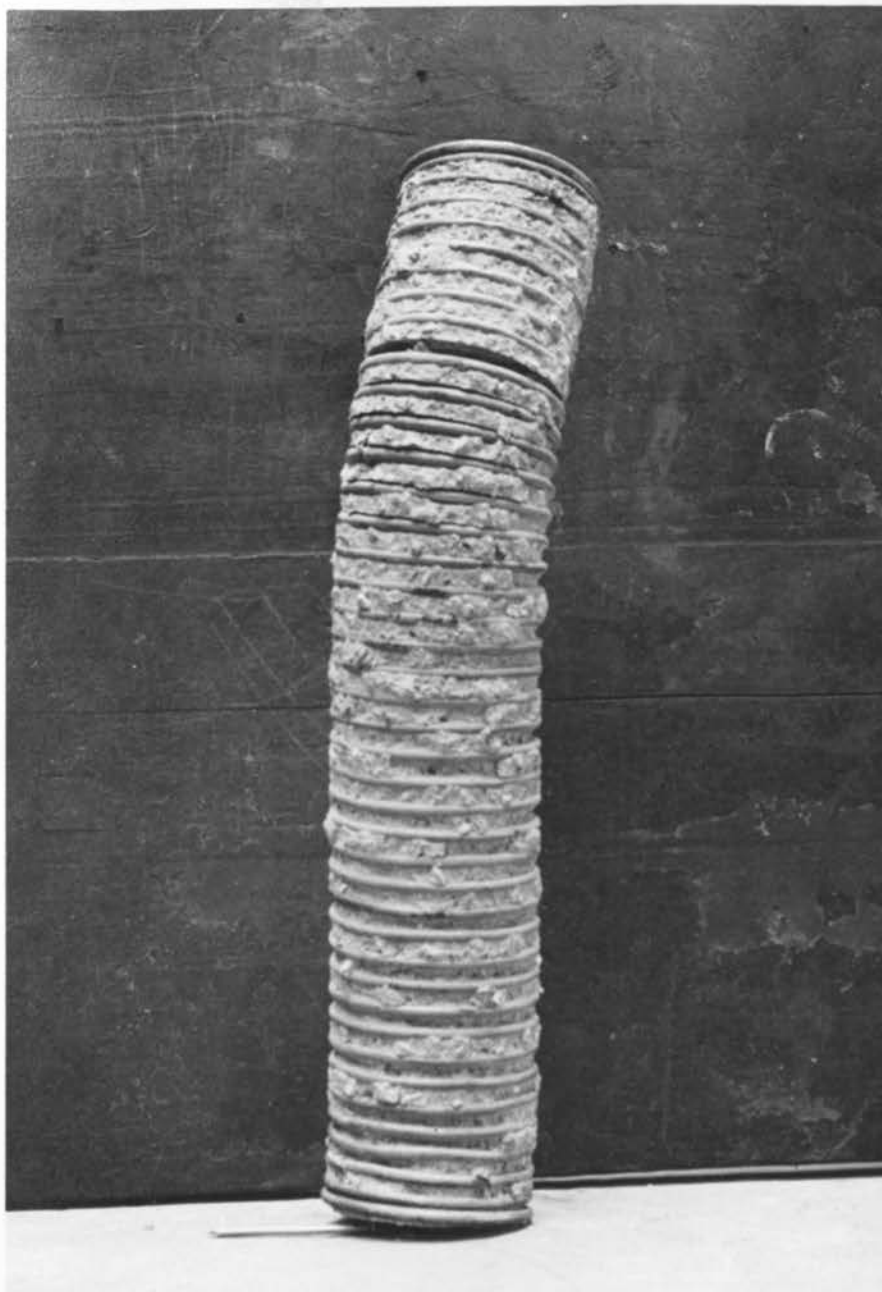
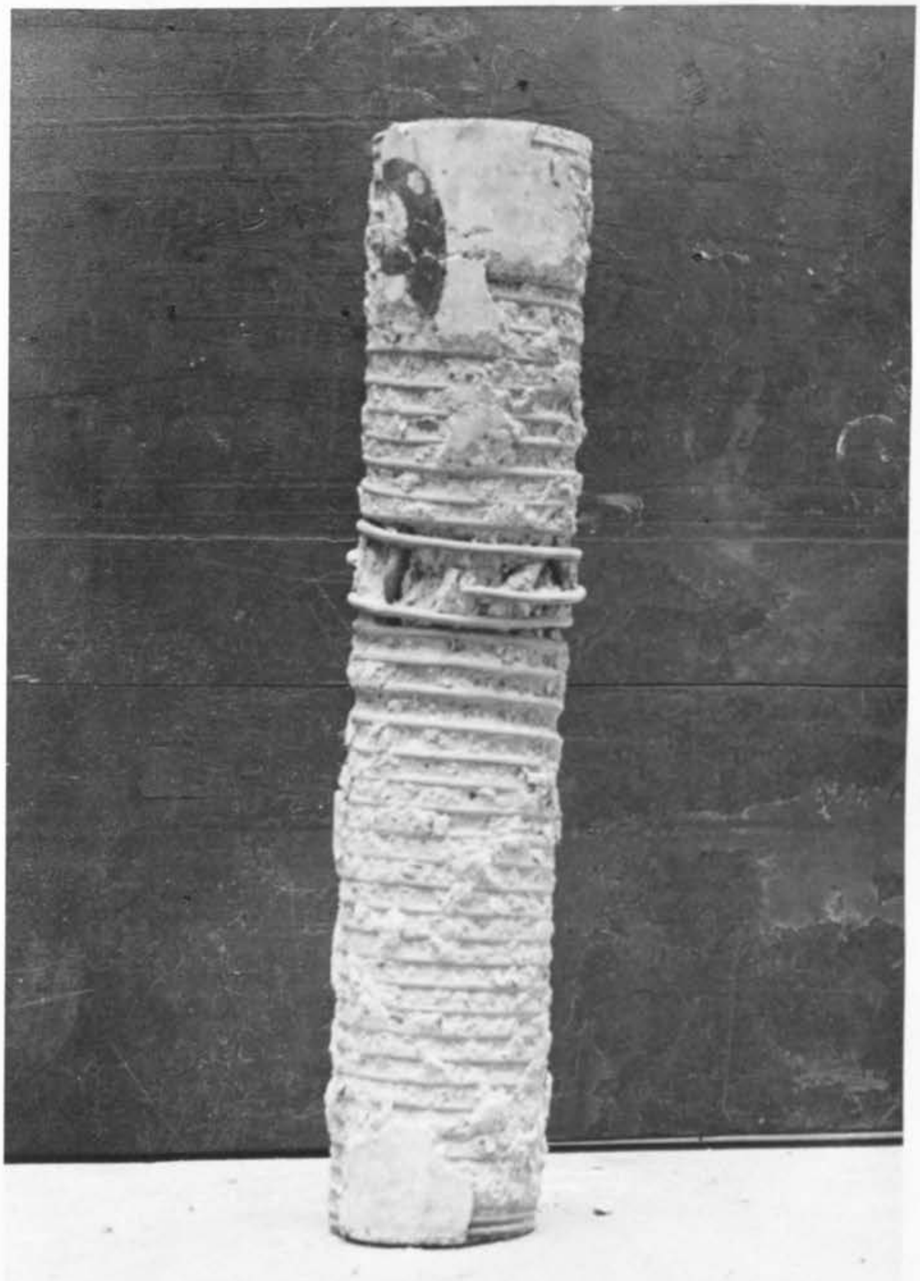


Column 18.



Column 59.

ends of the columns was that during the earlier stages of loading, in many cases the readings on one side of the column would be several times as much as those on the opposite side, and in starting out several negative readings on one of the sides would be taken. In such cases it was found that the deformations on the positive side were sufficiently large to offset those on the negative side and the algebraic mean of the two would give a very regular curve.

ELASTIC CURVES

AND

COMPUTATION OF VALUES.

In the computation of values from which the curves for elastic deformation and coefficient of elasticity have been plotted, all dimensions for the concrete column specimens, including core diameter and pitch of spiral hooping, have been assumed to be as stated under "Description of Columns". A gage length of sixteen inches has also been assumed thruout, altho noticeable divergence from this theoretical gage length occurred by reason of it being impossible to set the rings exactly as desired because of the concrete breaking up with the tightening of the screws.

Values of unit load for the reinforced concrete columns are based upon a core diameter between centers of spiral hooping. Observations on the spalling of the outer shell of concrete indicate that the concrete core remains intact to at least the center of the spiral wire, and in a great many cases to the outer surface of the spiral wire, right up to the ultimate strength of the specimens.

As described elsewhere the apparatus used for measuring longitudinal deformations included two dials set diametrically opposite each other on the column being tested. The values from which the elastic curves of longitudinal deformations and ratio of unit stress to unit deformation or coefficient of elasticity were plotted, are therefor the average of the readings on the two dials.

The type of instrument used for measuring lateral deformations allowed the use of but one dial and the curves for lateral deformations are therefor plotted from the readings on this single dial.

With the high percentages of spiral reinforcing used in the column specimens tested in this series, it has been found that but little importance may be attached to the values of ultimate strength, since great irregularities occur, which may be due to any one of a number of things, such as poor capping and resulting eccentricity of bearings in the testing machine, local weakness of concrete at tops or bottoms of specimens, insufficient anchorage of spiral wire at ends, tamping, curing, age, et cetera.

By plotting curves of the elastic deformations, however, all of the characteristics due to richness of mix, percentage of spiral reinforcement, percentage of longitudinal reinforcement, repeated loadings, age, et cetera, are clearly shown. The longitudinal and lateral deformations, the yield point and the modulus or coefficient of elasticity are thrown into visual prominence, and the relative importance of the different variables on the behavior of the columns more easily determined than would be the case were all values presented in tabular form. It has therefore been the intent of the writer to present all of the observed phenomena which it is possible to in the form of curves and give tabulated values only for such of the data as seems of particular value in such form.

For all, or nearly all of the column specimens tested to failure at the first progressive loading, the curve of lateral deformation is of a distinctive type. For the curves of longitudinal deformation it will be noticed particularly that once the ultimate strength of the plain concrete plus the elastic unit of the longitudinal reinforcing has been passed, as shown by a decisive increase in deformations, the curve quickly assumes the form of a straight line which is maintained up to extremely high values, corresponding to the elastic limit of the spiral reinforcing, then falls somewhat slowly until failure occurs. No better evidence of the function of spiral reinforcing in a concrete column could be given than is given in the characteristic form of these curves.

The values for lateral deformation are not as complete as might be desired, owing, as has been mentioned previously, to the lateness in obtaining the instrument for such readings, the time needed to adjust it once it was available, and for some of the specimens, on account of the Ames dial having too small a range. The limit of the Ames dial was, however, reached on only two specimens which were but 27 days old and had moreover been cured for 21 days in the moist air curing room, leaving only 6 days of dry air curing. For these two specimens the bulging effect, once it had started, progressed very rapidly, the hands of the dials making a complete revolution between readings, no slowing up whatever being observable during the interval of reading, for which the load was, of course, kept constant. The loading at which the bulging commenced is very apparent on the curves of lateral deformation for these two specimens. The effect of percentage of spiral reinforcement on lateral restraint is here clearly shown.

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The inclusion of curves plotted from values of the ratio of unit stress to unit (longitudinal) deformation is believed by the writer to be of outstanding importance in presenting the results of this series of tests. Certainly much thought may profitably be given to the characteristics shown in these curves. For the specimens tested to failure or to refusal at one progressive loading a distinctive type of curve results, which is independent of the different variables introduced.

For repetitive loadings, however, the curves of ratio of unit stress to unit deformation show a wide divergence not only between the individual loadings on a single column specimen, but between the several curves for each of the several column specimens subjected to repeated loadings. The effect of variable richness of mix is nevertheless distinctly apparent.

The writer has given particular attention in his tests to repetitive loading. Not only have the longitudinal deformations been recorded for these repetitive loadings, but also, in one series, the effect upon lateral deformations. Various ways of applying the repeated loadings have also been used, so as to obtain the effect of every possible condition. Recovery over a period of several hours, from the first or immediate set produced by each loading, was observed and is shown on the curves presented.

Two specimens of different richness of mix were subjected to repeated loadings of a uniformly advancing amount each day for four days. The unit stresses were approximately from 5000 pounds per square inch to 12,500 pounds per square inch.

Two specimens of different richness of mix were subjected to repeated loadings corresponding in amount to those on the two mentioned above but the successive loadings were applied immediately instead of 24 hours apart. These were both tested to destruction following the removal of the loading to 12,500 pounds per square inch.

One specimen was subjected to seven repeated loadings of an equal amount applied several hours apart, the maximum unit stress for each loading being approximately 5000 pounds per square inch. No spalling of the outer shell occurred on this specimen and it remains as perfect in appearance as an untested column.

One specimen of the same mix and reinforcing as that mentioned above was subjected to six repeated loadings applied several hours apart, and reaching each time a maximum stress of approximately 10,000 pounds per square inch and then tested to destruction. The ultimate strength for this specimen was very nearly the same as that of one of the specimens having the same mix and reinforcing which had been subjected to uniformly increasing values of repeated loadings applied immediately following the unloadings.

REPEATED LOADINGS

Of all the data from the tests of Considere and remarked upon in his published accounts of them, none is more interesting that those on the effect of repeated loadings.

Quoting from EXPERIMENTAL RESEARCHES ON REINFORCED CONCRETE, "The observation of the deformations during the unloading and reloading of the specimens, remaining always below the first load, has given results of great practical interest. The first thing shown, which could have been predicted, was a permanent shortening which increases if the same load is repeated, but more and more slowly, and tends rapidly towards a final limit. A reduction of the final deformations is thus obtained and with it an appreciable increase in the coefficient of elasticity for the succeeding unloadings and reloadings of the specimens. The second result, which is more important, could not have been foreseen. It is the form of the deformation curves and especially the direction of their curvature, which is convex to the pressure axis, while during the first application of load it curves in the inverse sense. It follows that <u>the coefficient of elasticity which is represented by the inclination of the tangent to the curve of deformation increases with the pressure in the unloading and reloading instead of decreasing with increasing pressure as under the first application of load.</u>

Evidently flexure is to be feared in a column under high pressures, and it is, therefore, unfortunate that the coefficient of elasticity, which is directly proportional to the column resistance, decreases with the increase of pressure. Such is the case under the first application of the load for hooped or otherwise reinforced concrete and also for structural iron and steel. On the other hand it must be considered especially fortunate that hooped concrete which has been subjected to a first load has a coefficient of elasticity which is the greater the higher the pressure becomes, provided it does not exceed the first load. This fact has to the author's knowledge never before been observed on other materials."*

*Experimental Researches on Reinforced Concrete, by Armand Considere, McGraw Publishing Company, New York, p. 143.

Further on he states, "It is natural, indeed, that a strong pressure should diminish the final deformability by bringing the particles nearer together, and that this effect should be greater the less the concrete has been tamped and the farther apart the particles were before."

Concluding his discussion of the experiments on repeated loadings and unloadings he states: "The application of a first pressure on a hooped prism, no matter how light the pressure may be, as long as it is below the breaking load, has the effect of raising its elastic limit up to that pressure. The coefficient of elasticity which is subsequently developed by the hooped concrete under all the variations of the pressures between the lowest and the previously applied load is higher than the highest coefficient of elasticity which the prism had before the test load and which held true for a low pressure only. The increase in the coefficient of elasticity of the concrete after the test load, as compared to the coefficient before, is so much the greater, the less the proportion of cement and the lower the quality of the concrete."*

*Experimental Researches on Reinforced Concrete, by Armand Considere, p. 147.

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If the longitudinal deformations for repeated loadings and unloadings as tabulated in Table XV1 of EXPERIMENTAL RESEARCHES ON REINFORCED CONCRETE* be plotted, the resulting curves will bring out very clearly and forcefully the above statements by Considere.

The description of similar curves in the conclusions of Talbot on the effect of repeated loading as observed in the two plain concrete columns which were subjected to repetitive loading in his tests is as follows:** "Whenever, after the repetition of a given load, the load is increased, the stress deformation curve at once rises until it joins the general direction of the stress deformation curve for a single application of the increased load.............If the points for the last repetition of each load be joined, a curve having the general form as the curve for single applications will be obtained, but with greater deformations."

Talbot also makes other interesting observations and conclusions on the effect of repeti-

*Experimental Researches on Reinforced Concrete, by Armand Considere, p. 145.

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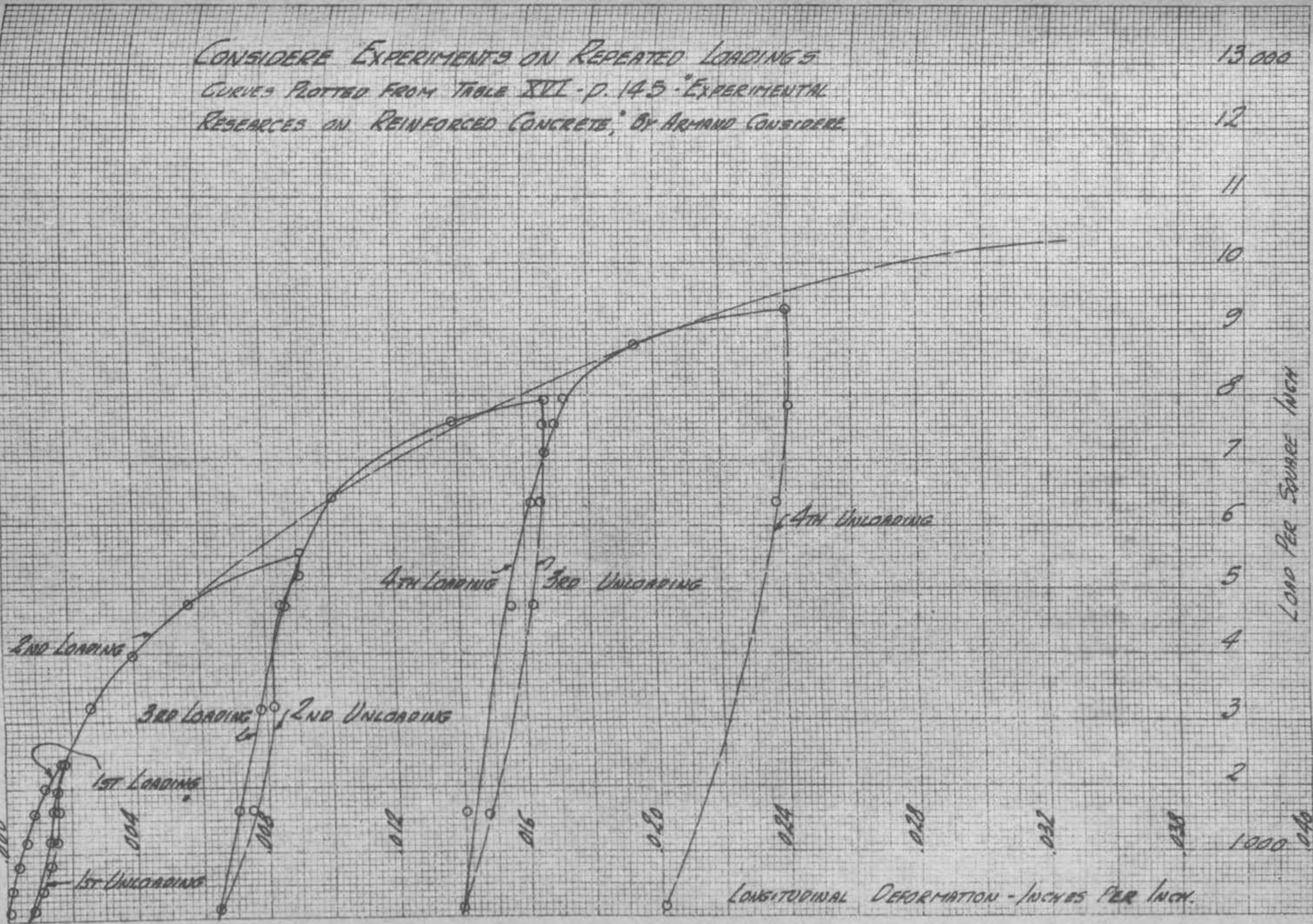

Considere Experiments on Repeated Loadings
Curves Plotted from Table XVI - p. 143 "Experimental Researces on Reinforced Concrete," By Armand Considere.
13 000
12
11
10
9
8
7
6
5
4
3
2
1000
Load Per Square Inch
.000
.004
.008
.012
.016
.020
.024
.028
.032
.036
.040
Longitudinal Deformation - Inches Per Inch.
2nd Loading
3rd Loading
2nd Unloading
1st Loading
1st Unloading
4th Loading
3rd Unloading
4th Unloading

tive loading, but in considering his statements it must be borne in mind that his data is from tests of plain concrete columns and not from hooped columns.

Quoting again from Talbot's observations:* "When a load is applied in any amount and released, the load then reapplied and this released, and this application and release repeated, the longitudinal deformation of the concrete generally increases, and there is also an increase in the set when the load is released. This statement is true even for low loads. For the smaller loads there is a limit to the increase in deformation due to repetition of the load. The total deformation and resulting set soon become constant or nearly constant. For the higher loads the deformation and set continue to increase during a larger and larger number of applications, and failure will occur under repetitive loading at a load below the maximum strength for a single application. The number of repetitions necessary to produce a limit to the increase, and the amount of the increase of deformations will of course vary with the quality and age of the concrete."

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It will be seen from what follows that the phenomena observed by Talbot for repeated loading on plain concrete columns hold true to a large extent of hooped concrete columns. It is, of course, clearly evident that under high stress the hooped concrete columns would show markedly different characteristics than plain concrete columns show for stresses approaching the ultimate strength of the plain concrete, for once the restraining action of the hooping becomes effective in a hooped specimen, the concrete would be more inclined to be benefited by repeated loading than otherwise up to very high stresses, since the more packing the particles of concrete within the spiral receive the greater the strength and toughness of the column becomes, so that whereas in a plain concrete column the effect of many repeated loadings would be to lessen the strength at which the column would fail and in fact finally produce failure, the same phenomenon could hardly be realized in a hooped column.

In the tests by Withey at the University of Wisconsin,* the effect of repetitive loading on hooped columns was studied in connection with the

*University of Wisconsin Bulletin No. 466.

effect of time yield. In this case not only the set after removal of each loading was observed, but also the recovery from the first or immediate set after a certain time had elapsed. In the statement of conclusions based upon the experiments made by him, Withey includes the following observations regarding repeated loading: "The amount of data presented on tests of columns subjected to repeated or time loading is far too small to warrant drawing definite conclusions as to the limiting stress for repeated loadings which will hold true for all kinds of columns and for an infinite number of repetitions, or for a prolonged loading. However, it does appear that there is practically no increase in set or deformation after a few repetitions of loads equal to 40 to 50 per cent of the yield points of the columns tested. The results of the repeated load tests also plainly indicate that there is considerable additional strength and toughness afforded by the spiral after the yield point of the longitudinal steel has been passed."*

*University of Wisconsin Bulletin No. 466.

The observation by Considere that, "The application of a first pressure on a hooped prism, no matter how light the pressure may be, as long as it is below the breaking load, has the effect of raising its elastic limit up to that pressure,"* is amply verified by the results of the present series of tests. However, his several statements, already quoted, to the effect that the coefficient of elasticity increases with the pressure under repeated loadings, as shown by a direction convex to the pressure axis of the deformation curves for such repeated loadings, do not agree so well with the results of the writer's tests. From the curves presented, it will be seen that a convexity of the curves of deformation to the pressure axis is shown for certain of the repeated loadings, but particularly those of the columns of a rich mixture. As shown by the writer's experiments, this increase in the values for coefficient of elasticity with increase of pressure occurs only within pressures of about six thousand pounds per square inch, or not exceeding to a very great extent the combined ultimate strength of the concrete and longitudinal reinforcing. In

*Experimental Researches on Reinforced Concrete, by Armand Considere, p. 147.

Considere's tests, however, the increase obtains up to considerably higher values, which would indicate that such results are dependent upon the quality of the concrete and percentage of reinforcement.

It is apparent from the erratic form assumed by the curves for values of coefficient of elasticity, particularly within the earlier stages of the initial loading, that such values are dependent upon many conditions incident to the making and curing of the concrete, and such effects are even noticeable for repeated loadings up to comparatively high pressures. Thus it will be observed for one of the columns of the leanest mixture employed, where a very slight convexity to the pressure axis of the curves for the last two of the repeated loadings is shown, whereas the curves for the columns of the intermediate mixture all show a decided tendency towards the opposite effect, except for very low pressures, where, as has been previously remarked, very erratic tendencies are revealed.

MODULUS, OR COEFFICIENT OF ELASTICITY

Much remains to be accomplished in regard to establishment of reliable and uniform values of modulus of elasticity in reinforced concrete members.

In the reports of the two or three principal tests on hooped concrete columns made in this country a total lack of agreement is shown also as to the actual meaning of the term modulus of elasticity. The tabulated values for modulus of elasticity as given in the bulletin describing the tests of Withey, are based upon stresses equal to one-fourth the ultimate, as are also the values of Poisson's ratio given.

Messrs. Wrentmore, Brodie and Carey, in reporting their tests, show curves of the values for the ratio of modulus of elasticity of steel to that of concrete for all values up to the limit of their observations of elastic deformations.

