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PHYSICAL PROPERTIES OF CONCRETE AT EARLY AGES

BY

CURTIS E. WEDDLE, JR.

A

THESIS

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APPROVED BY E. W. Carlton
Professor of Civil Engineering

ACKNOWLEDGMENT

This project could not have been completed without the services of a number of people, each of whose aid was greatly appreciated.

The author wishes to express his appreciation to: Professor E. W. Carlton of the Civil Engineering Department for his leadership, advice and constructive criticisms; Mr. F. V. Reagel of the Missouri State Highway Department and Mr. L. W. Teller, Physical Research Branch, Bureau of Public Roads, for outlining the problem and furnishing the materials and equipment necessary for the project; and the Mechanics Department of the Missouri School of Mines for the use of their testing facilities.

Also, the author is very grateful for the advice, guidance and criticism of Mr. Bengt Friberg, Consulting Engineer, of St. Louis, Missouri, during the analysis of the test results.

In addition, he wishes to acknowledge, with sincere gratitude, the aid of Mr. Peter G. Hansen on this project. His preliminary work in instrumentation, procedure, and analysis of results greatly simplified its completion and reduced the work load necessary to obtain the desired results.

Recognition is given to the members of the Civil Engineering Staff and the students in the department for their freely given suggestions and cooperation on various phases of this project.

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INTRODUCTION

The introduction of the motor vehicle and the subsequent rapid expansion of the highway systems of the United States have brought with them many problems.

The Civil Engineer, in his attempts to provide adequate safe avenues of travel for the populace, has been faced with many problems. Handicapped by the need for speed in design and lack of information of the trends in motor vehicle design, the engineer has been forced at times to utilize design methods inconsistent with good engineering practices.

Of the many types of pavement sections which have been designed in an effort to provide structurally and economically suitable transportation avenues, the rigid type portland cement section represents one of the best known and most durable in use today. Rigid and durable as they may be, these pavements are still cracking and breaking up under the action of traffic.

Engineers in an effort to adapt this design to increasingly heavy axle loadings and higher traffic volumes and eliminate cracking and subsequent shortening of pavement life, have followed two separate design trends. One of these has been the use of short, un-reinforced slabs, whose action under load would be as a complete unit in the transferrance of stresses to the subgrade. Also, attempt has been made to thoroughly and completely compact the sub-grade so as to obviate any necessity for so-called "bridging" and subsequent possibility of cracking. Still other designers have thought to handle heavier loadings by increasing the depth of paving section, thus lowering the sections flexibility, however, this procedure has increased the cost prohibitively.

These attempts have failed to eliminate completely cracking, infiltration of moisture to the sub-grade, and the relatively short pavement life.

Investigations have been, and are being conducted by various organizations throughout the United States in an effort to analyze pavement action under load, the effect of temperature change, and the possibility of developing new criteria for design. Effort is also being made to investigate the properties of the various materials used in highway construction so as to utilize them to better advantage. The last two mentioned items have led to this investigation.

Development of pre-stressing procedures and technique and better understanding of this useful construction method has suggested its' application to pavement design. If prestressing our highway slabs is to be practical, we must immediately consider the properties of the concrete to be used. Modern highway construction methods require continuity of action, no lost motion, no duplication of effort, and if we are to maintain the time sequence which has become standard we must understand the early age properties of the material we use.

It is hoped that the results of this project and others of similar nature may be utilized for the development of better, safer, more durable highways for the use of future generations.

HISTORICAL BACKGROUND AND OBJECT OF THE INVESTIGATION

Comparatively little is known about the early age properties of concrete. A considerable amount of work was done on this subject during the period from 1920 to 1930 when road building in the United States received its' initial impetus; however, the data compiled during this period was, in general, for the ranges from seven days up to one year. Due to the difficulty of obtaining true tensile stresses and lack of adequate equipment for the measurement of strains, various simplifying assumptions were made. The moduli of elasticity in tension and compression were assumed to be equal and the bending stress formula, $S = \frac{Mc}{I}$, was assumed to hold true for concrete beams.

The results of various tests run during this period are available and were reviewed to obtain an indication of results to be expected.

In a cooperative project between the University of Maryland, the State Roads Commission of Maryland, and the U. S. Bureau of Public Roads, conducted by Mr. A. N. Johnson(1), the following results were obtained:

(1) The ratio of the strength in tension to the strength in compression for concrete less than 90 days old varied from 0.15 to 0.08,

(2) for concrete older than 90 days the ratio was 0.08. Various concrete mixes were tested in this series at ages ranging from 18 to 250 days and a large number of 4 1/2 x 9 inch cylinders were tested.

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(1) Johnson, A. N., Concrete in Tension, American Society for Testing Materials, Proceedings, Vol. 26, Part II, p. 441, 1926.

In a series of tests performed by Mr. A. W. Johnson(2), at Iowa State College these conclusions were reached:

(1) The moduli of elasticity in tension and compression may be considered to be equal for design purposes at loads from zero to 50% of ultimate;

(2) the strength - modulus of elasticity relationship is a curve, the modulus of elasticity increasing less rapidly than the strength;

(3) The modulus rupture strength is 1.8 to 2.3 times the ultimate tensile strength;

(4) and the compressive strength of concrete is from 8 to 17 times the tensile strength.

Again, tests were made at ages when the concrete had developed considerable strength, e.g. from one day to nine months.

These tests were run on cement of poorer quality than today's cements and, in addition, were made using mix proportions other than those contemplated for this project. Therefore, as previously stated, the results of the above mentioned tests were taken only as an indication of possible results.

As this project was to determine the effect of temperature on the physical properties of concrete, available literature was studied for information concerning any previous work done on this subject.

Mr. W. H. Price(3), reported the results of a number of tests conducted.

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(2) Johnson, A. W., Relationship Between Strength and Elasticity of Concrete in Tension and Compression, Iowa State College Engineering Experiment Station Bulletin No. 90, Vol. XXVI, No. 72, 1928.

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(3) Price, W. H., Factors Influencing Concrete Strength, American Concrete Institute Proceedings, Vol. 47, pp. 417-432, 1941.

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(1) Curing temperatures have a pronounced effect on the strength development of concrete;

(2) specimens made and cured at higher temperatures had lower strengths at later ages than those made and cured at lower temperatures;

(3) the specimens made at the lowest temperature (40°F.) produced the highest strength;

(4) and compressive strength, tensile strength and flexural strength of concrete are all more or less directly affected. An increase in one is generally reflected in the others, though not necessarily to the same degree. Mr. Price found that concrete is apparently weakened by a very rapid setting, which effect is not overcome by subsequent curing operations. His results agree with those obtained by the U. S. Bureau of Reclamation(4), on some of their projects where the strengths of field control cylinders made in the summer months were found to be lower than those made during cooler months even though all cylinders were later moist cured at 70°F.

The object of this investigation was to determine the effects of a constant temperature upon the various characteristics of a particular concrete mixture. Information was expected to be obtained on the relationships between strengths in both tension and compression, and attempts were to be made to determine the critical nature of strains in specimens tested at very early ages. The results were expected to be indicative of the properties of design mixes used by the Missouri State Highway Department.

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(4) U. S. Bureau of Reclamation, Concrete Manual, Sixth Ed., Denver, p. 21, 1955.

DESCRIPTION OF FACILITIES
FOR
MAINTENANCE OF CONTROLLED TEMPERATURE

A preliminary analysis of the project disclosed the necessity for acquiring or developing some means for the maintenance of controlled temperature conditions. As the tests were to be made on a definite time sequence and all phases of the operation; storing of materials, mixing, curing and testings of specimens, were to be conducted at as near the design temperature as possible, it was evident that specific requirements would have to be met by these facilities. The testing area would need to be large enough to store the necessary materials and finished specimens, to provide space for proportioning the mix, and should be in close proximity to both a suitable mixing machine and testing apparatus.

Such a facility was conceived and built as shown in Figure 1. Full credit should be given to Mr. Peter G. Hansen for his work on this temperature control room.

As may be seen in Figure 1, the control room, built in space allocated by the Mechanics Department, fulfills all of the above mentioned requirements. The movement of aggregates from the storage area to the control room, the proportioning of the mix, the mixing and pouring of test specimens, the curing of specimens, and the final testing of specimens followed a smooth pattern without interruption. At no time did the temperature of the materials, poured specimens, or specimens being tested rise to over 49°F. after their removal from the constant 40± 2°F. of the control room.

The desired temperature was maintained in the control room by a thermostat-controlled, Heat Transfer Products air conditioner of one ton capacity placed as shown in Figure 1.

A - One ton air conditioner
B - Compressor unit for "A"
C - Scales for batching mix
D - Storage for specimens
E - Inside aggregate storage
F - Inside cement storage
G - Outside aggregate storage (also stored in basement)
H - Cylinder capping area
I - Elevator
J - Three cubic feet mixer
K - 0-60,000, 0-300,000# Riehle Testing Machine
L - 0-10,000# Tinius Olsen Beam Tester
M - 0-3,000, 0-6,000 0-12,000, 0-30,000 0-60,000# Riehle Testing Machine
N - Outside cement storage area

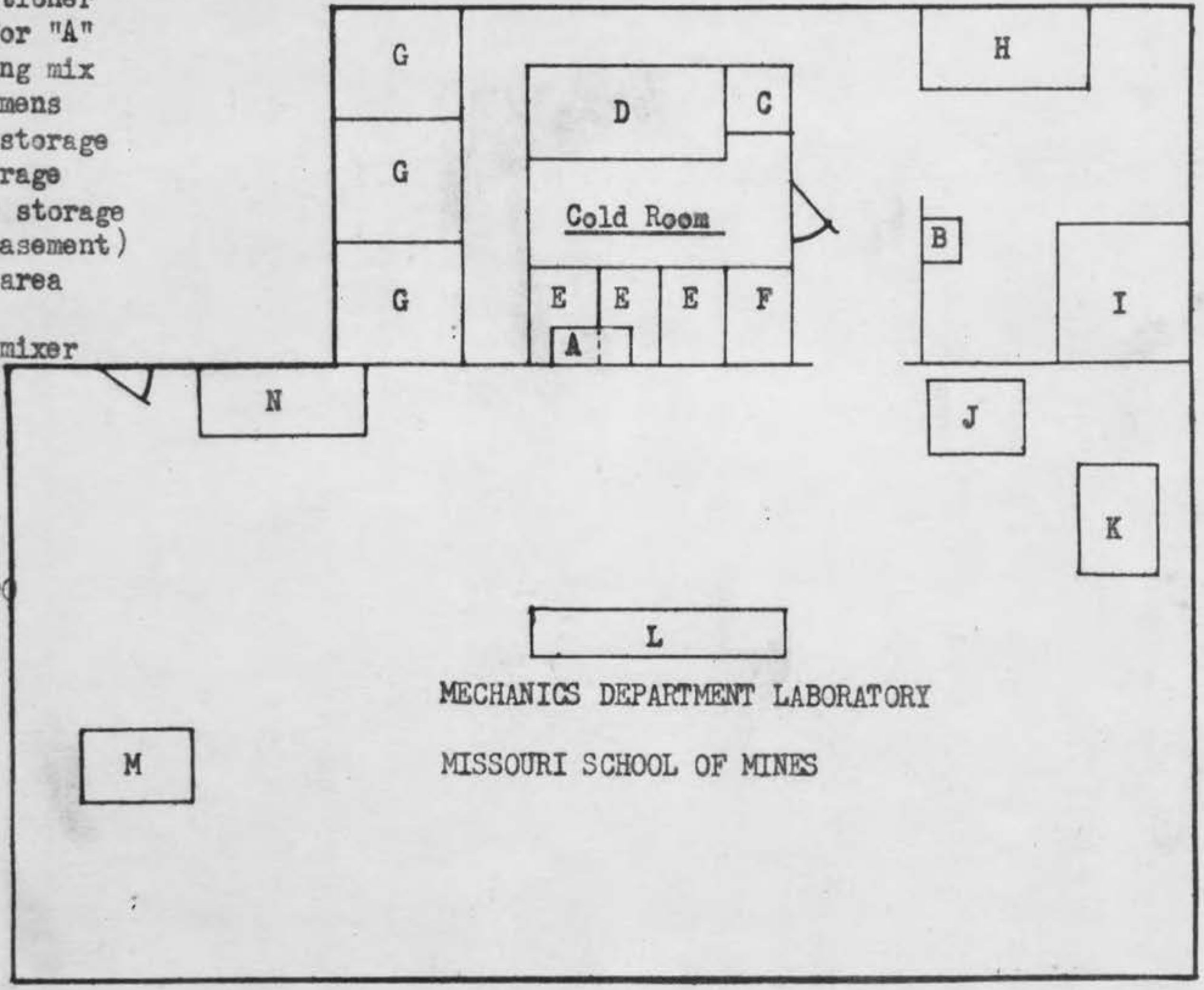


FIGURE 1 - GENERAL LAYOUT OF TESTING FACILITIES

It is the author's opinion that any variations in the physical properties of the specimens tested cannot be attributed to conditions caused by departure from the controlled temperature and humidity.

REQUIREMENTS FOR MATERIALS USED IN TESTS

As the results of this and other investigations were to be utilized by the Missouri State Highway Commission in their pavement designs, effort was made to use materials conforming to the 1955 Standard Specifications of this organization. All materials were carefully checked at both the Missouri School of Mines Laboratories and the Missouri State Highway Materials Laboratory at Jefferson City, Missouri.

Cement In order to maintain similarity of characteristics throughout the tests, two brands of cement were blended and used. Each of the manufacturers of these brands agreed to furnish material from the same burn and such cement was purchased. Cement specified was normal commercial Type I cement. At the inception of this series of tests it was found that the stock-piled material had become lumpy and the possibility of hydration seemed likely. Samples were checked at both laboratories and the results showed that hydration produced no detrimental effects upon the strength of the cement. It was decided to continue the use of stock-piled material after suitable screening to remove all lumps failing to pass through a No. 10 screen. Blending was accomplished during this screening process and equal amounts of each brand were used.

Coarse Aggregate The coarse aggregate for this series of tests was procured from the Bussen Quarry Company, Lemay, Missouri. Arrangements were made with this organization to purchase sufficient material for all of the series of tests without changing the type of aggregate used. The material was crushed limestone of specific gravity 2.66. The specifications for gradation were:

Passing	1 1/2" screen	100%
Passing	1" screen	95-100%
Passing	1/2" screen	25-60%
Passing	#4 screen	0-8%
Passing	#10 screen	0-3%

All material was to be screened, re-proportioned and remixed after removal from the storage bins so as to eliminate the possibility of segregation. The proportions by weight of coarse aggregate were:

Retained	1/2" screen	35%
Retained	#4 screen	60%
Retained	#10 screen	5%
	Total	100%

The size retained on the one-inch screen was eliminated from the mix after it was found to be a negligible quantity. At one time during the testing a shortage of the size aggregate retained on a number ten screen occurred. Rather than throw out the cycle being poured, sand was substituted for this portion of the mix. The results of this series of specimen were from 25 to 35% below those of similar tests, so it was decided to reject these results and re-run the series. No further attempt was made at substitution.

<u>Fine Aggregate</u> The fine aggregate used was river sand procured from the Meramac River Sand and Gravel Company, Pacific, Missouri. The specific gravity was found to be 2.55, and no specifications were imposed as to gradation. The segregation of fine aggregate in the storage bins was assumed to be negligible and no provision was made for correction.

<u>Water</u> Mixing water was procured from the system of the Missouri School of Mines and stored in earthen-ware crocks in the cold room

until used in the mix. The physical and chemical characteristics of the water used may be considered to be the same as that of water furnished by the Rolla Public Utilities System.

<u>Pre-mixing Procedure</u> To insure adequate temperature control, all materials to be used in a pouring cycle were brought to the cold room at least 72 hours previous to the time of mixing. Adequate storage space was provided in the design of the cold room and no difficulties were experienced in complying with this specification. The temperature in the cold room was maintained at 40± 2°F. and the relative humidity during this series was measured at from 87 to 92%. From two to twelve hours prior to mixing, a moisture test was run on the coarse and the fine aggregate to obtain the percentage by weight of moisture present. This percentage was found to be quite small, nevertheless, the necessary correction was made to maintain a constant water-cement ratio in the mix. Calculations for a typical mix design may be found on Page 99.

<u>Mixing Procedure</u> As shown by the sample calculations on Page 99 all materials were batched by weight. The mixing sequence was determined by trial and error to be as follows:

1. Wash mixer
2. Add coarse aggregate
3. Add fine aggregate
4. Add cement
5. Dry batch one minute
6. Add all batch water
7. Mix two minutes.

In order to make each batch under the same conditions the mixer was thoroughly washed before each mixing. After the combining of the various materials, and mixing as outlined above, the batch was dumped into a large pan and remixed to avoid any segregation caused by the mixer. The forms for both the beam and the cylinder test were filled and rodded according to the American Society for Testing Materials Specifications. Mechanical vibration was not used, however, forms were tapped and patted by hand to remove any entrapped air. In addition the beams were puddled with a trowel along both sides and the ends so as to minimize the formation of air pockets and voids. In general, the procedures used resulted in uniform-appearing, honey-comb free test specimens. The only variation was the occasional formation of a fine aggregate vein the the beams which seemed to have no detrimental effect upon test results.

Consistency of Concrete Specifications were not imposed as to the slump desired in this series of tests, therefore, no attempt was made to obtain uniformity. Each batch was checked by the standard American Society for Testing Materials slump test and the results recorded. Slumps varied from 1 1/4" to 2 3/4" during this series of tests, the lower readings invariably occurring in the first batch of a pour. This result was not accounted for, as each batch was mixed under identical circumstances, and each batch was designed for a constant water-cement ratio.

Randomization In a further attempt to minimize as many extraneous variables as possible, the pouring and testing of the various cycles was randomized by following procedures suggested by staff members of the Missouri State Highway Department Materials Testing Laboratory. This randomization was accomplished at the inception of this series of tests and the order of pouring and testing was established as a matter of chance. The complete testing schedule is shown in Figure 2.

POURING AND TESTING SCHEDULE - M.S.M. PROJECT 11 - 40°

Date	27Oct.	28Oct.	29Oct.	30Oct.	3 Nov.	4 Nov.	5Nov.	6 Nov.	10 Nov.	17Nov.	18Nov.	19Nov.	20Nov.	24Nov.	26Nov.	27Nov.	28Nov.	29Nov.	1Dec.	2Dec.	3Dec.
Test	B2				B3 C2				A1	A1					A3				A2		
12H	B28				B35 C21				SCRATCH	A112					A36				A28		
16H	B26				B311 C210					A111					A33				A26		
24H		B21				B33 C25					A11					A37				A21	
36H		B23				B39 C24					A16					A39				A210	
48H			B24				B37 C29					A13					A310				A23
60H			B29				B36 C212					A15					A31				A27
72H				B211				B32 C23					A18					A38			
7D					B27				B310 C22					A110							A32
14D									B25	B38 C26									A19		
28D																			B31 C27		
TEMP	B210				B34 C28					A12					A311				A25		
Date	8Dec.	9Dec.	10Dec.	11Dec.	15 Dec.	22Dec.	24Dec.	29Dec.	5Jan.	6Jan.	7Jan.	8Jan.	12Jan.	19Jan.	2Feb.		4Dec.				
Test	B1 C3								C1												
12H	B111 C35								C19												
16H	B18 C37								C18												
24H		B12 C311								C12											
36H		B13 C38								C14											
48H			B110 C31								C11										
60H			B15 C34								C15										
72H				B16 C39								C110					A211				
7D	A24				B19 C310								C17								
14D			A35		A29	B14 C32								C16							
28D					A14		A34	A22	B17 C36						C111						
TEMP.	B11 C33								C13												

FIGURE 2 - SCHEDULE OF TESTING

Curing of Specimens Soon after pouring, all specimens were placed in the temperature controlled room and kept there until the specified time for testing. The necessity for measuring the batch quantities inside the temperature room, and the problem of storage, resulted in some specimens remaining in the outside air for as long as 45 minutes; however, the temperature was never observed to have risen to more than 49°F. in any of the controlled specimens. Temperatures within the specimens were observed to return to the desired 40± 2°F. of the temperature control room within a short time after being placed inside. From zero to seventy-two hours of age the forms were removed from the desired specimen immediately prior to testing. At seventy-two hours all forms for the later age test cylinders and beams were removed and the specimens were cured for the remainder of the time with the forms removed. No attempt was made at special curing other than the maintenance of constant temperature and humidity. The measurement of temperature was accomplished with a continuous recording thermometer for the ambient temperature and a long stem Taylor thermometer placed within a control specimen for measuring the interior temperatures. The humidity was measured from three to five times a week with a wet and dry bulb thermometer (sling psycometer).

Forms Used During the Tests The purpose of these tests was to determine the characteristics of concrete used by the Missouri State Highway Department, and effort was made to utilize forms used by this organization. The forms used for the cylinders of the compression and indirect tensile tests were made of paraffined paper and were six inches in diameter by twelve inches high with metal bottoms. Stripping of these forms proved to be easily and conveniently done even at the earlier ages and all specimens were of the desired size and shape

FIGURE 3 - BEAM FORM - LAID OUT AND ASSEMBLED

within narrow tolerances. The forming of the beams for the modulus of rupture tests presented several complications because of the early age of some of the specimens. The forms as finally designed by Mr. Peter G. Hansen of the Mechanics Department and constructed in the Civil Engineering Department shop were completely satisfactory and greatly facilitated the running of this series of tests. These forms were constructed of 3/4 inch plywood and were designed with hinges four inches from each end of the bottom side. All parts of the form were removed from the specimens except the bottom, the hunge portions were folded under and the remainder of the form bottom served as a support for placing the beams on the testing machine. Each form was thoroughly oiled with motor oil prior to each pour. A beam form is shown in Figure 3.

Number of Specimens Tested As originally scheduled there were to be 190 specimens tested; however, it was decided to reduce this number. As finally tested there were 109 specimens; 44 compression cylinders, 33 indirect tension cylinders, and 33 beams. There were also several pilot specimens tested and extras which were used wherever needed.

In addition to the main series of test specimens, some 15 cylinders were poured and tested under varying conditions in an effort to substantiate theories evolved from test results.

DESCRIPTION OF TEST PROCEDURES USED, INSTRUMENTATION AND METHODS OF REDUCTION OF DATA

The project consisted of the three types of tests; compression, indirect tension and modulus of rupture. Each of these tests involved distinctively different methods of accomplishment and analysis; accordingly each will be discussed separately.

Compression Test

As mentioned previously the compression tests were performed on standard 6" by 12" cylinders cast in paraffined paper molds with metal bottoms. Tests were planned at ages ranging from six hours to 28 days; however, pilot tests disclosed the six and eight hour specimens to be insufficiently set up to handle, these were removed from the schedule. The 12, 16, 24, 36 and 48 hour specimens were tested on a Riehle Universal Screw Driven Testing Machine having ranges of 0-3000, 0-6000, 0-12,000, 0-30,000 and 0-60,000 pounds. The 60 and 72 hour specimens and those of the 7, 14 and 28 day ages were tested on a Riehle Hydraulic Compression Testing Machine of 0-60,000, 0-300,000 pounds capacity. Both of these machines were located in the laboratory of the Mechanics Department of the Missouri School of Mines. Calibration of the test machines was done by a Riehle representative and they were checked by members of the Mechanics Department staff and found to be within the allowable tolerance of one percent.

Description of Tests Specimens were tested at 12, 16, 24, 36, 48, 60, 72 hours and 7, 14 and 28 days. Prior to 48 hours the cylinders were not capped but were tested with fiber board on the top and bottom to distribute the load. After 48 hours each specimen was capped with approximately 1/4 inch of plaster of paris immediately prior to testing. Load versus deformation was measured and recorded for each cylinder

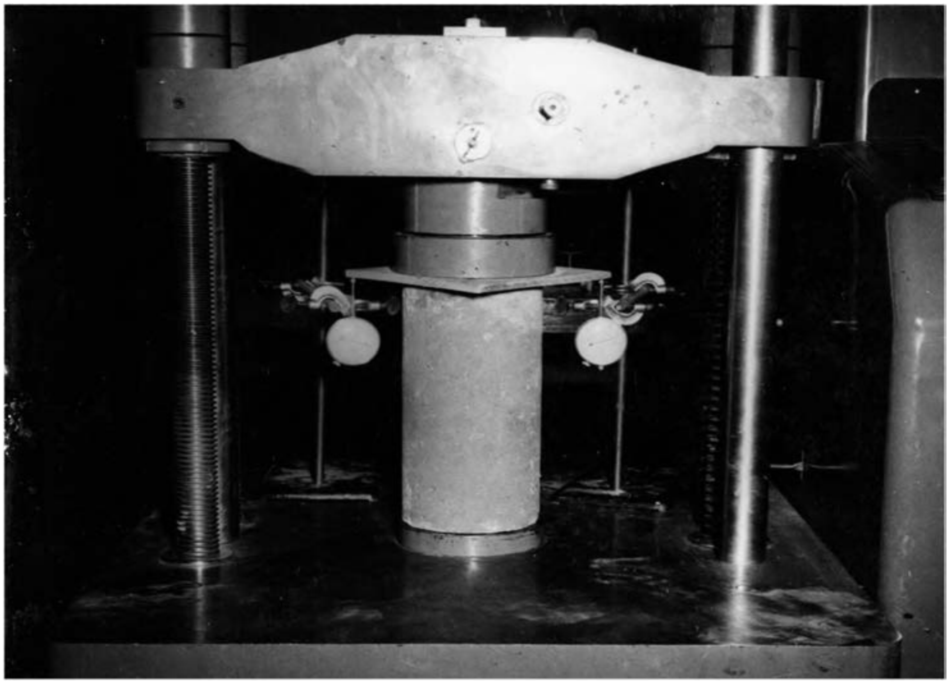


FIGURE 4 - COMPRESSION TEST USING AMES DIAL GAGES

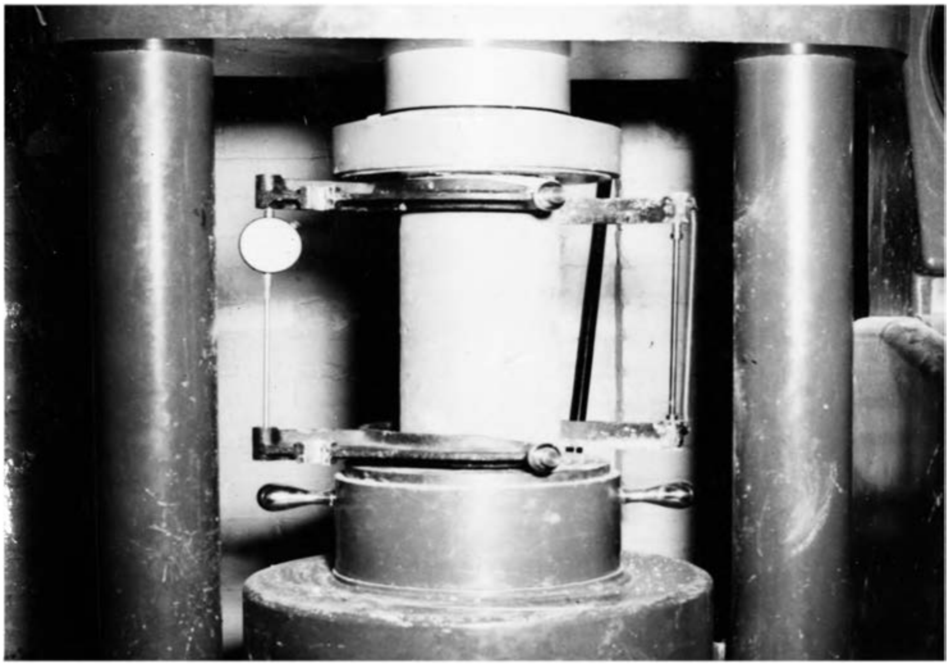


FIGURE 5 - COMPRESSION TEST USING RIEHLE COMPRESSOMETER

tested. Deformations were measured prior to 48 hours of age by the use of Ames dials. For later ages a Riehle compensating compressometer was used. The procedure followed was:

1. Remove form from specimen
2. Cap cylinder if after 48 hours
3. Place cylinder in testing machine
4. Place Ames dials for compressometers
5. Apply load of from ten to fifty pounds
6. Zero Ames dials or compressometer
7. Record load versus deformation during loading
8. Record ultimate load.

The loading rate used was determined from the speed at which readings of the gages and machine could be made and recorded. When this rate was determined, it was used throughout the tests.