Professor Talbot has very different ideas as to values for modulus of elasticity. In discussing this subject he states: "Modulus of elasticity is a term which has been used very loosely in connection with reinforced concrete. As a general property of materials, it is defined to be the ratio of the unit stress to the unit deformation within the elastic limit of the material. As applied in this way to materials having the property of proportionality of stress and deformation, the modulus of elasticity is a constant. For materials with a variable stress deformation relation like concrete, the modulus of elasticity as sometimes used is still considered to be the ratio of unit stress to unit deformation, regardless of the amount of load carried relatively to the ultimate strength. As thus defined the modulus of elasticity of concrete will be a variable and the value will decrease rapidly toward the ultimate strength of the concrete. For ordinary concretes the stress deformation relation may be considered to approach closely to a parabola with its vertex at the ultimate load.........The rate of change of stress and deformation at the beginning of loading is shown by the tangent to the parabola at the initial load and the value of the modulus of elasticity indicated by this tangent is called the initial modulus of elasticity."*

Considere thruout his writings refers to the "coefficient of elasticity" as a function of the degree of loading, or stress. For materials having

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a variable stress deformation within working loads and stresses as have both plain and reinforced concrete, the term "coefficient of elasticity" would seem to the writer to be a better term than "modulus of elasticity".

Whether, as Talbot infers, the tangent to the curve of deformation at zero load can logically be considered a fair measure for use in the design of reinforced concrete members is, in the writer's opinion, open to grave doubt. In the case of hooped columns, as shown by the present series of tests, and as observed in other tests, the beginning of the deformation curve is a very unsatisfactory basis for reliable conclusions, owing to the erratic values obtained, and which are undoubtedly affected by a great number of circumstances peculiar to the proportions of cement and aggregate used, the wetness of mix, tamping, age, curing, reinforcement, et cetera. Regardless of this fact, however, and considering the characteristics peculiar to reinforced concrete columns, the tangent to the inclination of the curve of deformation at the working stress to be adopted in design must logically be the only one to be considered in a comparison of the elastic properties of columns as affected by other variables and for all

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ordinary purposes of design.

The general characteristics of the curves for modulus, or coefficient of elasticity as here presented are intensely interesting. It will be observed that for stresses below the combined ultimate strength of concrete and longitudinal reinforcement a wide variation may, and usually does, exist for specimens of identical mix, reinforcement, age and curing, and furthermore that the forms of the curves do not follow any law at all except that in a very broad and general sense they show a decrease in the values for coefficient of elasticity with increase of pressure. That concrete unreinforced is subject to the same erratic tendencies is shown by the curves for plain concrete columns D2, F2, and K2.

For the columns reinforced with spiral hooping, however, a decided regularity in the shape of the curves for coefficient of elasticity is apparent once the combined ultimate strength of concrete and longitudinal reinforcement has been exceeded. Moreover, the effect of richness of mix and percentage of spiral hooping is as distinctly evident as in the curves for longitudinal deformations. Values of the coefficient of elasticity for these higher pressures, as affected by varying richness of mix and percentage of spiral reinforcement are included within a comparatively small range.

It would seem from the data here given that little confidence may be placed in the values for modulus of elasticity ordinarily used for design purposes, since such values for pressures within working loads and stresses are subject to a tremendous variation due to conditions which are practically impossible of predetermination.

If on the other hand, values for ultimate strength should be used in the design of concrete columns having spiral hooping, very definite values for coefficient of elasticity might well be adopted.

LATERAL DEFORMATION - POISSON'S RATIO

While it cannot be said that the lateral deformation of hooped, or of plain concrete, is a matter for great concern as related to the design of reinforced concrete members, yet a study of such data certainly leads to a better understanding of the properties and characteristics of plain and reinforced concrete.

The phenomena observed in the University of Minnesota tests by the writer as well as those observed by Withey* are extremely interesting when analyzed in their relation to the longitudinal deformations they accompany or result from, and when further considered in their relation to the percentage of spiral reinforcement should shed still more light on the effectiveness of spiral hooping in increasing the allowable working stresses which may properly be adopted.

The lateral deformations accompanying repetitive loading as shown by the curves presented should also be of great interest.

Withey, among other things, in determining the yield point of the hooped concrete columns tested by him observed an increase in the ratio of applied loads

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to lateral deformation, practically coincident with the increase in ratio of applied load to longitudinal deformation. He further observed that, "As spiral and longitudinal reinforcements affect the lateral deformation of columns but little, the values of Poisson's ratio are nearly the same as those for the concrete composing the columns."*

Here it may be objected that Poisson's ratio cannot be considered as applying to the relation between the longitudinal and lateral deformations of a hooped concrete column since Poisson's ratio strictly defined, is the relation between perpendicular deformations of a homogeneous material. The term is, however, commonly applied to such relations in reinforced concrete members in flexure, and indeed, has been considered as applying also to hooped concrete by Withey and others.

Messrs. Wrentmore, Carey and Brodie make no distinction between Poisson's ratio and the ratio of longitudinal to lateral deformations of hooped columns, in their account of the University of Michigan tests. Their observations of these properties are particularly interesting. They state that, "The curves show less uniformity than those of 'S2' (longitudinal deformation - writer) and 'e' (ratio of

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moduli of elasticity - writer).............The single column of group 2, tested at short time, gives values which for the lower stresses appear to be too high, but for the other points lie fairly close together, the value 7 for long time and 8 for short time representing fair averages........In cases where this constant has been used in discussions, as noted by the writers, it has been assumed as equal to 4, the value derived by Grashof under certain assumptions made by Saint Venant. Estimates based on this would evidently be considerably in error. The value, 7 to 8, as here found is not surprising when compared with the value for steel, which is about 4."*.......**

Considere, in EXPERIMENTAL RESEARCHES ON REINFORCED CONCRETE makes the following statement: "The value 'm',..............., refers to hooped concrete and no conclusive experiments have been made for its determination. The only experiment which can be mentioned referred to unreinforced concrete and gave for 'm' the value of 0.4. It is

*Transactions, American Society of Civil Engineers, Vol. LXXV111.
**It will be noted that Messrs. Wrentmore, Brodie and Carey give values which are the reciprocals of Poisson's ratio as used by Considere.

evident that smaller values will be found for hooped concrete, and they will be the smaller the greater the percentage of metal, because the hoops resist the swelling, increase the density, and make the molecules approach each other, which is the cause of the increase in the coefficient of elasticity."*

The conclusions of Considere, it may be gleaned from the above, agree not at all with those of Withey, whose conclusion was that, ".......spiral and longitudinal reinforcements affect the lateral deformation of columns but little,..............."**

Which of these two observers is closer to the actual facts may easily be judged from the curves for the writer's series of tests, which show conclusively that spiral reinforcing does affect this relationship, if the values generally used for Poisson's ratio applying to plain concrete are even approximately correct.

* Experimental Researches on Reinforced Concrete, by Armand Considere, p. 127.
** University of Wisconsin Bulletin, No. 466.

EFFECT OF RICHNESS OF MIX

The effect of richness of mix, as shown by the elastic curves for longitudinal deformations, is to make somewhat less abrupt the change in curvature at the yield point of the columns and to give higher values for the coefficient of elasticity above this yield point. It is worthy of note, however, that the rate of change of longitudinal deformation above the yield point of the columns is but little affected by the richness of mix.

As shown by these tests richness of mixture is a variable of considerable importance, its effect being evident up to the highest stages of loading. This in itself seems remarkable, and to be a fact of outstanding importance, since it has been generally assumed that once the combined ultimate strength of concrete and longitudinal reinforcing is exceeded the cohesion of the concrete is dissipated and the concrete becomes a mere granular mass confined by the spiral hooping.

That the cohesion of the concrete is retained right up to the ultimate strength of the column specimens is indicated by the consistency of the relationship between the curves for the specimens of different mixtures both in the longitudinal deformation curves and the curves for ratio of unit stress to unit deformation.

Considering the very high percentage of spiral used in the column specimens of varying richness of mixture, it is indeed remarkable that the effect of richness of mixture should be so distinctly revealed by the values of the longitudinal deformations. If the cohesion of the concrete can be maintained up to such extremely high unit pressures by using a high percentage of spiral hooping, as is evidenced by the present series of tests, then certainly all restrictions limiting the amount of spiral hooping which might be calculated as increasing the allowable pressure to be sustained by columns so reinforced, could well be dispensed with, were it not that other limiting conditions make such a course untenable.

The excessive deformations obtained under high stresses are the principal criterion on values which may justifiably be used in design. Flexure is another factor of considerable importance, but flexure is a theoretical consideration quite generally understood and could be provided for.

Shrinkage stresses and "time yield", the effects of which can only be ascertained to any degree of certainty by exhaustive tests, are factors of such vital importance that overstepping the bounds of conservatism until the effects of these conditions are better understood is certainly not warranted.

Attention has already been directed to the repetitive loading curves for ratio of unit stress to unit deformation, which show very decidedly the effect of richness of mixture upon the coefficient of elasticity of concrete columns reinforced with spiral hooping.

Agreement between the elastic curves for high percentage of spiral and extreme richness of mix is of considerable interest, and curves showing this agreement have therefore been plotted for both longitudinal deformations and coefficient of elasticity.

EFFECT OF PERCENTAGE OF LONGITUDINAL REINFORCEMENT

The effect of percentage of longitudinal reinforcing is shown in somewhat the same way as the effect of richness of mix, modifying the slope of the curves at the yield point but showing little variation in the coefficient of elasticity either above or below the yield point of the columns. The steepness of the slope of the curves, above the elastic limit of the columns, is affected by the percentage of longitudinal reinforcement, which, as noted before is not the case for variation in richness of mix.

This latter phenomenon would lead us to believe that percentage of longitudinal reinforcement has its effect upon the behavior of the columns after their yield point has been passed, due undoubtedly to the assistance it gives the spiral reinforcing in restraining lateral deformations. However, it should also be pointed out, as is revealed by the curves of longitudinal deformations, that not only percentage of longitudinal reinforcement, but the number and size of longitudinal rods are factors, and that an excessive percentage of such reinforcement might have a tendency to lessen the effect of spiral reinforcing.

EFFECT OF PERCENTAGE OF SPIRAL HOOPING.

In nearly all tests upon concrete columns reinforced with spiral hooping it has been brought out that the percentage of such reinforcing has but little effect upon the yield point of the columns, or upon the behavior of such columns below the yeild point. Indeed, the conclusions of most experiementers and students of test data have been that the use of more than a nominal percentage of spiral reinforcement is of little value, and have recommended that not more than from one to one and one-half percent of such reinforcing be used.

The results of the writers tests support these conclusions to a large extent, since as will be observed on the elastic curves for longitudinal deformations a comparatively slight difference in the yield point is evident in a range of almost eleven per cent, or more than seven times the maximum percentage of spiral hooping ordinarily used in building construction.

It is to be observed, however, that high percentages such as were employed in the writer's tests do have a very noticeable effect upon the rate of

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change of longitudinal deformation beginning at the point where the ultimate strength of the concrete and longitudinal reinforcing have been reached, and that the higher the percentage of spiral hooping the less abrupt the change in curvature at the yield point. Comparing the elastic curves of longitudinal deformations with those for the tests of Withey, Talbot, and others, who have not exceeded one and one-half or two per cent of spiral reinforcing, the very great difference in the steepness of the curves above the yield point will be observed. Indeed, such a comparison would seem to the writer to justify the use of values of working stress very slightly below the combined ultimate strength of the concrete and longitudinal reinforcing, if other conditions, such as those of flexure, shrinkage and the effect of time yield can be provided for.

Comment has already been made on the agreement between the effect of high percentage of spiral and richness of mixture, upon the values for longitudinal deformations and coefficient of elasticity. The writer desires to emphasize this point and direct attention to the possibilities of combining rich mixtures of concrete with high percentages of spiral hooping. A study of the effects of "time yield" and shrinkage stresses with this particular object in view would be of great value and considerable interest.

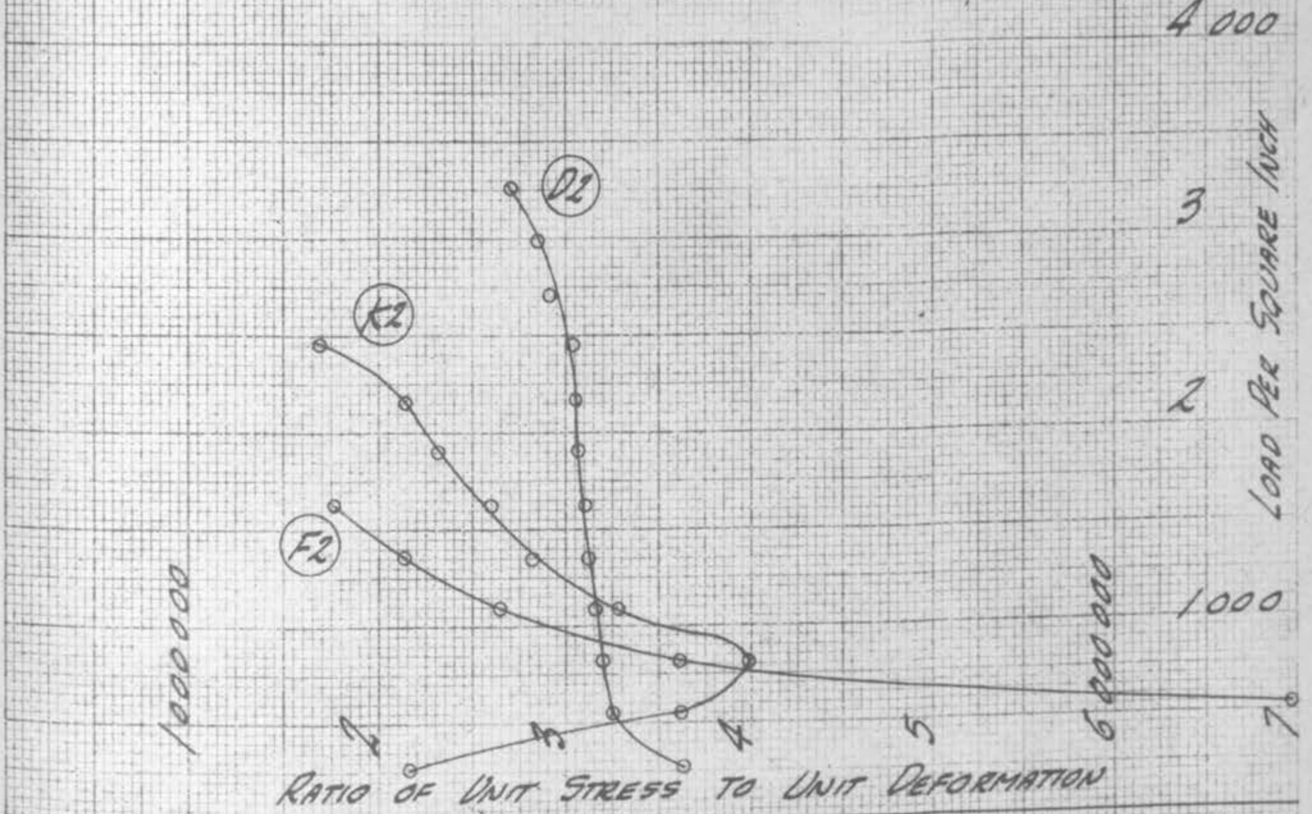
It will be observed that the curves for ratio of unit stress to unit deformation show a wider divergence in the variable percentages of spiral than in variable richness of mixtures.

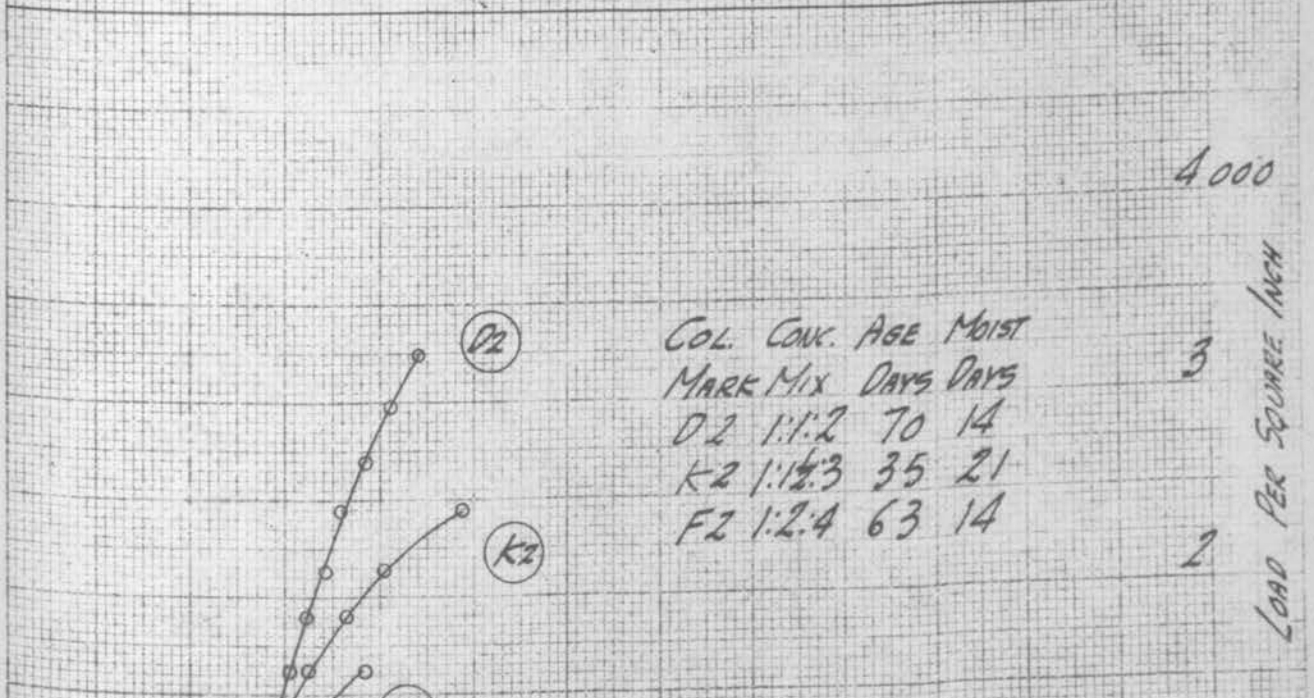
The elastic curves for lateral deformations are of interest chiefly in their consistency to the curves for longitudinal deformations. The sharp break in the curves for the two extremes of spiral percentage are due, in the writer's opinion, to a breaking down in the concrete from insufficient curing. The effect of percentage of spiral is all the more apparent for these two curves, however, because of the sharp break being so identical in form but so widely apart in value.

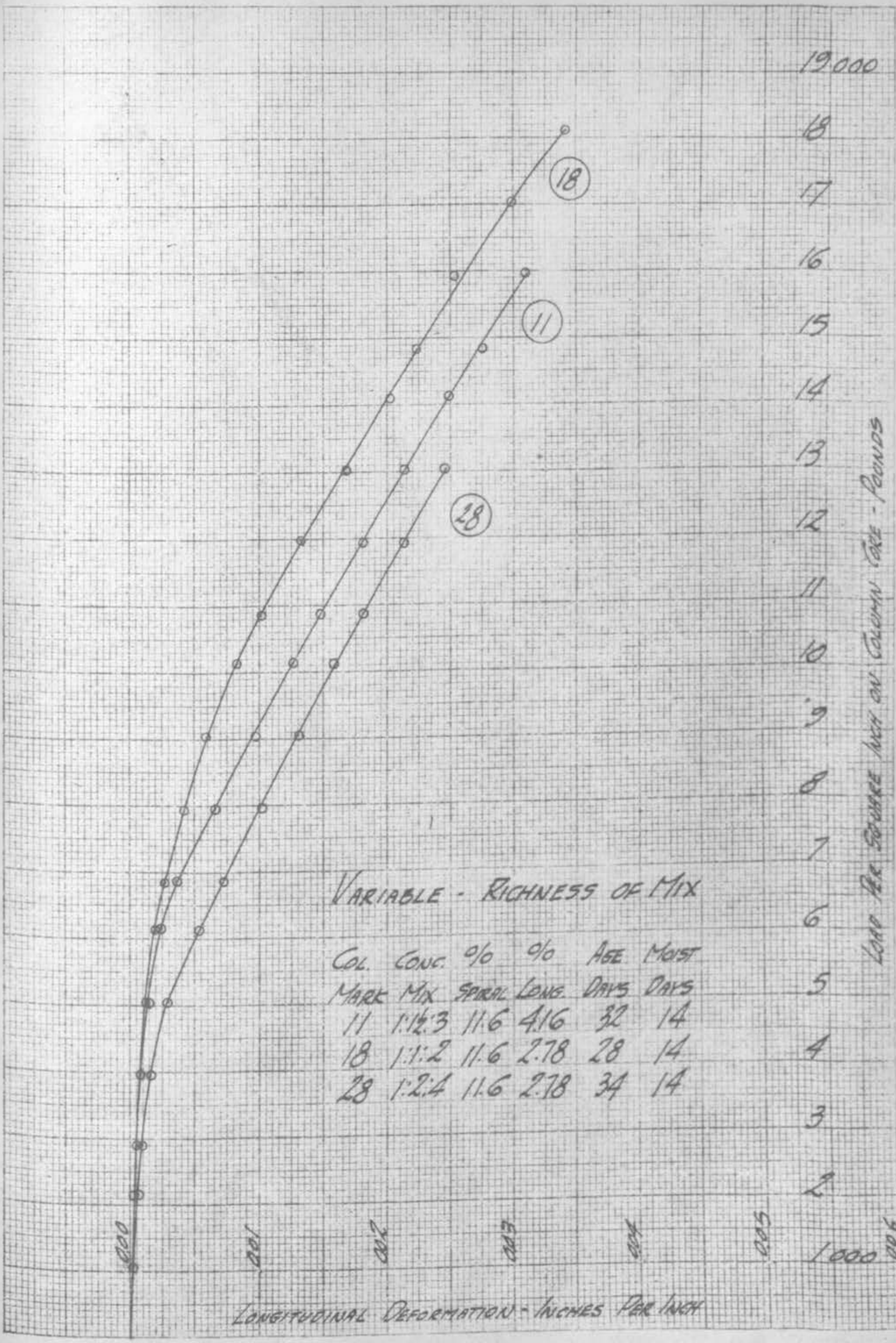
It is to be regretted that the relationship between varying percentages of spiral reinforcing on repetitive loading was not obtained in these tests. However, it has been shown that the effect of repetitive loadings, within the limit of the ultimate strength of columns reinforced with spiral hooping, is to raise the yeild point of column up to the maximum of the previously applied loading, from which premises we may advance the argument that higher values of working stress than those hereto- fore deemed justifiable or advisable, are warranted by reason of the agreement between the conditions of repetitive loading and those obtaining in structures in actual use.

However, until the effects of "time yield", which have a still closer relationship to actual construction conditions than those due to repetitive loading, are better understood, it would seem the part of wisdom to deviate but little from the values of working stress in general use at the present time.

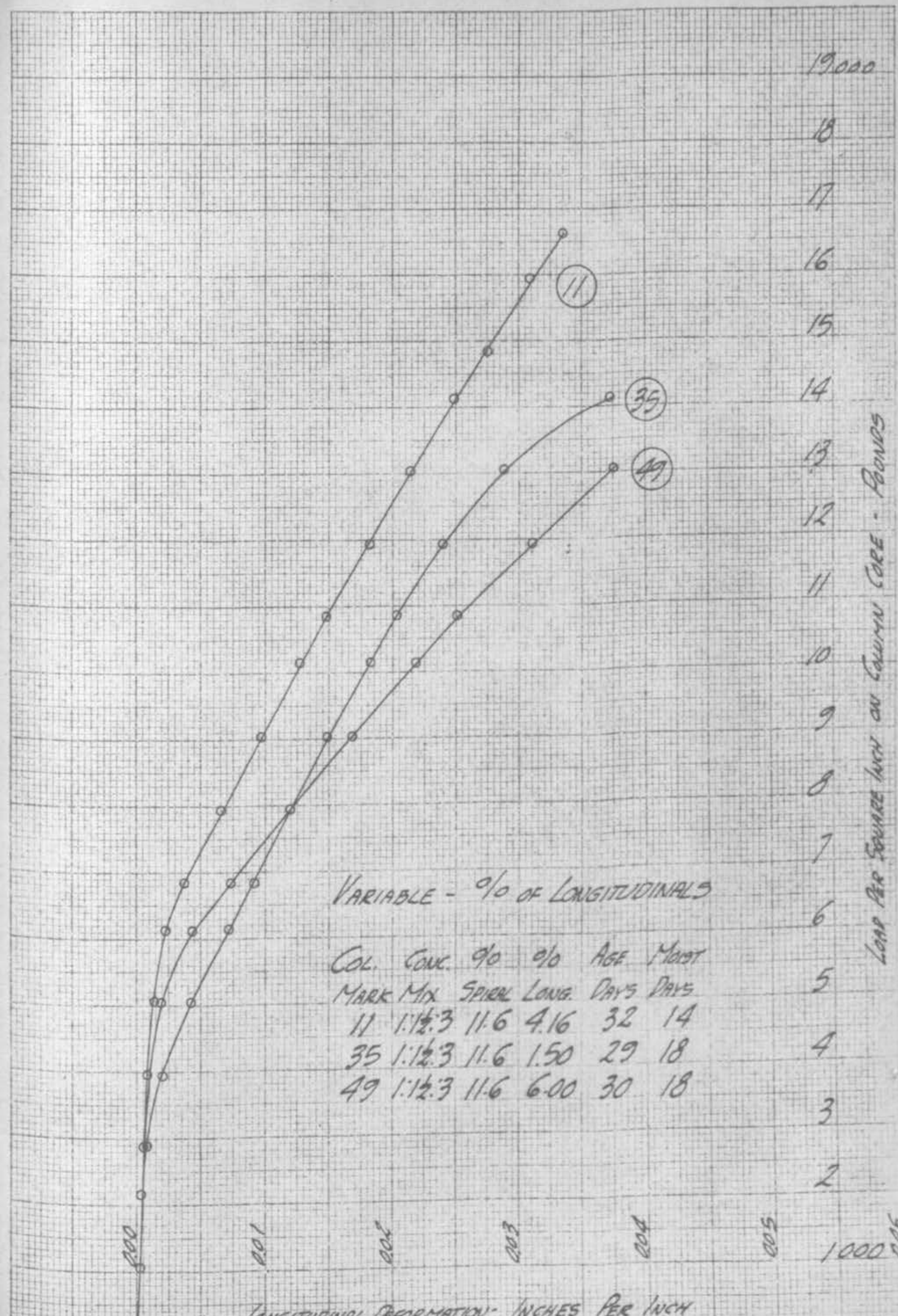
PLAIN CONCRETE COLUMNS.