Instrumentation Measurements were made of the load, and deformation from no load to ultimate. The Ames dials used for the tests from zero to forty-eight hours of age were placed diametrically opposite each other so as to compensate for any irregularities in the specimen. This arrangement is shown in Figure 4. Each gage had a least count of 0.001 inch. From 48 hours to 28 days deformations were measured by a Riehle compensating compressometer having a least count of 0.005 inches. This test set up is shown in Figure 5. The gage length using the Ames dials was taken as 12 inches; that using the Riehle compressometer was 10 inches, and unit deformations were calculated accordingly.

Method for Reducing Data The laboratory data of load versus deformation were used to determine the modulus of elasticity of the specimen in the age range considered. The cylinder's dimensions allowed it to be analyzed as a short column and loading was assumed to be free from eccentricity and uniformly distributed. Unit stress (s) was then determined to be equal to the load (P) divided by the cross-sectional area (A). Unit deformation (e) was equal to the total deformation (D) divided by the proper gage length (L).

Unit stress was then plotted against unit strain and the secant modulus of elasticity was used; primarily, because of the four standard measures of modulus of elasticity it represents the most definitely determinable quantity. Other curves for this series were drawn either from laboratory data or calculated data taken from laboratory results.

EXPLANATION OF TABLES AND GRAPHS
COMPRESSION SERIES

Tables All laboratory data gathered dueing the investigation are included in tabular form. The stress and strain measurements for all cylinders tested at each age are listed on pages 22 to 31. In addition, the average strain reading for each increment of stress is shown. Immediately following on page 32 is a compilation of stress, strain and modulus of elasticity data gathered either from the laboratory data or taken from the graphs which follow.

Graphs All laboratory data was not visually presented as it was felt average curves would be most indicative of the results obtained. Pages 33 to 42 contain graphs of stress versus strain for the ages tested. Attention is directed to the departure from normal stress - strain relationships for concrete of the curves drawn for the ages of 16, 36, 48, 60 and 72 hours. This variation is further elaborated upon in the discussion of this series of tests. The next series of graphs show modulus of elasticity and ultimate stress data obtained from the stress - strain curves and are presented for the two age ranges, zero to seventy-two hours and zero to twenty-eight days, so as to better show the very early age characteristics of the concrete tested. The last graph in this series shows the variation of strain at 50% of the ultimate compressive stress with age.

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 12 HOURS

STRESS PSI	STRAIN IN / IN x 10-5				
	C1	C2	C3	4 X-1	AVG.
0	0		0	0	0
0.88	0	NO RESULTS OBTAINED	83	228	104
1.76	258		379	604	414
2.65	587		708	1088	794
3.54	893		992	1575	1153
4.42	1222		1280	2022	1508
5.30	1505		1580	2580	1888
6.18	1822		1892		1857
ULTIMATE	6.93	----	6.63	5.48	6.35

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 16 HOURS

STRESS PSI	STRAIN IN / IN x 10-5				
	C1	C2	C3	4 X-3	AVG.
0	0		0	0	0
0.88	233	NO RESULTS OBTAINED	0	321	277
1.76	525		429	754	569
2.65	812		763	1145	906
3.54	1054		1146	1525	1242
4.42	1250		1397	1880	1509
5.30	1441		1560	2175	1725
6.18	1600		1722	2555	1959
7.07	1777		1872		1825
7.95	1988		2050		2019
8.83	2163		2240		2202
9.72	2340		2490		2415
10.60			2845		
ULTIMATE	10.24	----	10.88	6.88	9.33

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 24 HOURS

STRESS PSI	STRAIN IN / IN x 10^{-5}				
	C1	C2	C3	4 X-6	AVG.
0	0	0	0	0	0
3.54	336	333	437	429	383
7.07	669	667	712	980	757
10.60	1046	1018	825	1566	1114
14.13	1362		1021	2104	1496
17.68	1688		1280		1484
21.20			1538		
24.70			1828		
ULTIMATE	19.95	11.82	26.0	15.01	18.20

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 36 HOURS

STRESS	STRAIN IN / IN x 10^{-5}				
PSI	C1	C2	C3	4 X-5	AVG.
0	0	0	0	0	0
3.54	195	----	95.5	75	121.8
7.07	307.5	233		150	230.2
10.6	412.5		214	242	289.5
14.2	505	446		350	433.6
17.65	592		306	467	455.0
21.2	682	662		600	648
24.75	767		486	783	678.7
28.3	855	890		958	901
31.8	946		645	1168	919.6
35.4	1032	1136		1550	1239.3
38.85	1117		815		
42.4	1208				
	1298		1020		
	1409		1280		
ULTIMATE	52.1	38.01	51.0	35.55	44.20

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 48 HOURS

STRESS	STRAIN IN / INx10^{-5}				
PSI	C1	C2	3 X-4	4 X-2	AVG.
0	0	0	0	0	0
7.08	171	179	334	388	268
14.16	288	287.5	505	615	423.8
21.2	385	358	671	779	548.3
28.3	447	420	834	896	649.3
35.4	478	477	984	971	727.5
42.4	528	525	1129	1025	801.8
49.4	558	571	1271	1075	868.8
56.6	581	604	1375	1125	921.3
63.6	600	675	1450	1166	972.3
70.7		740	1529	1210	1193
77.8		875	1666	1279	1273
84.8					
ULTIMATE	128.2	80.8	82.2	85.2	82.7

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 60 HOURS

STRESS PSI	STRAIN IN / IN x 10^{-5}				
	C1	C2	C3	4 X-2	AVG.
0	0	0	0	0	0
17.68	189.5	62.5	412.5	208	218
35.4	279	161.4	549	298	322
53.0	354	262	607	331.5	389
70.8	417	341.5	652.5	383	448.5
88.4	470.5	421	693	427	503
106.0	553	502	726	462.5	561
123.8	611.5	595.5	751	501	615
141.2	662	683	772	537	663.5
159.0	701	791	782	569.5	711
176.6	767		792	602	720
194.2	829.5			624.5	727
212.0	892			662	777
229.5				697	
247.0				731	
ULTIMATE	252.0	174.5	325.0	266.0	254.4

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 72 HOURS

STRESS	STRAIN IN / IN x 10^{-5}				
PSI	C1	C2	C3	4	AVG.
0	0	0	0		0
17.65	108	62.7	356		275.6
35.4	225	138	546		303
53	300	196	667		388
70.8	350	244	733		442
88	400	292	792		495
106	437	333	850		540
124	471	379	883		578
141	500	426	923		616
159	525	473	958		652
177	558	522	988		689
194	575	563	1017		718
212	592	598	1042		744
229.5	612	624	1071		769
247	633	661	1096		797
265	652	701	1122		825
282.5	672	767	1146		862
317.5	704		1204		954
354	738		1238		988
423	812		1358		1085
ULTIMATE	462.5	296.5	443.0		400.7

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 7 DAY

STRESS PSI	STRAIN IN / IN X 10^{-5}				
	C1	C2	C3	4	AVG.
0	0	0	0	0	0
71	0.5	2.5	0		1.0
141	2.5	4.0	2.5		3.0
212	5.0	7.0	4.5		5.5
283	7.0	9.0	5.0		7.0
353.5	8.5	11.5	6.5		8.8
424	11.0	14.0	10.0		11.7
494	13.5	17.5	13.5		14.8
565	15.0	21.5	16.5		17.7
637	17.5	25.3	20.0		20.9
707	20.0	30.0	22.0		24.0
778	24.0	36.5	25.0		28.3
848	27.5	43.0	29.0		33.2
918	31.5	51.5	32.5		38.5
989	35.0	60.0	37.5		44.2
1060	40.0	80.00	41.5		53.8
1130		100.0			
1200					
1236	70.0		57.5		63.8
ULTIMATE	1,284.0	1,162.0	1,351.0		1,265.5

COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 14 DAY

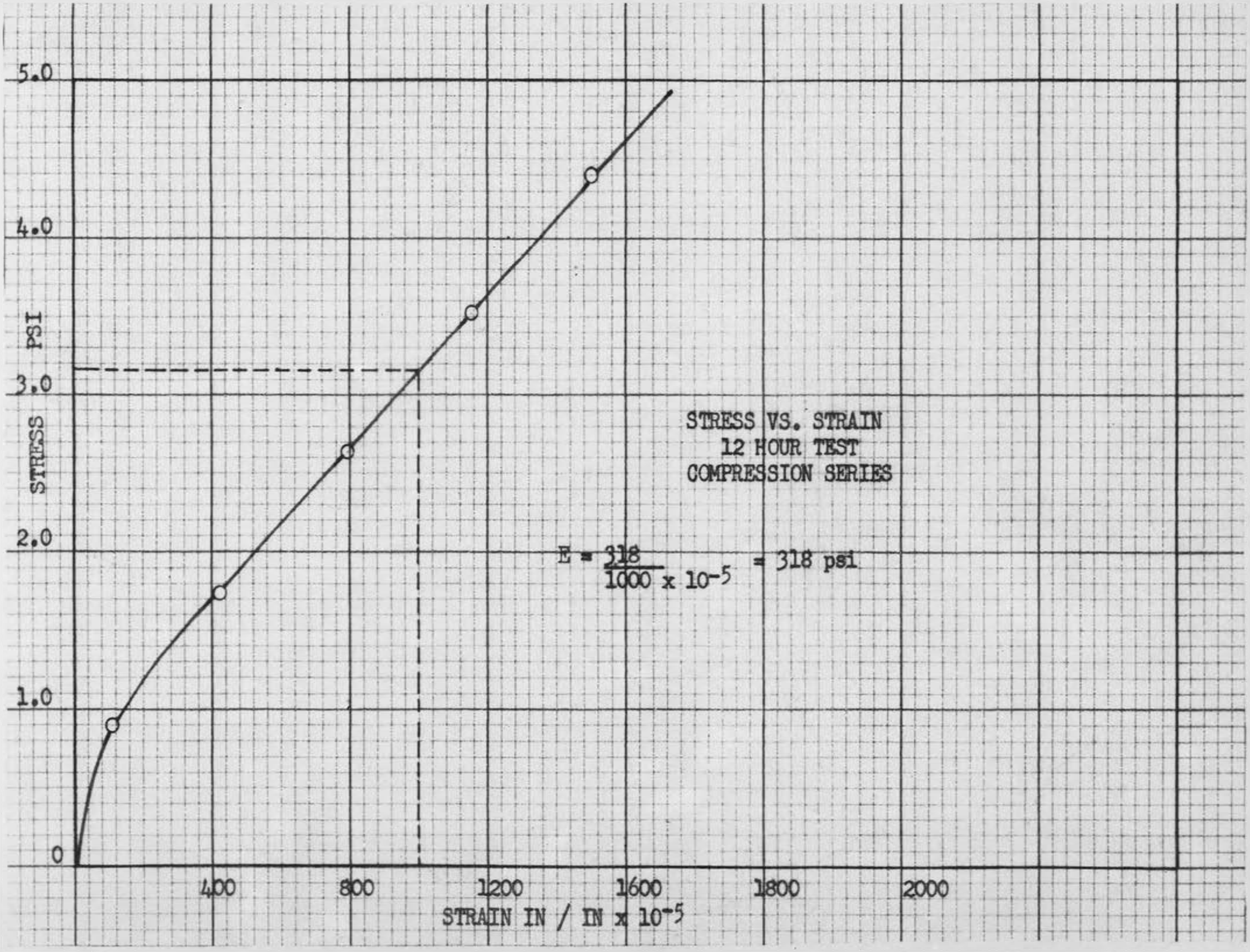
STRESS PSI	STRAIN IN / IN x 10^{-5}				
	1 C-2	2 C-3	3 x-3	4 X-1	AVG.
0	0	0	0	0	0
176.5	3.75	5.0	3.5	3.75	4.0
353	8.5	10.0	9.0	7.0	8.6
530	15.0	17.5	14.75	11.25	14.6
707	21.75	25.0	20.0	17.0	20.9
884	27.5	32.5	25.0	22.5	26.9
1060	37.5	38.75	31.5	28.5	35.4
1235	50.0	47.5	38.0	34.5	42.5
1412	77.0	55.0	44.0	41.0	54.3
1590		65.0	50.0	49.5	
1765		76.25	56.5	57.5	
1942		88.75	69.0	67.5	
2120		107.5	73.5	84.0	
2295		130.0	83.5		
2470			95.0		
2645			115.0		
ULTIMATE	1,462.0	2,490.0	2,685.0	2,260.0	2,476.0

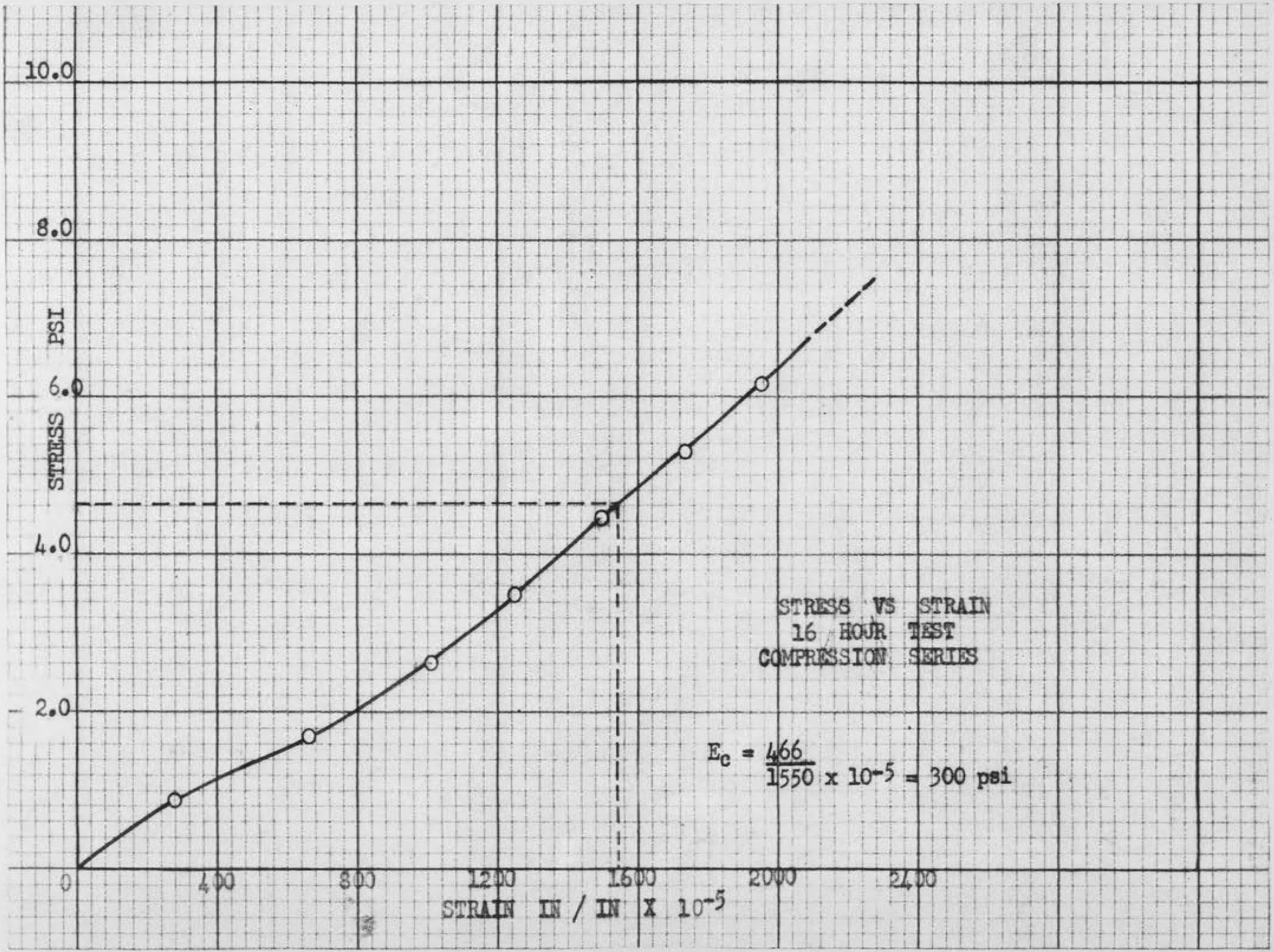
COMPRESSION SERIES
STRESS AND STRAIN MEASUREMENTS
6" x 12" CONCRETE CYLINDERS
AGE - 28 DAY

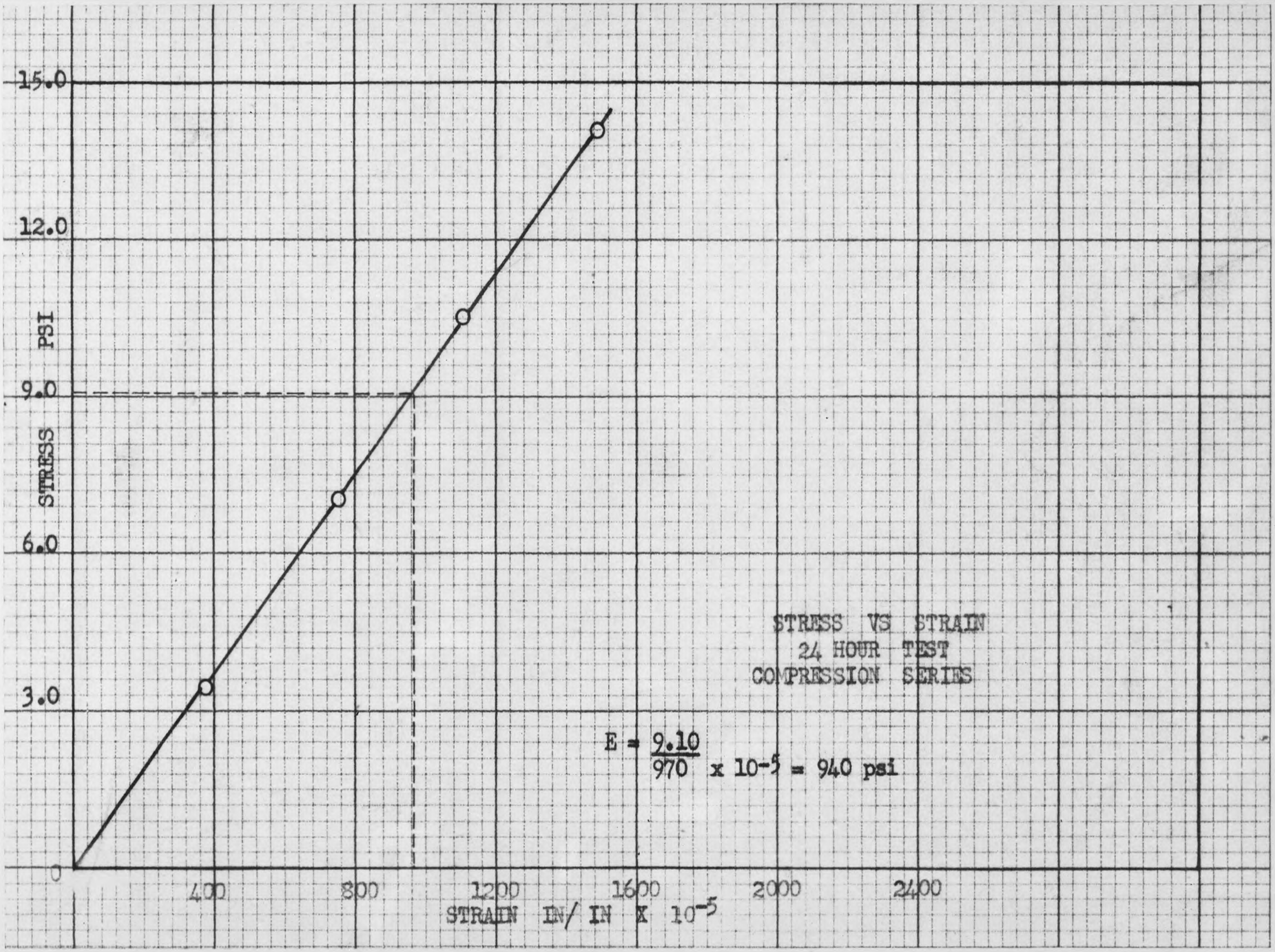
STRESS PSI	STRAIN IN / IN x 10^{-5}				
	C1	C2	C3	4	AVG.
0	0	0	0	0	0
17.65	2.5	3.75	3.75		3.31
353	7.0	10.63	7.5		8.41
530	10.0	19.5	11.75		13.8
707	14.0	27.5	15.0		18.8
884	17.5	34.5	20.3		24.1
1060	21.0	42.0	25.0		29.3
1235	27.5	48.8	29.8		35.4
1412	32.5	57.5	34.0		41.3
1590	37.5	66.3	39.3		47.7
1765	45.0	76.5	45.0		55.5
1942	57.5		51.3		
2120	65.0		56.5		
2295					
2470			75.0		
2645					
2825					
ULTIMATE	2,320	1,950	2,780		2,550

COMPRESSION SERIES TABULATION OF STRESS, STRAIN AND MODULUS OF ELASTICITY DATA

AGE OF SPECIMEN	MODULUS OF ELASTICITY (SECANT) PSI	ULTIMATE STRESS (AVERAGE) PSI	STRAIN 50% ULTIMATE IN./IN. (AVERAGE)
12 Hr.	318	6.35	0.01000
16 Hr.	300	9.35	0.01560
24 Hr.	940	18.20	0.00970
36 Hr.	3,450	44.20	0.00642
48 Hr.	5,200	82.7	0.00800
60 Hr.	20,500	254.4	0.00622
72 Hr.	27,500	400.7	0.00730
7 Day	3,010,000	1,266.0	0.00021
14 Day	2,860,000	2,476.0	0,00043
28 Day	3,450,000	2,550.0	0.00037

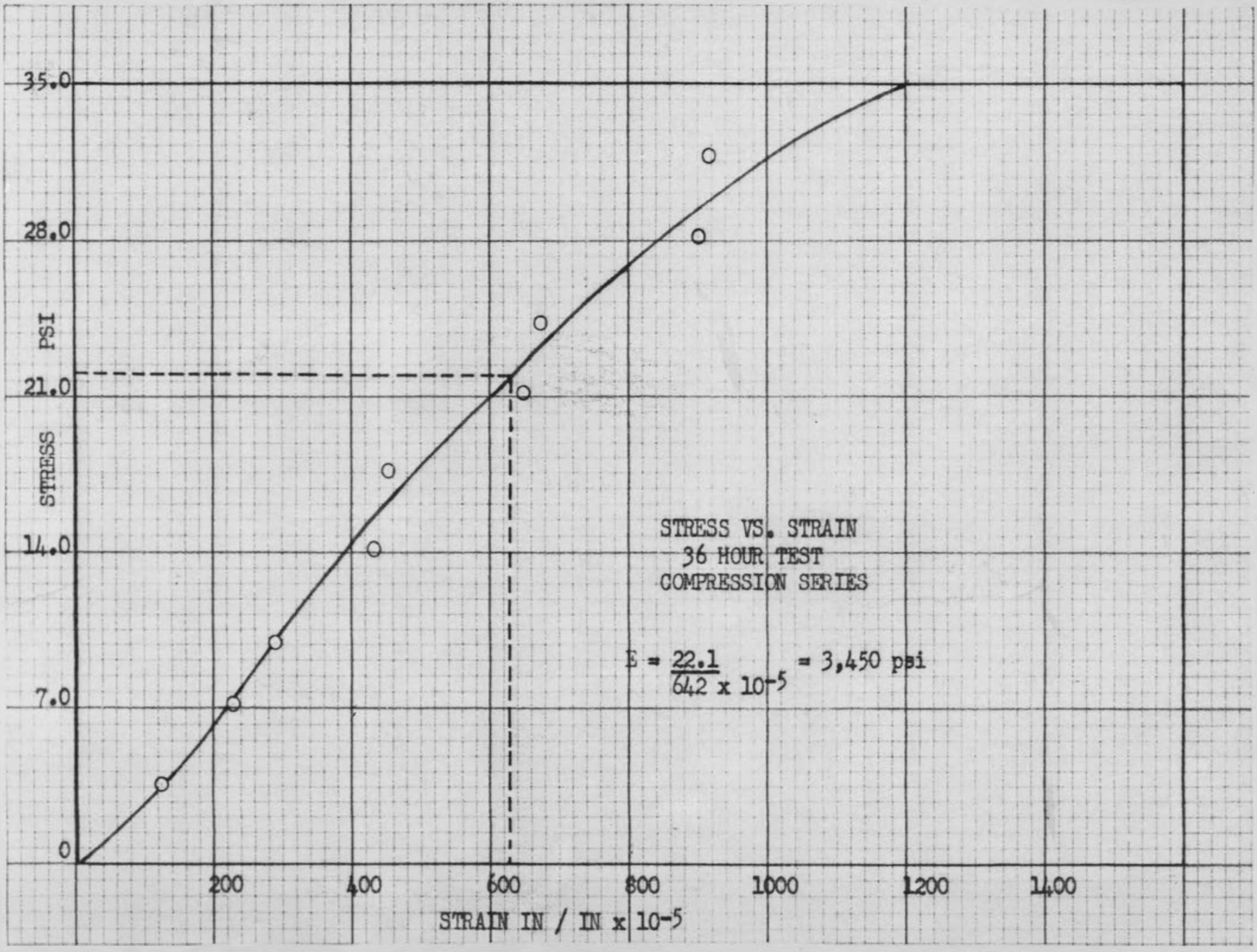

STRESS VS. STRAIN
12 HOUR TEST
COMPRESSION SERIES
E = 318 / 1000 x 10-5 = 318 psi
STRESS PSI
STRAIN IN / IN x 10-5
5.0
4.0
3.0
2.0
1.0
0
400
800
1200
1600
1800
2000


10.0
8.0
6.0
4.0
2.0
STRESS PSI
0
400
800
1200
1600
2000
2400
STRAIN IN / IN X 10^{-5}
STRESS VS STRAIN
16 HOUR TEST
COMPRESSION SERIES
$E_c = \frac{466}{1550 \times 10^{-5}} = 300$ psi