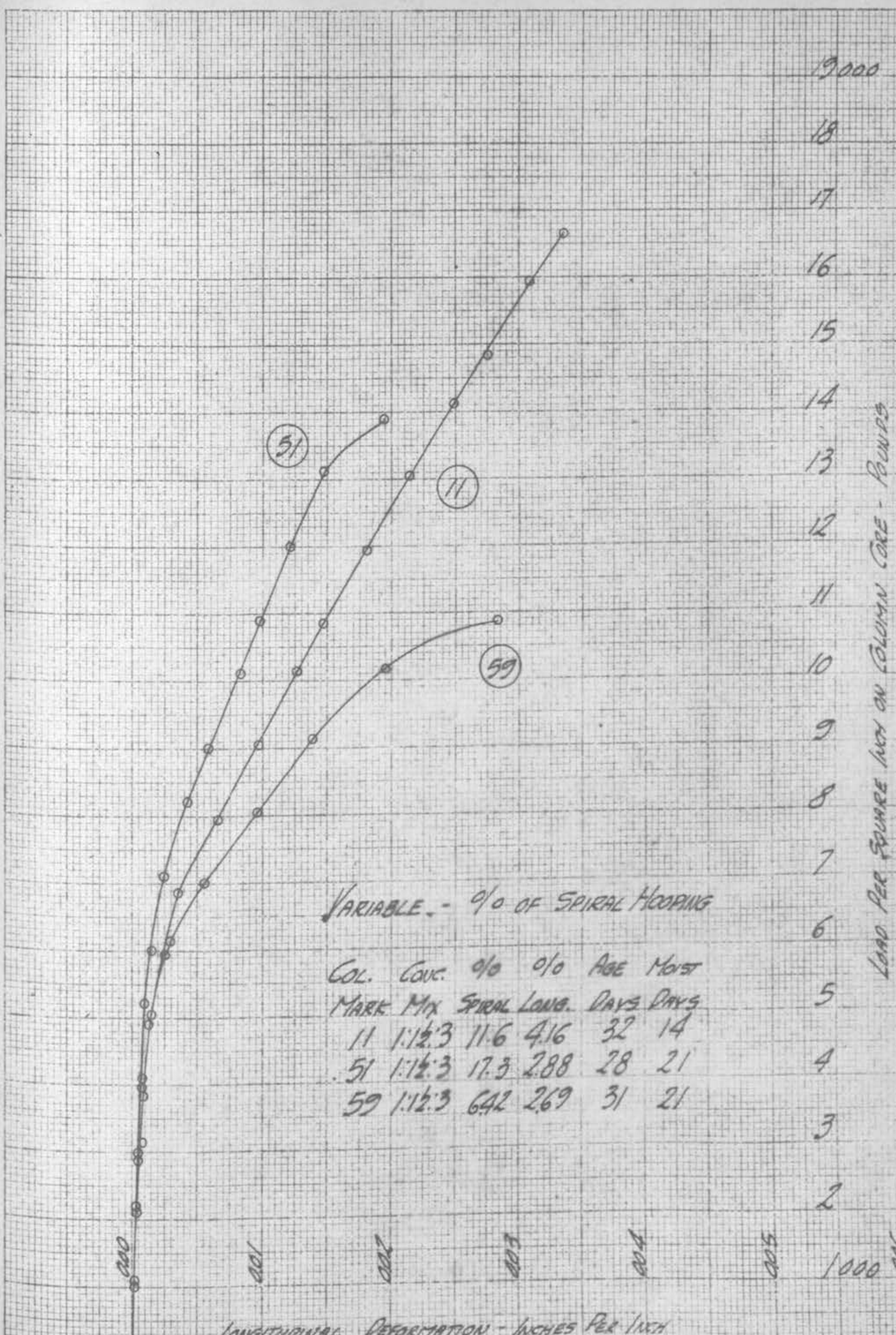


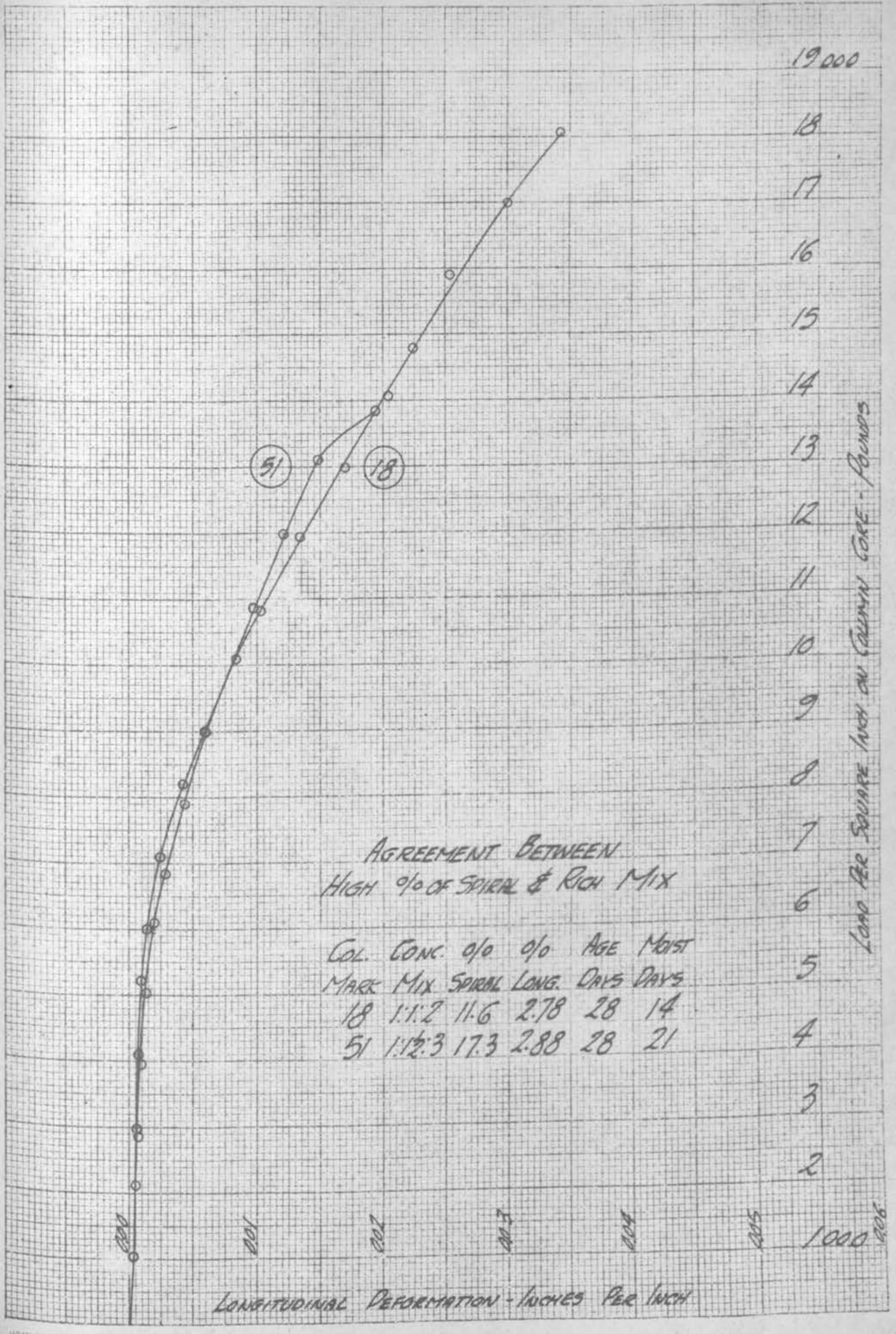


VARIABLE - RICHNESS OF MIX
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
11 | 1:1½:3 | 11.6 | 4.16 | 32 | 14
18 | 1:1:2 | 11.6 | 2.78 | 28 | 14
28 | 1:2:4 | 11.6 | 2.78 | 34 | 14
18
11
28
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
.000
.001
.002
.003
.004
.005
.006
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
LONGITUDINAL DEFORMATION - INCHES PER INCH

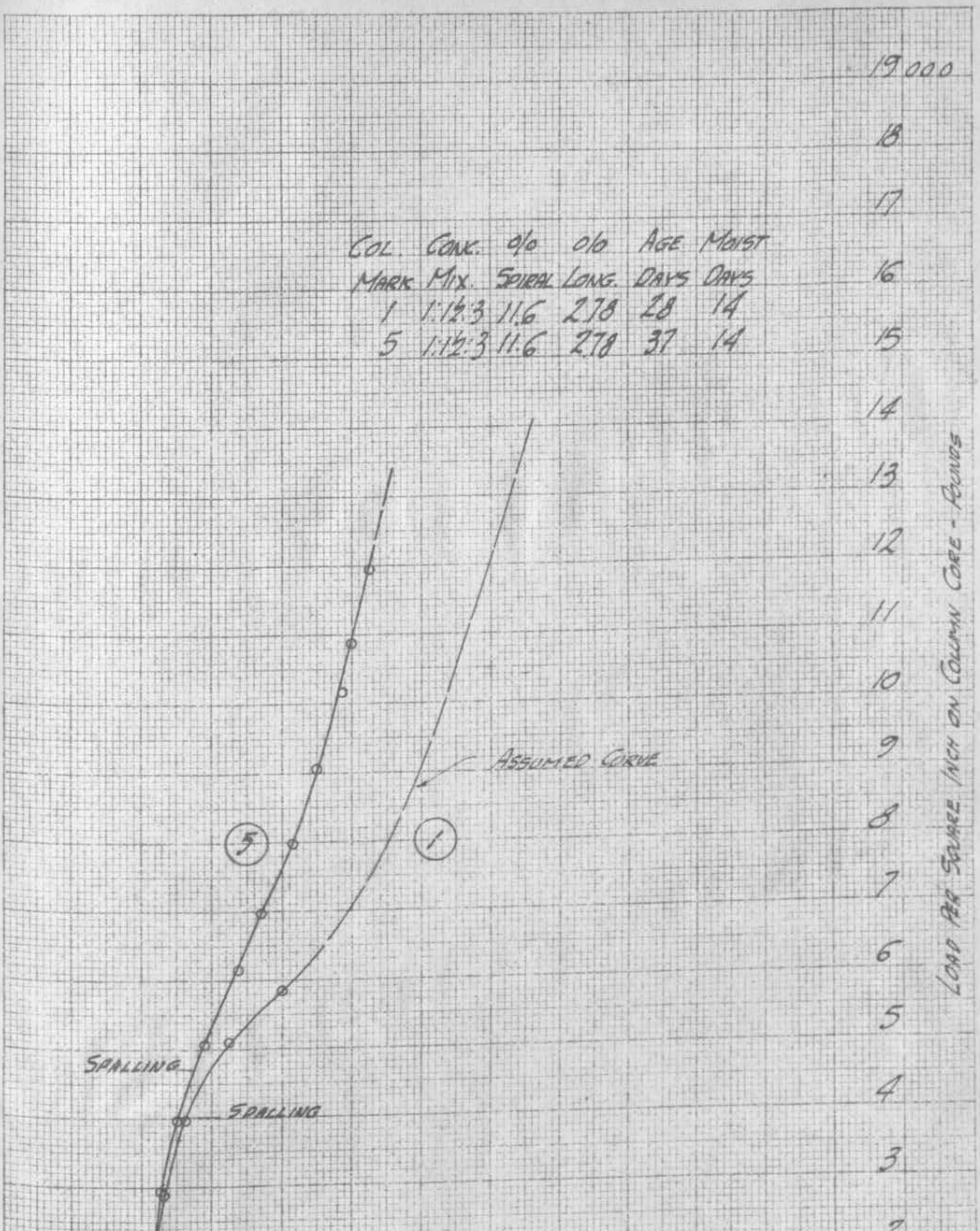


VARIABLE - % OF LONGITUDINALS
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
11 1:1½:3 11.6 4.16 32 14
35 1:1½:3 11.6 1.50 29 18
49 1:1½:3 11.6 6.00 30 18
11
35
49
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
.000
.001
.002
.003
.004
.005
.006
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
LONGITUDINAL DEFORMATION - INCHES PER INCH

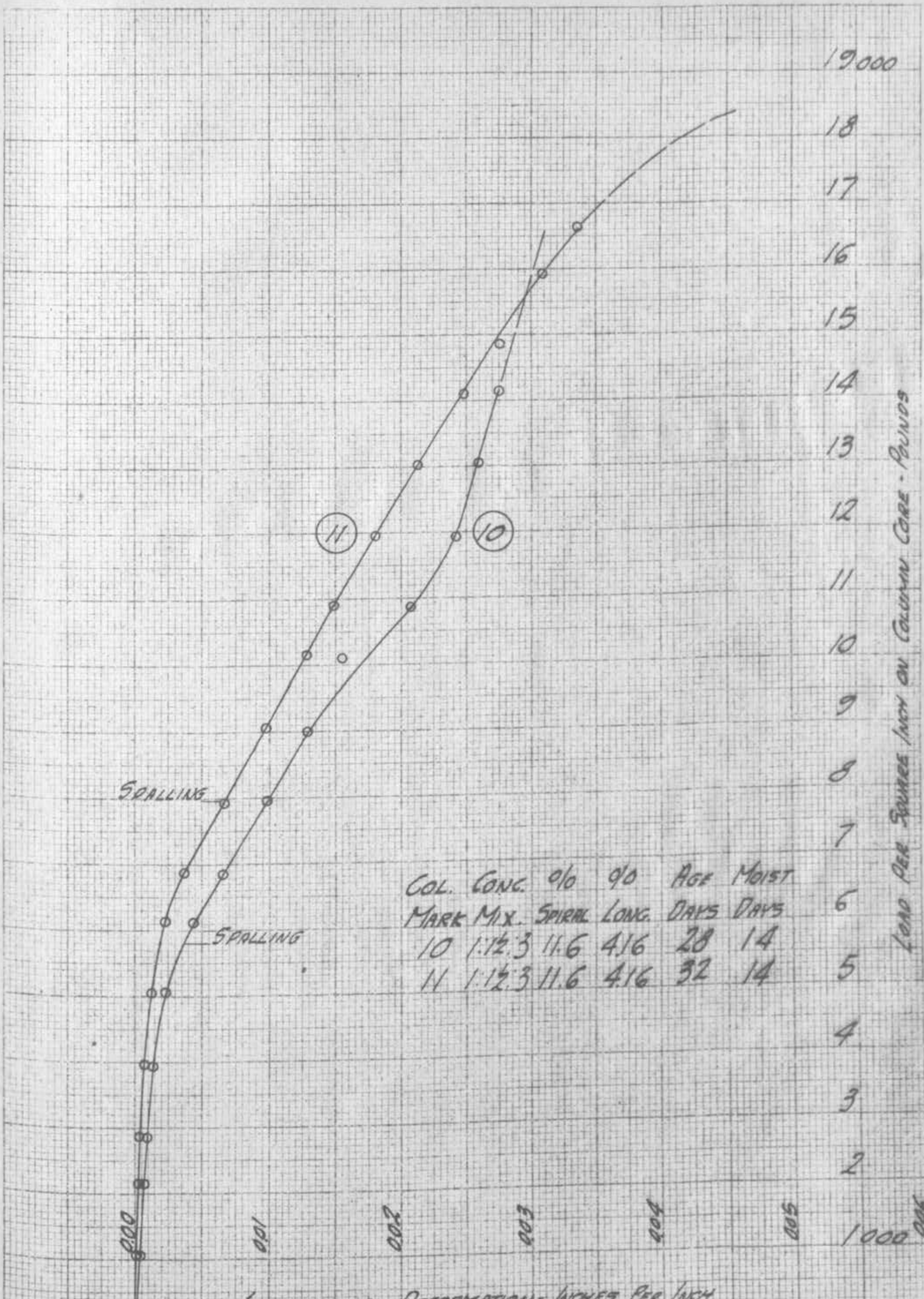

51
11
59
VARIABLE.- % OF SPIRAL HOOPING
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
11 1:1½:3 11.6 4.16 32 14
51 1:1½:3 17.3 2.88 28 21
59 1:1½:3 6.42 2.69 31 21
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
.000
.001
.002
.003
.004
.005
.006
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS

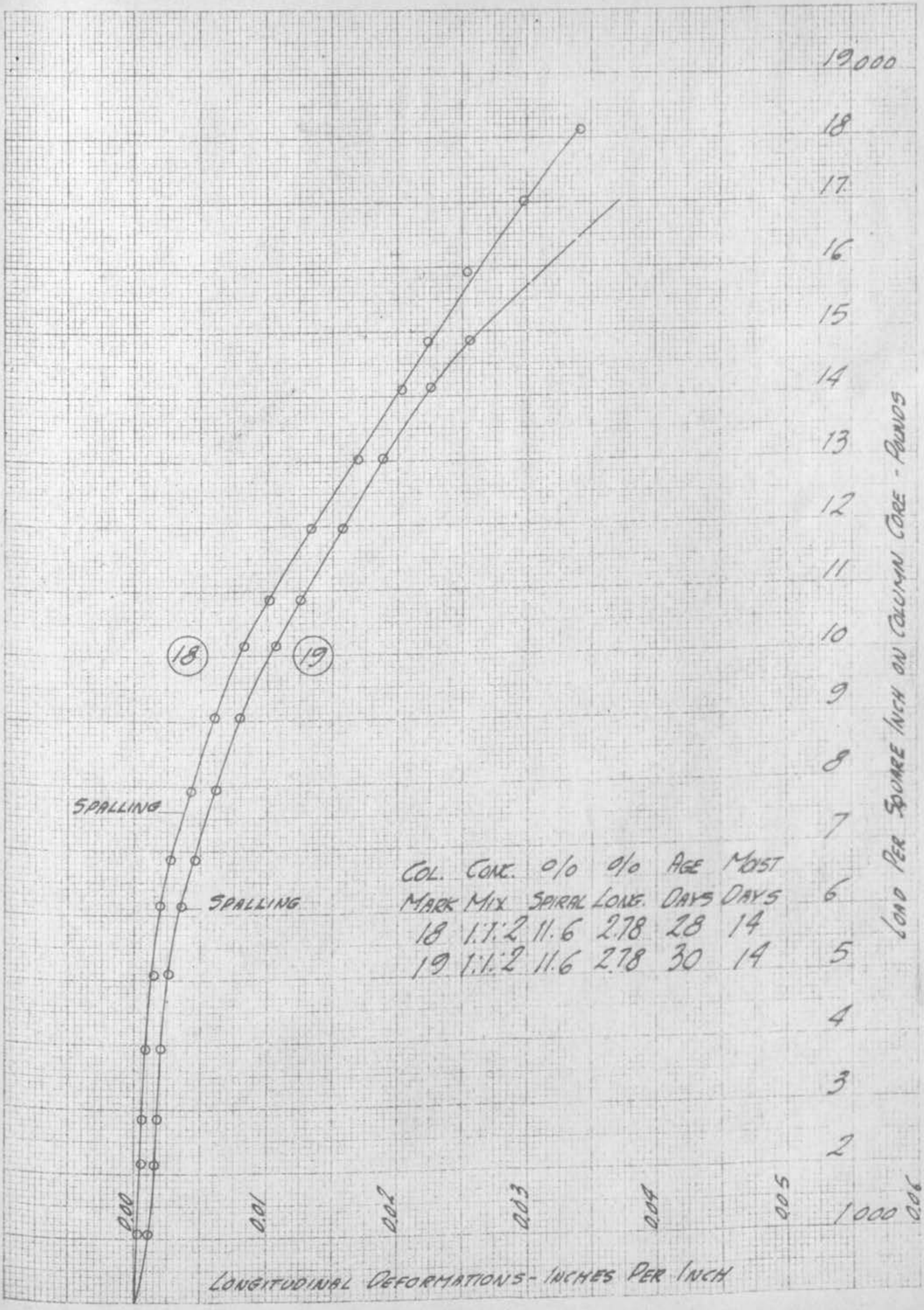


AGREEMENT BETWEEN
HIGH % OF SPIRAL & RICH MIX
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
18 | 1:1:2 | 11.6 | 2.78 | 28 | 14
51 | 1:1½:3 | 17.3 | 2.88 | 28 | 21
51
18
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
.000
.001
.002
.003
.004
.005
.006
LONGITUDINAL DEFORMATION - INCHES PER INCH

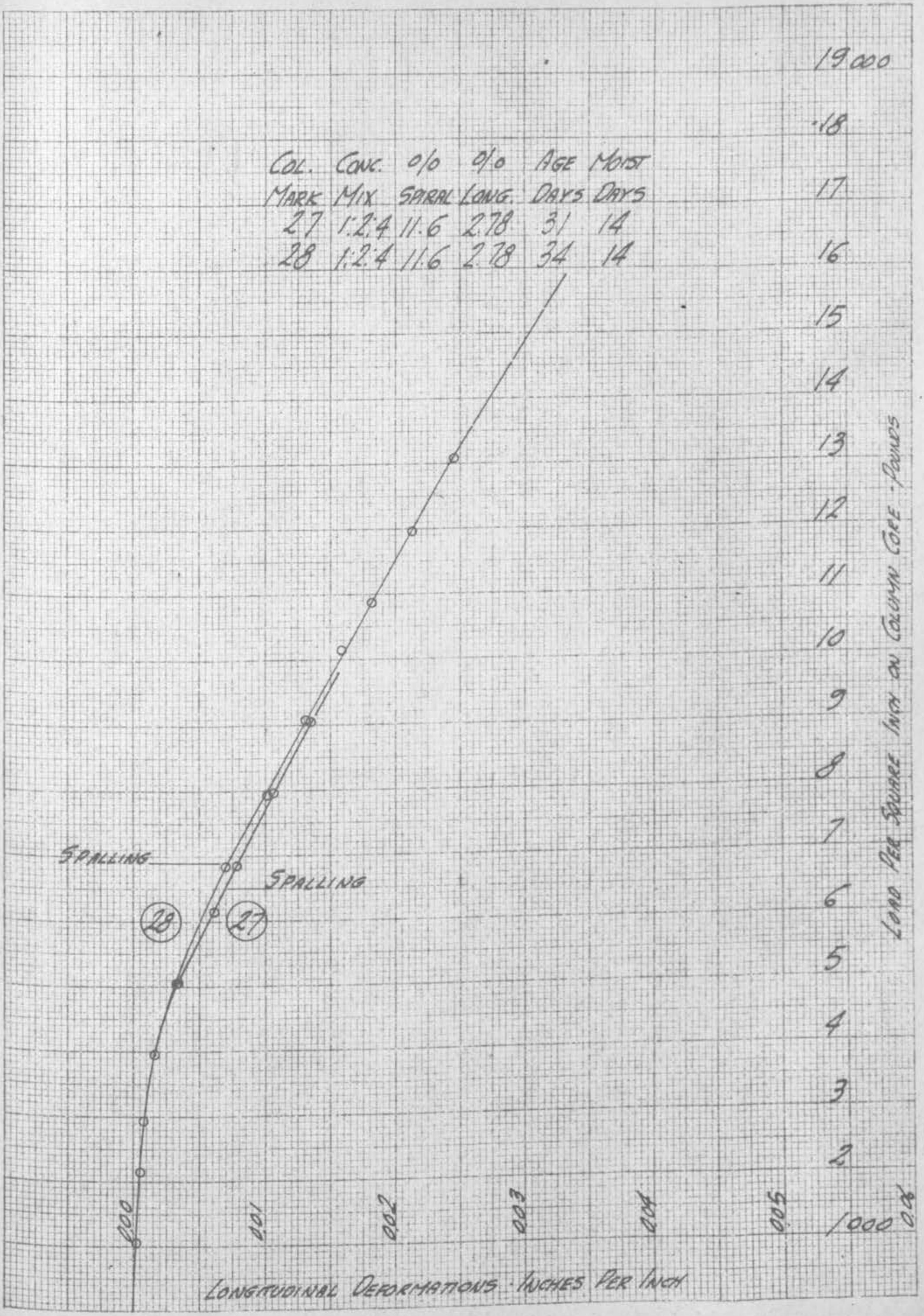


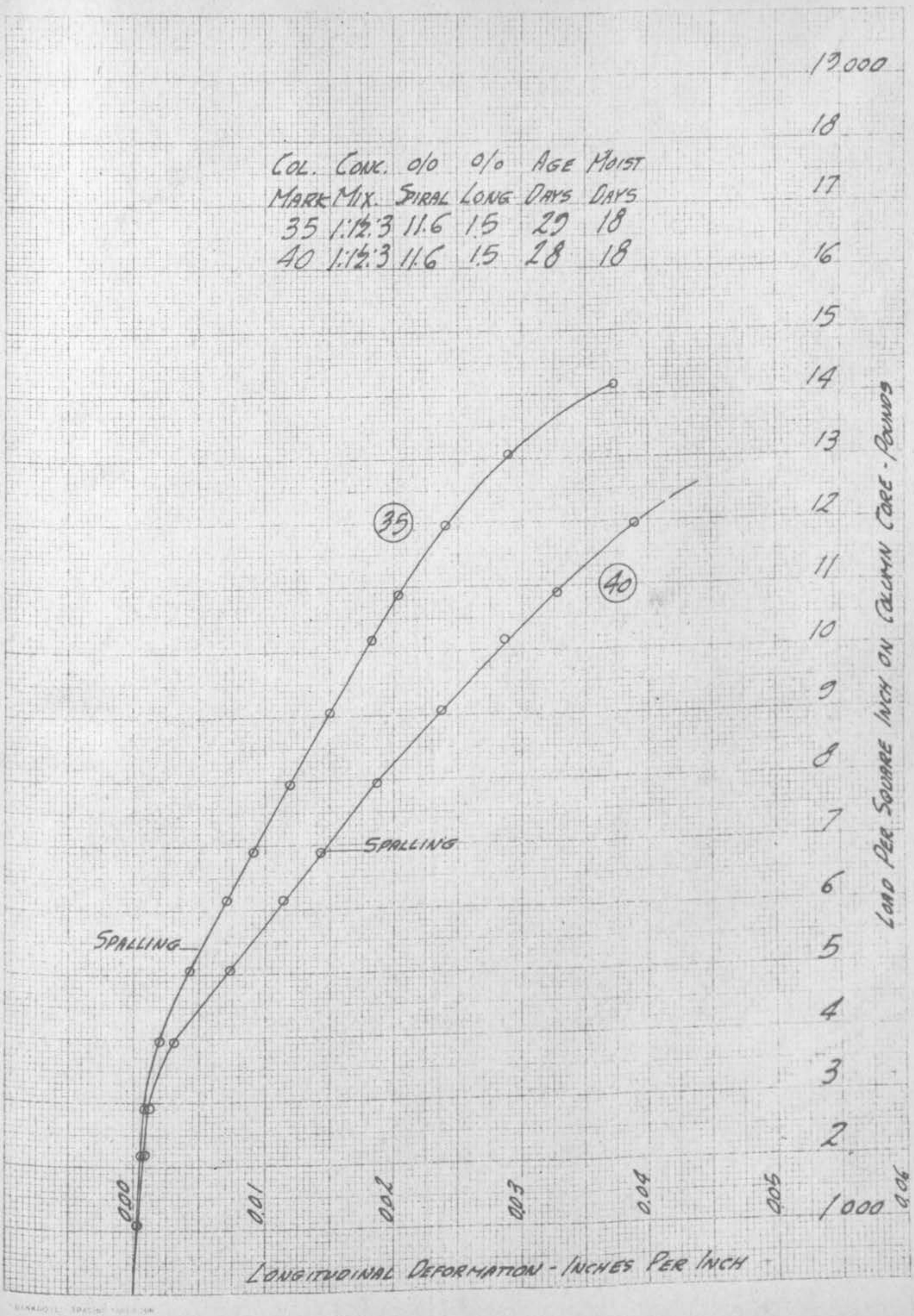
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
1 | 1:1½:3 | 11.6 | 2.78 | 28 | 14
5 | 1:1½:3 | 11.6 | 2.78 | 37 | 14
ASSUMED CURVE
5
1
SPALLING
SPALLING
0.00
0.01
0.02
0.03
0.04
0.05
0.06
1000
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19000
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS


19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
11
10
SPALLING
SPALLING
COL. MARK
CONC. MIX.
% SPIRAL
% LONG.
AGE DAYS
MOIST DAYS
10 1:1½:3 11.6 4.16 28 14
11 1:1½:3 11.6 4.16 32 14
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATION - INCHES PER INCH

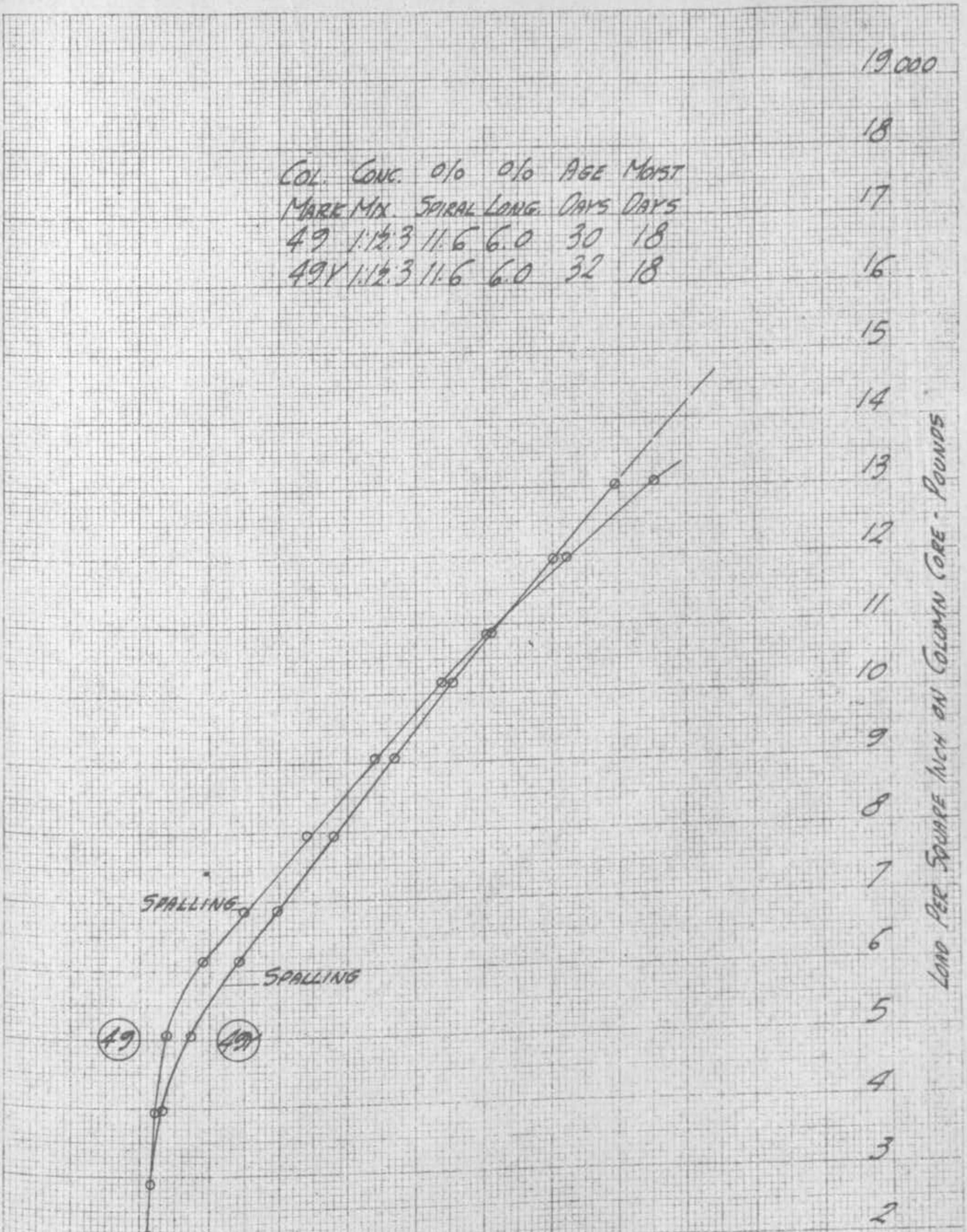


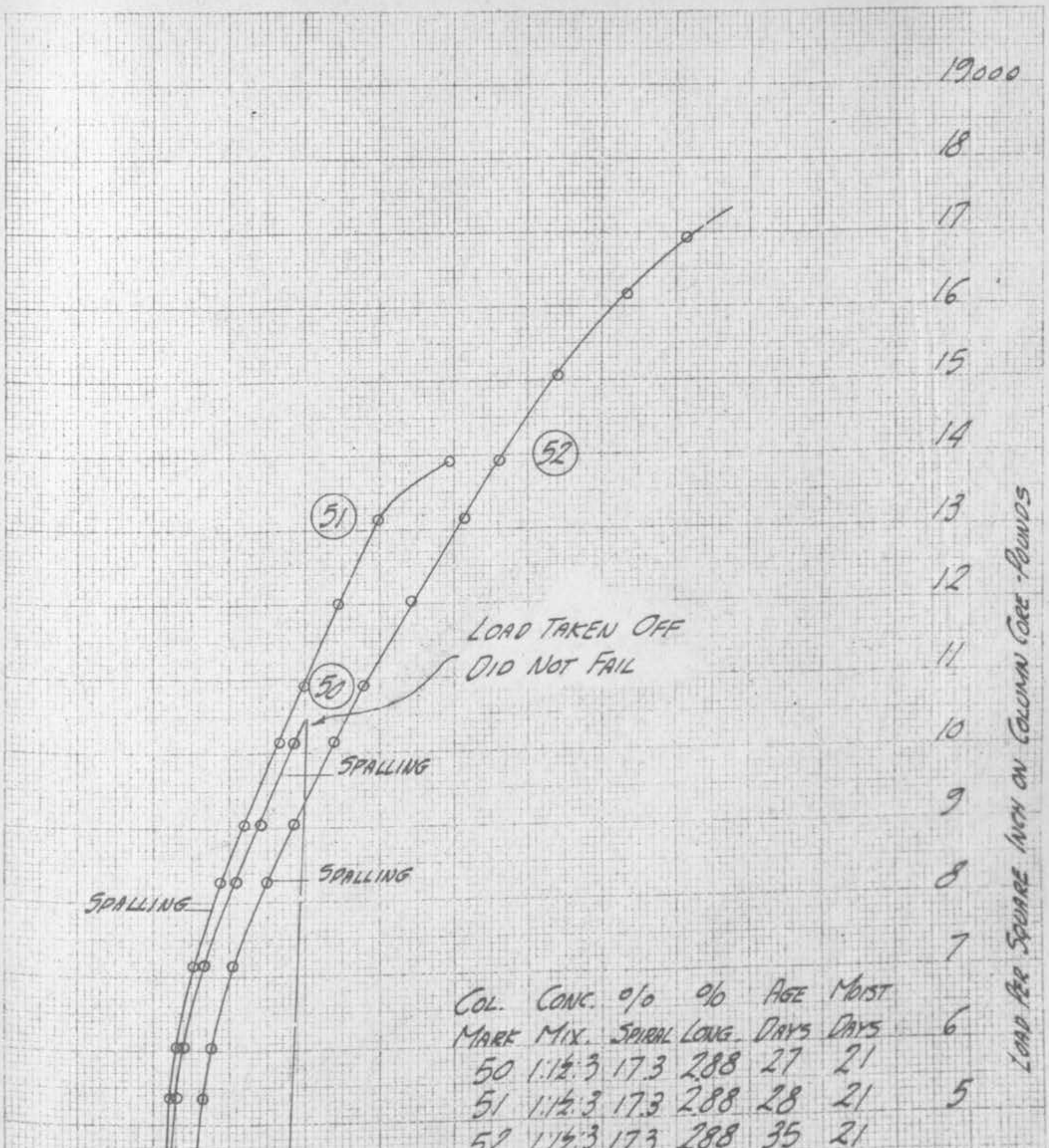
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATIONS - INCHES PER INCH
18
19
SPALLING
SPALLING
COL. MARK
CONC. MIX
0/0 SPIRAL
0/0 LONG.
AGE DAYS
MOIST DAYS
18 1:1:2 11.6 2.78 28 14
19 1:1:2 11.6 2.78 30 14


COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
27 | 1:2:4 | 11.6 | 2.78 | 31 | 14
28 | 1:2:4 | 11.6 | 2.78 | 34 | 14
SPALLING
SPALLING
28
27
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
0.0
.000
.001
.002
.003
.004
.005
.006
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
LONGITUDINAL DEFORMATIONS - INCHES PER INCH

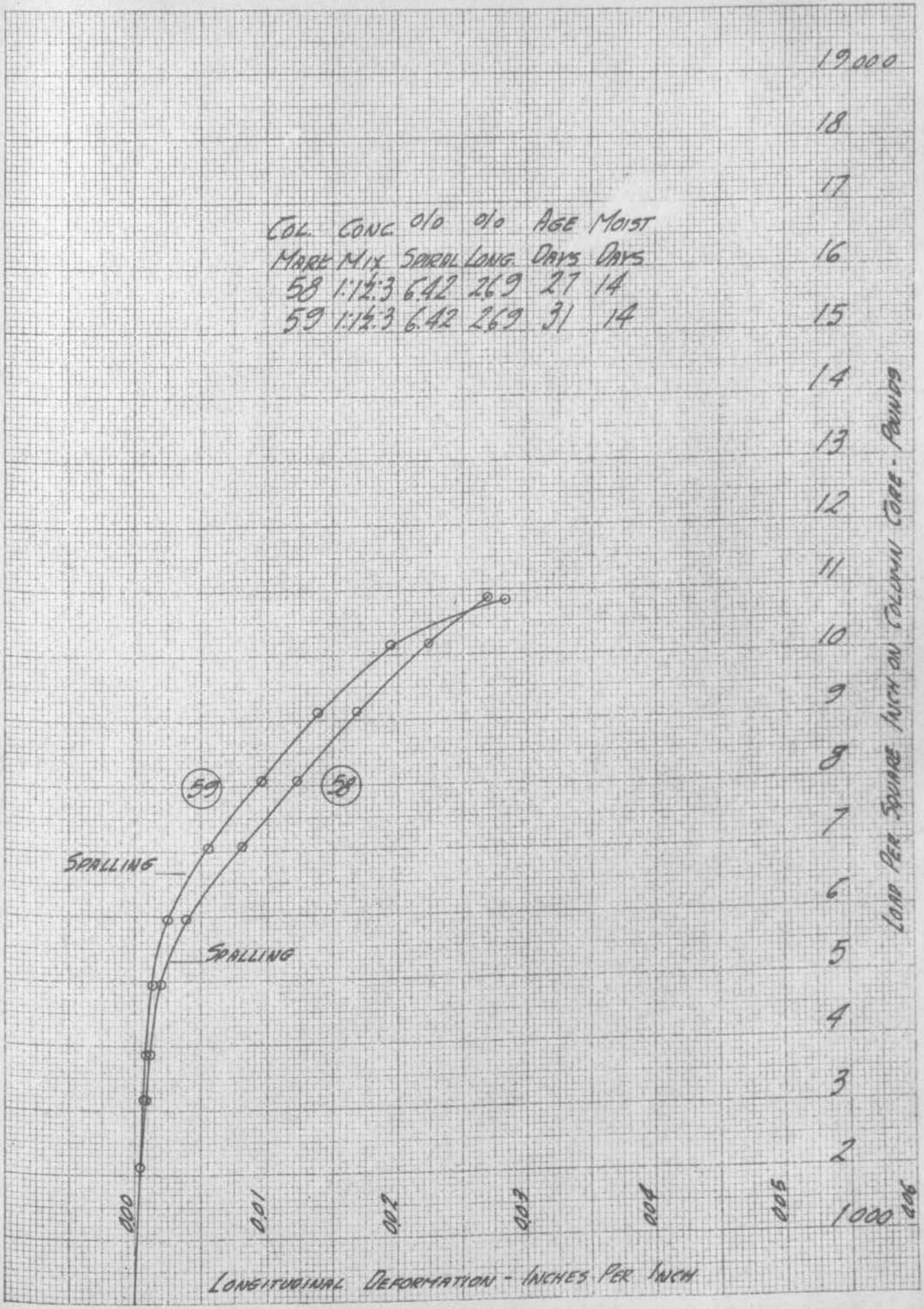


Col. Mark | Conc. Mix. | % Spiral | % Long | Age Days | Moist Days
35 | 1:1½:3 | 11.6 | 1.5 | 29 | 18
40 | 1:1½:3 | 11.6 | 1.5 | 28 | 18
35
40
Spalling
Spalling
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Load Per Square Inch on Column Core - Pounds
Longitudinal Deformation - Inches Per Inch

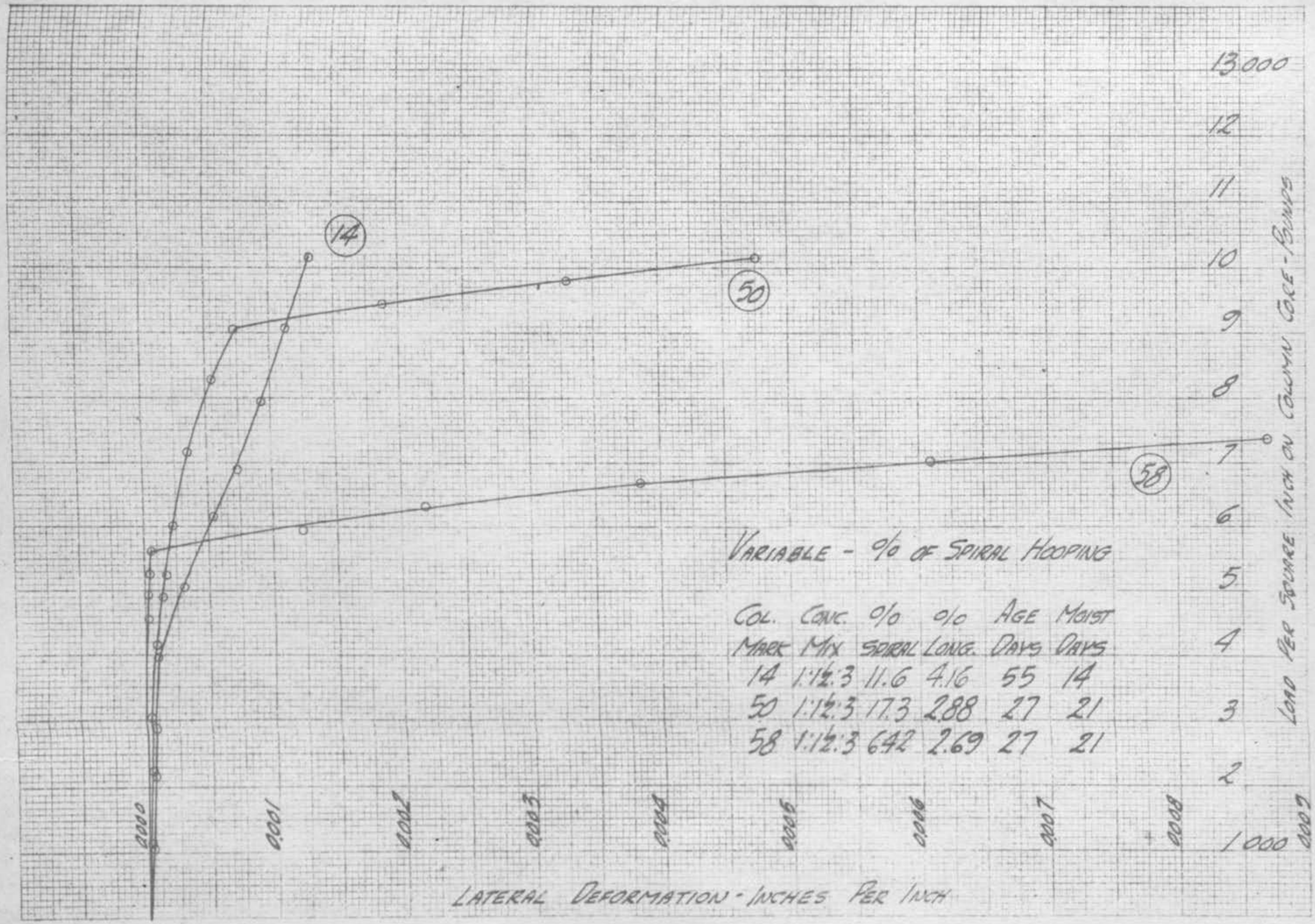

COL. MARK | CONC. MIX. | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
49 | 1:1½:3 | 11.6 | 6.0 | 30 | 18
49Y | 1:1½:3 | 11.6 | 6.0 | 32 | 18
SPALLING
SPALLING
49
49Y
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATIONS - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



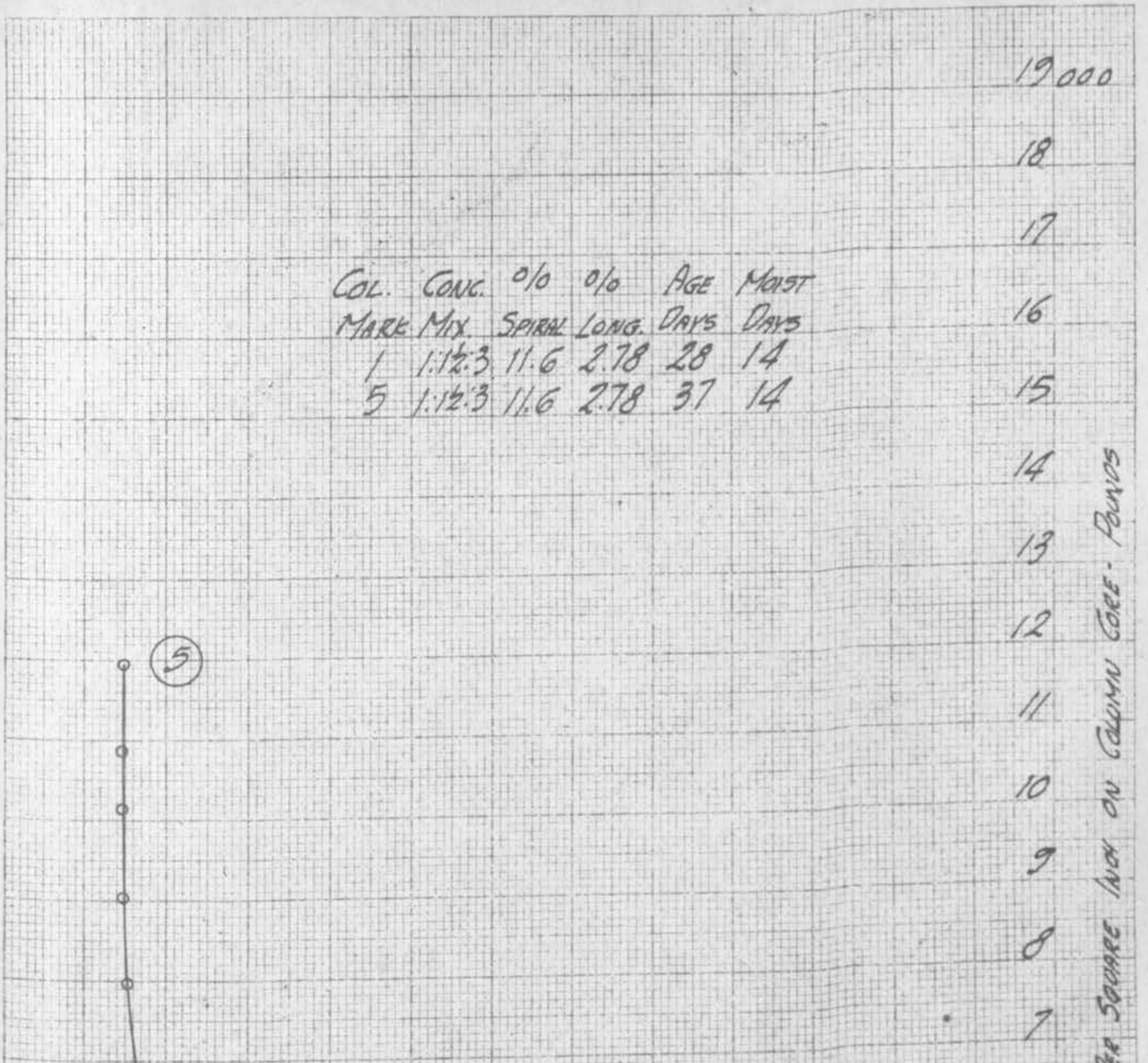
51
52
50
LOAD TAKEN OFF
DID NOT FAIL
SPALLING
SPALLING
SPALLING
COL. MARK | CONC. MIX. | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
50 1:1½:3 17.3 2.88 27 21
51 1:1½:3 17.3 2.88 28 21
52 1:1½:3 17.3 2.88 35 21
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