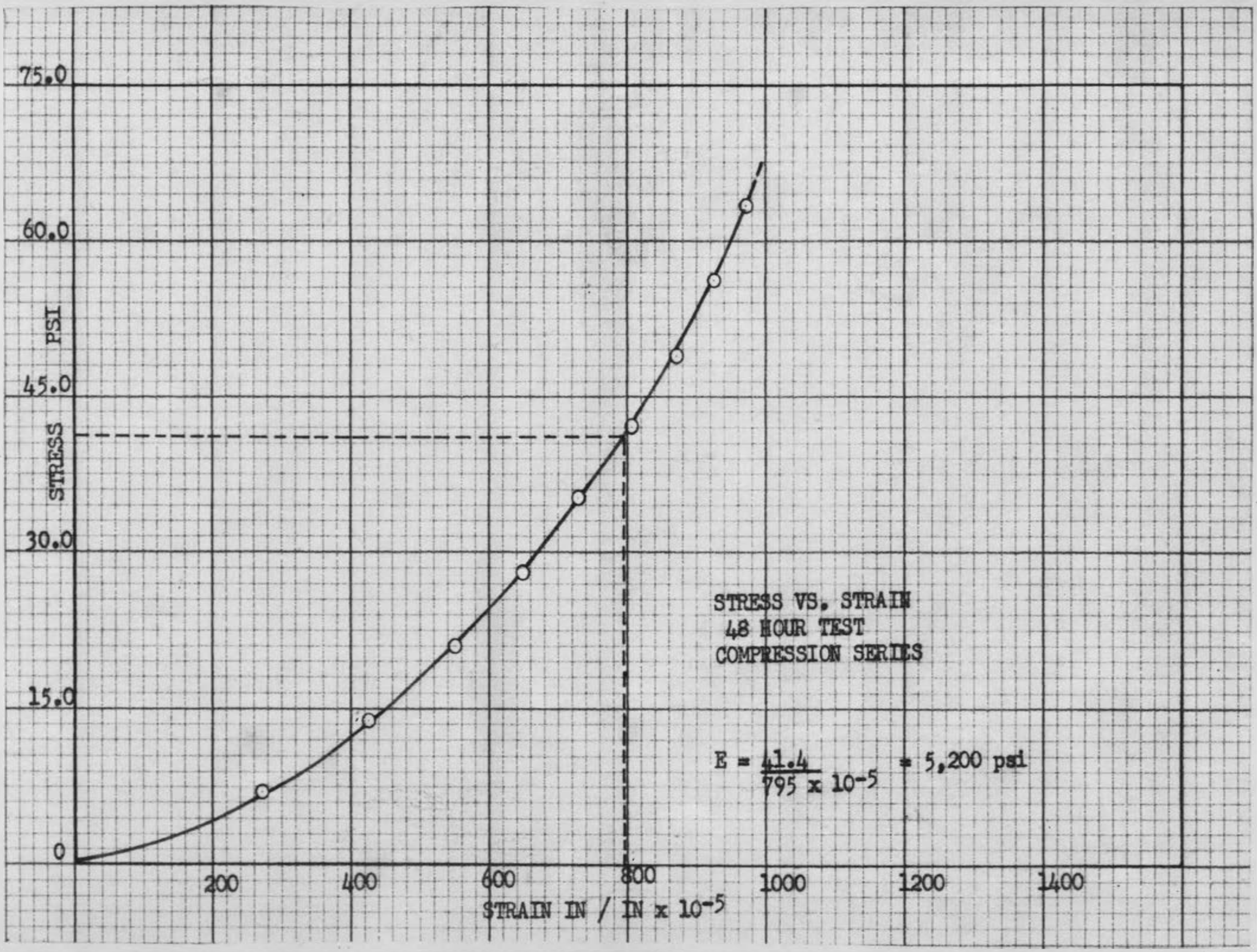
STRESS VS STRAIN
24 HOUR TEST
COMPRESSION SERIES

$$E = \frac{9.10}{970} \times 10^{-5} = 940 \text{ psi}$$



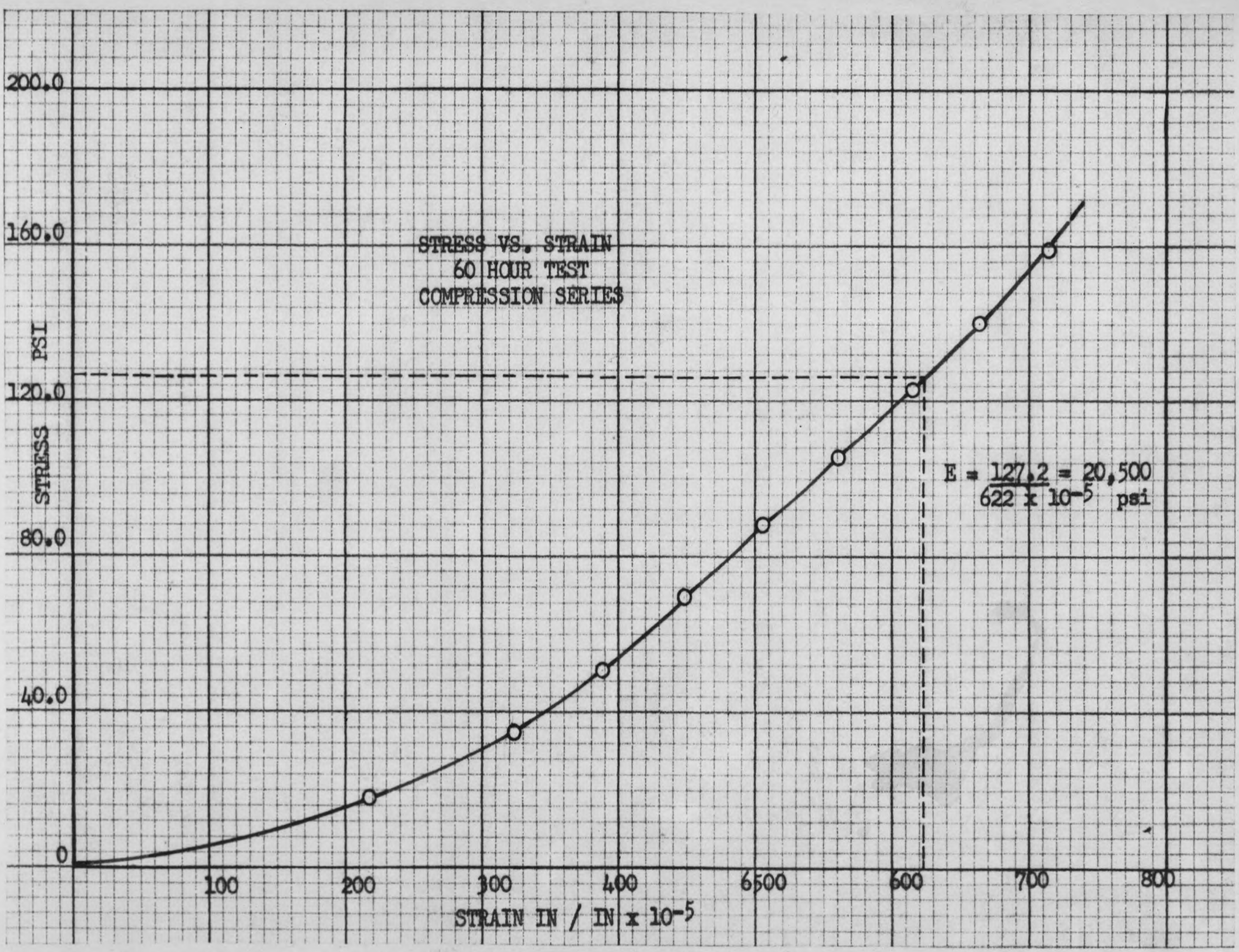
STRESS VS. STRAIN
36 HOUR TEST
COMPRESSION SERIES

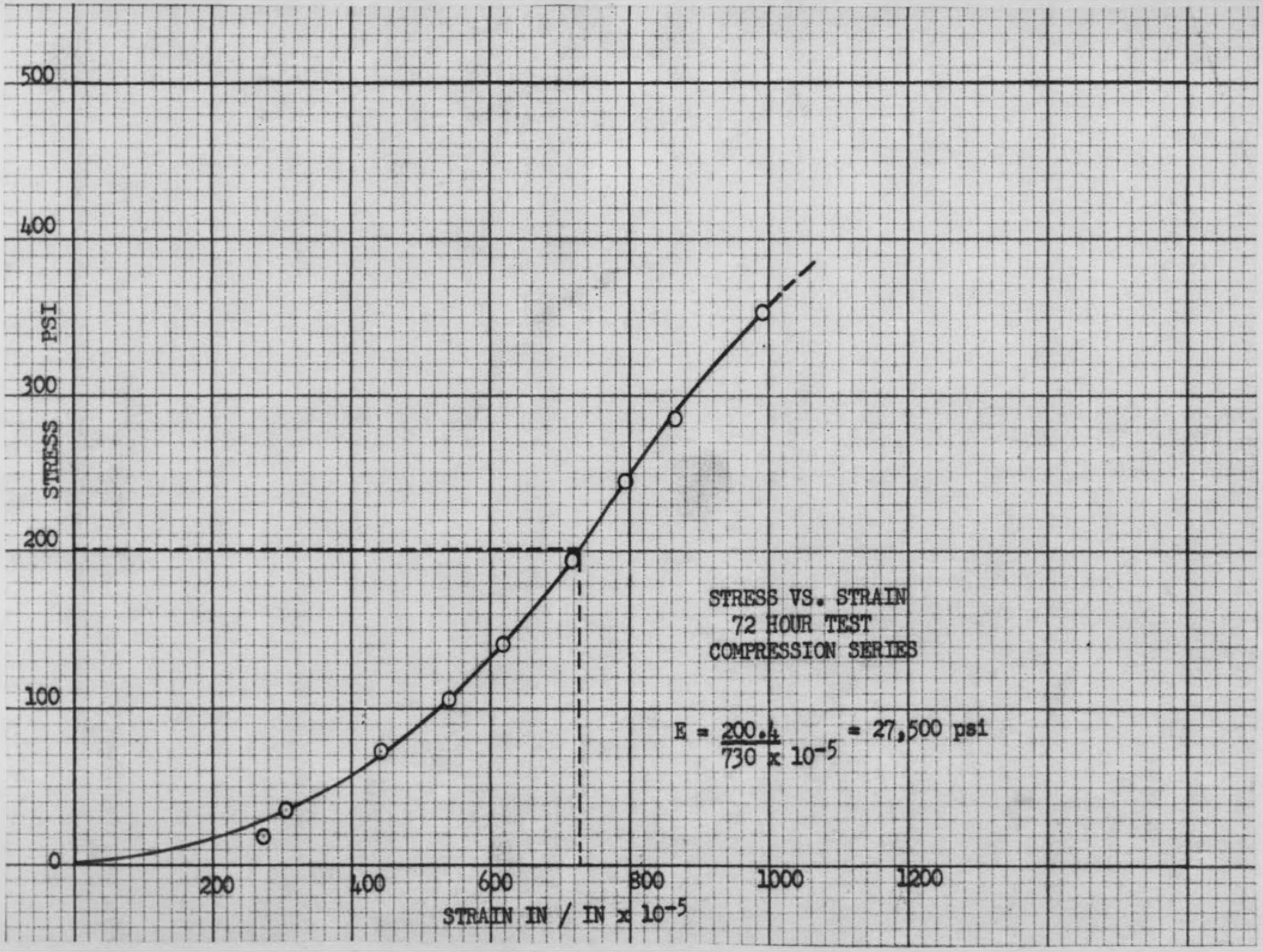
$$E = \frac{22.1}{642 \times 10^{-5}} = 3{,}450 \text{ psi}$$



STRESS VS. STRAIN
48 HOUR TEST
COMPRESSION SERIES

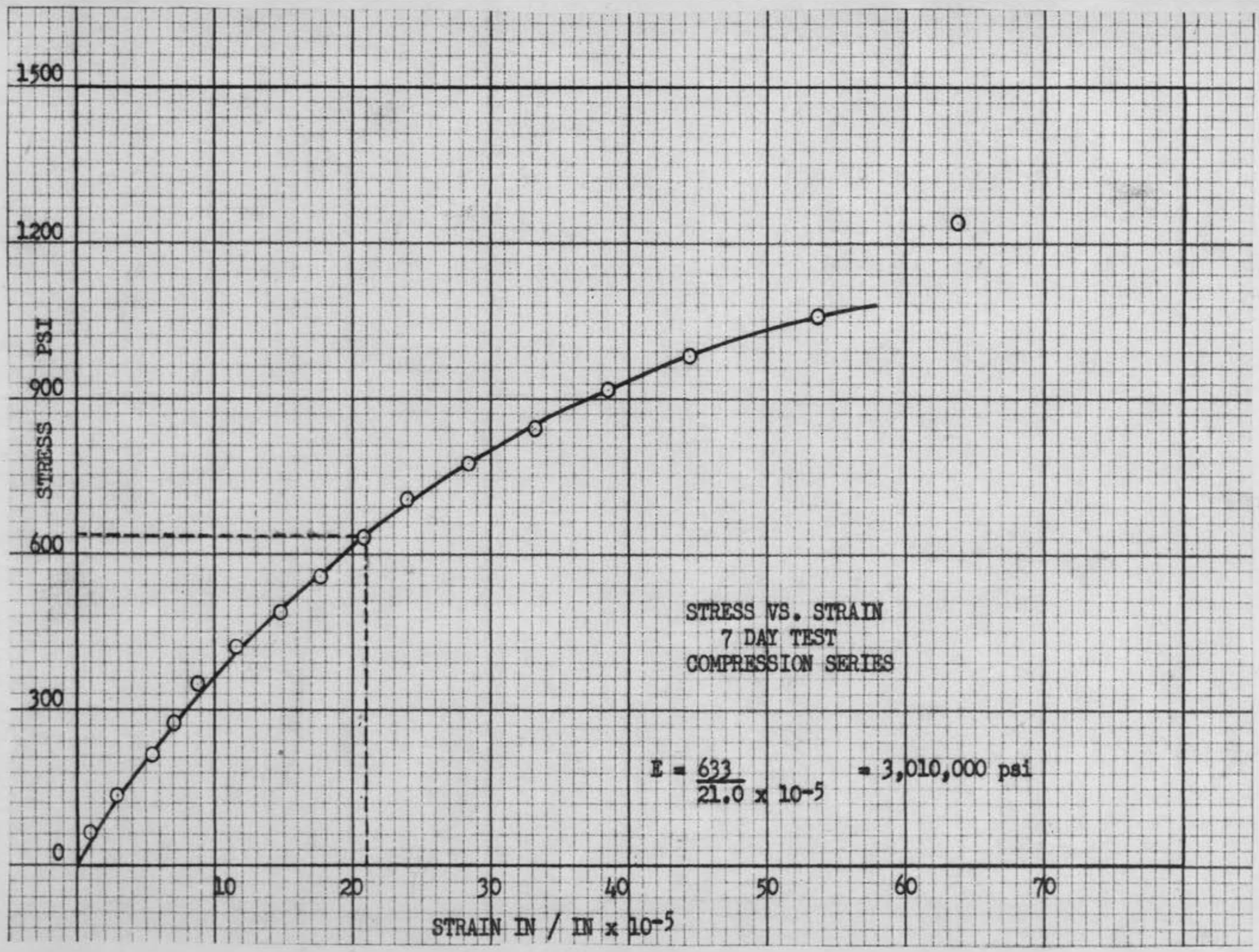
$$E = \frac{41.4}{795 \times 10^{-5}} = 5,200 \text{ psi}$$

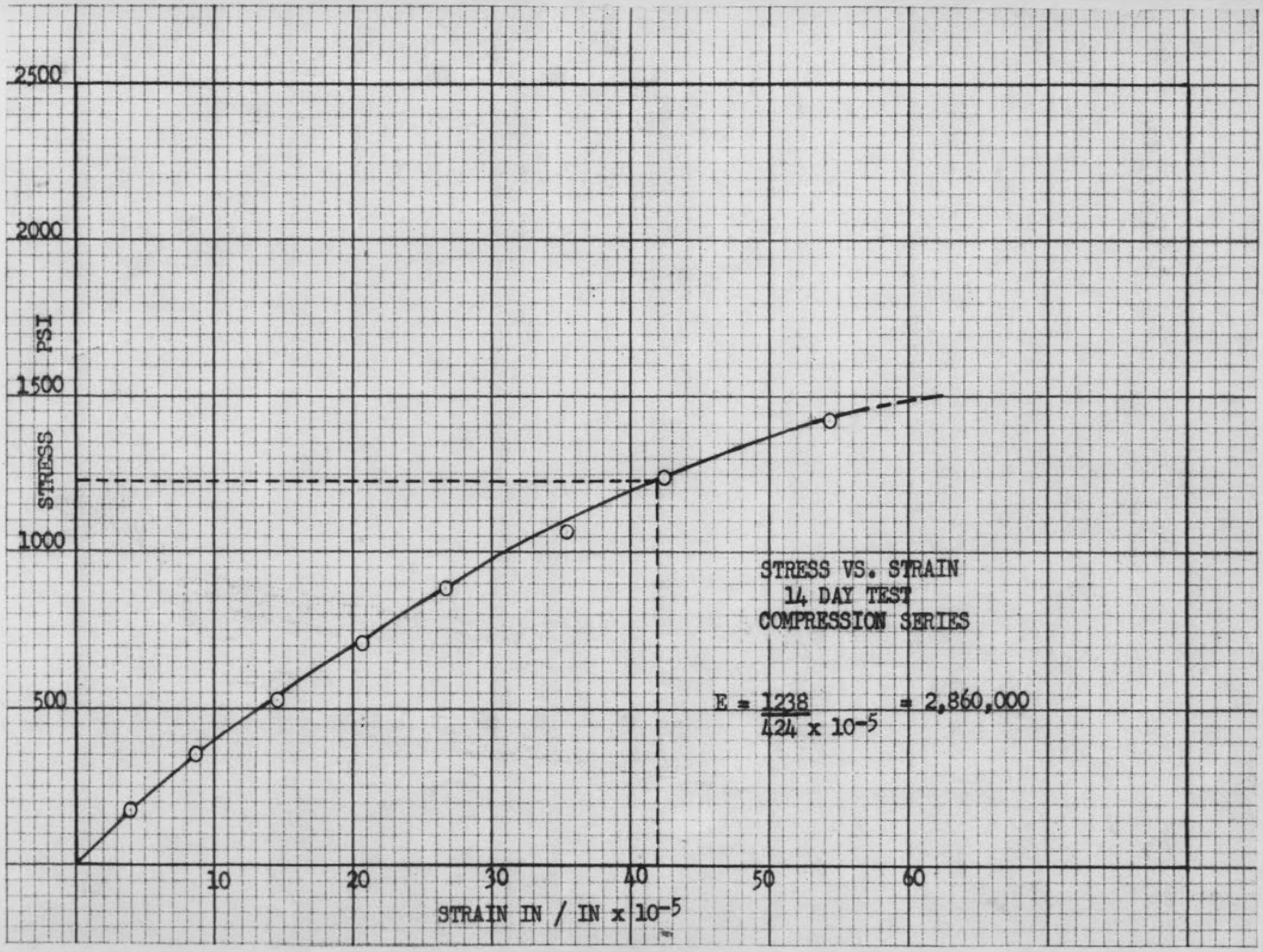

STRESS VS. STRAIN
60 HOUR TEST
COMPRESSION SERIES
STRESS PSI
200.0
160.0
120.0
80.0
40.0
0
100
200
300
400
6500
600
700
800
STRAIN IN / IN x 10-5
E = 127.2 / 622 x 10-5 = 20,500 psi



STRESS VS. STRAIN
72 HOUR TEST
COMPRESSION SERIES

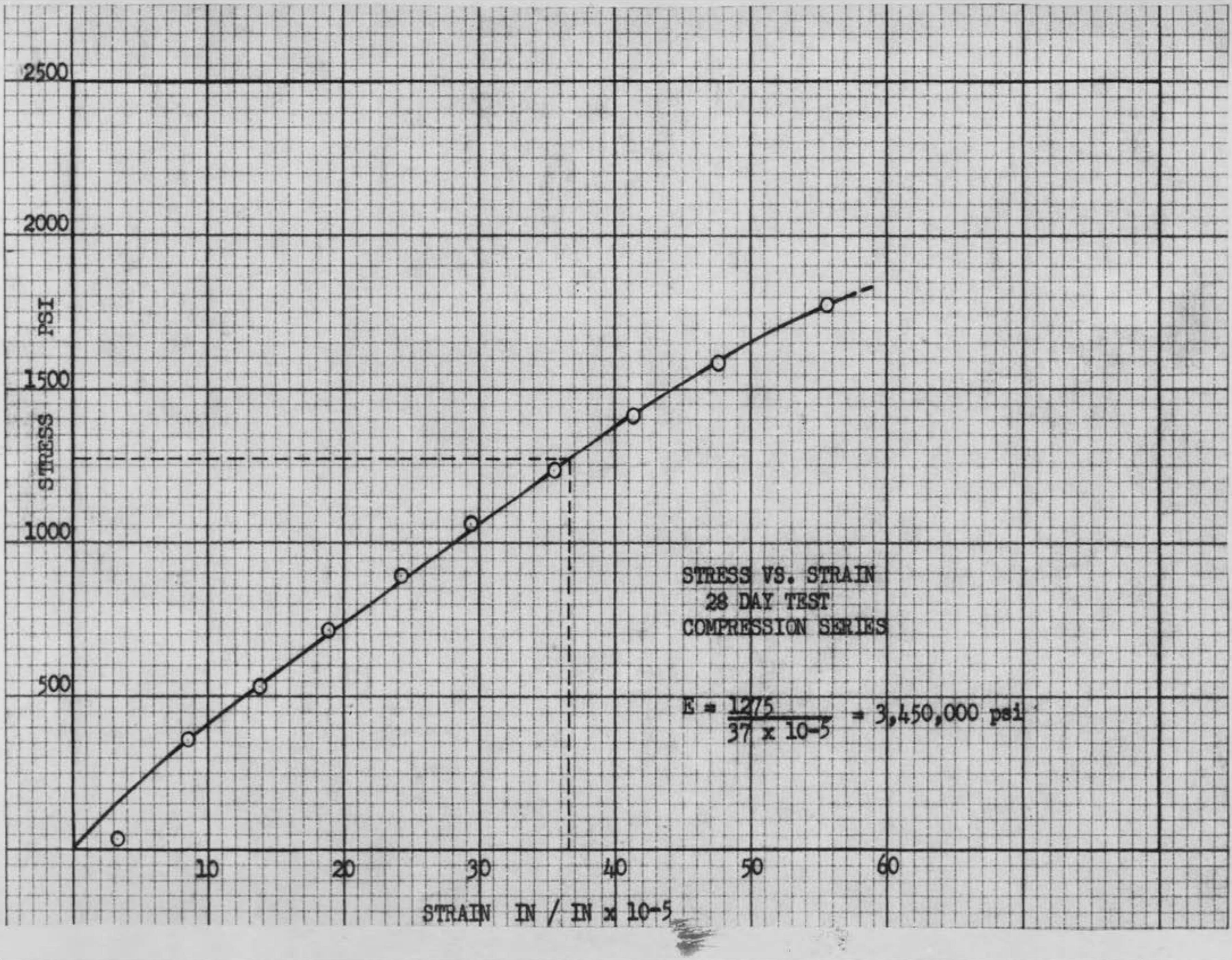
$$E = \frac{200.4}{730 \times 10^{-5}} = 27{,}500 \text{ psi}$$





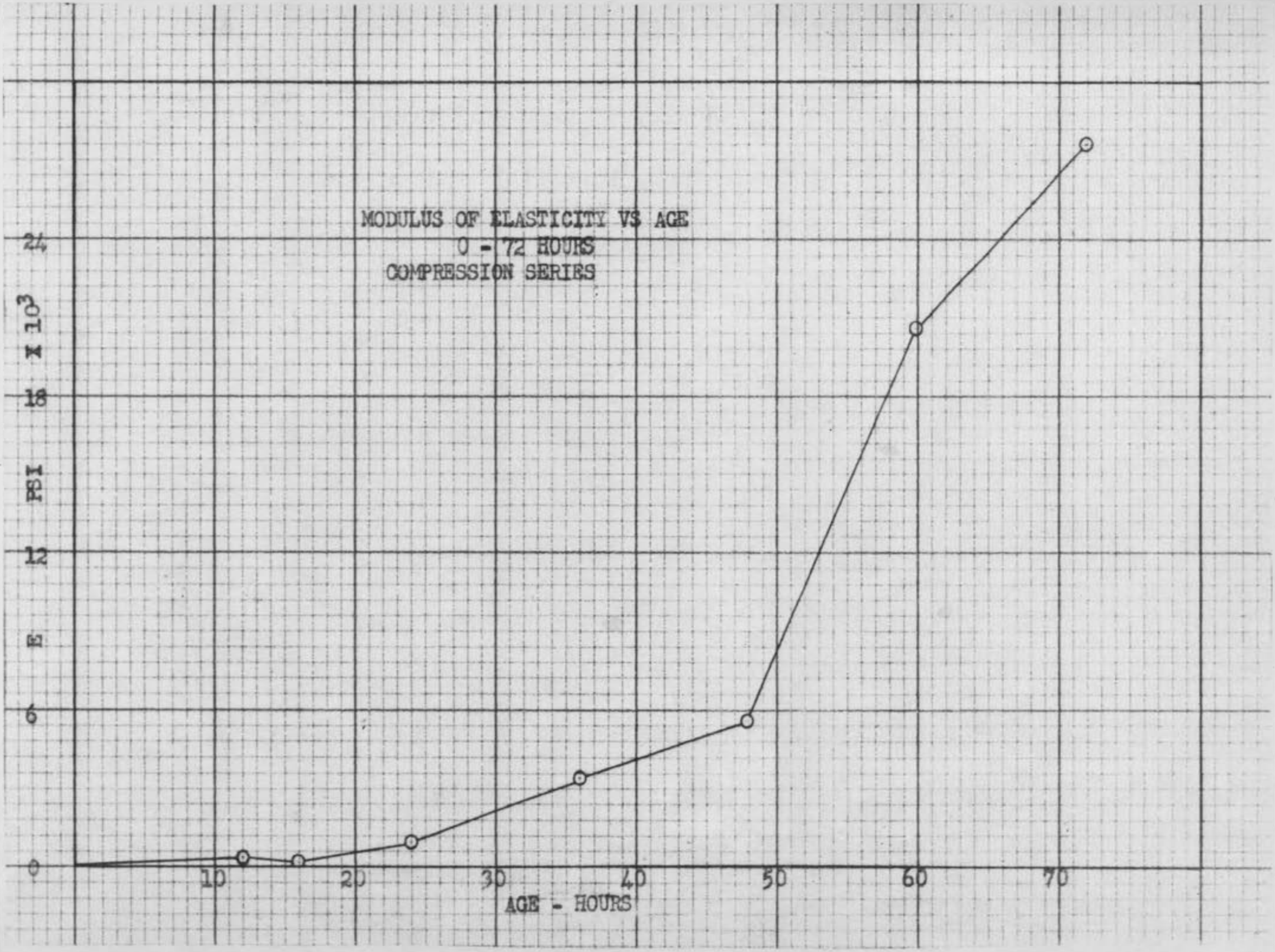
STRESS VS. STRAIN
14 DAY TEST
COMPRESSION SERIES

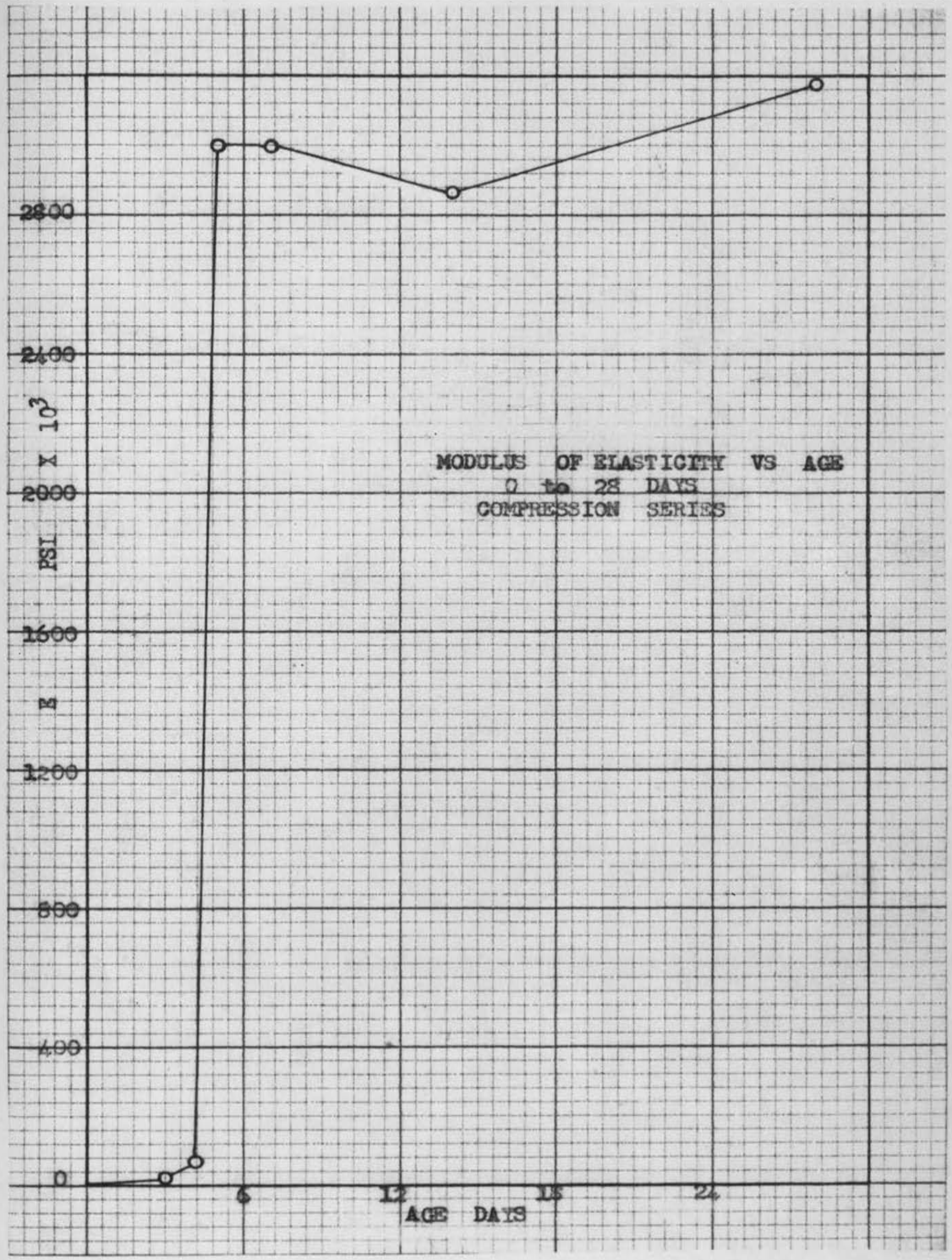
$$E = \frac{1238}{424 \times 10^{-5}} = 2,860,000$$