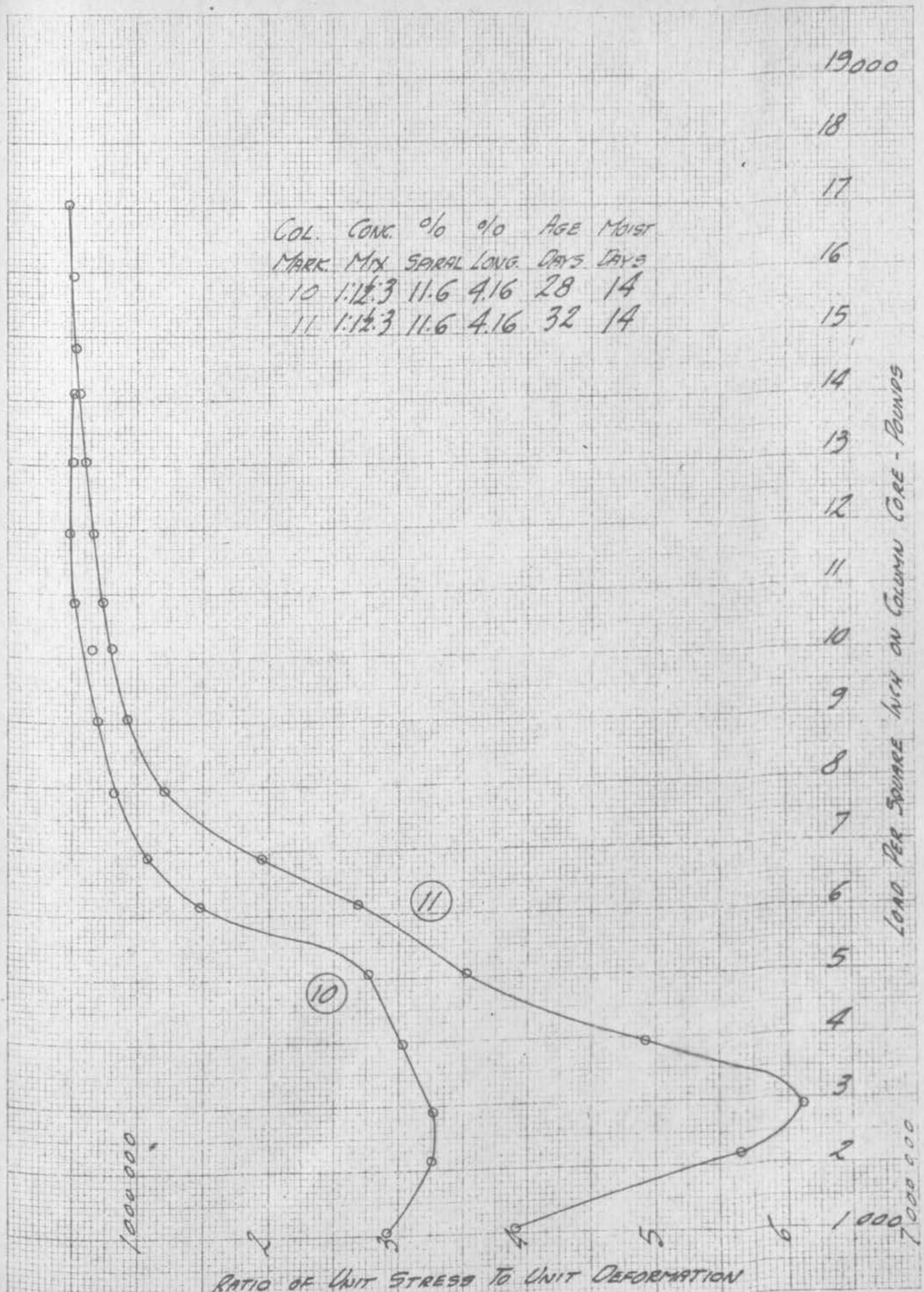
COL. MARK
CONC. MIX
0/0 SPIRAL
0/0 LONG.
AGE DAYS
MOIST DAYS
58 1:1½:3 6.42 2.69 27 14
59 1:1½:3 6.42 2.69 31 14
59
58
SPALLING
SPALLING
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



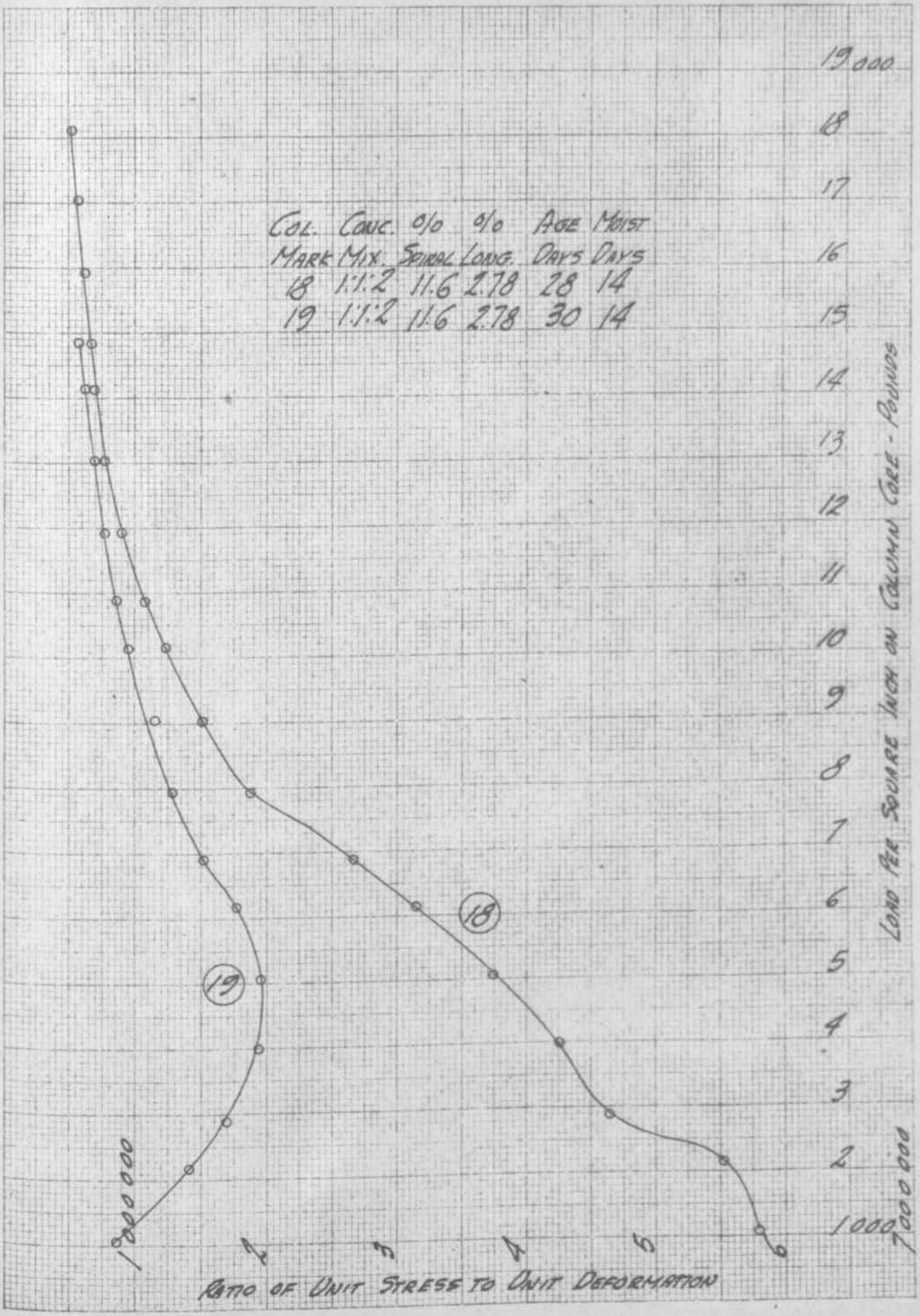
13,000
12
11
10
9
8
7
6
5
4
3
2
1,000
14
50
58
VARIABLE - % OF SPIRAL HOOPING
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
14 1:1½:3 11.6 4.16 55 14
50 1:1½:3 17.3 2.88 27 21
58 1:1½:3 6.42 2.69 27 21
LATERAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



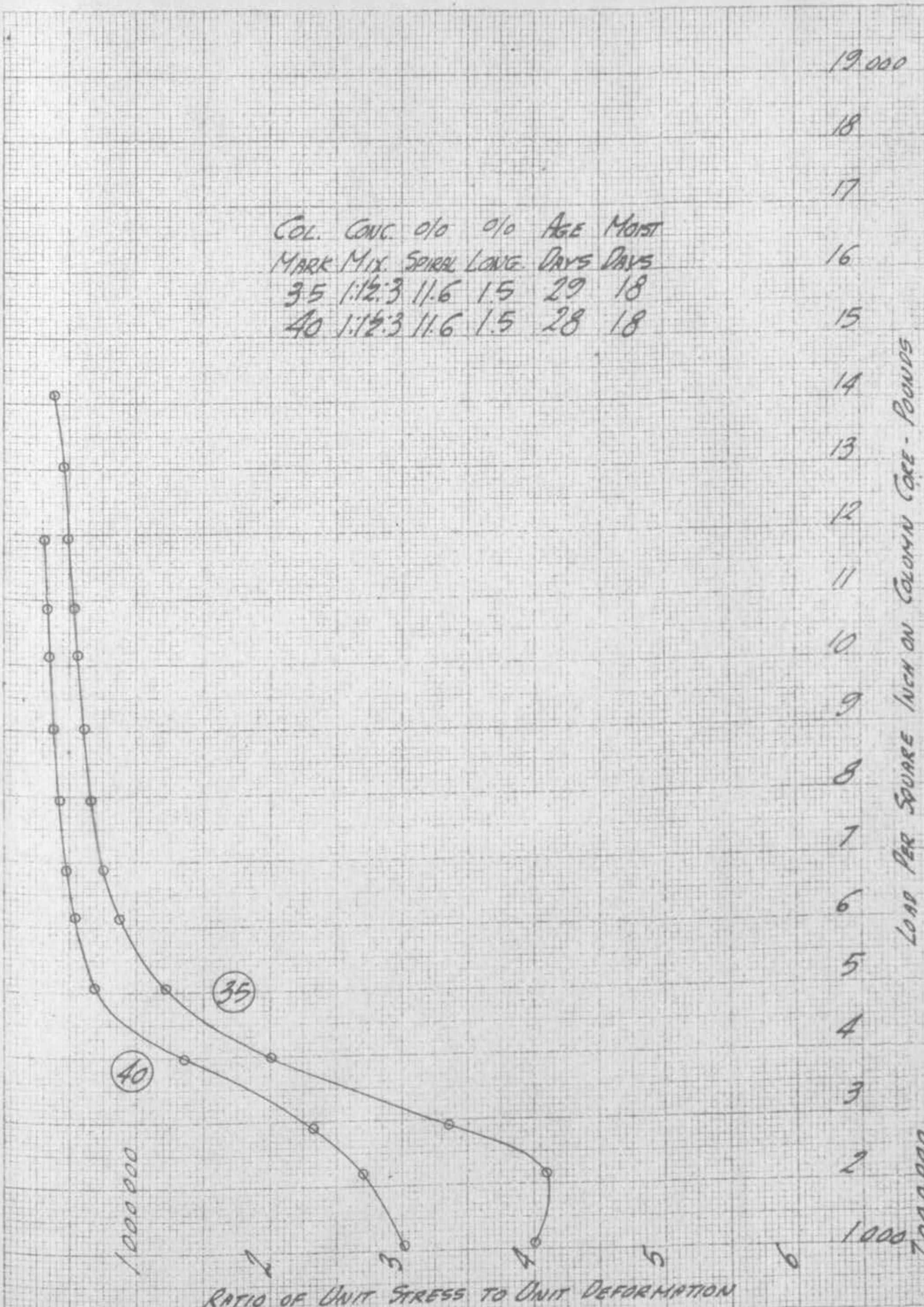
Col. Mark | Conc. Mix | % Spiral | % Long. | Age Days | Moist Days
1 | 1:1½:3 | 11.6 | 2.78 | 28 | 14
5 | 1:1½:3 | 11.6 | 2.78 | 37 | 14
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
Load per Square Inch on Column Core - Pounds
5
1
1000000
2
3
4
5
6
7000000
Ratio of Unit Stress to Unit Deformation



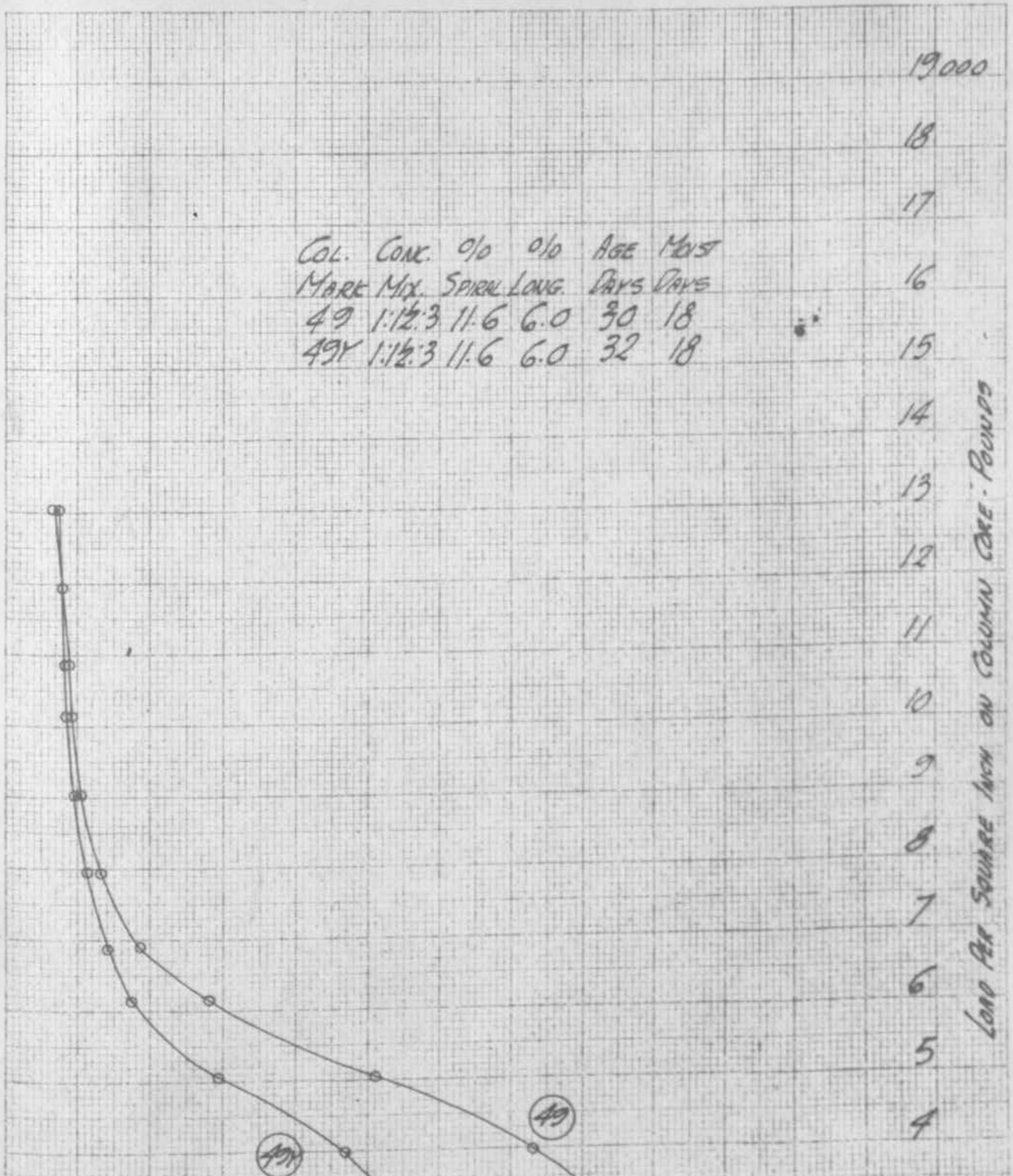
COL. MARK. CONC. MIX % SPIRAL % LONG. AGE DAYS MOIST DAYS
10 1:1½:3 11.6 4.16 28 14
11 1:1½:3 11.6 4.16 32 14
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION
10
11



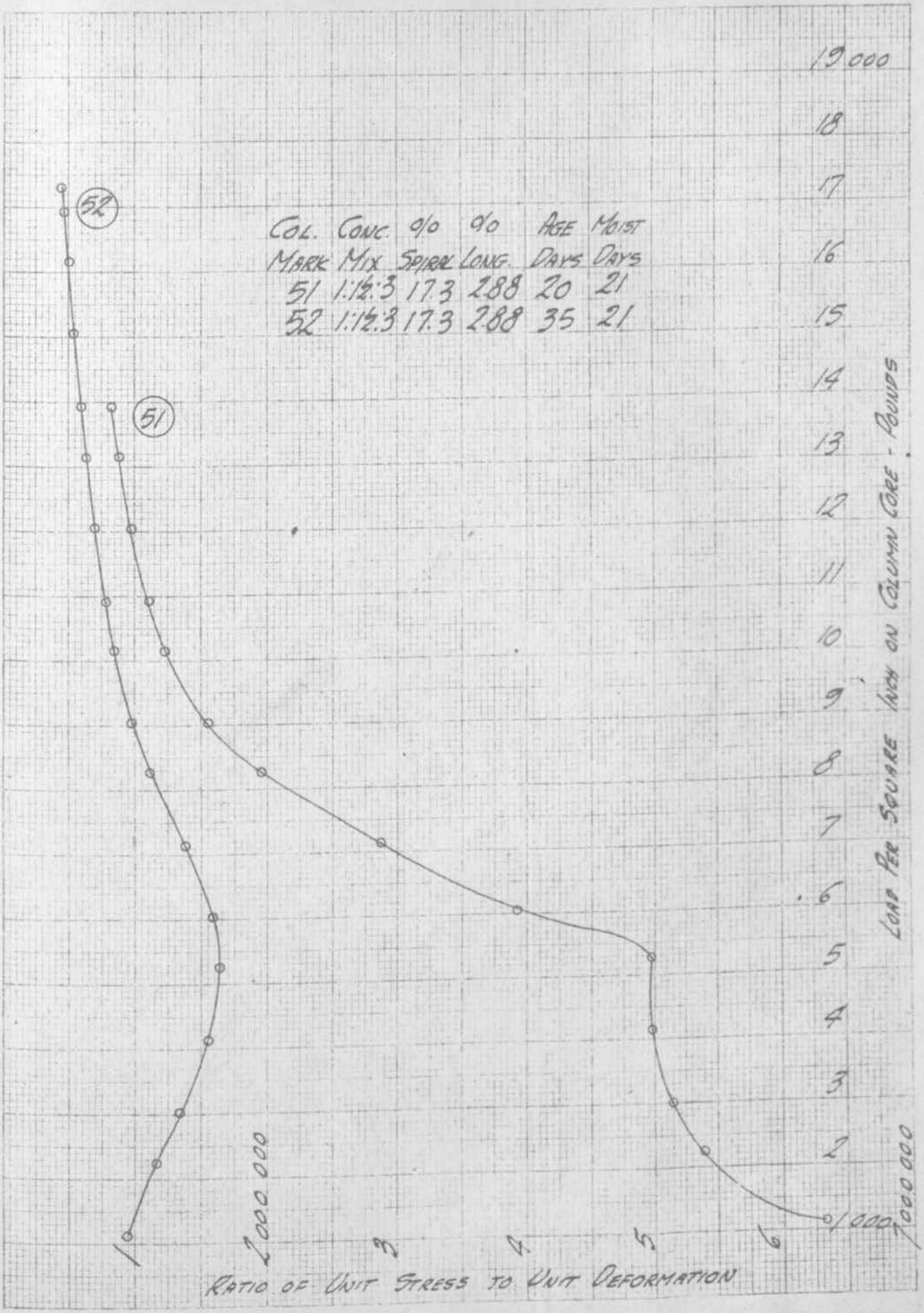
Col. Mark | Conc. Mix. | % Spiral | % Long. | Age Days | Moist Days
18 | 1:1:2 | 11.6 | 2.78 | 28 | 14
19 | 1:1:2 | 11.6 | 2.78 | 30 | 14
18
19
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
Load per Square Inch on Column Core - Pounds
1000000
2
3
4
5
6
7000000
Ratio of Unit Stress to Unit Deformation



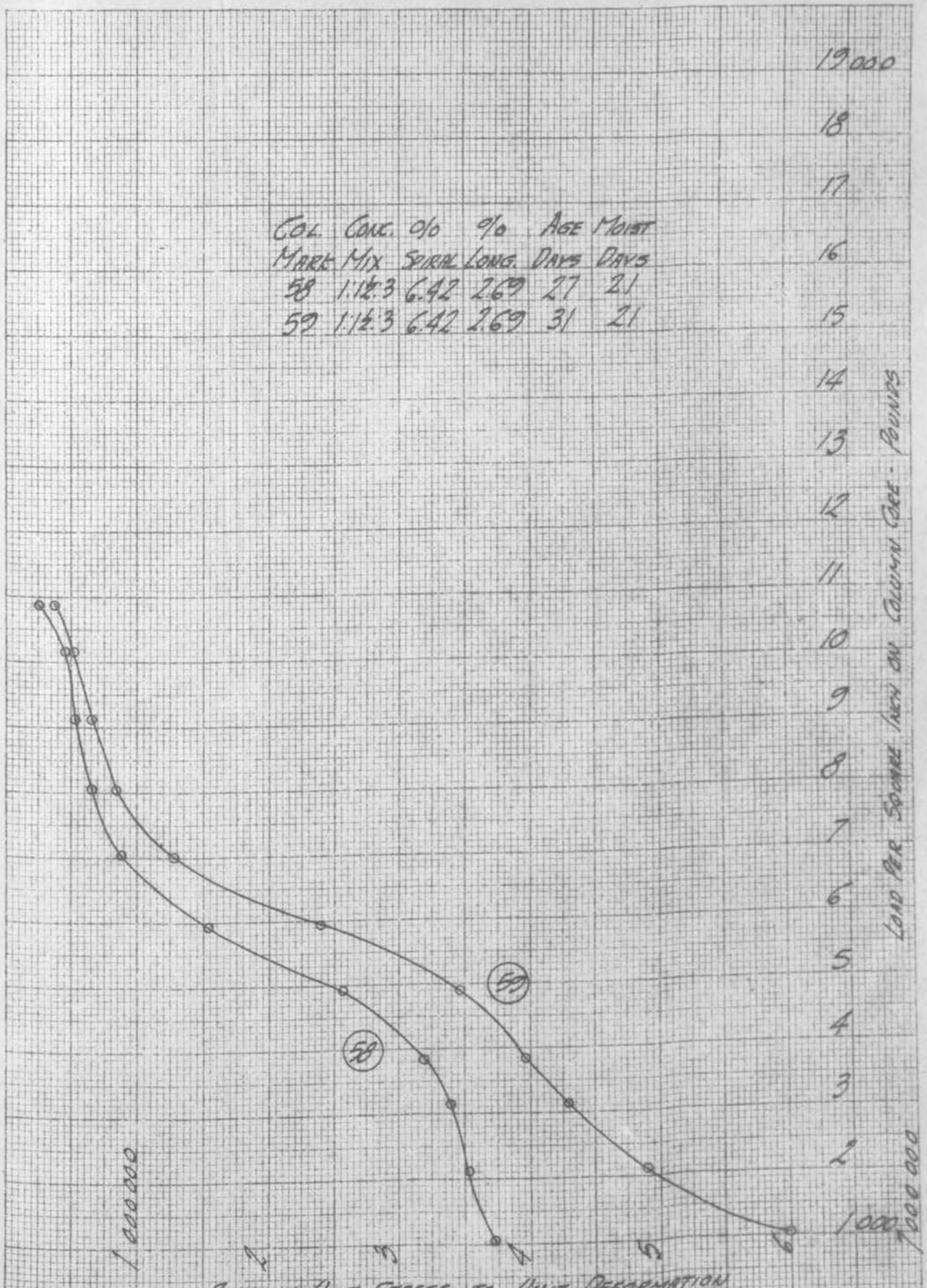
COL. MARK | CONC. MIX. | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
35 | 1:1½:3 | 11.6 | 1.5 | 29 | 18
40 | 1:1½:3 | 11.6 | 1.5 | 28 | 18
19.000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1.000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
35
40
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION