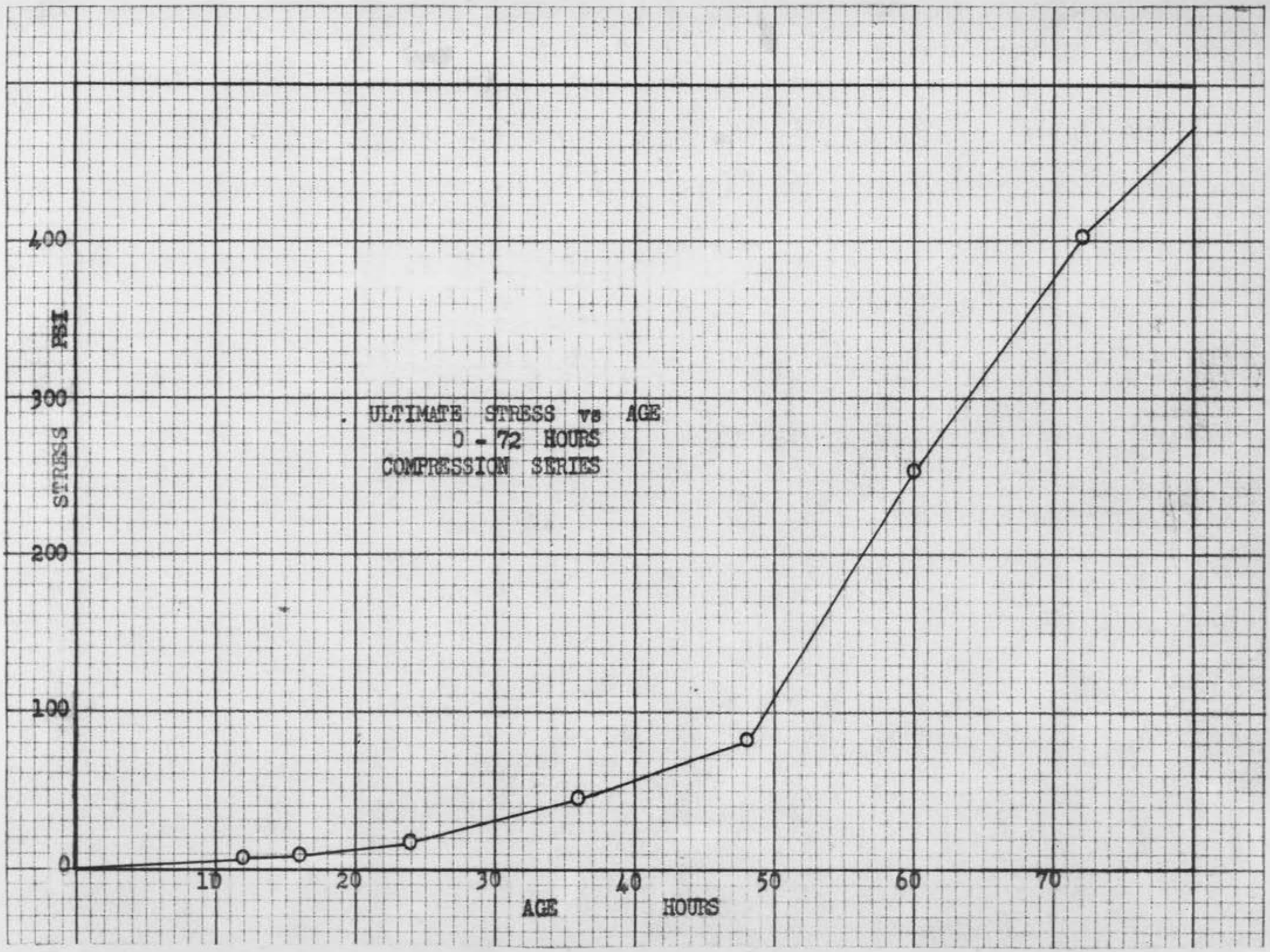


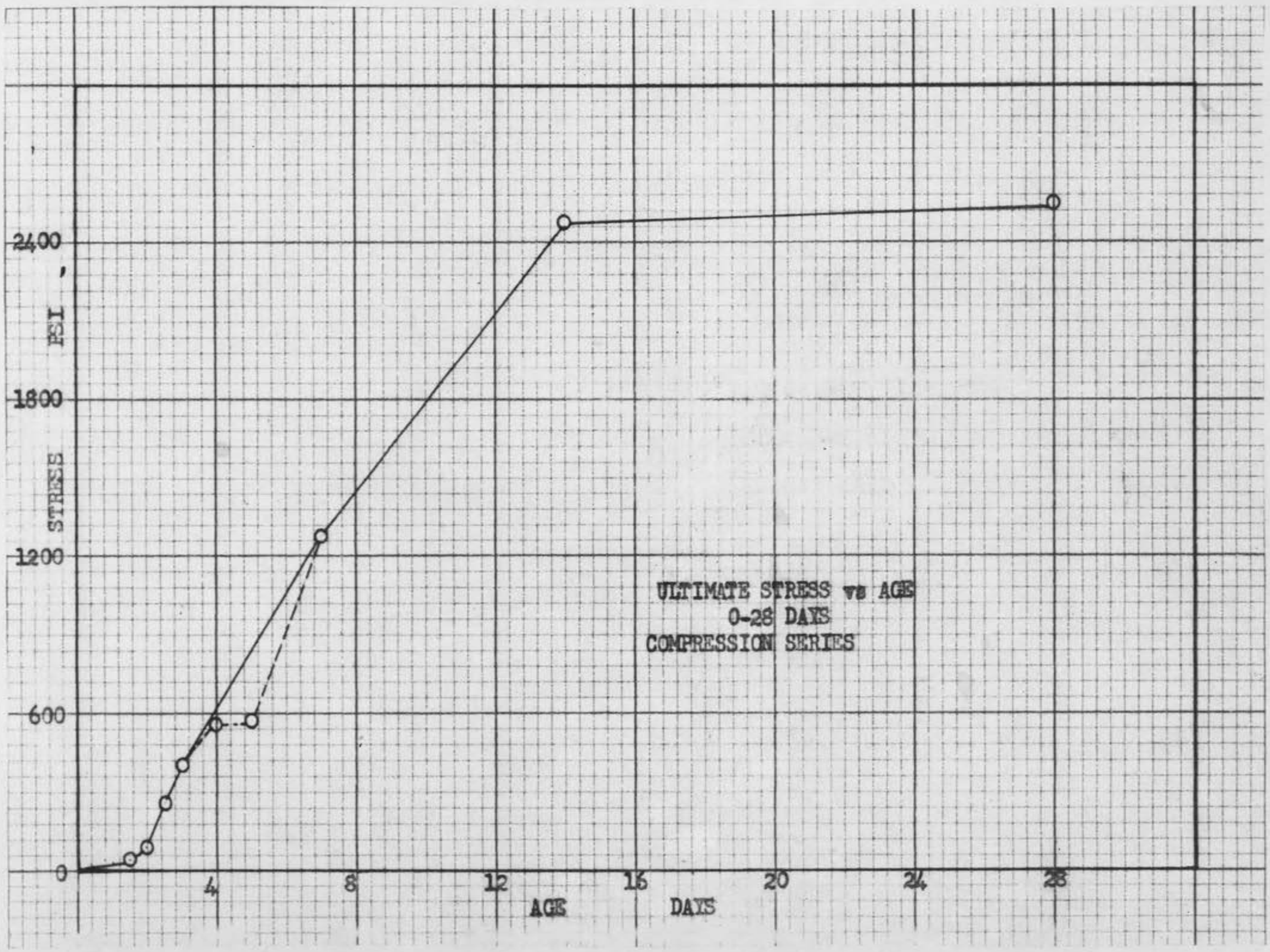
STRESS VS. STRAIN
28 DAY TEST
COMPRESSION SERIES

$$E = \frac{1275}{37 \times 10^{-5}} = 3,450,000 \text{ psi}$$

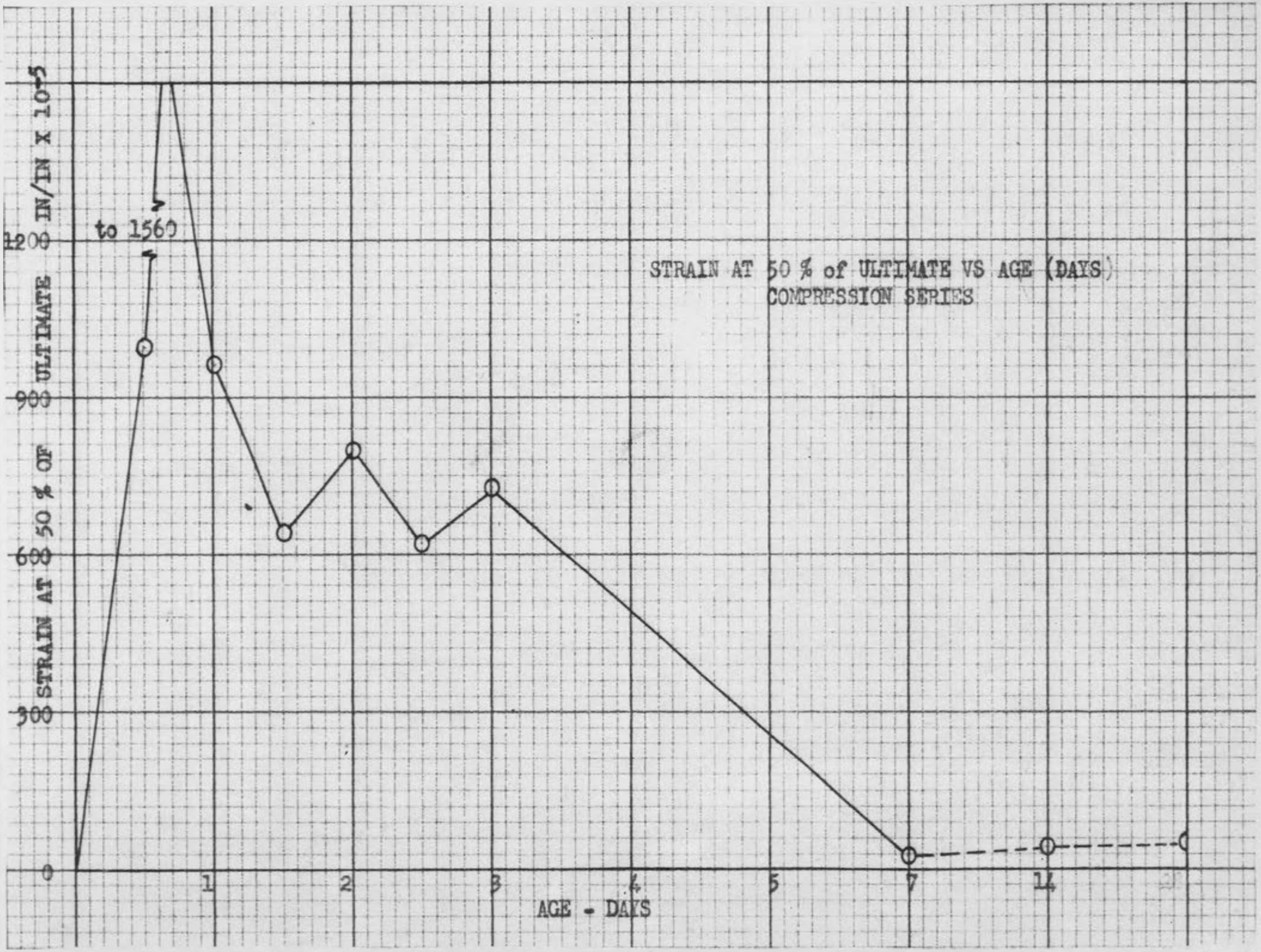

MODULUS OF ELASTICITY VS AGE
0 - 72 HOURS
COMPRESSION SERIES
E PSI X 10^3
0
6
12
18
24
10
20
30
40
50
60
70
AGE - HOURS


MODULUS OF ELASTICITY VS AGE
0 to 28 DAYS
COMPRESSION SERIES
E PSI X 10^3
0
400
800
1200
1600
2000
2400
2800
6
12
18
24
AGE DAYS


ULTIMATE STRESS vs AGE
0 - 72 HOURS
COMPRESSION SERIES
STRESS PSI
400
300
200
100
0
10
20
30
40
50
60
70
AGE HOURS



ULTIMATE STRESS vs AGE
0-28 DAYS
COMPRESSION SERIES


STRAIN AT 50 % of ULTIMATE VS AGE (DAYS)
COMPRESSION SERIES

INDIRECT TENSILE TEST

A consideration of standard tests in use for the determination of the tensile strength of concrete, shows none to be completely satisfactory. The various shapes of specimens used in direct tension tests have all suffered from stress concentrations, and their making and testing have been comparatively difficult processes requiring considerable skill and care. The flexural test, although easier and requiring no unusual details, gives results in excess of the true tensile strength and is thus unsatisfactory. Effort was made to develop or utilize a new method for the determination of the tensile strength.

Such a new test was introduced by Mr. F. Carniero(5), of Brazil and it was decided to include this test in the current series. Mr. Carniero's method utilized a compressive load applied to a cylinder along two opposite generators. This loading sets up a uniform stress over the diametral plane containing the load and failure occurs along that plane. A cylinder set up for testing is shown in Figure 6.

The tests were conducted on a Riehle Universal Testing Machine with a capacity of 0-60,000, 0-300,000 pounds. Strips of aluminum, faced with plywood, were placed between the platens of the machine and the specimen to obtain the desired results. Tests were scheduled on specimens ranging in age from six hours to twenty-eight days; however, the six and eight hour cylinders proved too plastic for handling and these test ages were omitted. The forming and pouring of cylinders for this series was done in the same manner as for the compression series. This similarity of specimens and utilization of the same testing machine were two of the most attractive features of the new test.

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(5) Carniero, F., Une nouvelle methode d'essai pour determiner la resistance a'la traction du breton, Paris, Reunion des Laboratories d'Essai de Materiaux, June 1947.

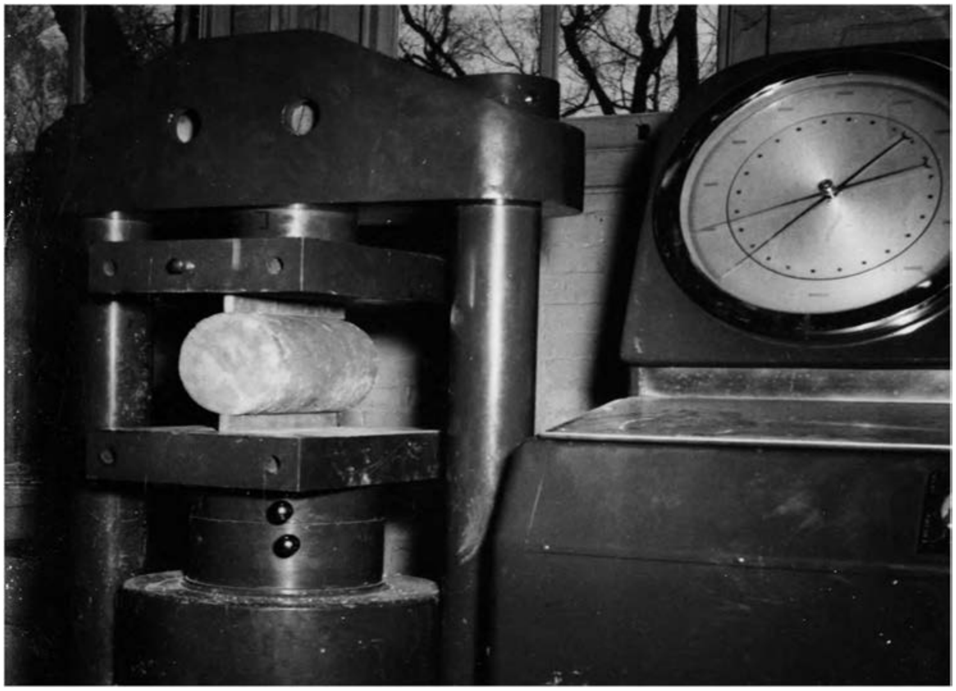

FIGURE 6 - CYLINDER IN PLACE FOR INDIRECT TENSILE TEST

<u>Description of Testing Procedure</u> The procedure used was the same for all ages tested. Tests were made at 12, 16, 24, 36, 48, 60 and 72 hours, 7, 14 and 28 days. Testing was as follows:

1. Remove form from cylinder
2. Place cylinder on testing machine platen
3. Align the aluminum and plywood strips
4. Check strip alignment to insure diametral opposition
5. Apply load to specimen
6. Record ultimate load.

The loading rate was the same as for the compression series.

<u>Instrumentation</u> The ultimate load was the only data needed for the analysis of this test; therefore, no instrumentation was used.

<u>Method of Analyzing Test Results</u> The ultimate tensile stress was calculated from formulae deduced by a mathematical analysis of the stress distribution in the specimen. This analysis, from Frocht(6), shows that

a compression load applied perpendicularly to the axis of the cylinder, and in a diametral plane, gives rise to a uniform tensile stress over that plane. The theoretical analysis of this loading condition shows the uniform tensile stress developed to be $\sigma = \frac{2P}{DL}$; where P is the load, D is the diameter of the specimen and L is the length. This calculation represents an exact solution of the ideal case considered whereas the test, as actually conducted, deviates from the ideal in several respects. These differences between the ideal case and the practical test were taken from a paper by Mr. P. J. F. Wright(7), in the Magazine of Concrete Research, London, England. His comments are as follows:

(1) Heterogenous Nature of Concrete.

The mathematical analysis of stress assumes a homogeneous material, whereas concrete is not homogeneous. This applies to all tests on concrete and the effect on the general stress distribution cannot be determined.

(2) Deviation from Hook's Law.

The theory assumes that the concrete obeys Hook's Law that strain is proportional to stress. This does not hold as the apparent value of Young's Modulus is decreasing as the stress increases. A stress-strain curve of this nature tends to relieve the more highly stressed parts of the specimen and to throw the stress on to those parts of lower stress. This factor would tend to increase the ultimate load and thus give a higher value to the stress.

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(6) Frocht, M. M., Photoelasticity, Vol. 2, New York, John Wiley and Sons, Inc., London, Chapman and Hall Ltd., pp. 121-129, 1948.

(7) Wright, P.J.F., Comments on an Indirect Tensile Test on Concrete Cylinders, Magazine of Concrete Research, Vol. 7, No. 20, July 1955, pp. 87-96, London, England.

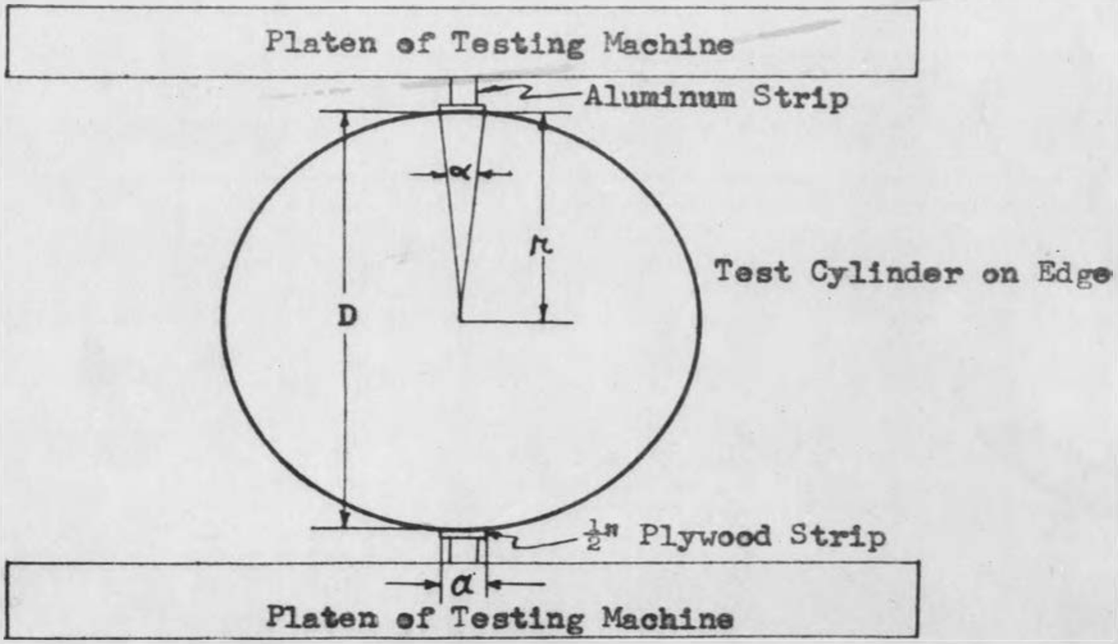


FIGURE 7 - LOADING ARRANGEMENT FOR INDIRECT TENSILE TEST AND SYMBOLS USED FOR COMPUTATION OF STRESS.

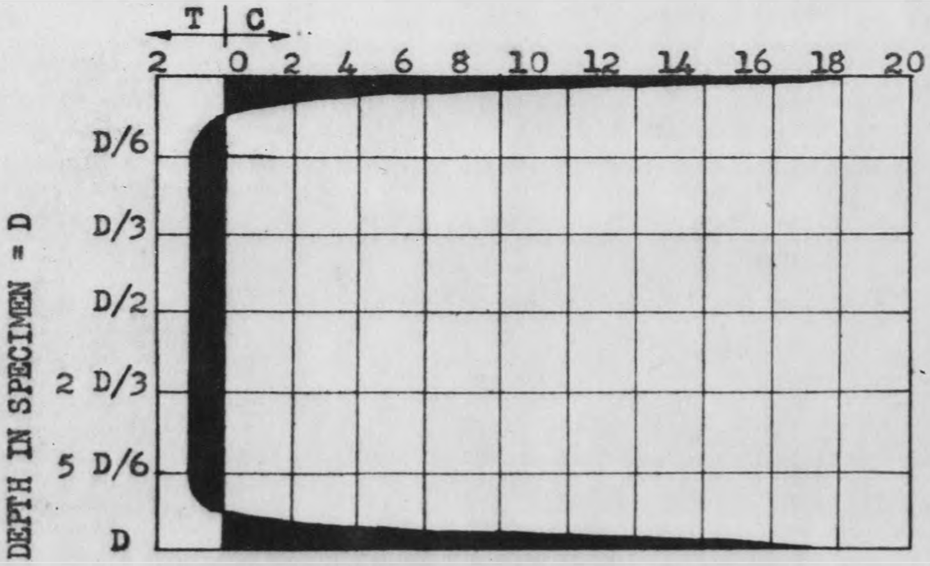


FIGURE 8 - HORIZONTAL STRESS DISTRIBUTION IN CYLINDER LOADED OVER A WIDTH a/d=1/12.
(STRESS = σ = 2P/ DL X C)

(3) Deviation from Conditions of Plane Stress.

The theory assumes a state of plane stress and in the practical case this is not obtained. The conditions in a thin disc approximate plane stress, while those in a long cylinder approximate plane strain. The mathematical analysis has not been developed for conditions of plane strains.

(4) Distribution of Applied Load.

The theory assumes a point load on a thin plate corresponding to a line loading along the generator of the cylinder while the load is actually distributed over an appreciable width. This is shown in Figure 7.

If the width of a loading strip is (a), and the load is assumed to be uniformly distributed, it can be shown that if (a) is less than $\frac{d}{10}$, the tensile stress on the vertical diameter approximates $\sigma = \frac{2P}{\pi t d}\left[1 - \frac{d}{2a}(\alpha - \sin\alpha)\right]$ with sufficient accuracy. The effect of this load distribution is as shown in Figure 8, when $\frac{a}{d} = \frac{1}{12}$. An inspection of Figure 8 shows the existence of a comparatively high compressive stress in the region directly below the loaded area. This indicates the possibility of failure due to local compression, but the actual test did not show this to be true. An explanation for this action lies in an inspection of the stress distribution. The conditions imposed upon the cylinder are more comparable to a triaxial test than to an ordinary compression test. A compressive stress much higher than that ordinarily necessary to produce failure could be sustained.

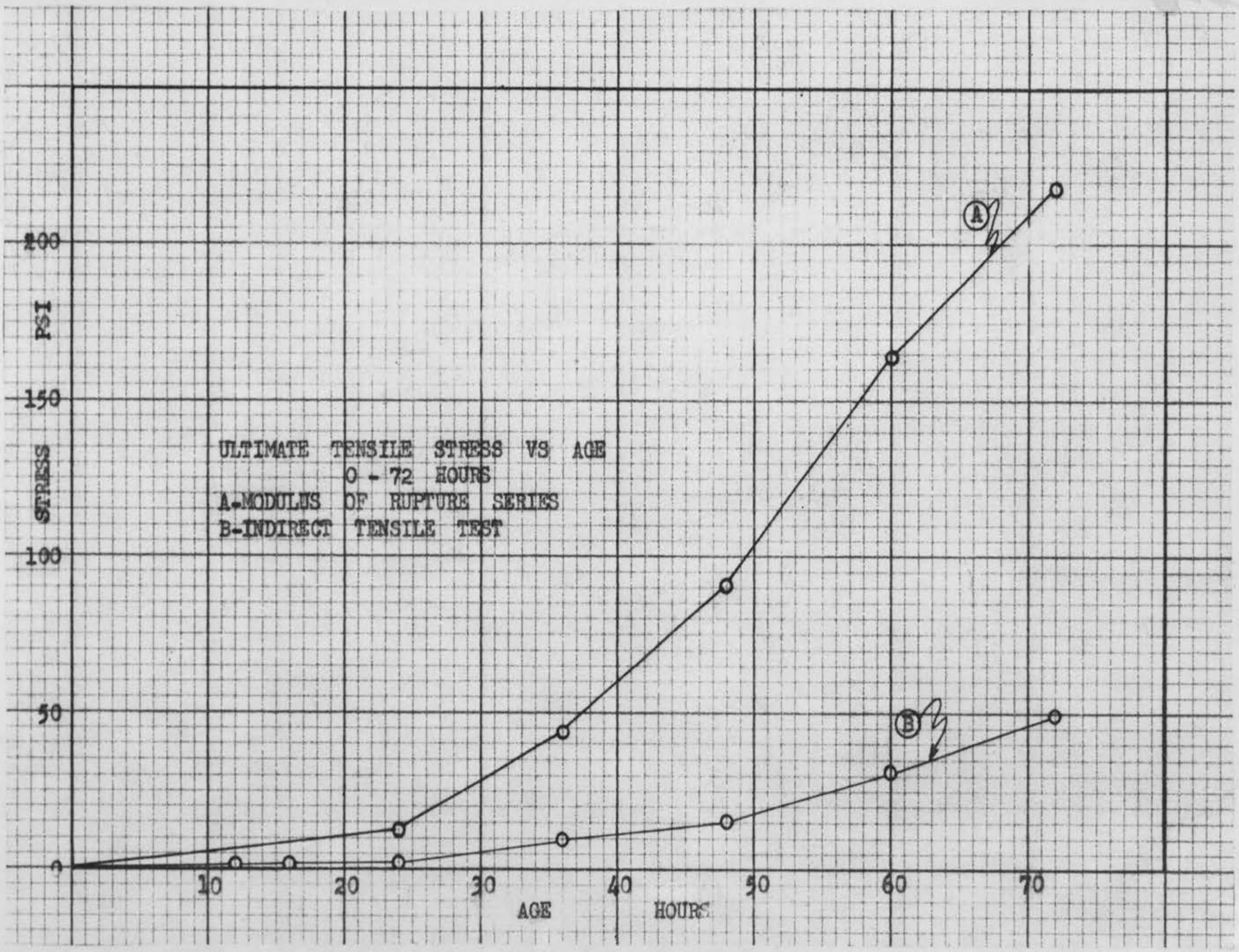
EXPLANATION OF TABLES AND GRAPHS
INDIRECT TENSION SERIES

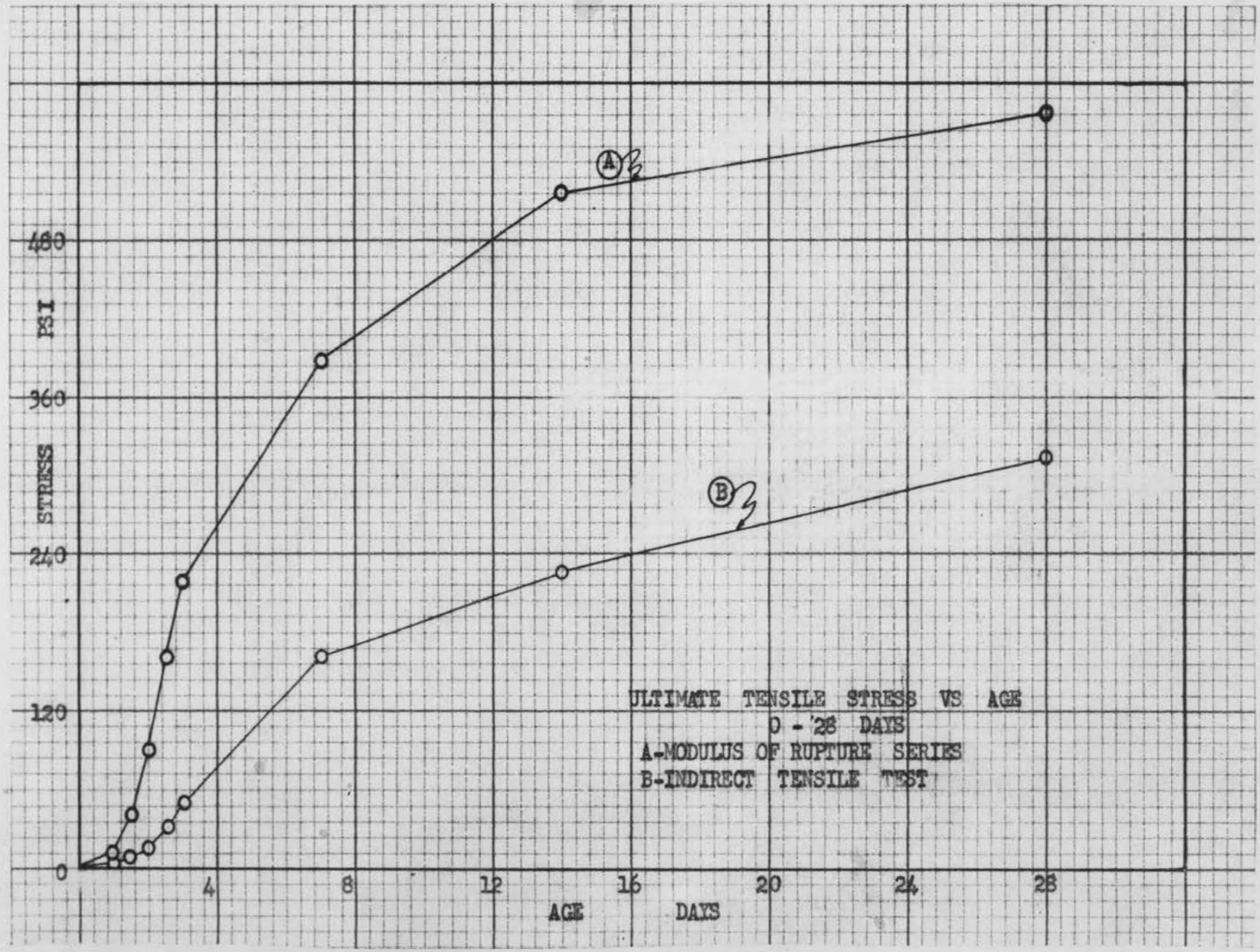
Tables All laboratory data and the computed results are shown in the **table** on page 54.

Graphs The ultimate tensile stresses obtained from this series of tests are shown along with similar information from the modulus of rupture series for the purposes of comparison. Two age ranges, zero to seventy-two hours and zero to twenty-eight days, are again shown for easier interpretation of the lower age results.

INDIRECT TENSILE TEST

AGE OF TEST	B1	B2	B3	AVERAGE	AVG. ULT. STRESS
		ULTIMATE LOAD - POUNDS			PSI
12 HR.	90	100	100	96.6	0.85
16 HR.	125	125	125	125.0	1.11
24 HR.	250	150	250	216.6	1.92
36 HR.	1900	625	800	1,108.0	9.79
48 HR.	1650	1850	1680	1,726.6	15.25
60 HR.	4890	3200	2700	3,596.6	31.8
72 HR.	8100	4500	4350	5,650.0	49.9
7 DAY	21,400	15,800	17,850	18,350.0	162.1
14 DAY	31,450	20,200	25,500	25,716.0	227.0
28 DAY	45,750	35,900	24,825	34,492.0	314.0


ULTIMATE TENSILE STRESS VS AGE
0 - 72 HOURS
A-MODULUS OF RUPTURE SERIES
B-INDIRECT TENSILE TEST



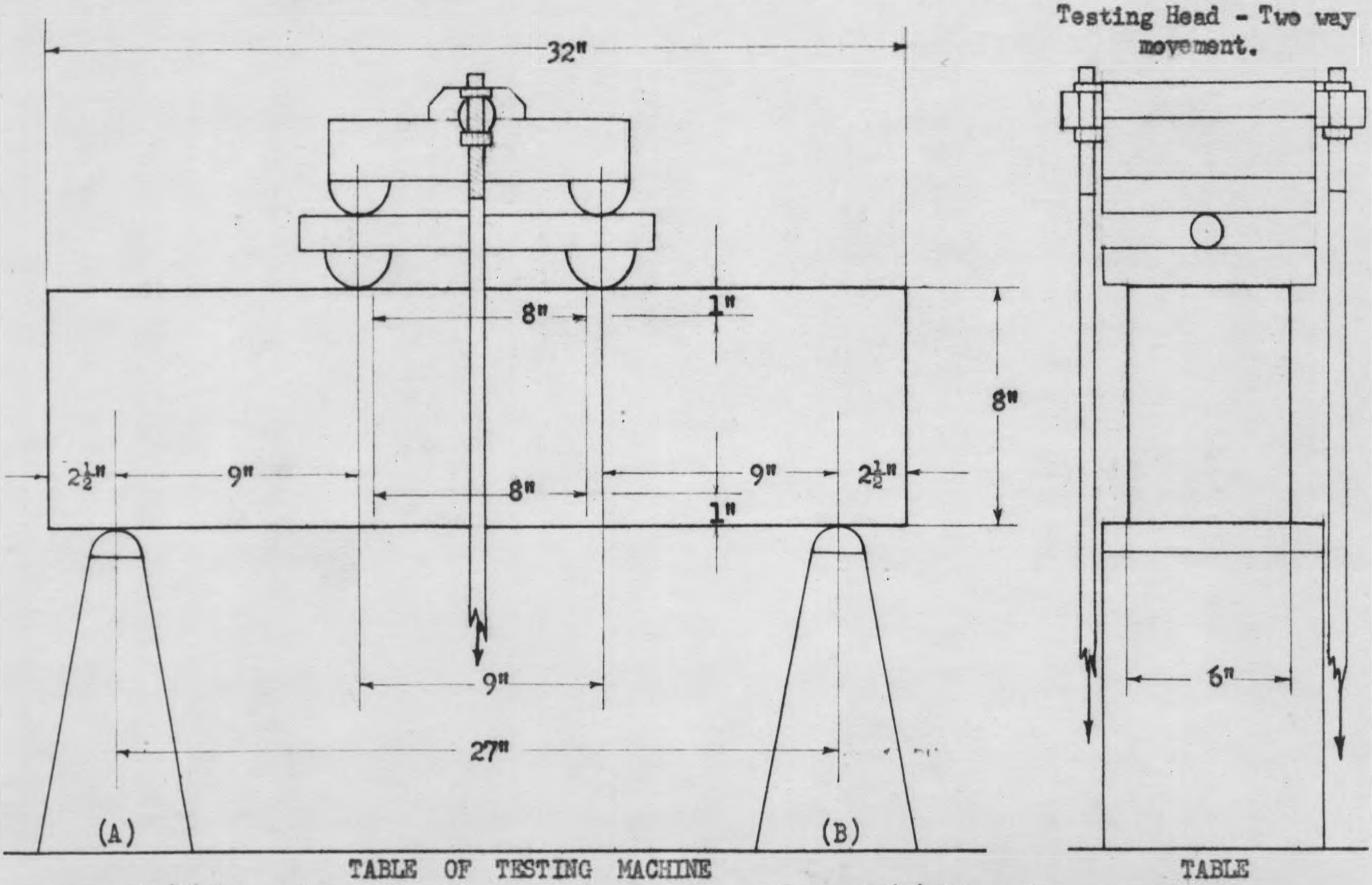
ULTIMATE TENSILE STRESS VS AGE
0 - 28 DAYS
A-MODULUS OF RUPTURE SERIES
B-INDIRECT TENSILE TEST

MODULUS OF RUPTURE TEST

Specimen for the modulus of rupture tests were 6" x 8" x 32" beams. The beams were simply supported at points 27 inches apart and were loaded at the third points of the 27 inch span. Load versus longitudinal strain readings were taken on beams ranging from 24 hours to 28 days of age. An attempt was made to test the beams at ages earlier than 24 hours, but the specimens failed while being placed on the testing machine. The beams were tested on a hand operated Tinius Olsen Beam testing machine of 10,000 pounds capacity. This machine had been newly purchased by the Mechanics Department, and had been calibrated by a factory technician after installation in early 1956.

<u>Description of Test Procedure</u> The schedule for testing specimen in this series called for tests at 6, 8, 12, 16, 24, 36, 48, 60 and 72 hours, in addition to 7, 14 and 28 days. As mentioned above, the pilot tests showed 24 hours to be the earliest age at which the beams would support their own weight. Tests at ages earlier than 24 hours were therefore discontinued. The testing sequence was:

1. Remove form from specimen
2. Place specimen on supports
3. Place testing head in position
4. Place Huggenberger gages
5. Zero test machine and Huggenberger gages
6. Record readings of load versus strain during loading from zero to approximately 75% of ultimate load.
7. Remove Huggenberger gages at approximately 75% ultimate load.
8. Continue loading to failure
9. Record ultimate load and observe position of failure point.



Support (A)-Fixed longitudinally;
free to move transversely.

Support (B)-Fixed transversely;
free to move longitudinally.

FIGURE 9 - SPECIMEN SET UP FOR TESTING - BEAM

Instrumentation of Test Measurements were desired of longitudinal strain at two locations on the test specimen; on the side of the beam between third points, one inch above the bottom and one inch below the top of the beam. These strains were measured with Huggenberger Tensometer gages orientated so as to measure strains in the direction of the longitudinal axis of the beams. The placement of these gages on a specimen set up for testing is shown in Figure 9. The gage length used was eight inches throughout this series of tests. The multiplication factor for the Huggenberger Tensometers used in these tests was determined to be 1240 x 20 x 8, or scale reading divided by 198,400 equalled strain. A view of a test specimen in place for testing is shown in Figure 10. This photograph was taken of a beam which was a part of a comparable series of tests being run at a temperature of 100°F. Attention is directed to the full-round bars beneath the third-point loading head. This detail was introduced after the testing of the 40° series and replaces the half-round bar used at this point during those tests.

Method of Reduction of Data As shown in Figures 9 and 10, a third point loading was imposed upon the beams. This loading arrangement resulted in the elimination of vertical shear in the analysis of test results. The beam tester used recorded a load equal to twice the left reaction, (beneath support "A" in Figure 9), which would be equal to "P", the total load acting on the beam. One-half "P" was then assumed to be acting at the third-points of the beam. This gave a maximum bending moment due to the live load of $\frac{PL}{6}$. The weight of the beam was not considered in the analysis of the test results. If considered, this weight would have increased the bending moment at the third-points, and consequently the stress at these points. This stress increase would have been greatest at the earlier ages, decreasing as the age increased to 28 days, and in this series of tests would not have exceeded 10%.

All specimens tested were observed to fail in the middle third of the section. Also, all specimens were observed to fail from the lowermost fibers upward.

The flexure formula $S = \frac{My}{I}$ was used to determine the stresses in the specimen of this series at the instant of failure. This formula indicates that the flexural stress in any section varies directly with the distance of the section from the neutral axis, and is derived on the basis of the following assumptions.

1. Plane sections of the beam, originally plane, remain plane after loading.
2. The material of the beam is homogeneous and obeys Hooke's Law.
3. The moduli of elasticity for tension and compression are equal.
4. The beam is initially straight and of constant cross-section.

Hooke's Law, $S = Ee = \left(\frac{E}{\rho}\right) y$, indicates that the stress in any fiber varies directly with its location "y" from the neutral surface, since it is assumed that the modulus of elasticity "E" in tension and in compression are equal, and the radius of curvature "ρ" of the neutral surface after loading is independent of the location "y" of the fiber under investigation. However, the stresses must not exceed the proportional limit, for this would be at variance with Hooke's Law on which this stress variation is based. Accordingly, for the flexural formula to be valid, investigations must be made within the limits of the stress-strain curve, where this relationship is a straight, or very nearly straight line. It may be seen from the graphs which follow that the stress-strain diagrams for the various specimen tested exhibit this straight line characteristic only on the tension side of the beam. This would be indicative of several possibilities. The neutral axis of the specimen could be located at the centroid of the beam, and the strain variation

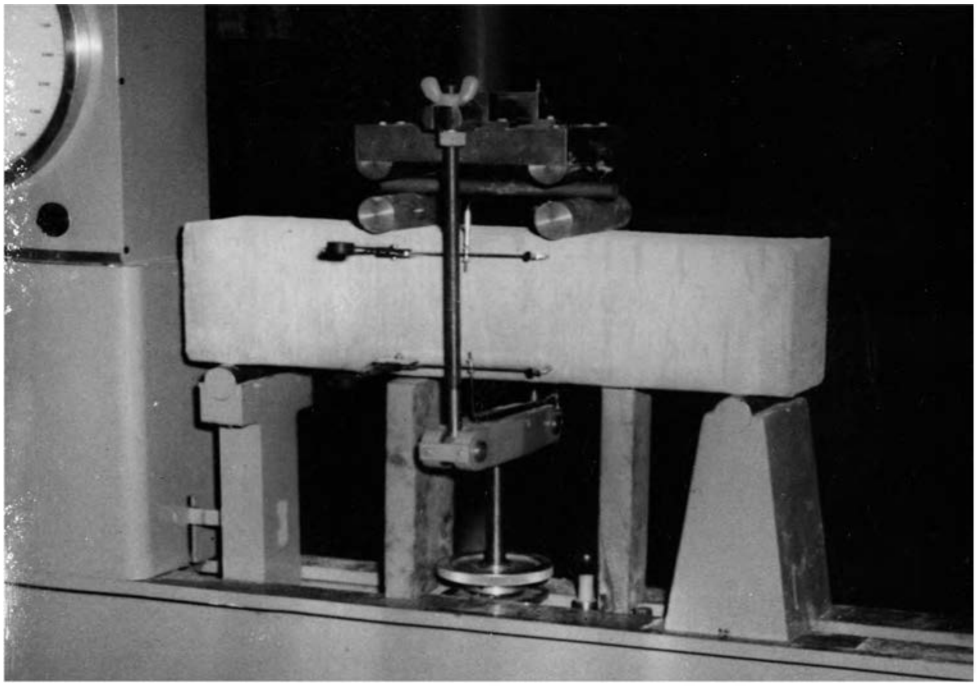


FIGURE 10 - BEAM IN PLACE FOR MODULUS OF RUPTURE TEST

exhibit linear characteristics from the bottom extreme fiber to the neutral axis beyond which it becomes curvilinear through the compressive side of the beam to the top extreme fiber. Also the neutral axis could be other than assumed at the centroid due to the nonhomogenity of the material being tested. If this were true the assumption that the moduli of elasticity in tension and compression are equal would not be true. The proof of either of these possibilities would rest upon definite knowledge of the location of the neutral axis of the specimen, or more complete knowledge of the strain variations from top to bottom. Recommendations to this effect are discussed later in this paper.

As mentioned in the discussion of the instrumentation for this series of tests, strains were measured with Huggenberger Tensometers placed at two locations; one inch up from the bottom of the beam, and one inch below the top. Measurements of strain were made only in the loading range from zero to approximately 75% of the ultimate for the specimen being tested. This was done as a precautionary measure in order to protect the Huggenberger Tensometer from the excessive strains which would occur at failure. The strains measured were plotted against load and the apparent rate of curvature or linearity was then projected up to the ultimate load to obtain the apparent strain at failure. These values would represent the strains at failures at the locations of the Huggenberger Tensometers.

No attempt was made to evaluate the moduli of elasticity in tension and compression in this series of tests due to the uncertainties mentioned previously.

EXPLANATION OF TABLES AND GRAPHS
MODULUS OF RUPTURE SERIES

Tables All laboratory readings taken during this series are tabulated on pages 64 through 71. Average results were plotted and this information is shown. The last table shows a compilation of the average results obtained, either by measurements or computation of: ultimate load, strains at failure, bending moment at failure, and tensile stress at failure.

Graphs Load versus measured strain for the agest tested is shown in the first eight graphs. These curves were used to obtain the strains in tension and compression at the ultimate, as mentioned in the previous discussion. The ultimate stress in tension, computed by the flexural formula, is compared to the ultimate stress in tension, obtained from the indirect test, on pages 55 and 56. The final curves in this series represent measured strains, in tension and compression, at ultimate, plotted against age. Two age ranges, zero to seventy-two hours and zero to twenty-eight days, are presented for easier interpretation of the results.

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 24 HOUR

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
50		---	0.2	1.0	0.4
100		1.0	0.8	0.5	0.8
150		1.6	3.4	1.8	2.9
200		---	---	3.0	3.0
0	1" UP FROM BOTTOM	0	0	0	0.
50		---	1.0	0.7	0.6
100		1.6	1.9	2.0	1.5
150		3.3	4.9	3.9	4.3
200		---		5.5	5.5
ULTIMATE	POUNDS	160	160	210	177

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 36 HOUR

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
100		0.04	0.0	0.8	0.28
200		0.08	1.0	2.0	1.03
300		1.2	1.5	3.0	1.9
400		1.8	2.25	4.4	2.82
500		3.0	3.5		3.25
600		3.5	4.5		4.0
700			6.0		6.0
800			7.0		7.0
0	1" UP FROM BOTTOM	0	0	0	0
100		0.1	2.0	2.0	1.4
200		1.5	4.0	3.8	3.1
300		2.5	5.25	5.0	4.25
400		3.0	7.0	7.0	5.67
500		4.5	8.25		6.4
600		5.5	10.0		7.8
700			12.0		12.0
800			14.0		14.0
ULTIMATE	POUNDS	640	800	430	623

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 48 HOUR

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
100		0.0	0	0	0
200		0.25	0	0	0.08
300		0.4	0.2	0	0.20
400		0.5	0.4	0.3	0.40
500		0.75	0.7	0.3	0.58
600		1.0	0.8	0.3	0.70
700		1.25	1.1	0.5	0.95
800		1.66	1.5	0.6	1.25
900		2.0	1.5	1.0	1.50
1000		2.4	1.8		2.10
1100		2.75	——		
1200			2.4		
0	1" UP FROM BOTTOM	0	0	0	0
100		0.6	1.0	1.0	0.86
200		1.0	1.3	1.5	1.26
300		1.5	1.7	2.3	1.83
400		2.0	2.0	2.6	2.20
500		2.4	2.5	3.7	2.86
600		2.9	3.0	4.4	3.43
700		3.5	3.5	4.7	3.90
800		4.0	4.0	5.5	4.50
900		4.5	4.2	5.7	4.80
1000		5.1	5.0		5.05
1100		6.0	——		
1200			6.0		
ULTIMATE	POUNDS	1,250	1,390	1,530	1,281

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 60 HOUR

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
200		0.2	0.2	0.3	0.23
400		0.5	0.4	0.7	0.53
600		0.8	0.8	1.2	0.93
800		1.3	1.3	1.5	1.36
1000		1.7	1.5	1.8	1.66
1200		2.2	2.0	2.5	2.23
1400		2.6	2.5	3.0	2.70
1600		3.0		3.5	3.25
1800		3.8		4.1	3.95
2000		4.2		4.7	4.45
2200		5.5			
0	1" UP FROM BOTTOM	0	0	0	0
200		1.0	0.8	0.5	0.76
400		1.3	1.5	1.0	1.26
600		2.0	2.2	1.6	1.93
800		2.6	3.0	2.0	2.53
1000		3.2	3.5	2.6	3.10
1200		3.8	4.5	3.3	3.86
1400		4.5	5.0	4.0	4.50
1600		5.0		4.5	4.75
1800		5.8		5.3	5.55
2000		6.5		6.2	6.35
2200		8.0			
ULTIMATE	POUNDS	2,210	2,565	2,210	2,328

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 72 HOUR

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A1	A2	A3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
4		0.4	0.3	0.3	0.33
8		1.0	0.5	1.1	0.86
12		1.5	0.8	1.7	1.33
16		2.3	1.1	2.7	2.03
20		3.0	1.6	3.5	2.70
24		4.0	1.7	4.5	3.40
28		5.8	2.4		4.10
32					
0	1" UP FROM BOTTOM	0	0	0	0
4		0.6	0.6	0.5	0.55
8		1.5	1.8	1.5	1.65
12		2.5	2.6	2.5	2.55
16		3.5	3.8	3.6	3.70
20		4.4	4.4	4.4	4.40
24		5.3	5.9	5.9	5.90
28			7.0	7.5	7.25
32					
ULTIMATE	POUNDS	2800	3650	2820	3090

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 7 DAY

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
400		0.5	0.0	0.2	0.23
800		1.0	0.3	0.6	0.63
1200		1.4	0.8	0.7	0.96
1600		1.9	1.2	1.3	1.46
2000		2.4	1.4	1.6	1.80
2400		2.8	1.7	1.7	2.06
2800		3.3	2.2	2.5	2.66
3200		3.8	2.4	2.8	3.00
3600		4.4	2.7	3.3	3.46
4000		4.9	3.2	3.5	3.86
4400		5.5	3.7		
4800		6.1	4.0		
5200			4.6		
0	1" UP FROM BOTTOM	0	0	0	0
400		0.7	0.5	0.6	0.60
800		1.2	1.1	1.5	1.26
1200		2.0	1.8	2.0	1.93
1600		2.8	2.5	2.8	2.70
2000		3.5	3.0	3.7	3.40
2400		4.3	3.6	4.5	4.13
2800		4.9	4.3	5.0	4.73
3200		5.6	5.0	6.0	5.53
3600		6.5	5.5	6.9	6.30
4000		7.3	6.2	7.6	7.03
4400		8.6	6.8		
4800		10.4	7.6		
5200			9.0		
ULTIMATE	POUNDS	4,830	5,590	6195	5,505

LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 14 DAY

LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
400		0.3	0.2	0.2	0.23
800		0.5	0.2	0.3	0.33
1200		0.8	0.3	0.6	0.56
1600		1.0	0.7	1.0	0.90
2000		1.1	1.0	1.2	1.10
2400		1.4	1.3	1.6	1.43
2800		1.8	1.4	1.8	1.60
3200		1.8	1.6	2.1	1.83
3600		2.3	1.8	2.4	2.00
4000		2.6	2.1	2.7	2.36
4400		3.0	2.3	2.7	2.53
4800		3.2	2.5	3.0	2.83
5200					
0	1" UP FROM BOTTOM	0	0	0	0
400		0.8	1.0	0.5	0.76
800		1.5	1.5	1.2	1.40
1200		2.0	2.1	1.8	1.96
1600		2.5	2.8	2.5	2.60
2000		3.0	3.5	3.1	3.20
2400		3.4	4.0	3.7	3.70
2800		4.2	4.6	4.5	4.43
3200		4.8	5.1	5.0	4.96
3600		5.5	5.7	5.6	5.60
4000		6.0	6.5	6.3	6.26
4400		6.3	7.1	7.0	6.80
4800		7.0	7.7	7.5	7.40
5200		7.8	8.2		8.00
ULTIMATE	POUNDS	7,680	8,250	6,215	7,348

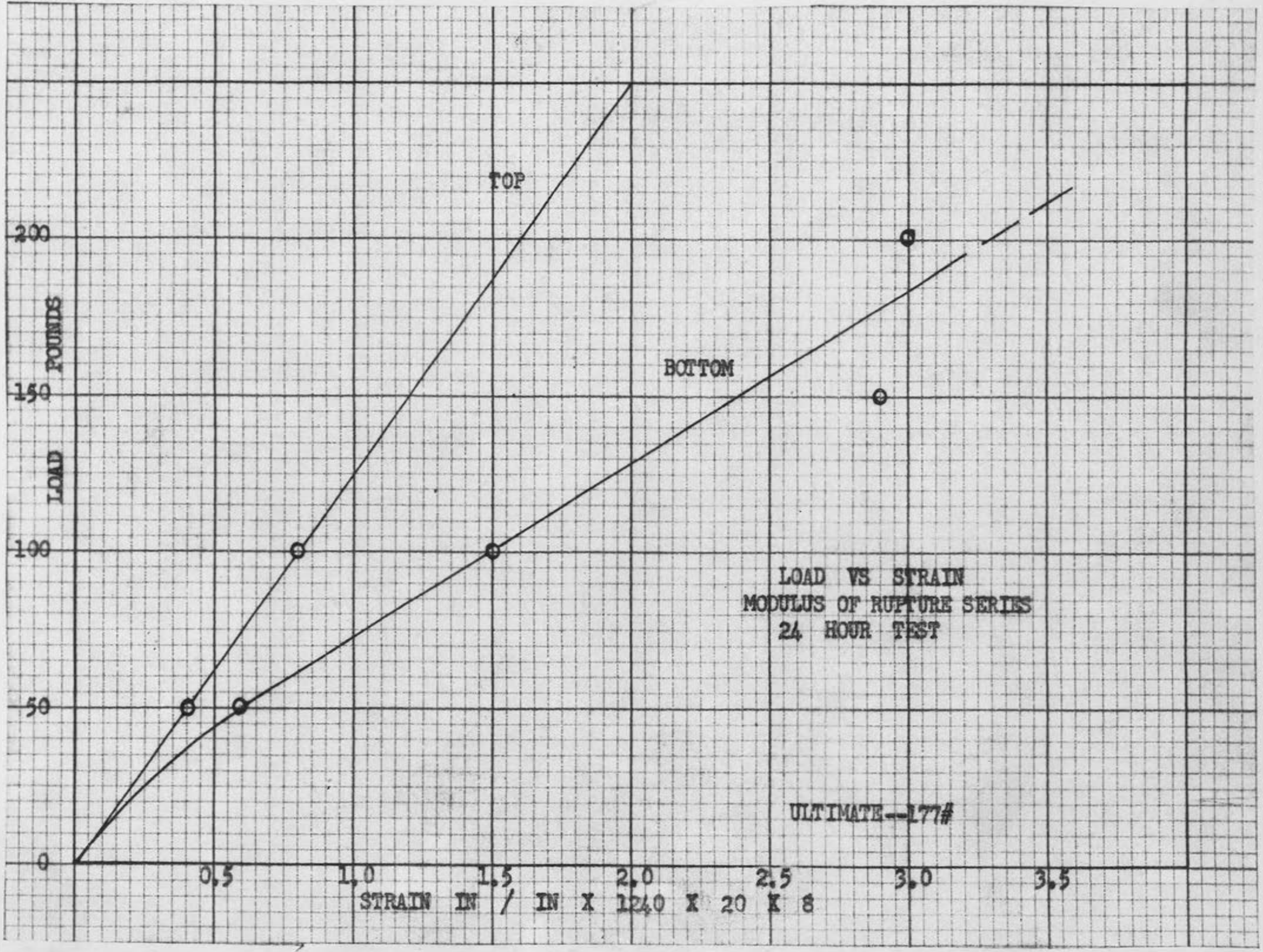
LOAD VS. STRAIN
MODULUS OF RUPTURE SERIES
AGE - 28 DAY

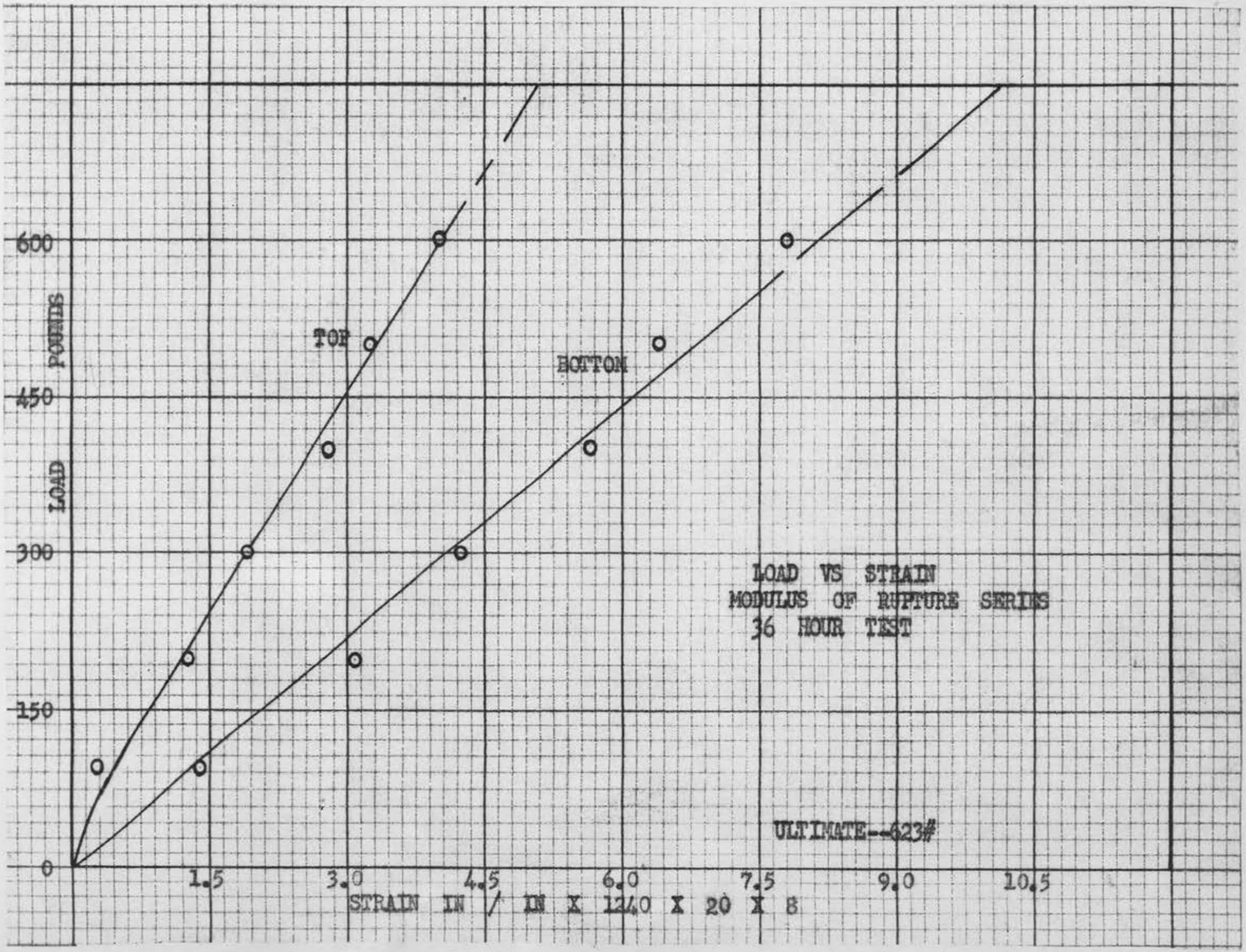
LOAD	STRAIN INCHES / 1240 x 20 x 8 INCHES				
POUNDS	CYCLE	A-1	A-2	A-3	AVERAGE
0	1" DOWN FROM TOP	0	0	0	0
500		0.0	0.5	1.0	0.5
1000		0.0	1.5	2.0	1.2
1500		0.3	2.25	3.0	1.85
2000		0.8	3.25	4.25	2.76
2500		0.8	4.25	5.25	3.43
3000		1.0	5.25	6.75	4.33
3500		1.2	6.25	8.0	5.15
4000		1.6	7.25	9.0	5.95
4500		1.7	8.25	10.25	6.90
5000		2.2	9.5	11.5	7.73
5500		2.2	10.5	13.0	8.60
6000		2.3	11.5	14.25	9.45
6500		2.6			
		3.0			
0	1" UP FROM BOTTOM	0	0	0	0
500		1.2	1.0	1.0	0.73
1000		2.0	2.25	2.25	2.2
1500		2.8	3.5	3.5	3.26
2000		3.6	4.5	5.0	4.36
2500		4.5	6.0	6.0	5.50
3000		5.5	7.0	7.25	6.58
3500		6.2	8.25	8.5	7.65
4000		7.1	9.5	10.0	9.86
4500		8.0	10.5	11.25	9.91
5000		8.7	12.0	12.75	11.15
5500		9.5	13.0	14.0	12.16
6000		10.5	15.0	15.5	13.66
6500		11.2			
7000		12.0			
7500					
ULTIMATE	POUNDS	8,320	7,660	8,640	8,207