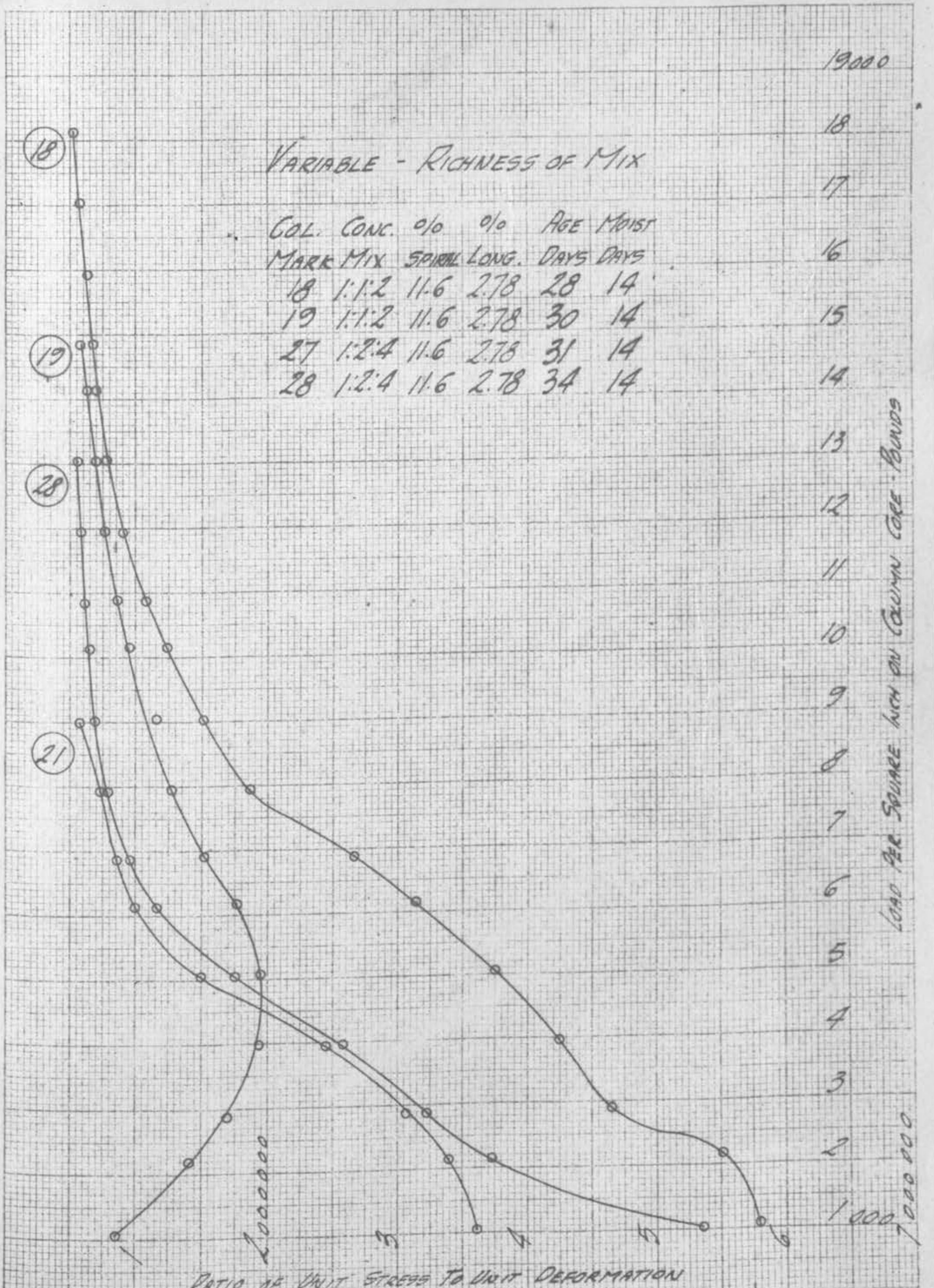


Col. Mark | Conc. Mix. | % Spiral | % Long. | Age Days | Moist Days
49 1:1½:3 11.6 6.0 30 18
49Y 1:1½:3 11.6 6.0 32 18
49
49Y
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
Load per Square Inch on Column Core: Pounds
1,000,000
2
3
4
5
6
7,000,000
Ratio of Unit Stress to Unit Deformation

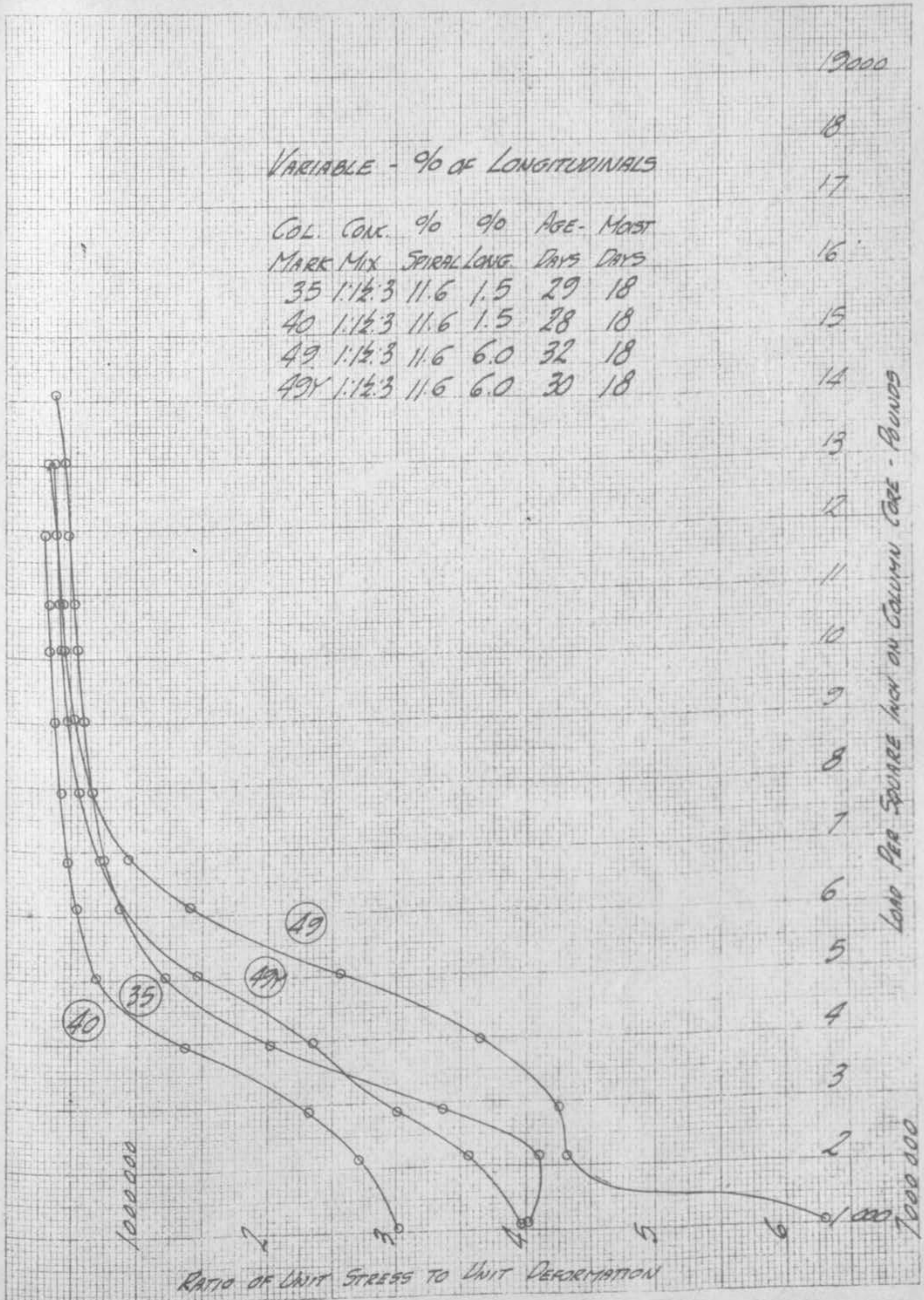


Col. Conc. % % Age Moist
Mark Mix Spiral Long. Days Days
51 1:1½:3 17.3 2.88 20 21
52 1:1½:3 17.3 2.88 35 21
52
51
19 000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1 000
1
2 000 000
3
4
5
6
7 000 000
Ratio of Unit Stress to Unit Deformation
Load per Square Inch on Column Core - Pounds

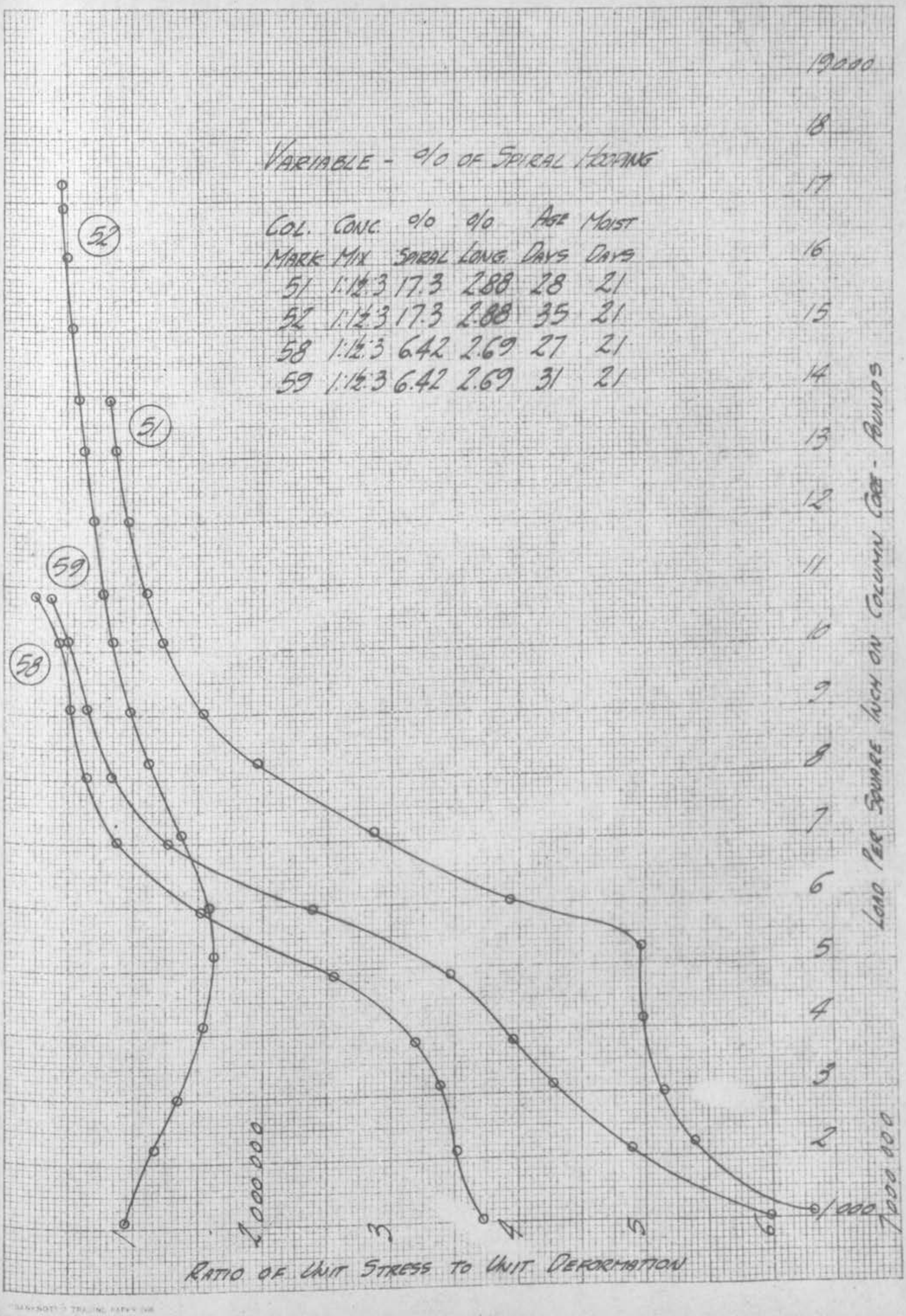

COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
58 | 1:1½:3 | 6.42 | 2.69 | 27 | 21
59 | 1:1½:3 | 6.42 | 2.69 | 31 | 21
58
59
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
1,000,000
2
3
4
5
6
1,000,000
RATIO OF UNIT STRESS TO UNIT DEFORMATION

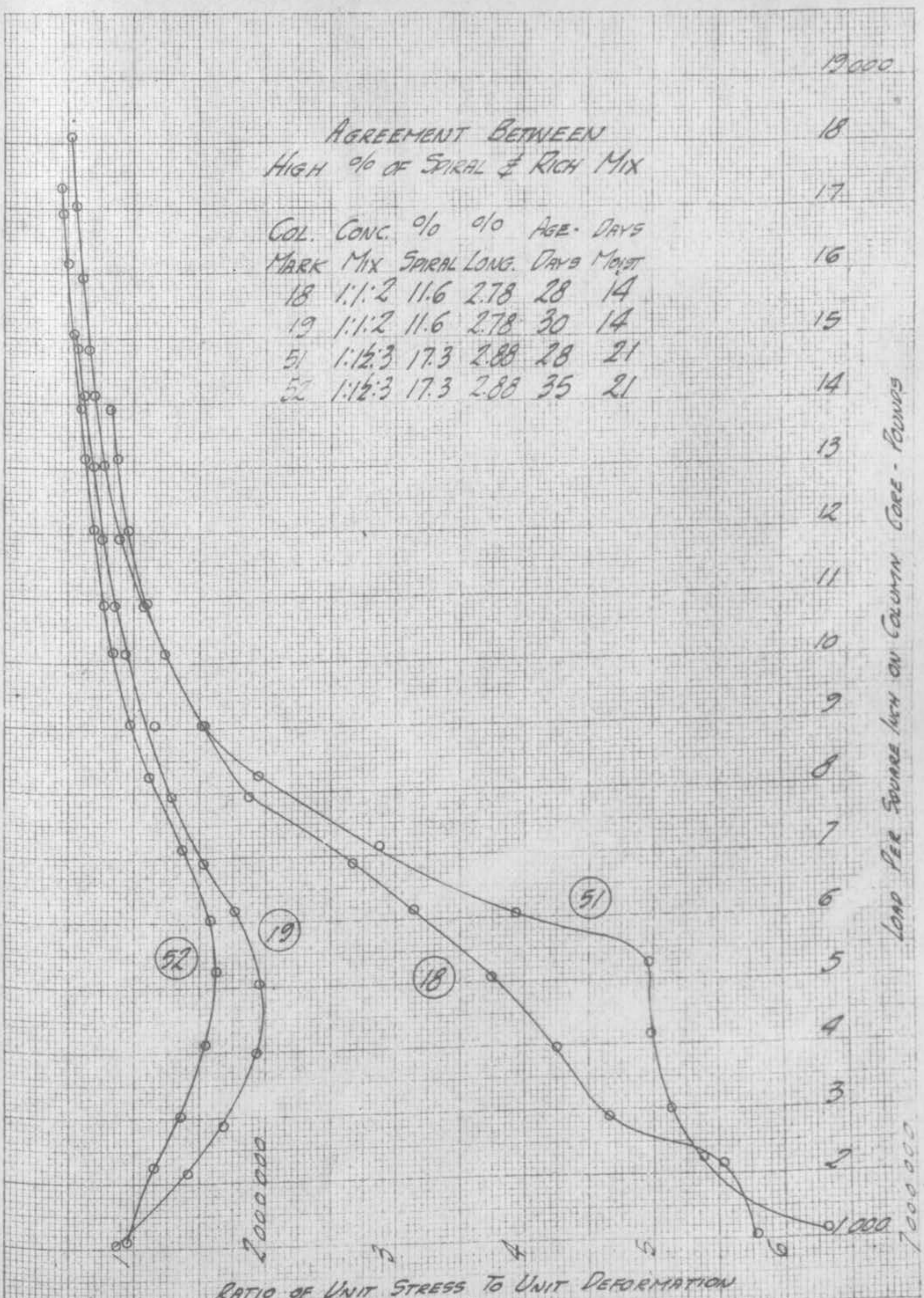


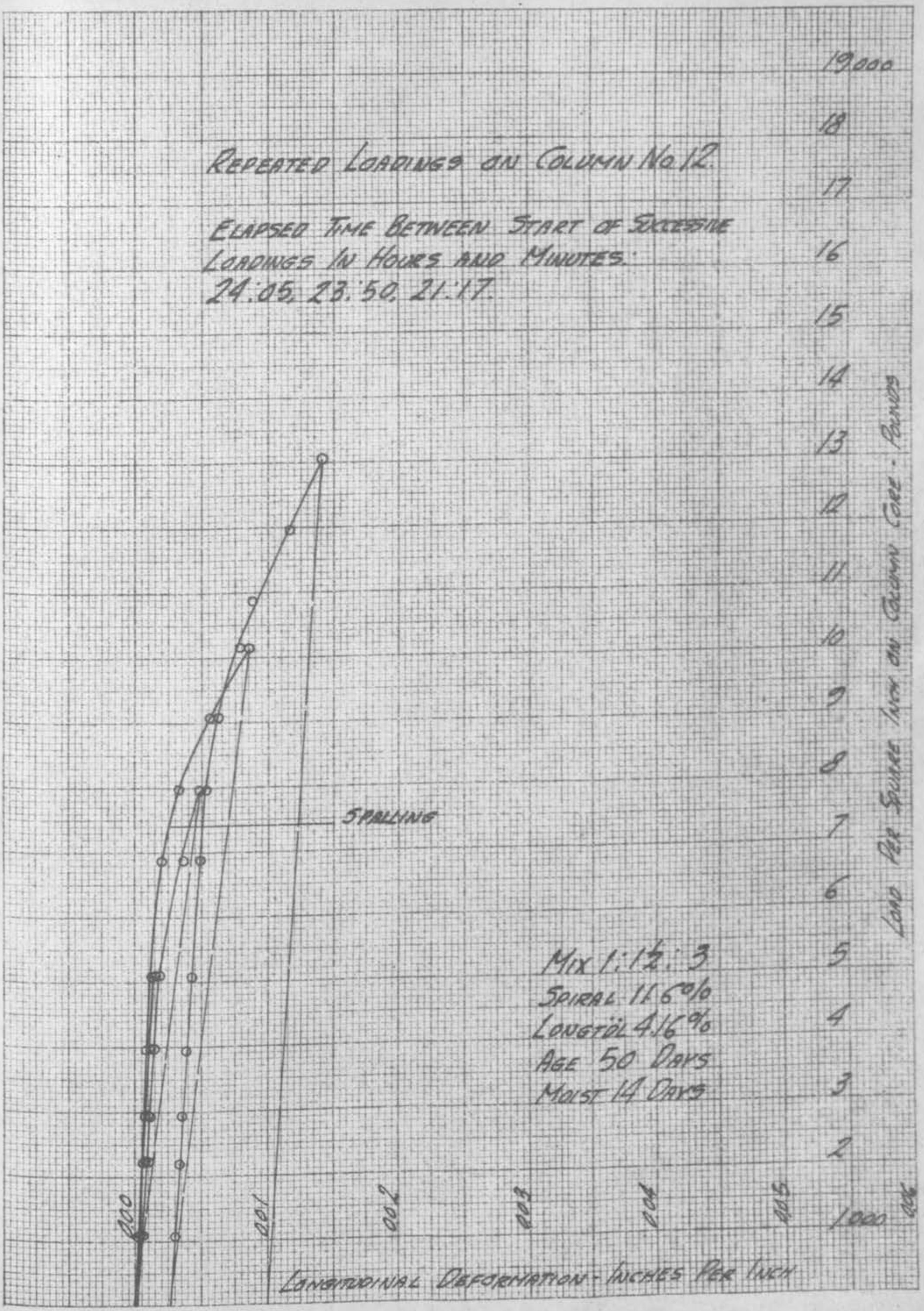
VARIABLE - RICHNESS OF MIX
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
18 1:1:2 11.6 2.78 28 14
19 1:1:2 11.6 2.78 30 14
27 1:2:4 11.6 2.78 31 14
28 1:2:4 11.6 2.78 34 14
18
19
28
21
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
1 000 000
2 000 000
1
3
4
5
6
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
RATIO OF UNIT STRESS TO UNIT DEFORMATION



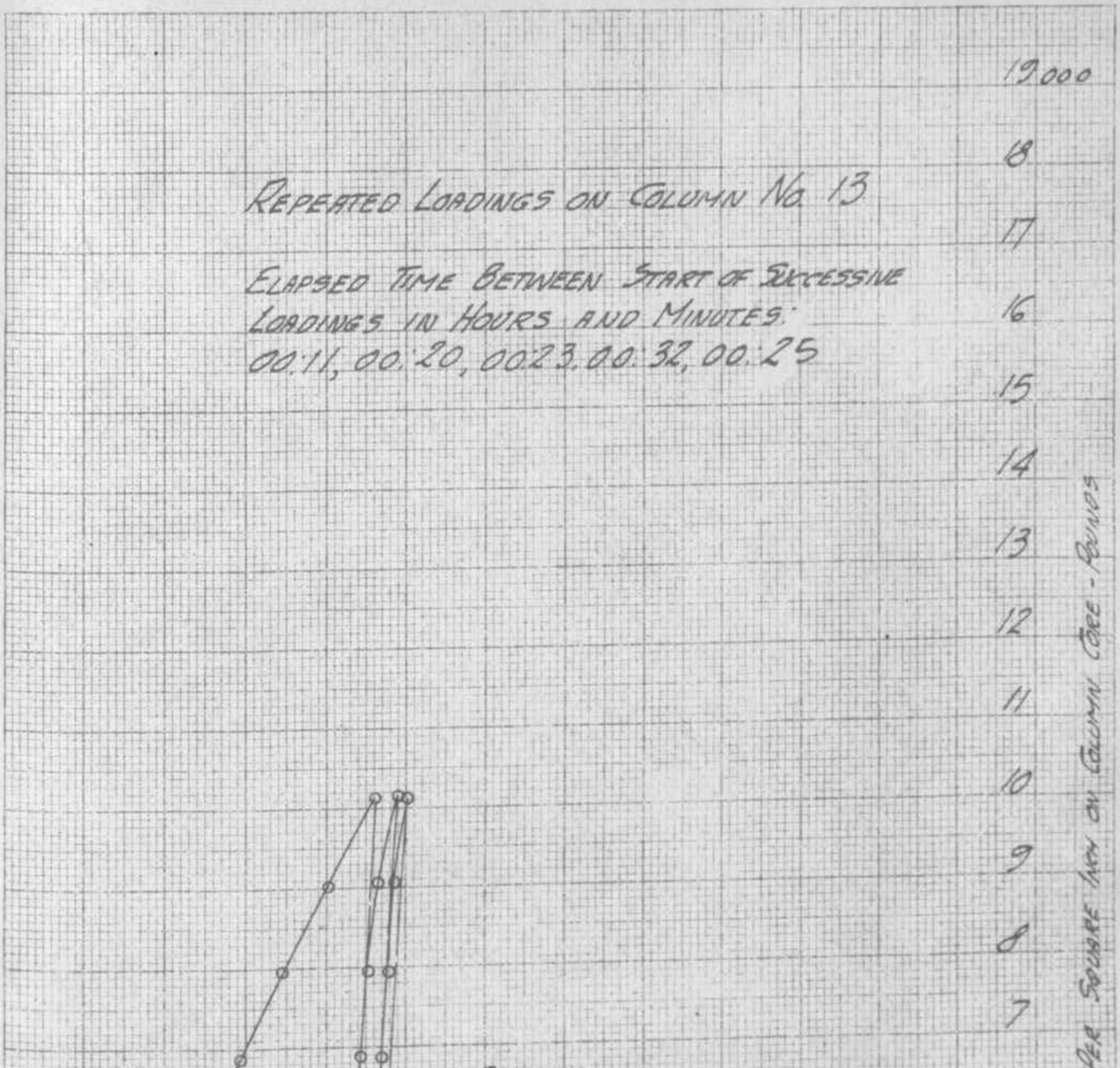
VARIABLE - % OF LONGITUDINALS
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE- DAYS | MOIST DAYS
35 | 1:1½:3 | 11.6 | 1.5 | 29 | 18
40 | 1:1½:3 | 11.6 | 1.5 | 28 | 18
49 | 1:1½:3 | 11.6 | 6.0 | 32 | 18
49Y | 1:1½:3 | 11.6 | 6.0 | 30 | 18
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
49
49Y
35
40
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION


VARIABLE - % OF SPIRAL HOOPING
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE DAYS | MOIST DAYS
51 | 1:1½:3 | 17.3 | 2.88 | 28 | 21
52 | 1:1½:3 | 17.3 | 2.88 | 35 | 21
58 | 1:1½:3 | 6.42 | 2.69 | 27 | 21
59 | 1:1½:3 | 6.42 | 2.69 | 31 | 21
52
51
59
58
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
1
2000000
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION