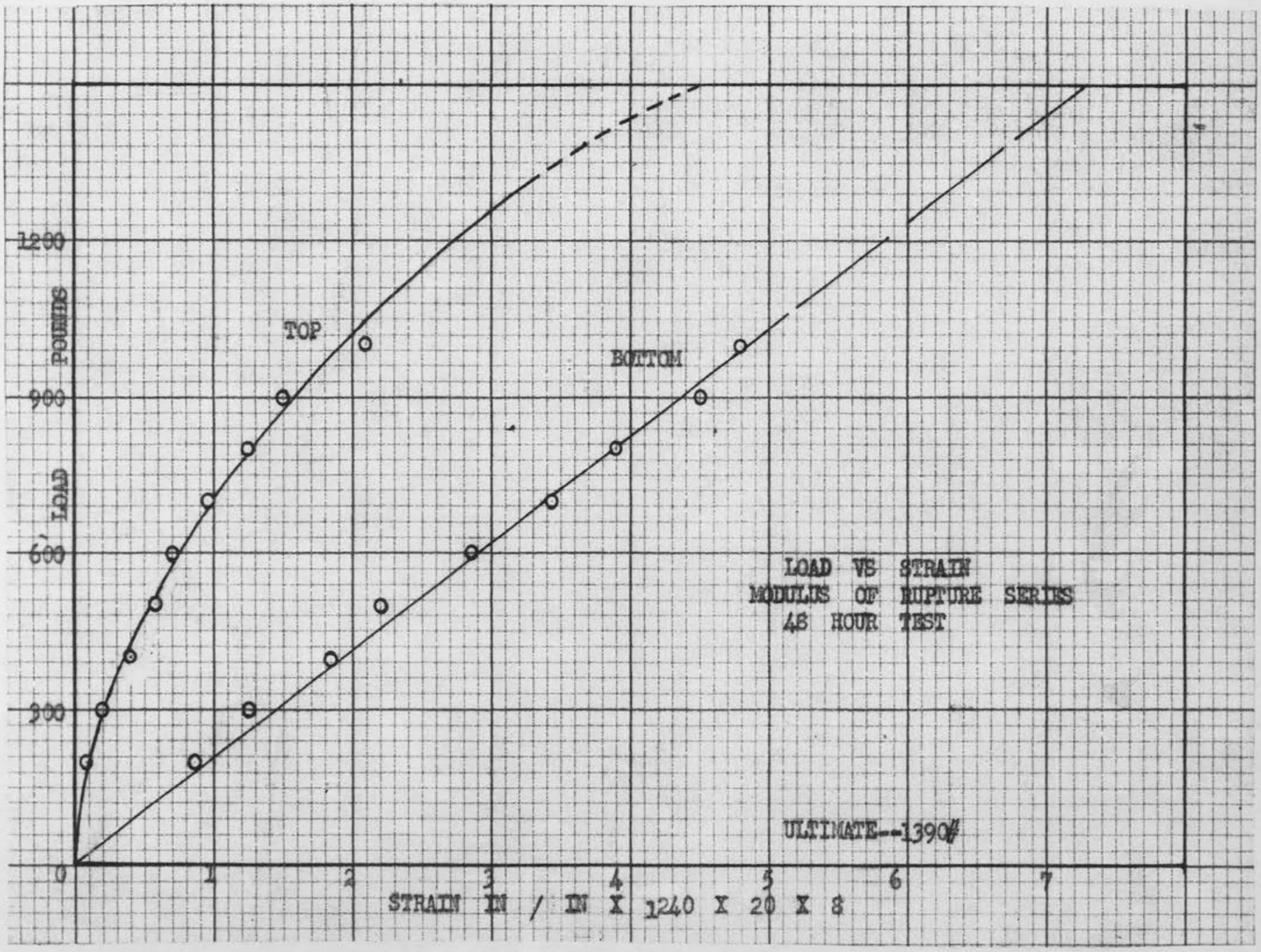
MEASURED AND COMPUTED DATA

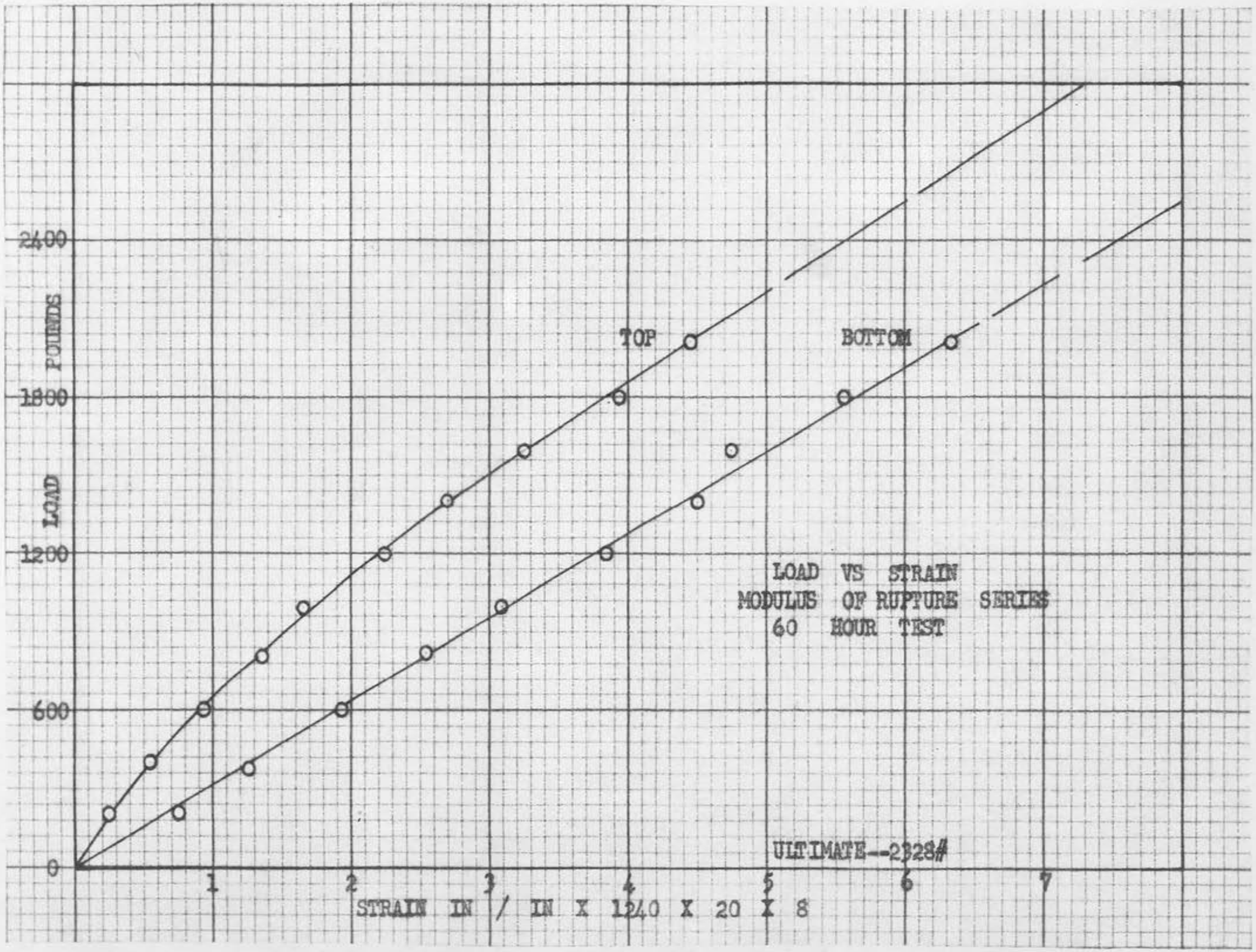
MODULUS OF RUPTURE SERIES

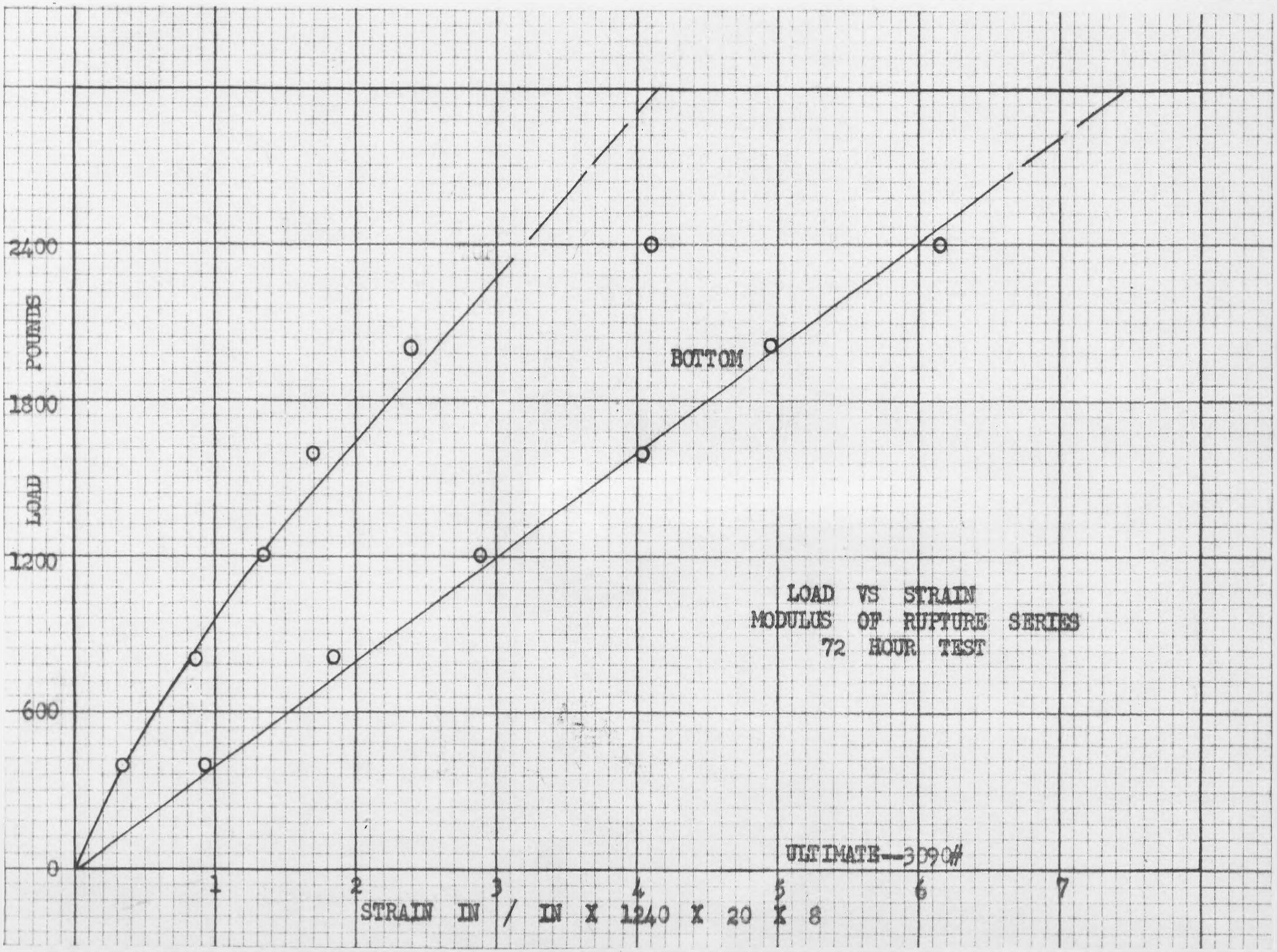
Age of Beam	Ultimate Load (Average) #	Strains at Failure (From Graphs) In/In x 1240 x 20 x 8		Moment at Failure (Average) in#	Stress at Failure (Tensile) Modulus of Rupture
		e_c	e_t		
24 Hrs.	177	1.41	2.88	796.5	12.4
36 Hrs.	623	5.15	8.42	2803.5	43.8
48 Hrs.	1281	4.29	6.91	5764.5	90.1
60 Hrs.	2328	5.54	7.30	10476.0	163.7
72 Hrs.	3090	4.52	7.85	13905.0	217.3
7 Day	5505	5.33	9.64	24772.5	387.1
14 Day	7348	4.40	11.30	33066.0	516.7
28 Day	8207	13.10	18.30	36931.5	577.1


TOP
BOTTOM
LOAD POUNDS
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
STRAIN IN / IN X 1240 X 20 X 8
LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
24 HOUR TEST
ULTIMATE--177#

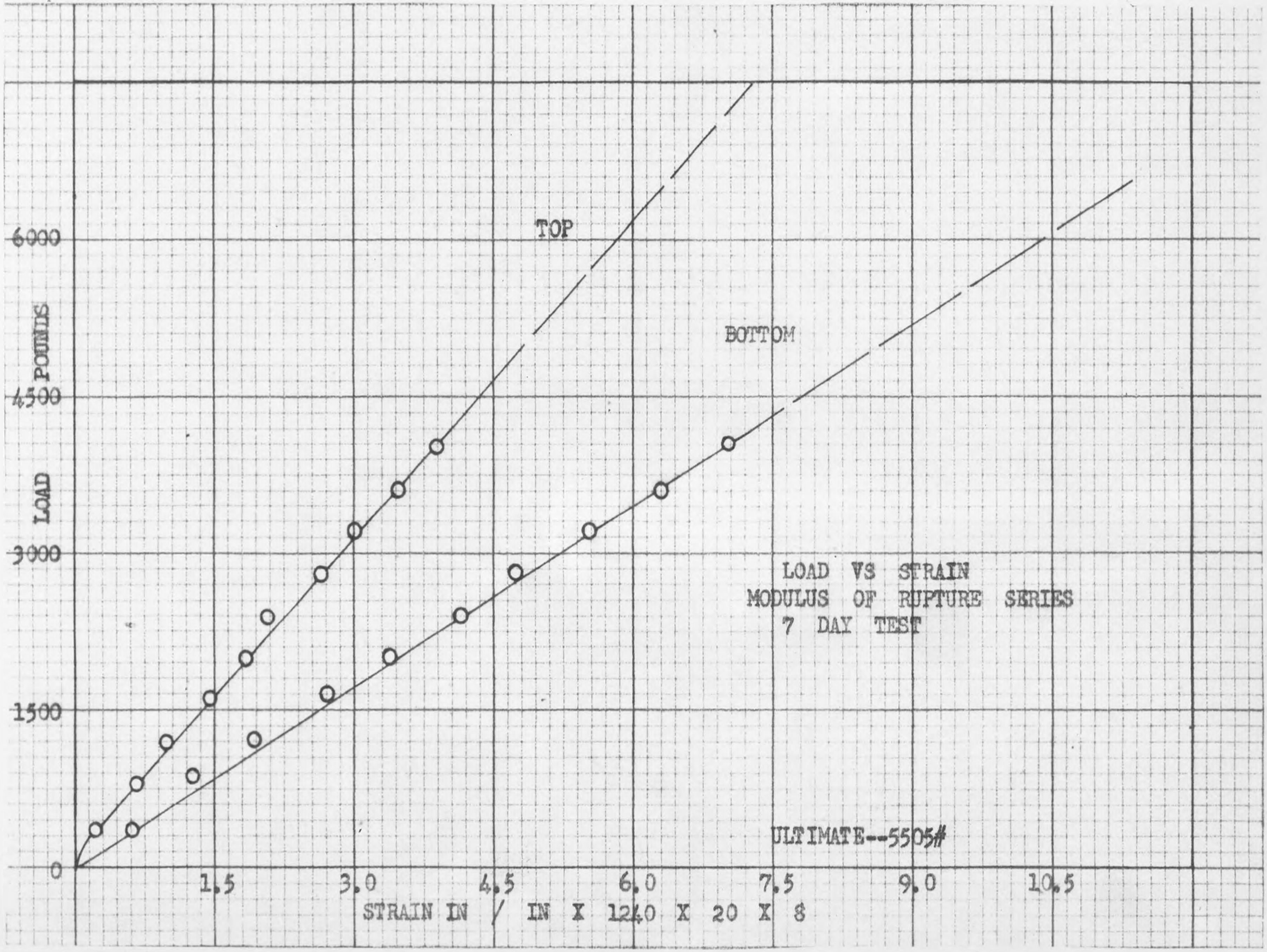

LOAD POUNDS
600
450
300
150
0
TOP
BOTTOM
1.5
3.0
4.5
6.0
7.5
9.0
10.5
STRAIN IN / IN X 1240 X 20 X 8
LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
36 HOUR TEST
ULTIMATE--623#

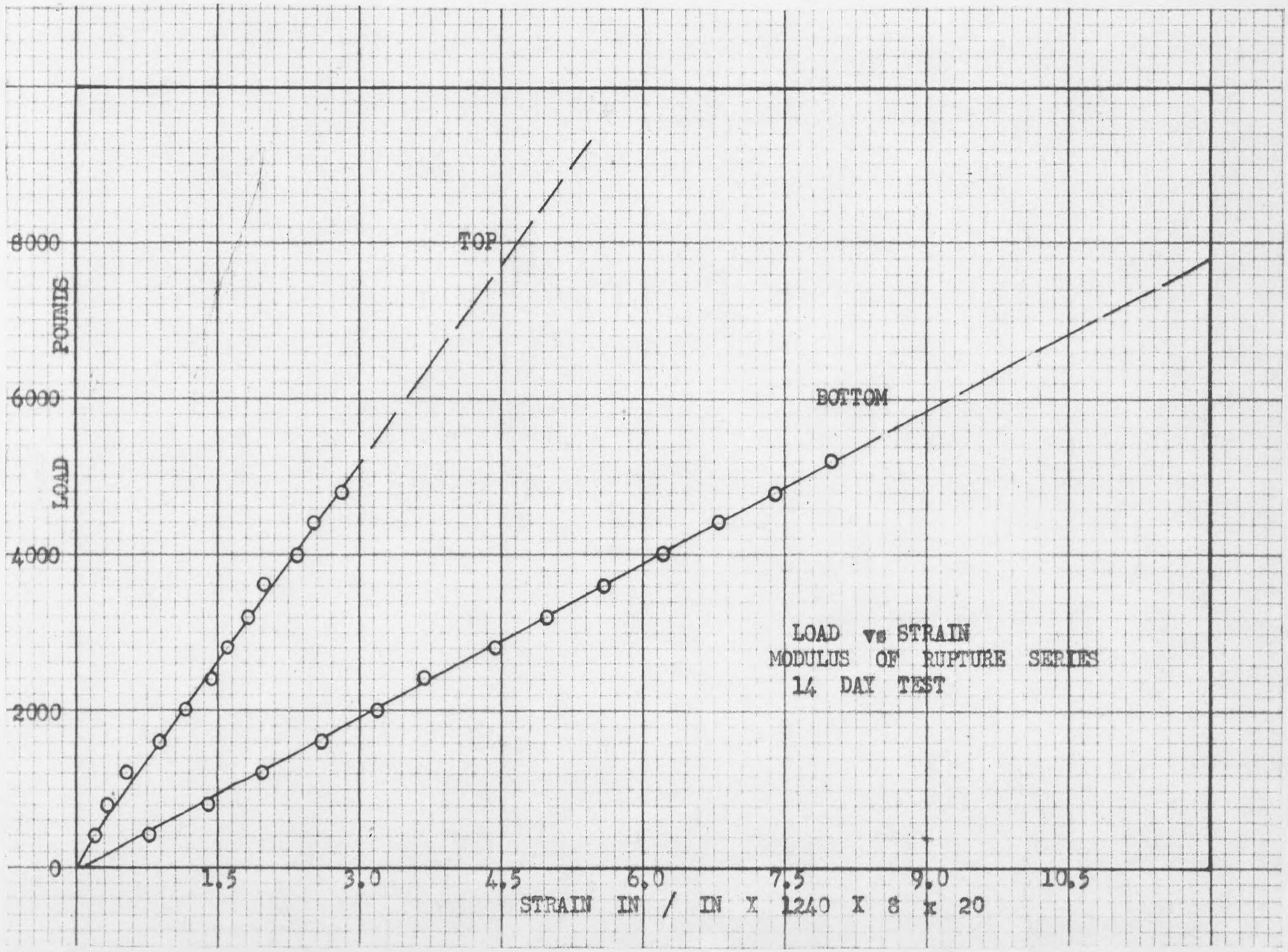

LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
48 HOUR TEST
TOP
BOTTOM
ULTIMATE--1390#
LOAD POUNDS
0
300
600
900
1200
1
2
3
4
5
6
7
STRAIN IN / IN X 1240 X 20 X 8

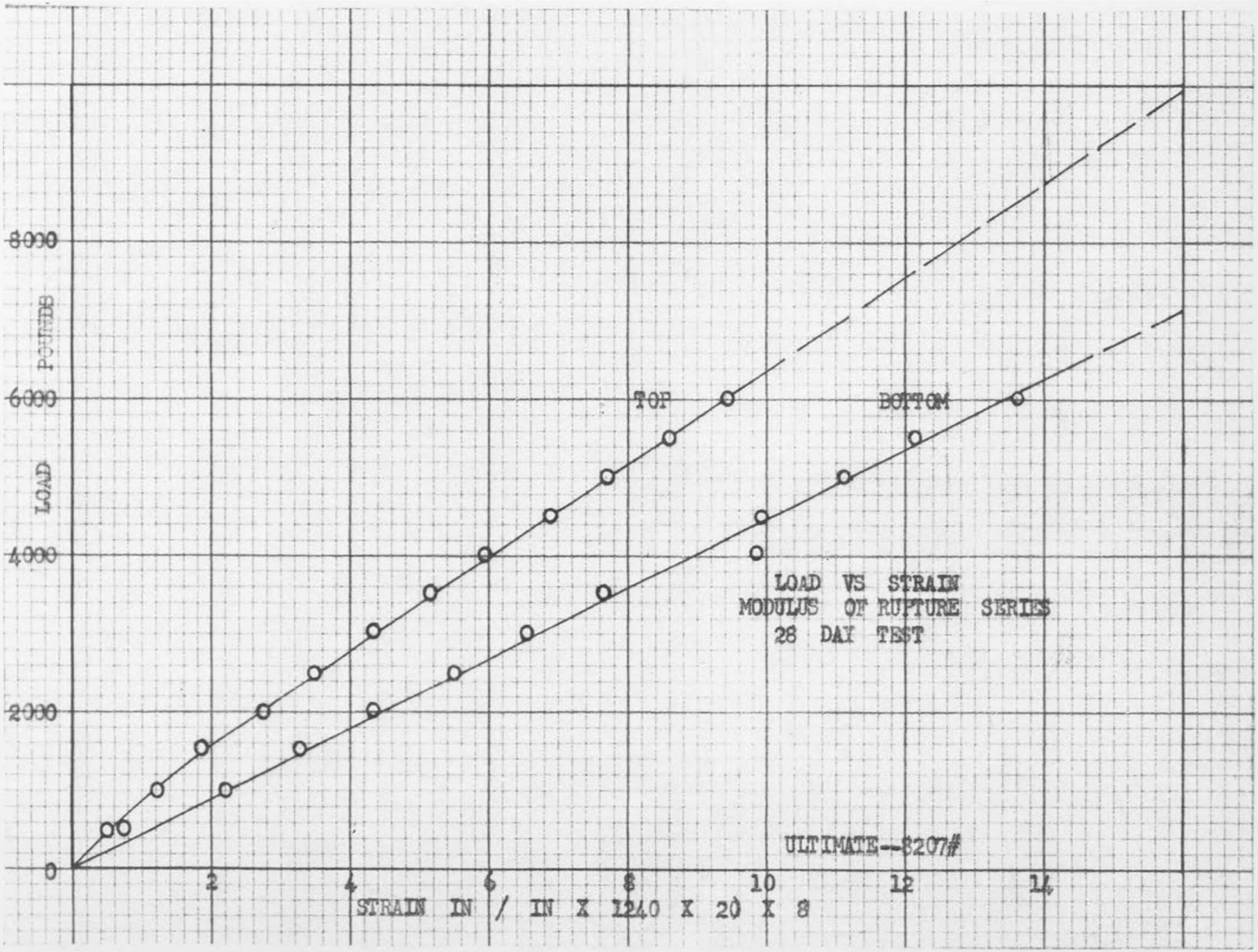

2400
1800
1200
600
0
LOAD POUNDS
TOP
BOTTOM
LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
60 HOUR TEST
ULTIMATE--2328#
1
2
3
4
5
6
7
STRAIN IN / IN X 1240 X 20 X 8