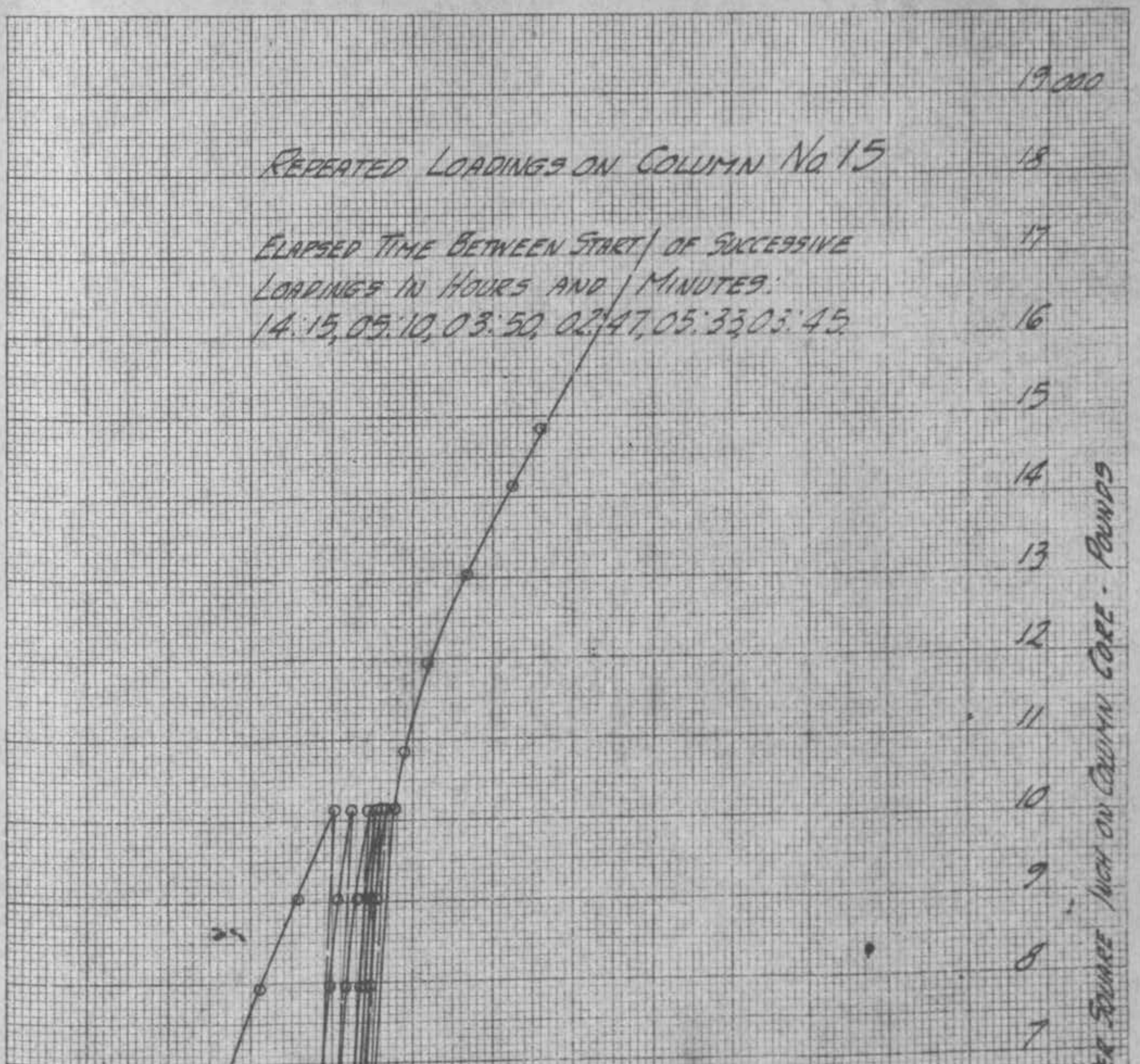

AGREEMENT BETWEEN
HIGH % OF SPIRAL & RICH MIX
COL. MARK | CONC. MIX | % SPIRAL | % LONG. | AGE-DAYS | DAYS MOIST
18 | 1:1:2 | 11.6 | 2.78 | 28 | 14
19 | 1:1:2 | 11.6 | 2.78 | 30 | 14
51 | 1:1½:3 | 17.3 | 2.88 | 28 | 21
52 | 1:1½:3 | 17.3 | 2.88 | 35 | 21
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
51
52
19
18
1
2,000,000
3
4
5
6
7,000,000
RATIO OF UNIT STRESS TO UNIT DEFORMATION



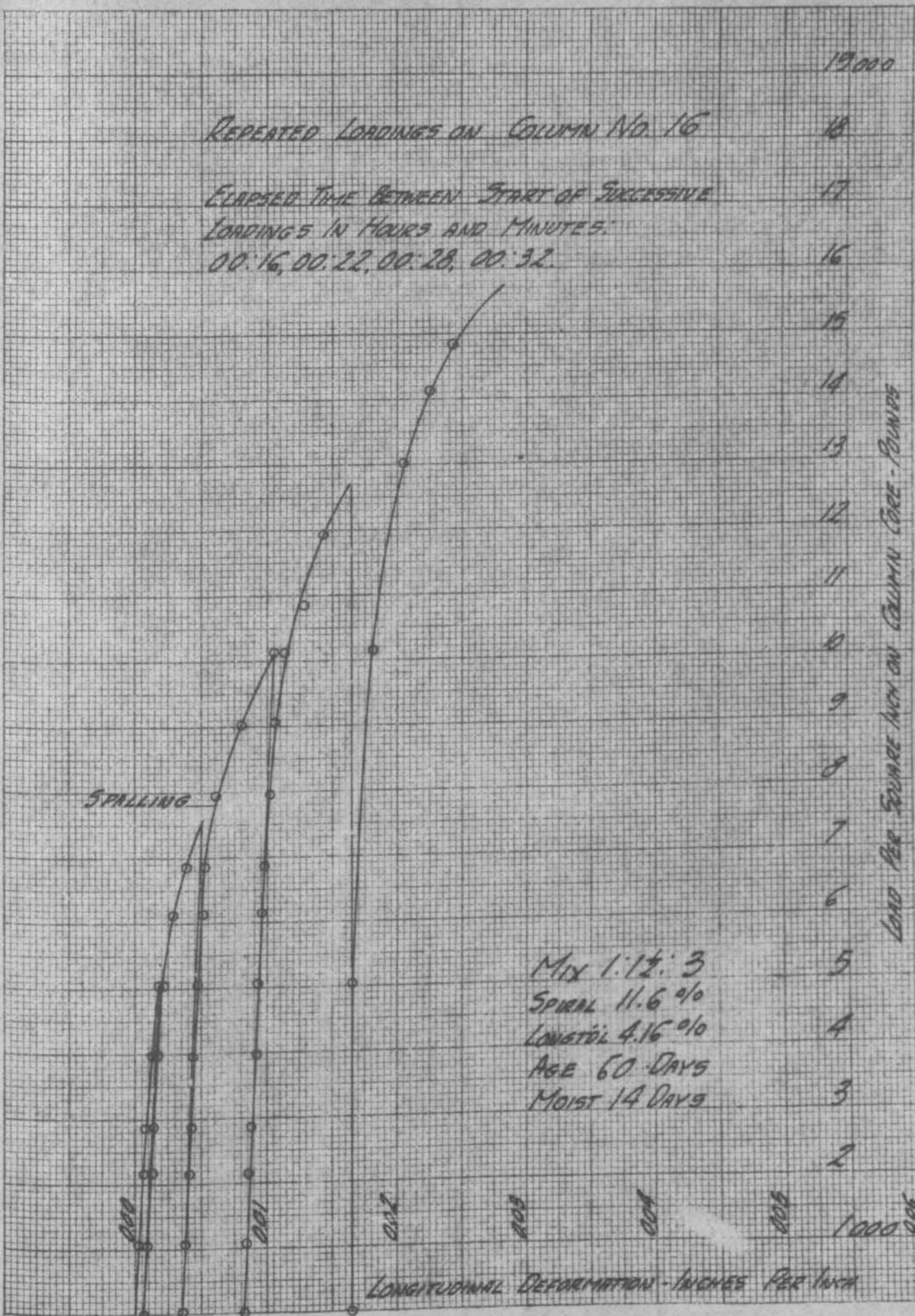
REPEATED LOADINGS ON COLUMN NO. 12.
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES.
24:05, 23:50, 21:17.
SPALLING
MIX 1:1½:3
SPIRAL 1.16%
LONGTÖL 4.16%
AGE 50 DAYS
MOIST 14 DAYS
.000
.001
.002
.003
.004
.005
.006
1,000
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19,000
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



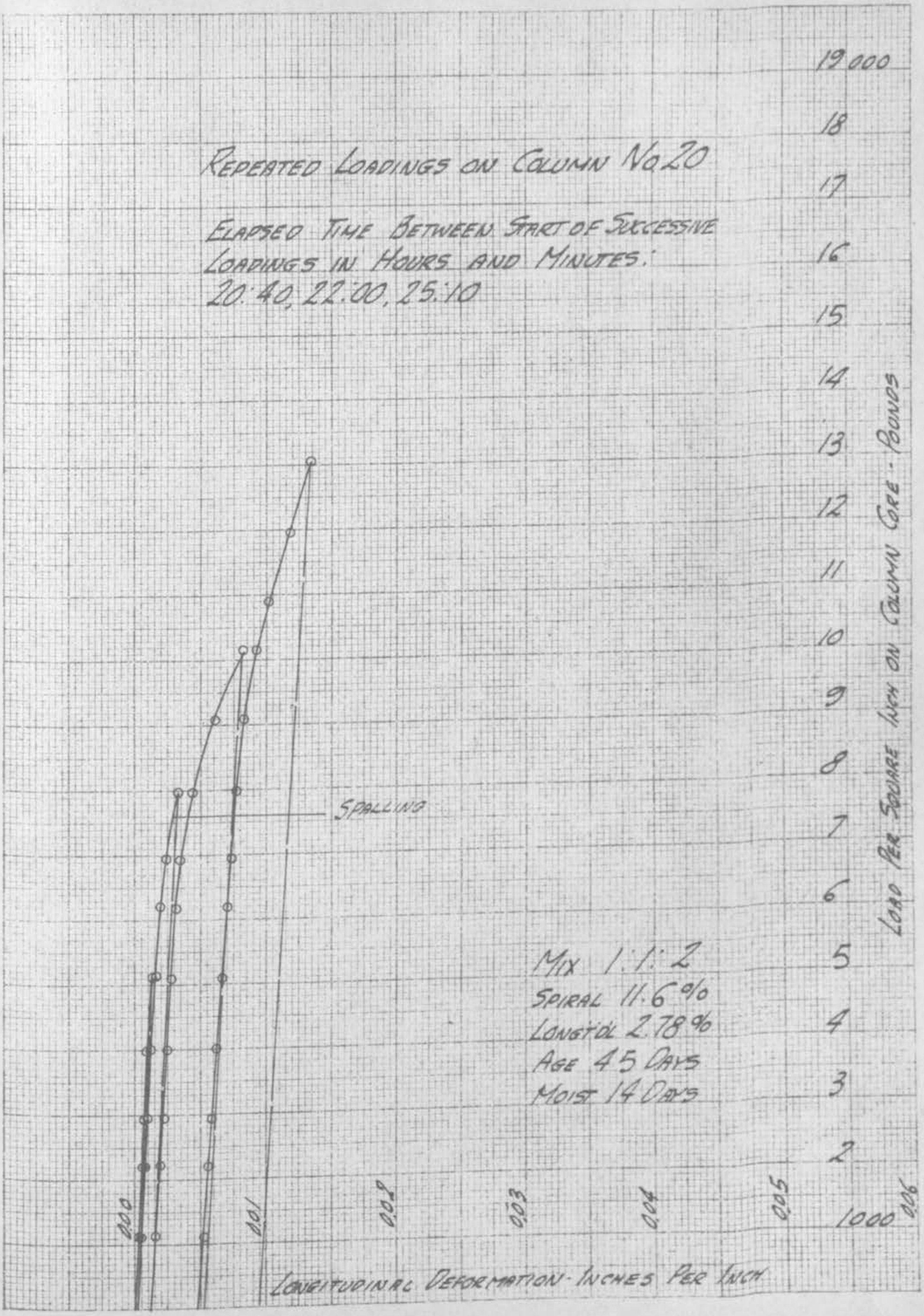
REPEATED LOADINGS ON COLUMN No. 13
ELAPSED TIME BETWEEN START OF SUCCESSIVE
LOADINGS IN HOURS AND MINUTES:
00:11, 00:20, 00:23, 00:32, 00:25
SPALLING
MIX 1:1½:3
SPIRAL 11.6%
LONGT'DL 4.16%
AGE 53 DAYS
MOIST 14 DAYS
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
0.000
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS

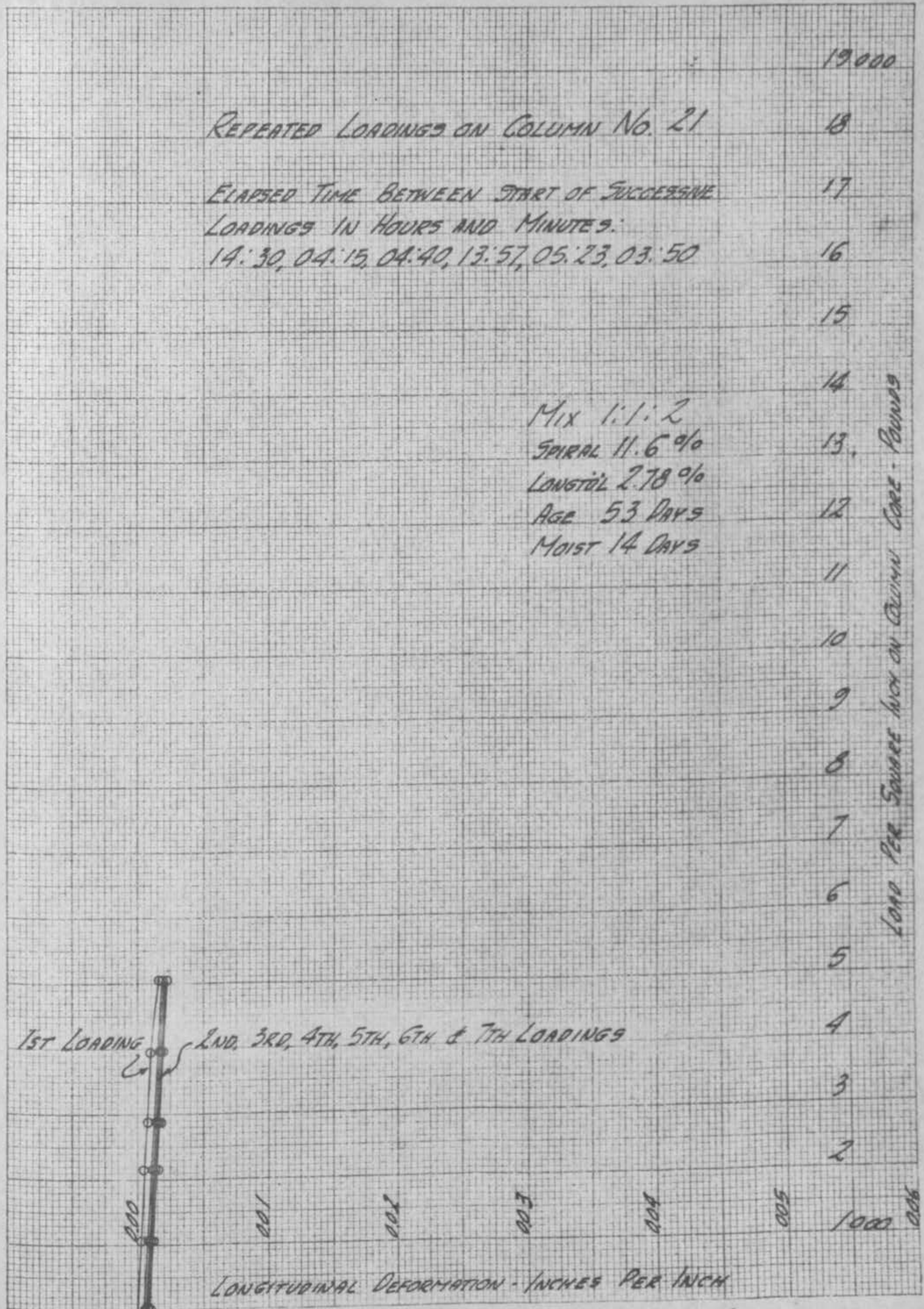


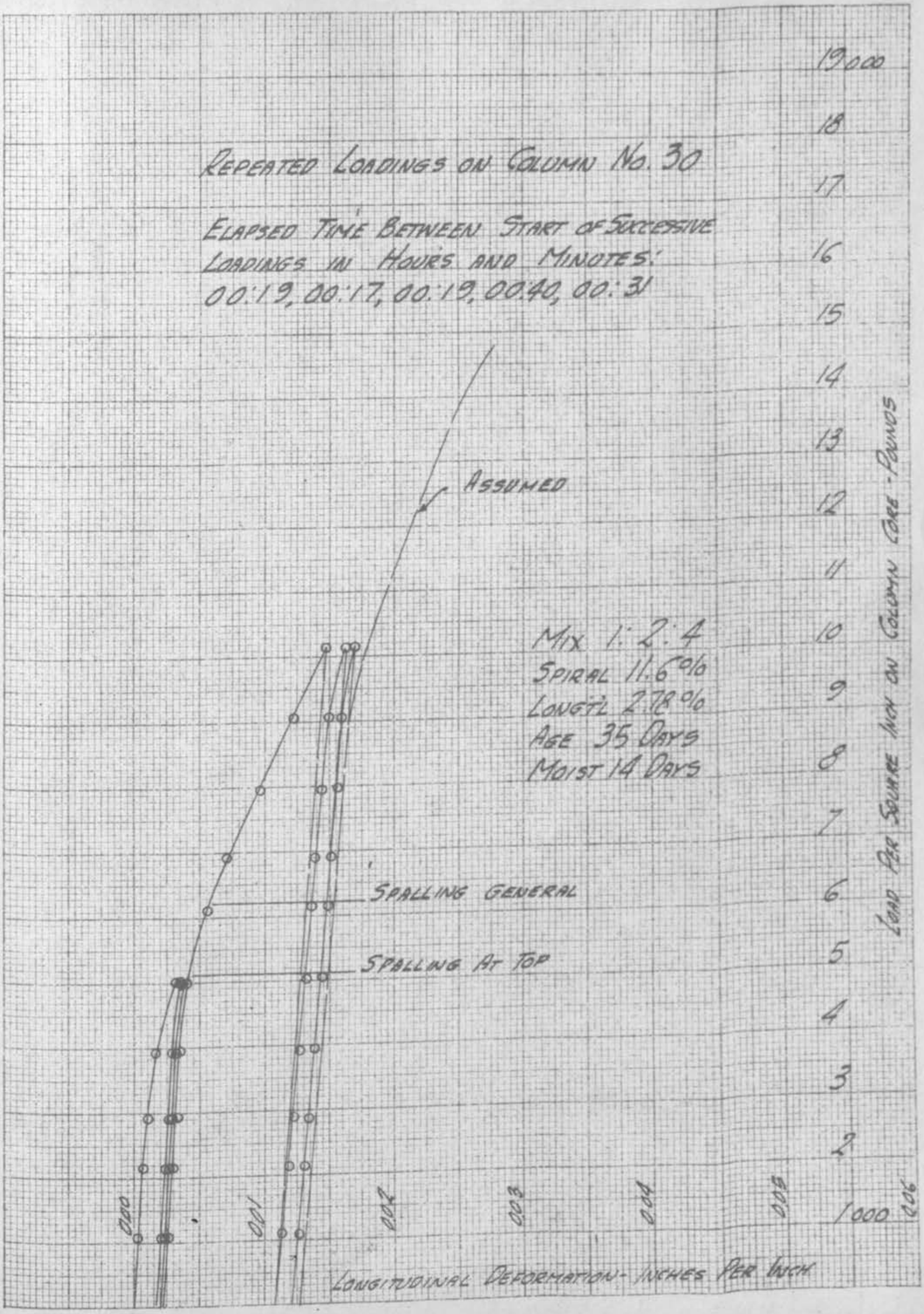
REPEATED LOADINGS ON COLUMN No. 15
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES:
14:15, 05:10, 03:50, 02:47, 05:33, 03:45
MIX 1:1½:3
SPIRAL 11.6 %
LONGT'DL 4.16 %
AGE 58 DAYS
MOIST 14 DAYS
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATION - INCHES PER INCH



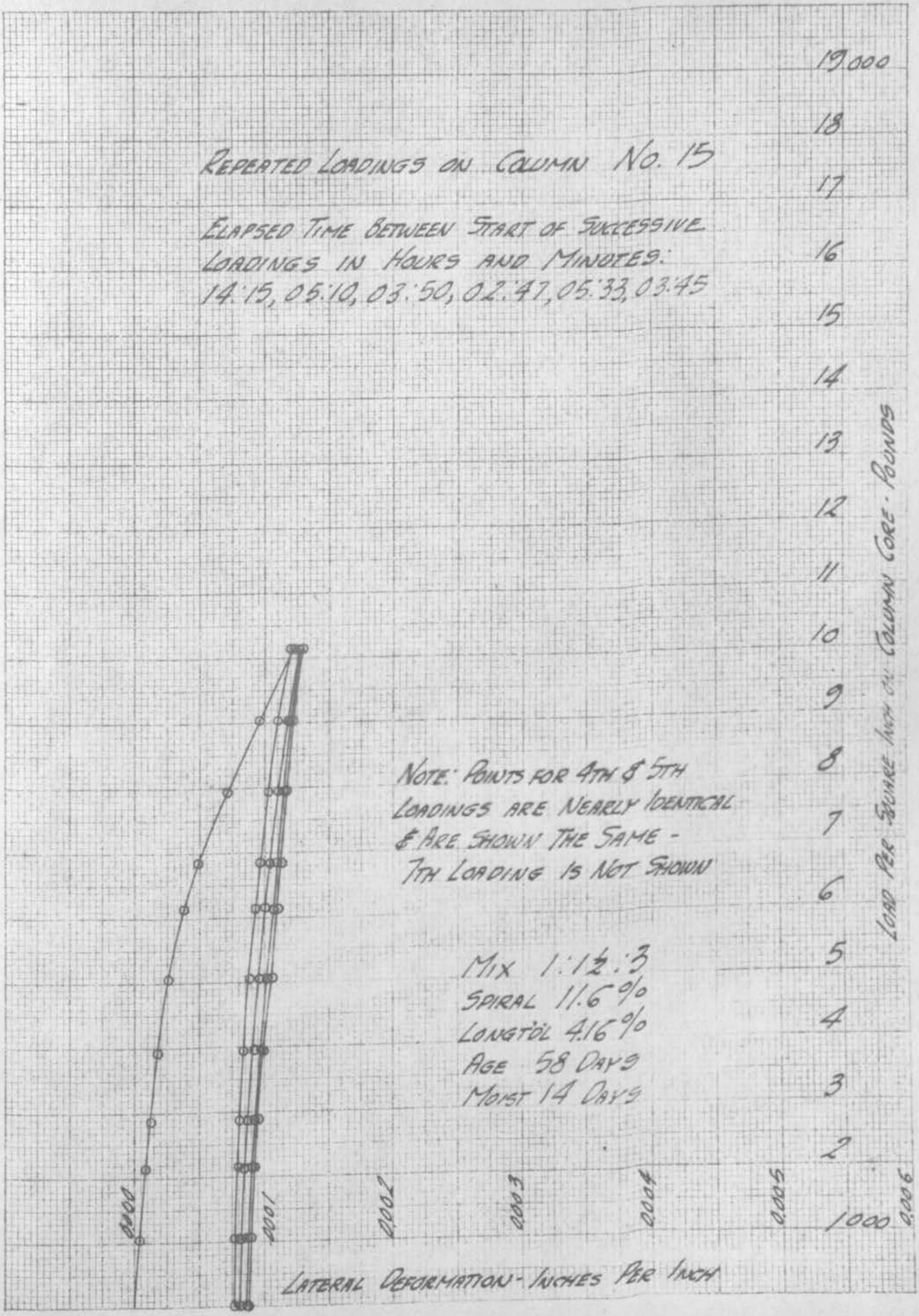
"BANKNOTE" TRACING PAPER
K. & E. CO., N. Y.

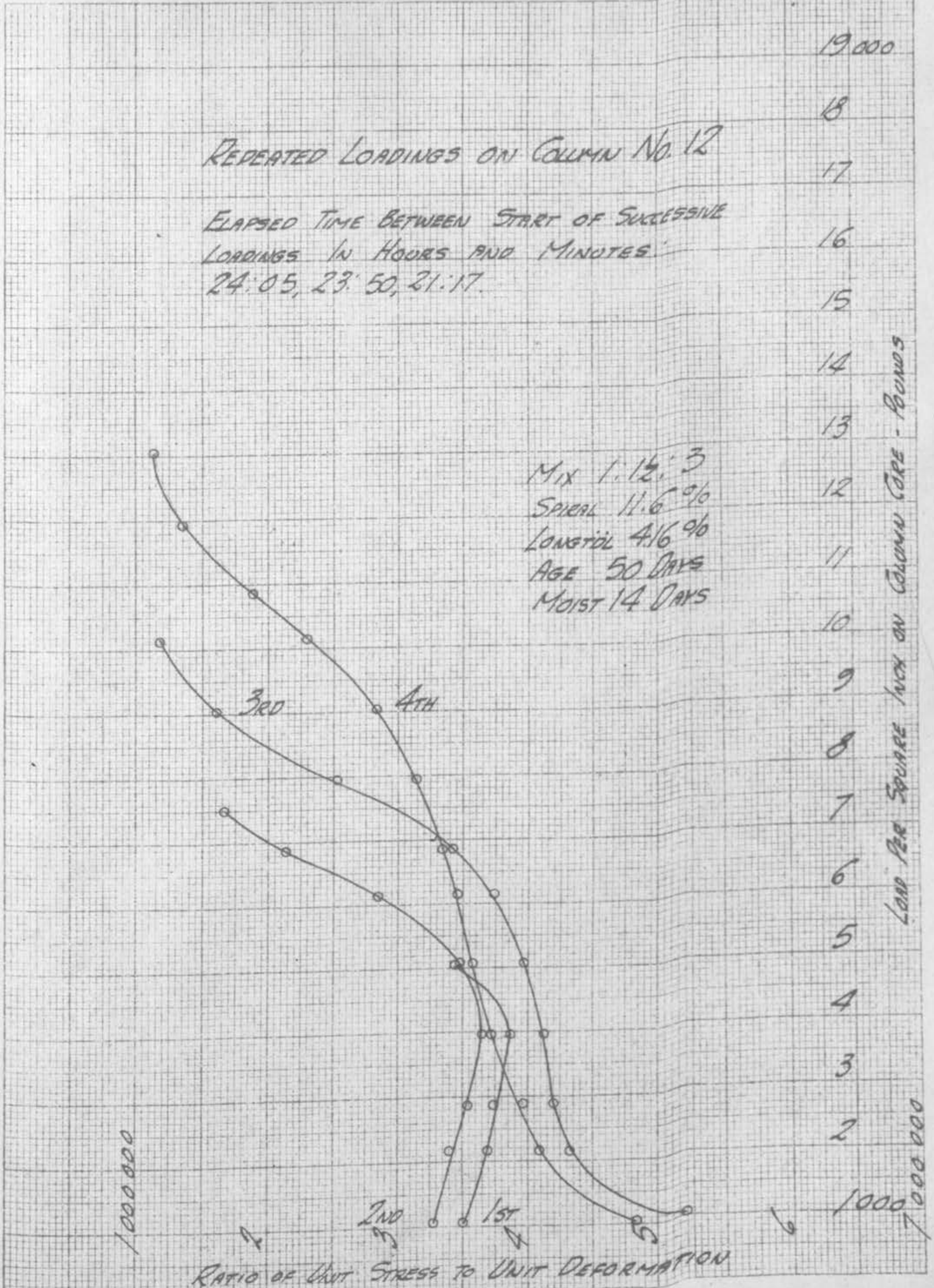

REPEATED LOADINGS ON COLUMN No 20
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES:
20:40, 22:00, 25:10
SPALLING
MIX 1:1:2
SPIRAL 11.6 %
LONGT'DL 2.78 %
AGE 45 DAYS
MOIST 14 DAYS
19 000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
LONGITUDINAL DEFORMATION - INCHES PER INCH

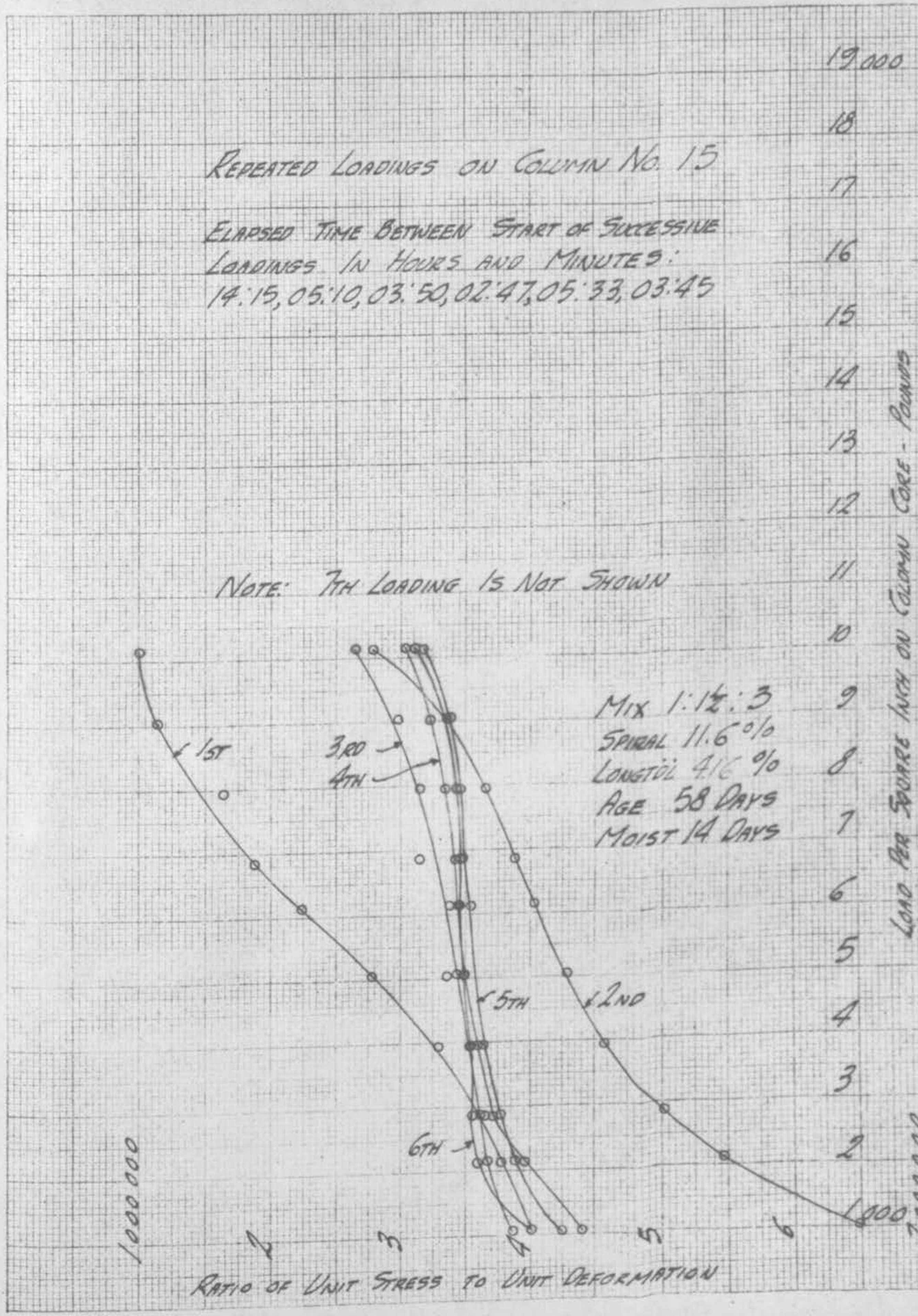

REPEATED LOADINGS ON COLUMN No. 21
ELAPSED TIME BETWEEN START OF SUCCESSIVE
LOADINGS IN HOURS AND MINUTES:
14:30, 04:15, 04:40, 13:57, 05:23, 03:50
MIX 1:1:2
SPIRAL 11.6 %
LONGTÜL 2.78 %
AGE 53 DAYS
MOIST 14 DAYS
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
1ST LOADING
2ND, 3RD, 4TH, 5TH, 6TH & 7TH LOADINGS
.000
.001
.002
.003
.004
.005
.006
LONGITUDINAL DEFORMATION - INCHES PER INCH
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



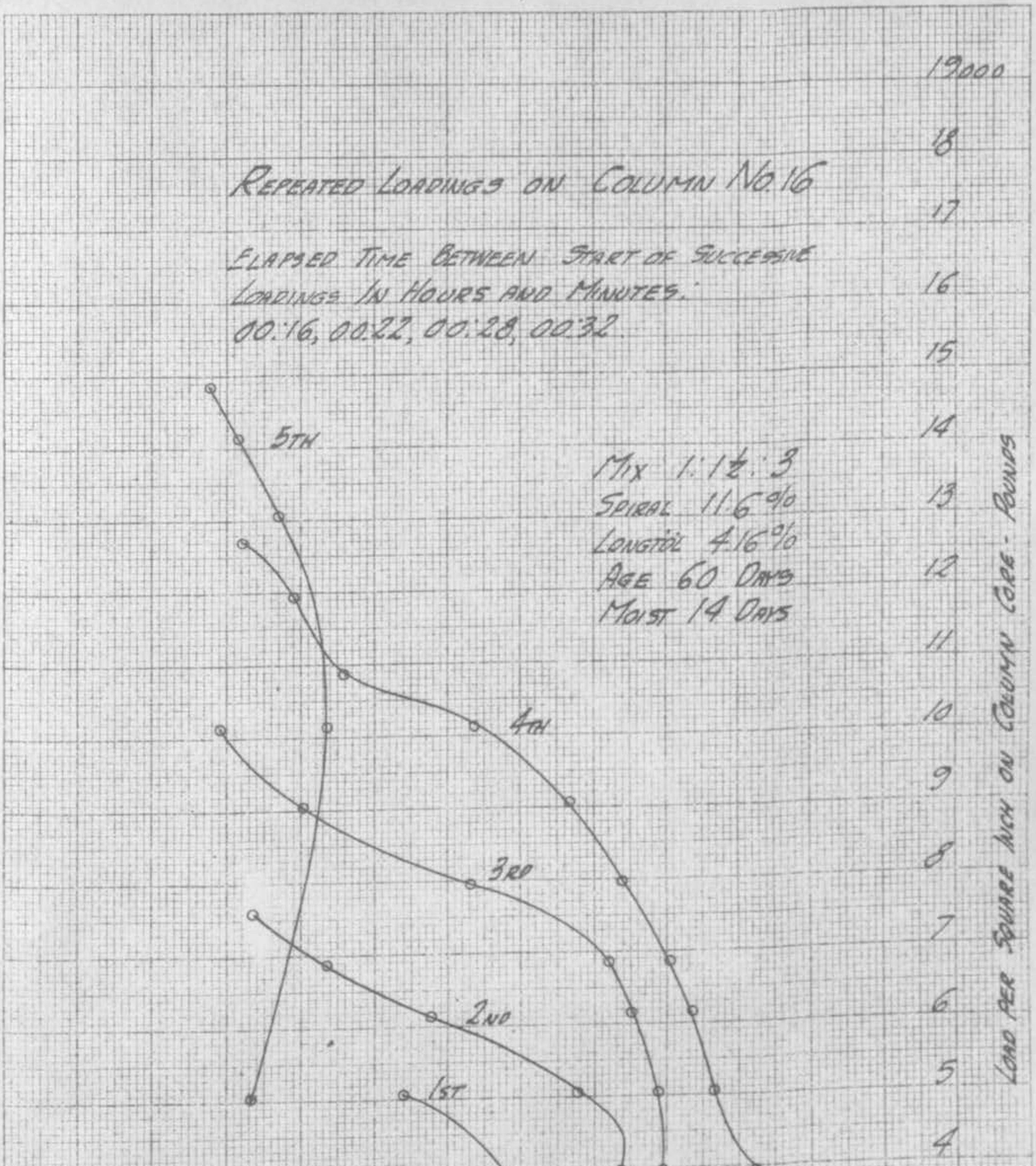
REPEATED LOADINGS ON COLUMN NO. 30
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES:
00:19, 00:17, 00:19, 00:40, 00:31
ASSUMED
MIX 1:2:4
SPIRAL 1.16%
LONGT'L 2.78%
AGE 35 DAYS
MOIST 14 DAYS
SPALLING GENERAL
SPALLING AT TOP
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LONGITUDINAL DEFORMATION - INCHES PER INCH


REPEATED LOADINGS ON COLUMN NO. 15
ELAPSED TIME BETWEEN START OF SUCCESSIVE
LOADINGS IN HOURS AND MINUTES:
14:15, 05:10, 03:50, 02:47, 05:33, 03:45
NOTE: POINTS FOR 4TH & 5TH
LOADINGS ARE NEARLY IDENTICAL
& ARE SHOWN THE SAME -
7TH LOADING IS NOT SHOWN
MIX 1:1½:3
SPIRAL 1.16 %
LONGT'DL 4.16 %
AGE 58 DAYS
MOIST 14 DAYS
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
.0000
.0001
.0002
.0003
.0004
.0005
.0006
LATERAL DEFORMATION - INCHES PER INCH

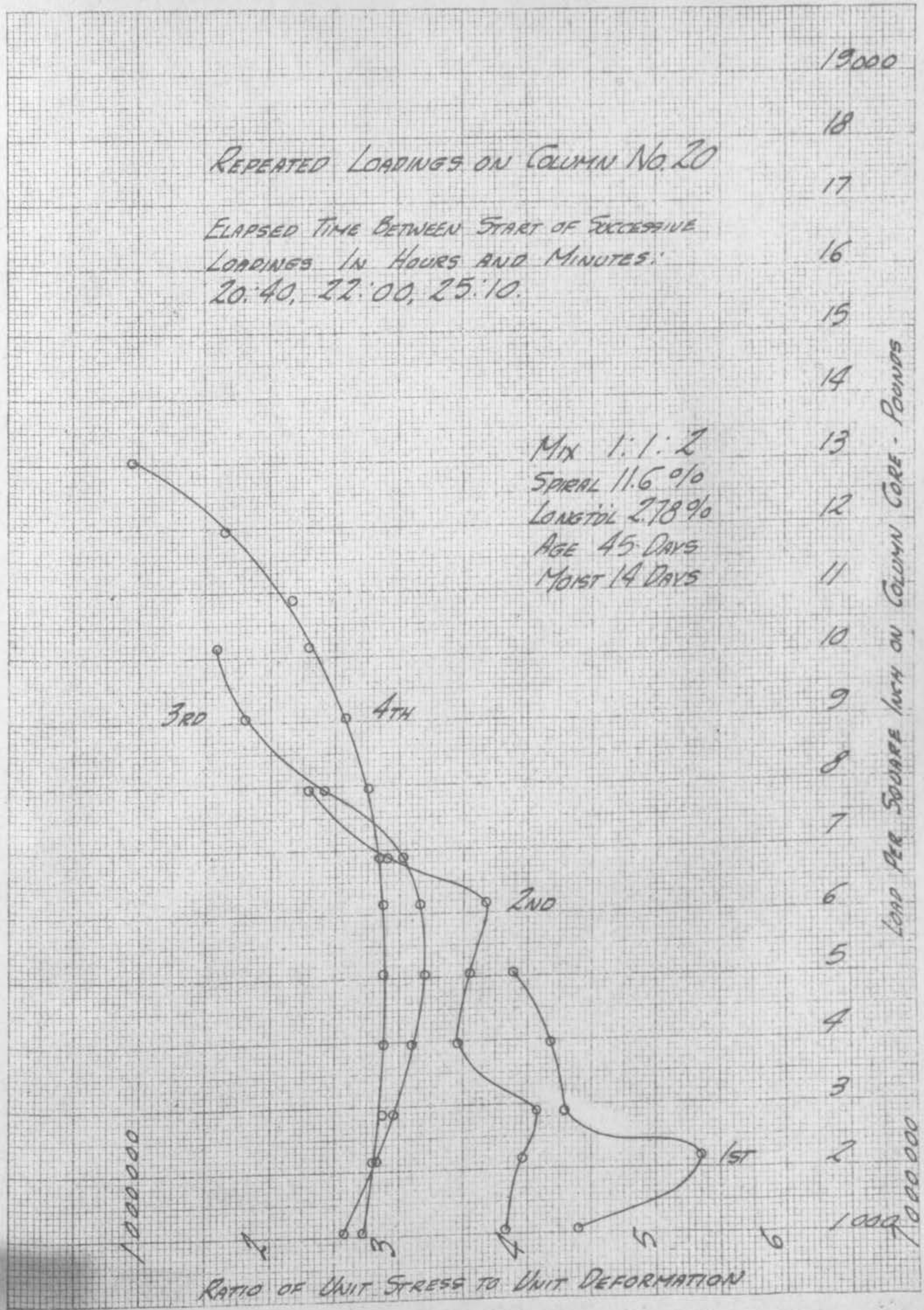

REPEATED LOADINGS ON COLUMN No. 12
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES.
24:05, 23:50, 21:17.
MIX 1:1½:3
SPIRAL 1.16 %
LONGTÖL 4.16 %
AGE 50 DAYS
MOIST 14 DAYS
3RD
4TH
2ND
1ST
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS



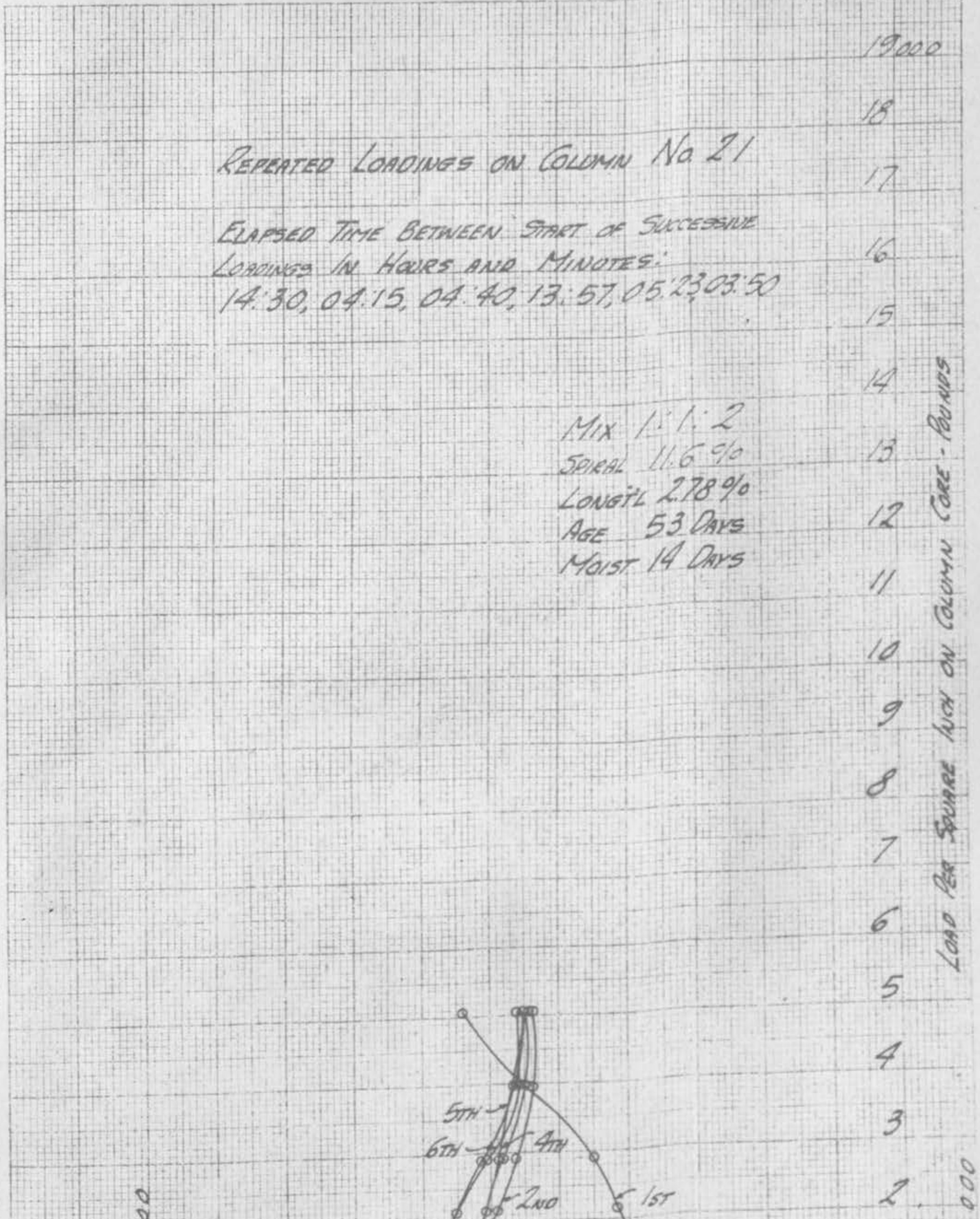
REPEATED LOADINGS ON COLUMN No. 15
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES:
14:15, 05:10, 03:50, 02:47, 05:33, 03:45
NOTE: 7TH LOADING IS NOT SHOWN
MIX 1:1½:3
SPIRAL 11.6 %
LONGTÖL 4.16 %
AGE 58 DAYS
MOIST 14 DAYS
1ST
2ND
3RD
4TH
5TH
6TH
19,000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1,000
1,000,000
2
3
4
5
6
7,000,000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
RATIO OF UNIT STRESS TO UNIT DEFORMATION

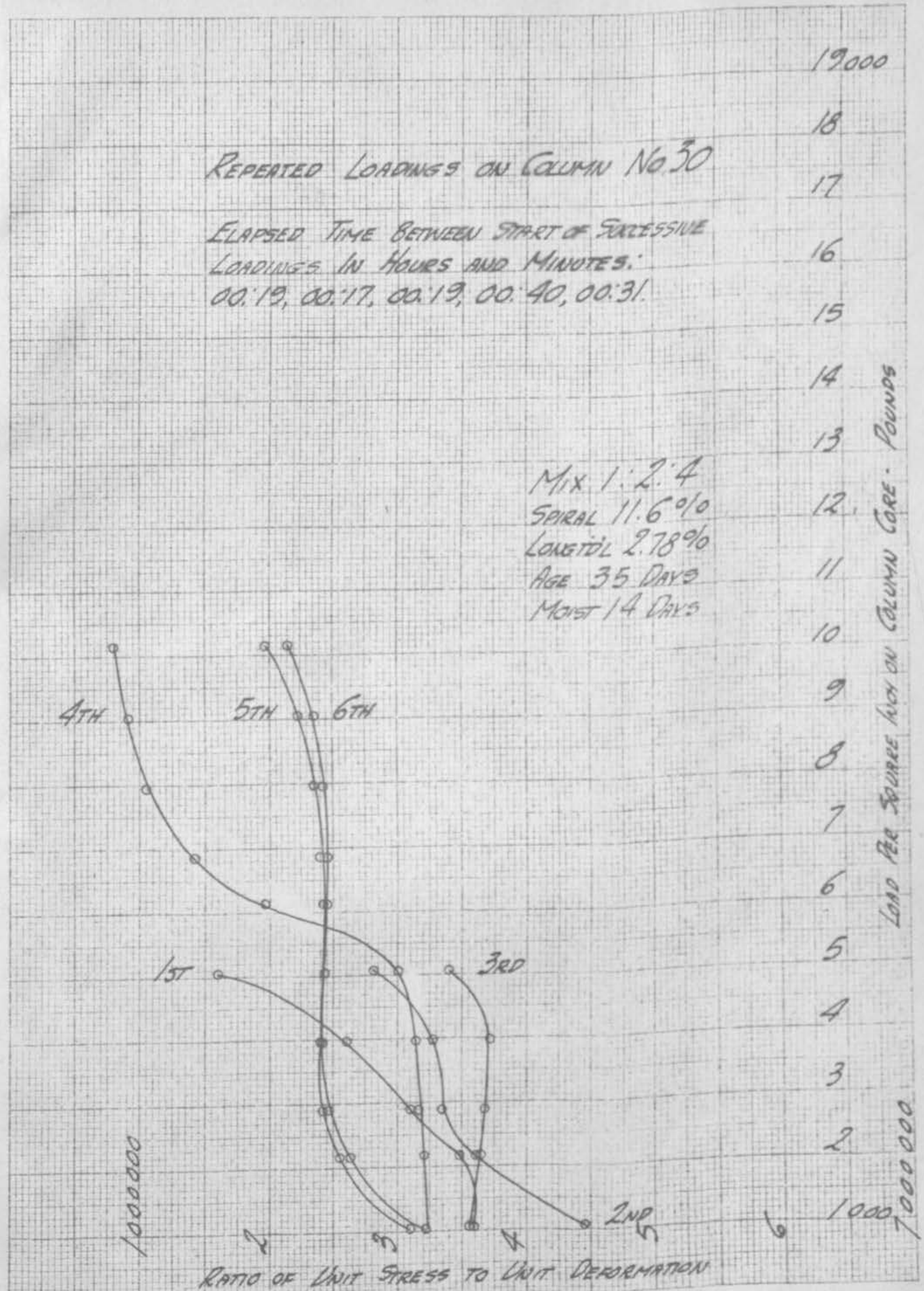


REPEATED LOADINGS ON COLUMN No. 16
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES.
00:16, 00:22, 00:28, 00:32
MIX 1:1½:3
SPIRAL 1.16 %
LONGIT'L 4.16 %
AGE 60 DAYS
MOIST 14 DAYS
5TH
4TH
3RD
2ND
1ST
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION



"BANKNOTE" TRACING PAPER


REPEATED LOADINGS ON COLUMN No. 21
ELAPSED TIME BETWEEN START OF SUCCESSIVE
LOADINGS IN HOURS AND MINUTES:
14:30, 04:15, 04:40, 13:57, 05:23, 03:50
MIX 1:1:2
SPIRAL 11.6 %
LONGT'L 2.78 %
AGE 53 DAYS
MOIST 14 DAYS
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
5TH
6TH
4TH
2ND
1ST
3RD
7TH
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION



REPEATED LOADINGS ON COLUMN No 30
ELAPSED TIME BETWEEN START OF SUCCESSIVE LOADINGS IN HOURS AND MINUTES:
00:19, 00:17, 00:19, 00:40, 00:31.
MIX 1:2:4
SPIRAL 11.6%
LONGT'L 2.78%
AGE 35 DAYS
MOIST 14 DAYS
1ST
2ND
3RD
4TH
5TH
6TH
19000
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1000
LOAD PER SQUARE INCH ON COLUMN CORE - POUNDS
1000000
2
3
4
5
6
7000000
RATIO OF UNIT STRESS TO UNIT DEFORMATION