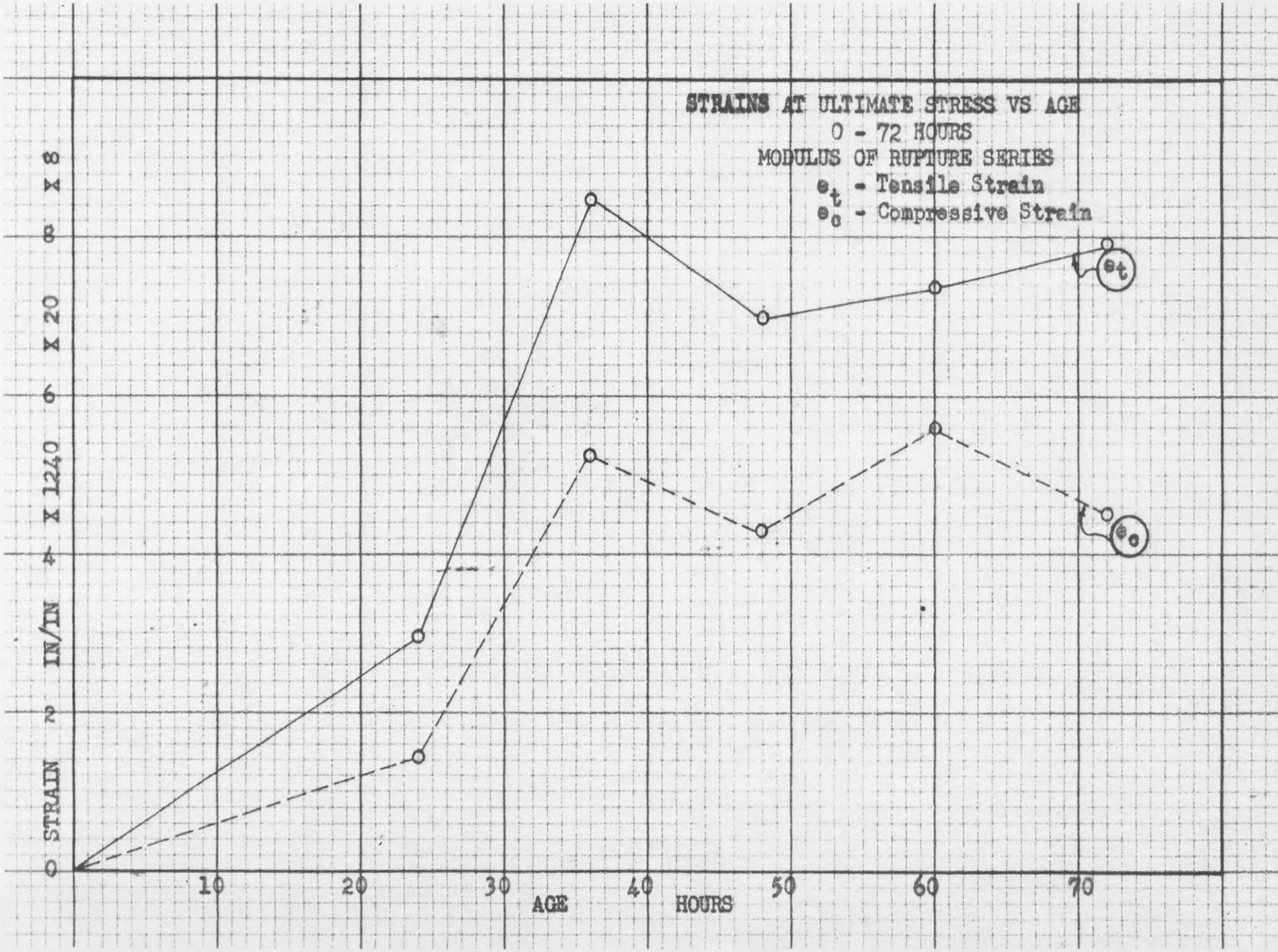
LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
72 HOUR TEST

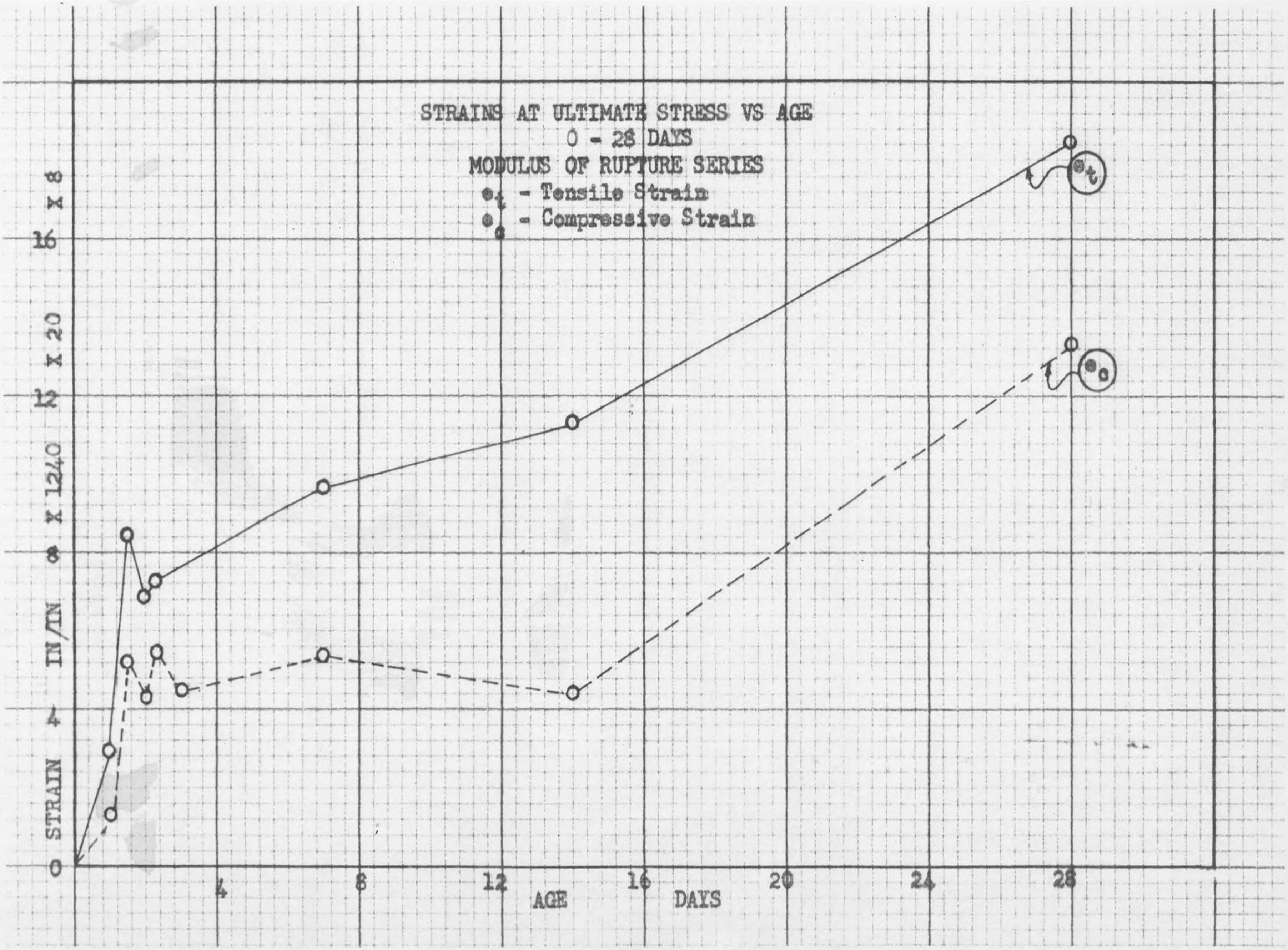

TOP
BOTTOM
LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
7 DAY TEST
ULTIMATE--5505#
LOAD POUNDS
6000
4500
3000
1500
0
1.5
3.0
4.5
6.0
7.5
9.0
10.5
STRAIN IN / IN X 1240 X 20 X 8


TOP
BOTTOM
LOAD vs STRAIN
MODULUS OF RUPTURE SERIES
14 DAY TEST
LOAD POUNDS
8000
6000
4000
2000
0
1.5
3.0
4.5
6.0
7.5
9.0
10.5
STRAIN IN / IN X 1240 X 8 x 20



LOAD POUNDS
8000
6000
4000
2000
0
2
4
6
8
10
12
14
STRAIN IN / IN X 1240 X 20 X 8
TOP
BOTTOM
LOAD VS STRAIN
MODULUS OF RUPTURE SERIES
28 DAY TEST
ULTIMATE--8207#


STRAINS AT ULTIMATE STRESS VS AGE
0 - 72 HOURS
MODULUS OF RUPTURE SERIES
e_t - Tensile Strain
e_c - Compressive Strain
e_t
e_c
STRAIN IN/IN X 1240 X 20 X 8
0
2
4
6
8
10
20
30
40
50
60
70
AGE HOURS


STRAINS AT ULTIMATE STRESS VS AGE
0 - 28 DAYS
MODULUS OF RUPTURE SERIES
e_t - Tensile Strain
e_c - Compressive Strain
e_t
e_c
STRAIN IN/IN X 1240 X 20 X 8
0
4
8
12
16
4
8
12
16
20
24
28
AGE DAYS

DISCUSSION OF RESULTS

It is felt that the procedures used, instrumentation and methods of analysis have resulted, in general, in satisfactory results. Controlled conditions were within the specified limits and, in-so-far as possible, the personnel conducting the tests eliminated the human variables. The possibility of obtaining other results with the development of more accurate instruments and new testing techniques should not be neglected.

Compression Series The results of the tests of this series will be discussed in this section. Comparison with the results of other investigators will be made under a separate heading.

The information gathered indicates the compressive strength of the mixture tested requires a considerable time interval to obtain values comparable to the 28 day strength. At three days of age the compressive strength has reached only 16% of the 28 day value. The gain in compressive strength in this time interval is quite gradual, beyond three days of age the rise is more rapid. At seven days, approximately 50% of the 28 day strength has been obtained.

These results follow the trend of any chemical action under reduced temperature conditions. The lower temperatures can be expected to produce a retarding action at earlier ages, and such is observed. After seven days, the rise in strength is normal and gradual, however, the 28 day strength did not reach the anticipated design value of 3,000 to 4,000 psi. Later tests should reach this value.

The graphs of modulus of elasticity versus age indicates these values follow the same general pattern of the compressive strength. Values for this property, however, are much lower than might be expected. At 72 hours the modulus of elasticity had reached only one percent of its 28 day value, and during the interval between three and seven days is seen to rise quite rapidly. An attempt was made to more definitely determine the age at which the modulus attained normal value. The results of tests for this purpose are more fully discussed in the appendix. Comparing the two values, compressive strength and modulus of elasticity, shows the modulus to have attained its full 28 day value at seven days, while the compressive strength has reached only one-half its full 28 day value.

The calculated values for compressive strain at 50% of the ultimate strength exhibit unanticipated characteristics. In the age range below seven days these values are considerably higher than those obtained for later ages, those at twelve, sixteen, and twenty-four hours being particularly so. In direct contrast to the compressive strength and the modulus of elasticity during these time intervals, the resistance to strain is at its highest value. Contrary to expectations the resistance to strain attains a high value at early ages than falls later. This may be explained in part by the fact the mixture is in a plastic condition. Having, as yet not attained initial set the material reacts more as a fluid than as a solid. After initial set the characteristics are more comparable to those of an elastic solid and the strain resistance is correspondingly lowered.

Indirect Tensile Series The curves drawn for the ultimate tensile stress obtained from the indirect tensile and modulus of rupture tests are similar to one another although they exhibit different values at comparable ages. Comparison of these results with the gain in compressive stress with age shows them to follow the same general trend. The indirect tensile test gives values consistently lower than those obtained by the flexural formula. The variations between the two curves ranges from 16 to 55%, which gives a 30% average. The gain of tensile stress with age is comparatively slow during the early ages, having reached only 16% of its 28 day value at 7 days, as measured by the indirect method, and 38% of this value using the data from the modulus of rupture tests. The lower values obtained by the indirect tests are undoubtedly due to the triaxial-type loading conditions mentioned previously. This condition will be discussed later together with other conclusions reached.

Modulus of Rupture Series As mentioned in the discussion of the indirect test results, values of ultimate tensile stress computed by the two methods follow similar patterns of somewhat different magnitudes. From the plot of measured tensile and compressive strains against age it may be seen that these values follow the same general trends. The resistance to strain, both tensile and compressive, increases with age, being approximately one-third of the 28 day value at the age of 72 hours. The age range prior to 72 hours appears to be particularly critical as far as resistance to strain is concerned. There is a definite reduction in resistance to tensile and compressive strains at the age of 48 hours. Although this reduction is not to values obtained at the age of 24 hours, it is indicative of a definite change in the physical properties of the mixture. In the discussion of additional tests in the appendix, it is pointed out that this age exhibited unusual characteristics and should be further investigated.

Comparison of 40° and 70° Results A comparison of the several properties investigated at these two temperatures shows considerable variation in the values obtained. In each case values obtained by Mr. Hansen(8), are lower than those of the 40° tests. The lower temperature

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(8) Hansen, P. G., Physical Properties of Concrete at Early Ages, Thesis, Missouri School of Mines and Metallurgy, Rolla, Missouri, 1956.

at which the chemical reactions of these test specimens took place explains, in part, the reduced values at early ages; however, it was not anticipated that retardation would continue into the 28 day tests.

The compressive stress of the 40° series is 22% of the 70° value at the age of 72 hours, and rises to 86% at the age of 14 days. From 14 days to 28 days it is seen that the slope of the two curves is very nearly the same. Theoretically, the results indicate the specimens under 40° conditions would never attain the compressive strength values of the 70° series.

The values of modulus of elasticity obtained in the two series are markedly different in the early age ranges, (from zero to seventy-two hours), and as mentioned previously it was found by additional tests that this dissimilarity was apparent until the interval between four and five days. The seventy-two hour value of the 40° tests had attained only 1% of the 70° value. This reduction in the modulus of elasticity at early ages requires a re-evaluation of our construction procedures. The removal of forms at these age ranges could be disastrous. Further aging of specimens fails to produce modulus of elasticity values as high as the 70° series although the results of the 40° tests fall in the range generally given for concrete (3 to 6,000,000 psi).

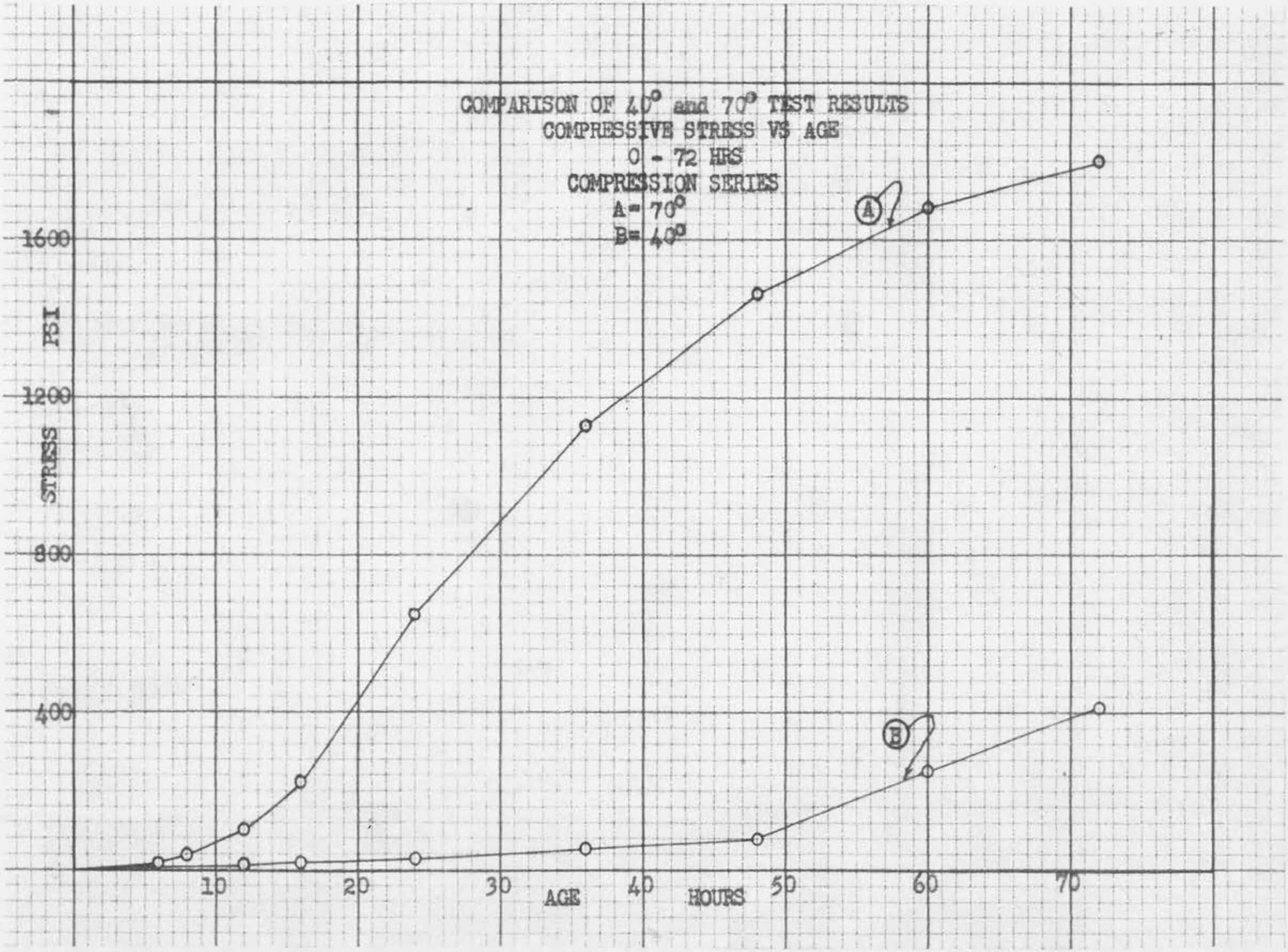
The resistance to compressive strains shows interesting variations. It will be noted that the 40° results are plotted to a scale of inches per inch times 10^{-5}, while those of the 70° tests are two inches per inch times 10^{-6}. The 16 hour value at 40° is 0.0150 inches per inch, while the 70° value is 0.001 inches per inch. Considering a ten inch gage length, this means a specimen at 40° would be deformed 0.15 inches while a 70° specimen would be deformed only 0.001 inches at a stress of 50% of the ultimate. Evidently the concrete mixtures at these two temperatures represent two different physical states; the 40° mixture is in the plastic range while the 70° mixture has been transformed into a partially elastic solid. This condition seems to exist until the age of seven days, when the 40° results show a strain of 0.00030 inches per inch and the 70° results a strain of 0.00028 inches per inch, or almost exactly equal values. From seven days to fourteen days both series exhibit similar resistance to strain.

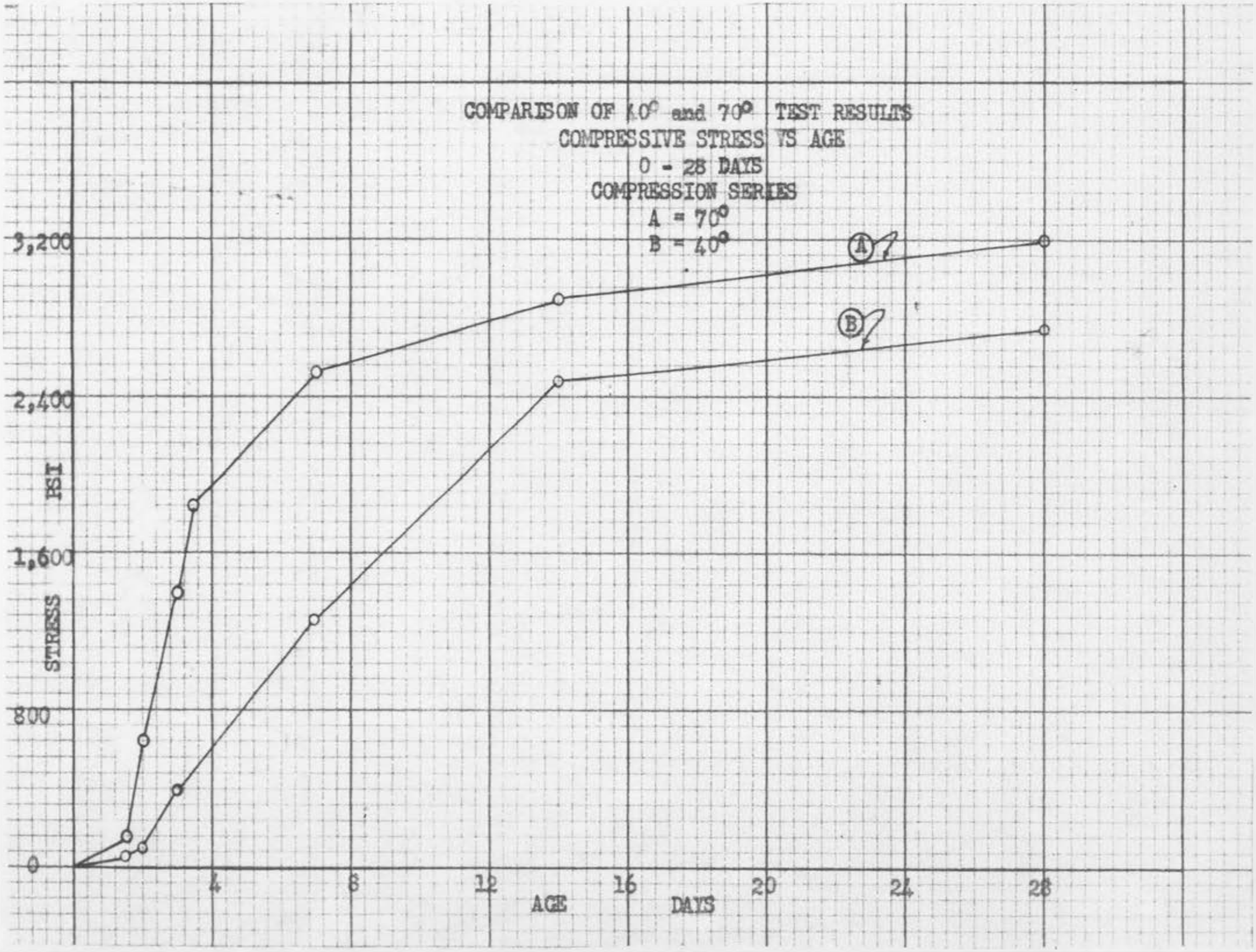
Comparison of 40° and 70° results for ultimate tensile stress shows conditions and values similar to the other physical properties. The stresses obtained by the flexural tests are lower for the 40° series as are those obtained by the indirect method. The reduction in modulus of rupture values is 48% at 72 hours and 50% at seven days, the two series reaching comparable values at 14 days. The indirect tensile tests show a reduction of 76% at 72 hours and 40% at seven days; this test not producing comparable values until after 28 days of age.

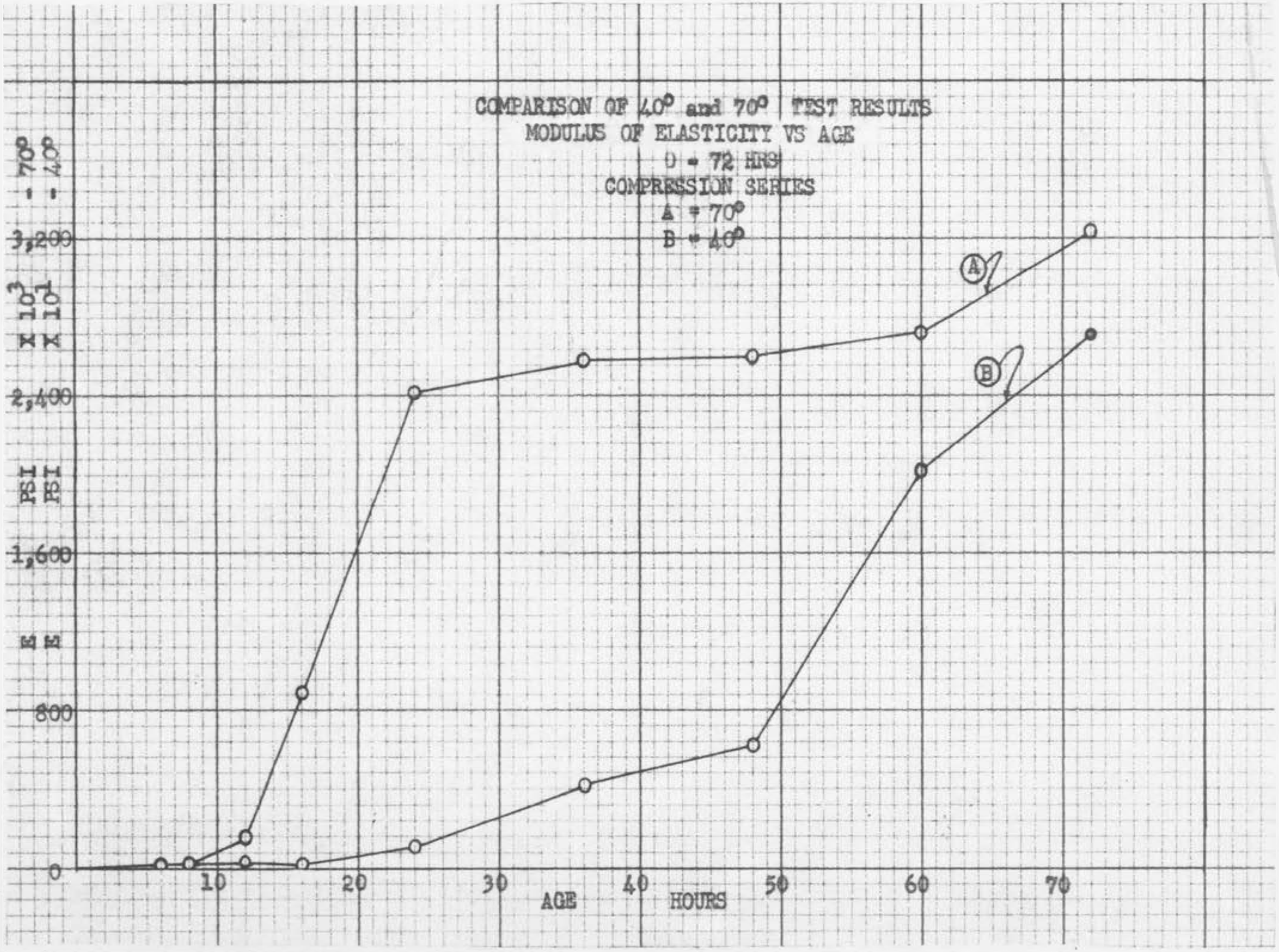
COMPARISON OF 40° and 70° RESULTS

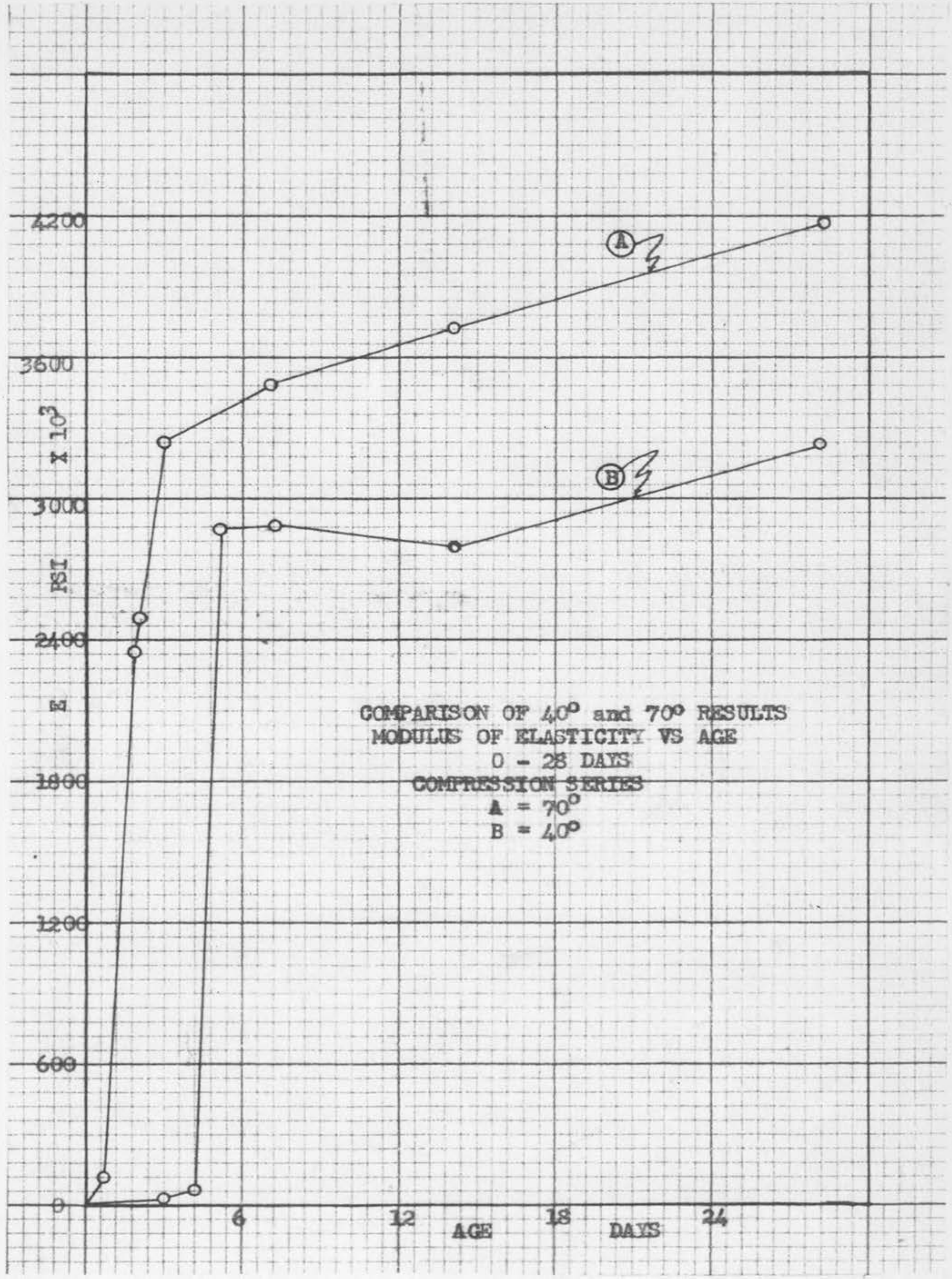
Graphs The **graphs** that follow are presented to show the variation between the results of the two series of tests.

Compressive stress versus age, from 0-72 hours and 0-28 days, is shown in the first two graphs. The modulus of elasticity versus age curves are shown on pages 91 and 92, strain at 50% of ultimate versus age follows. The last two graphs show a comparison of the ultimate tensile stress versus age for both the indirect and the modulus of rupture tests.

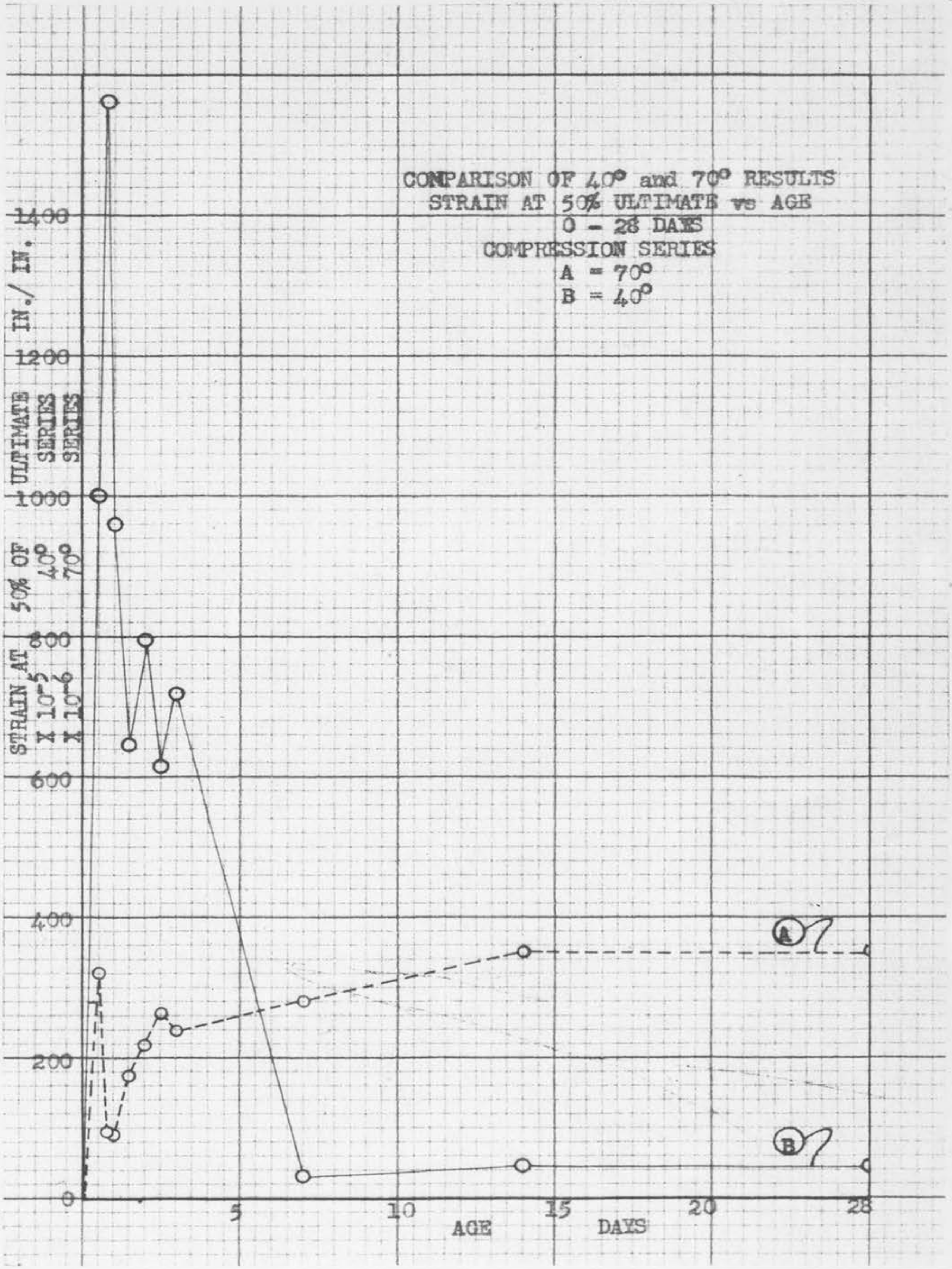

COMPARISON OF 40° and 70° TEST RESULTS
COMPRESSIVE STRESS VS AGE
0 - 72 HRS
COMPRESSION SERIES
A = 70°
B = 40°
A
B
STRESS PSI
1600
1200
800
400
10
20
30
40
50
60
70
AGE HOURS

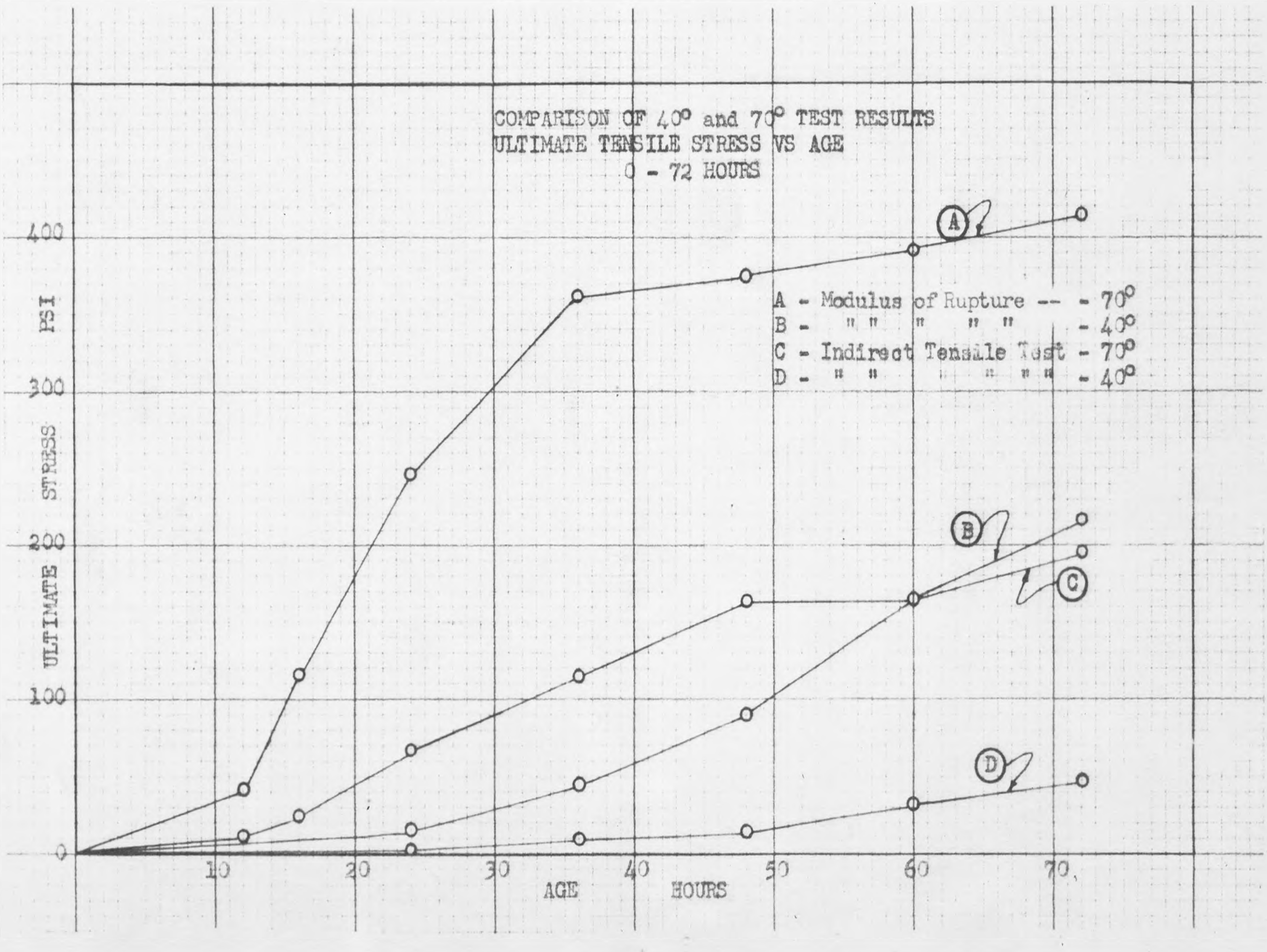

COMPARISON OF 40° and 70° TEST RESULTS
COMPRESSIVE STRESS VS AGE
0 - 28 DAYS
COMPRESSION SERIES
A = 70°
B = 40°
A
B
STRESS PSI
3,200
2,400
1,600
800
0
4
8
12
16
20
24
28
AGE DAYS

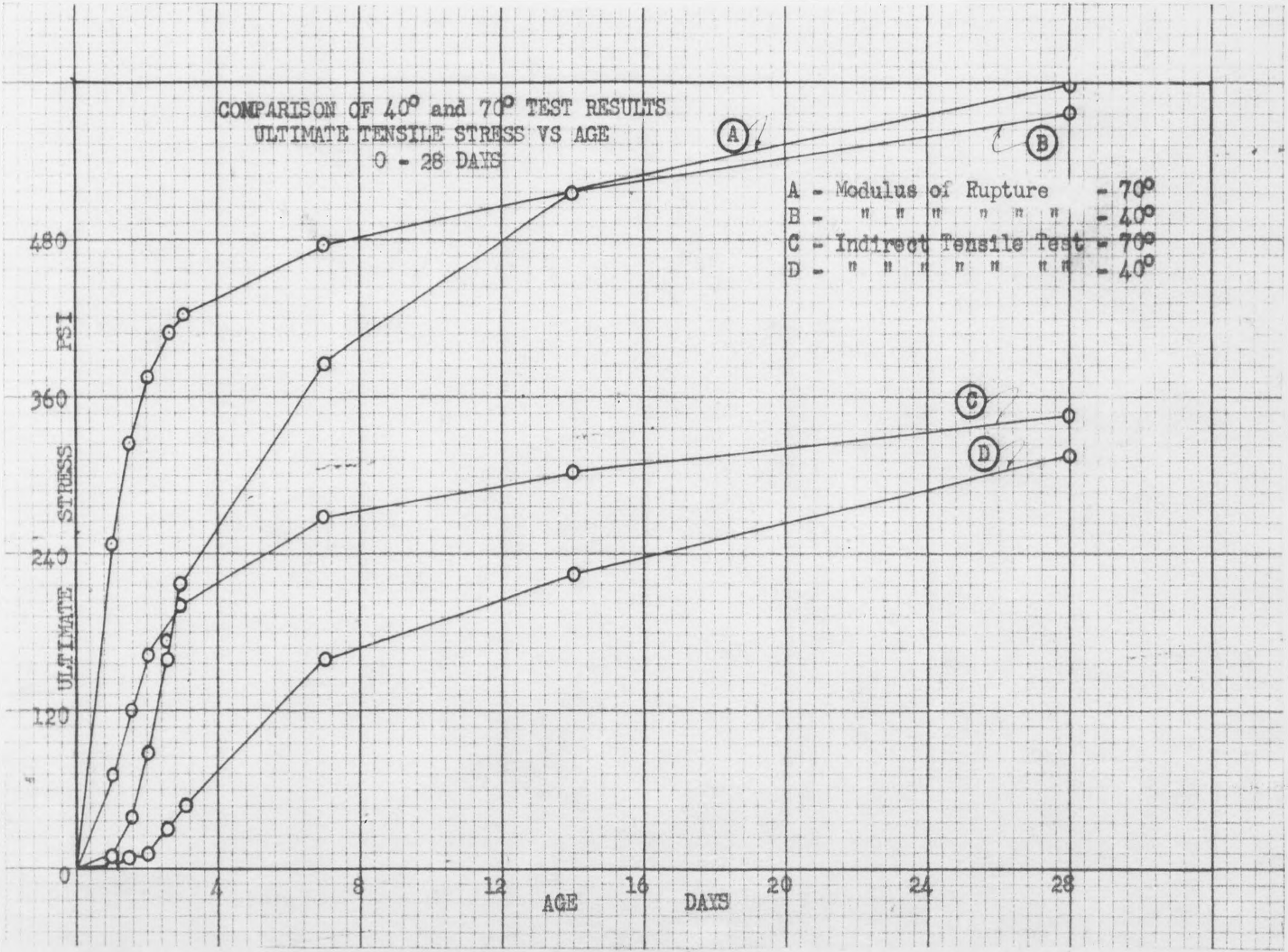

COMPARISON OF 40° and 70° TEST RESULTS
MODULUS OF ELASTICITY VS AGE
D = 72 HRS
COMPRESSION SERIES
A = 70°
B = 40°
E PSI X 10^3 - 70°
E PSI X 10^1 - 40°
3,200
2,400
1,600
800
0
10
20
30
40
50
60
70
AGE HOURS
A
B



COMPARISON OF 40° and 70° RESULTS
MODULUS OF ELASTICITY VS AGE
0 - 28 DAYS
COMPRESSION SERIES
A = 70°
B = 40°


COMPARISON OF 40° and 70° RESULTS
STRAIN AT 50% ULTIMATE vs AGE
0 - 28 DAYS
COMPRESSION SERIES
A = 70°
B = 40°
STRAIN AT 50% OF ULTIMATE IN./IN.
X 10^-5 40° SERIES
X 10^-6 70° SERIES
1400
1200
1000
800
600
400
200
0
5
10
15
20
28
AGE DAYS
A
B


COMPARISON OF 40° and 70° TEST RESULTS
ULTIMATE TENSILE STRESS VS AGE
0 - 72 HOURS
A - Modulus of Rupture -- - 70°
B - " " " " " - 40°
C - Indirect Tensile Test - 70°
D - " " " " " - 40°
A
B
C
D
ULTIMATE STRESS PSI
0
100
200
300
400
10
20
30
40
50
60
70
AGE HOURS


COMPARISON OF 40° and 70° TEST RESULTS
ULTIMATE TENSILE STRESS VS AGE
0 - 28 DAYS
A
B
C
D
A - Modulus of Rupture - 70°
B - " " " " " " - 40°
C - Indirect Tensile Test - 70°
D - " " " " " " " - 40°
ULTIMATE STRESS PSI
0
120
240
360
480
4
8
12
16
20
24
28
AGE DAYS

CONCLUSIONS

The results of this series of tests show that the effect of a controlled temperature upon the physical properties of a concrete mixture is very pronounced. The various tests, planned to cover as early ages as practicable, show markedly reduced values for the modulus of elasticity, compressive stress and tensile stress under 40° conditions. These values are particularly low in the age range below seven days, showing a definite retardation of the chemical reaction which takes place. This is in accordance with the laws of chemical change. Retarding the set of the mixture has the effect of keeping the concrete in the plastic state, and this condition explains the resistance to strain which was found in the early ages.

The following conclusions have been made either from the test results or by observation.

<u>Compressive Tests</u> The stress - strain curves for the ages of 24, 36, 48, 60 and 72 hours and the additional tests at four days are surprisingly different than normal stress - strain curves for concrete. At these ages the mixture seems to be susceptible to consolidation action and the possibility exists for analyzing its behavior by the methods of soil mechanics. Between four and five days of age, the concrete undergoes a complete physical change, its properties also showing marked change at, or near, this age interval. Particularly affected during this transition period is the modulus of elasticity of the mixture. The modulus of elasticity increases at a slower rate than the compressive strength up to approximately four days, then it rises quite rapidly. The compressive stress is nearly twice the tensile stress duringthe first three days of age, after which the compressive stress gains in value faster than the tensile stress. At 28 days the compressive

stress gains in value faster than the tensile stress. At 28 days the compressive stress is over five times the tensile stress.

Indirect Tension Tests The indirect tensile test furnishes a reasonably simple means of ascertaining the comparative tensile stress in a concrete cylinder. The use of a similar specimen and the same testing machine as the compressive test makes it particularly attractive. The indirect test tends to give more uniform results than other types of tension tests, although not as uniform as the compression test. The results obtained give values approximately one-third of those obtained by the modulus of rupture test.

Modulus of Rupture Tests The results of this series of tests show the need for additional information concerning the flexural behavior of a concrete beam. Measured strains in tension and in compression show a large variation and indicate the possibility of a different type of distribution than is now used for design purposes. The assumptinns made in the derivation of the flexural formula are at considerable variance with test results and additional tests should be run to evaluate the properties of the concrete under this type of loading.

It is hoped that the information obtained from this series of tests will be of use in the future design of concrete, either for highway slabs or other types of construction. The information on stresses and strains and modulus of elasticity show a definite need for further tests to determine the effects of lowered temperatures on a concrete mixture during its early age.

RECOMMENDATIONS

The results of these tests indicate the need for considerable additional information concerning the behavior of the concrete mixture at early ages.

A series of tests to determine the true location of the neutral axis in a concrete beam and the distribution of both tensile and compressive stresses under a flexural loading would be useful.

Further tests should be run to determine the properties of concrete after a consolidation-type loading has been imposed. The early age ranges should produce particularly informative results and it is hoped these tests will be conducted.

Analogy might be drawn between the action of a concrete mixture and certain types of soils, under long-time loading. The subject of creep and related matters concerning concrete might well be better evaluated by consideration of this possible similarity.

SAMPLE CALCULATIONS

Computation of one-sack batch absolute volume

Batch information furnished by Missouri State Highway Department:

1:1.97:3.36 with 5.6 gallons of water

Material	Absolute Volume (cubic feet)
Cement - one sack	0.4782
Fine Aggregate - 1.97 x 0.6850	1.34945
Coarse Aggregate - 3.36 x 36 x 0.5573	1.872528
Water - 5.6/2.5	0.746667
Total yield =	4.446845 $(\text{ft.})^3$

Computation of Mix   Cycle A-1 Modulus of Rupture Series

Yield desires - 6 x 8 x 11 = 16.896 in.^3

= 10% surplus = 1,690

total = 18.586 in.^3

$$\frac{18{,}586}{1728} = 10.755787 \ (\text{ft.})^3$$

$$\text{Total sacks / cycle} = \frac{10.755787}{4.446845} = 2.41874565$$

Capacity of mixer = 3.0 $(\text{ft.})^3$ maximum

Therefore mix in four batches at $\frac{10.755787}{4} = 2.68894675 \ (\text{ft.})^3$ per batch. Sacks / Batch = $\frac{2.68894675}{4.446845} = 0.604686412$

Determination of Percent Moisture in Aggregate

Type of sample-fine aggregate   Cycle A-1

Weight of pan -------------------- 0.66 lb.

Weight of pan + sample ------------ 3.66 lb.

Net weight of sample (wet) -------- 3.00 lb.

Weight of pan + sample (dry) ------ 3.548 lb.

Net weight of sample (dry) -------- 2.888 lb.

Loss of weight in sample ----------------- 0.112 lb.

Percent moisture = $\frac{0.112}{3.000} \times 100 = 3.74\%$

TYPE OF SAMPLE-COARSE AGGREGATE - CYCLE A-1

Weight of pan ---------------------- 1.10 lb.

Weight of pan + sample (wet) -------- 6.10 lb.

Net weight of sample (wet)----------- 5.00 lb.

Weight of pan + sample (dry) -------- 6.07 lb.

Net weight of sample (dry) ---------- 4.97 lb.

Loss of weight in sample ------------ 0.03 lb.

Percent moisture = $\frac{0.03}{5.00} \times 100 = 0.06\%$

Entrapped air = 0.6% (ignore in calculations)

Fine aggregate: Specific gravity = 2.55, Weight = $\frac{109 \text{ lb.}}{(\text{ft.})^3}$

Coarse aggregate: Specific gravity = 2.66, Weight = $\frac{92.5 \text{ lb.}}{(\text{ft.})^3}$

Mix Computation

Yield desired - 6 x 8 x 32 x 11 = 16,896 $(\text{in.})^3$

= 10% surplus = 1,690 $(\text{in.})^3$

total = 18,586 $(\text{in.})^3$

$\frac{18,586}{1728} = 10.755787 \ (\text{ft.})^3$

Total sacks / per cycle = $\frac{10.75587}{4.446845} = 2.41874565$

Capacity of mix in four batches at $\frac{10.755767}{4}$ or

2.68894675 $(\text{ft.})^3$ per batch

sacks/batch = $\frac{2.68894675}{4.446845} = 0.060496412$

Batch Quantities (By Weight)

Cement = 0.0604686412 x 1 x 94 = 56.84 lb.

Fine = 0.0604686412 x 197 x 109 = 129.84 lb.

Coarse (total) 0.0604686412 x 3.36 x92.5 = 187.94 lb.

Water = 0.0604686412 x 5.6 x 8.333 = 30.23 lb.

Scale Weights (Per Batch)

Cement (no correction) = 56.84 lb.; 2 buckets at 33.42 lb.

Fine aggregate = 129.84 (1.000+0.0763) = 139.60 lb.

3 buckets at 50.00 lb.

1 bucket at 9.60 lb.

Coarse Aggregate = 187.94 (1.000+0.0763) = 191.20 lb.

1/2 lb. at 35% x 191.20 = 66.82; 2 buckets at 38.41 lb.

4 lb. at 60% x 191.20 = 114.82; 2 buckets at 50.00 lb.

10 lb. at 5% x 191.20 = 9.56; 1 bucket at 14.56 lb.

Check: Total = 191.20 lb.

Compression Series

S = unit stress

E = unit deformation

D = total deformation

P = load in pounds

A = cross-sectional area (square inches)

L = gage length

Cycle C-3, Specimen 4, Age 60 hrs.

S = P/A = 500/28.33 = 1768 lb. per in.^{2}

Average reading Ames dials = 7.5×10^{-3}

$E = D/L = 7.5 \times \frac{10^{-3}}{12} = 62.5 \times 10^{-5}$ **inches**

E = Modulus of Elasticity

$E = \frac{127.2}{622} \times 10^{-5} = 20{,}500$ lb. per sq. inch

Indirect Tension Series:

$$= \frac{2P}{\pi t d} \left[1 = \frac{d}{2a} \left(\alpha = \sin \alpha \right) \right]$$

= 0.00884 P

= Tensile stress (horizontally)

t = thickness

P = load in pounds

d = diameter of specimen

a = width of loaded area

α = angle subtended by loaded area (consider from edges of loading strip to center of cylinder)

Average 60 hours ultimate load = 3,596.6

$$= \frac{2 \times 3{,}596.6}{\times 1 \times 12} \left[1 - \frac{12}{2 \times 1} \quad (0.1663 - 0.1656) \right]$$

= 31.8 lb. per inches squared

Note: All **calculations** were rounded off to three significant figures for use.

APPENDIX

ADDITIONAL TESTS

Modulus of Elasticity It was noted during the analysis of the data from the compression series of tests that a gap existed in the information for the modulus of elasticity curves. During the time interval of four days between the 72 hour tests and the seven day tests, the modulus of elasticity was observed to rise from an average value of 27,500 psi to 3,010,000 psi. The original scheduling of age groups to be tested did not foresee these results and no provision was made to further determine the properties of the mix at other ages. Obtaining information of a more specific nature between these ages would be desirable. It was felt that additional tests at four, five and six days of age would satisfactorily determine, at least within 24 hours, the age at which the specimen's modulus of elasticity increased so rapidly. These tests were accordingly conducted; only one specimen at each age being tested.

The stress versus strain measurements for these tests are presented in tabular form and are also plotted.

It may be seen that the four day old specimen did not exhibit an exceptional rise in its modulus of elasticity. Also note the similarity between the stress-strain curve of this test and those of the 16, 36, 48, 60 and 72 hour tests. This pecularity has already been mentioned. The modulus of elasticity of the five day old specimen has risen to over 3,000,000 psi or to within the range normally specified for concrete. The stress-strain curve has also assumed a more familiar form being similar to the results obtained for the previous 7, 14 and 28 day tests. The six day old specimen is found to be near the 3,000,000 psi value of modulus and the mixture appears to exhibit the characteristics of normal temperature-range concrete.

Although this series of additional tests was made on only one specimen at each age, the results may be taken to be reasonably indicative of the general trends exhibited by the properties of the mixture. Within the twenty-four period between the four and the five day test, the modulus of elasticity increases over forty times, the resistance to strain increases to over thirty times its previous value while the ultimate stress remains at very nearly the same value. There is a definite and considerable change in the physical makeup of the mixture during this time interval. The limited information we have available concerning these changes should certainly be expanded.

Pre-Compression Tests As mentioned in earlier paragraphs, the unusual curvature of the stress-strain relationships of the 16, 36, 48, 60 and 72 hour tests was noted and discussed. Attention was directed to the similarity between these curves and consolidation curves obtained for certain types of soils. The possibility existed that the concrete mixture could be subjected to some form of consolidation during the age range suggested by these test results. If such consolidation could be effected, and the mixture exhibited actions similar to soil samples so treated, beneficial results might be obtained. Consolidated soils have been found to be more resistant to plastic flow and have also been able to resist much higher strains before failure. An increase in either of these physical properties in concrete would be interesting, if not indicative of application to design. Consolidation could be effected during the construction sequence by the application of a compression load in the case of highway slabs.

An investigation of the possibilities mentioned was made by running additional tests. A seven-cylinder cycle of specimens were scheduled, and specimens at the ages of 24, 36, 48, 60 and 72 hours were subjected to a compressive load resulting the imposition of a strain of 600 X 10^{-5} inches per inch on each specimen. They were then returned to the temperature controlled room for further curing. The remaining two specimens were not subjected to this preliminary loading but were cured under the same controlled conditions as all other tests.

The results of these tests are presented in tabular form and graphically, and are compared with the results of the normal 14 day test for comparison.

Test Age (Hrs.)	Strain at 50% of Ultimate (In./In.)	Ultimate Stress (Psi)	Modulus of Elasticity (Psi)
14 Day (Normal)	43 x 10^{-5}	2476	2,860,000
24P	33.6 X 10^{-5}	1910	2,840,000
36 P	49.8 X 10^{-5}	1670	1,680,000
48 P	11.5 X 10^{-5}	1130	4,920,000
60 P	28.7 X 10^{-5}	1650	2,875,000
72 P	21.0 X 10^{-5}	1350	3,215,000
14 Day (Extra)	42.4 X 10^{-5}	2400	2,835,000

In every instance where the specimen was subjected to a compressive load (consolidation) prior to testing the ultimate stress was reduced considerably below the normal 14 day results. This reduction in resistance to stress varies from as high as 53% to 20%, averaging approximately 36%. The resistance to strain rises except for the 36 hour specimen. This increase varies from 73% to 21%, averaging approximately 45%. While the comparative resistance to stress has been lowered by the consolidation loading imposed and the apparent resistance to strain has been increased, the modulus of elasticity or; perhaps more appropriately, the modulus of stiffness, has not been affected except in two instances. The 36 hour test shows a lower modulus while the 48 hour test shows a considerable rise in this important property.

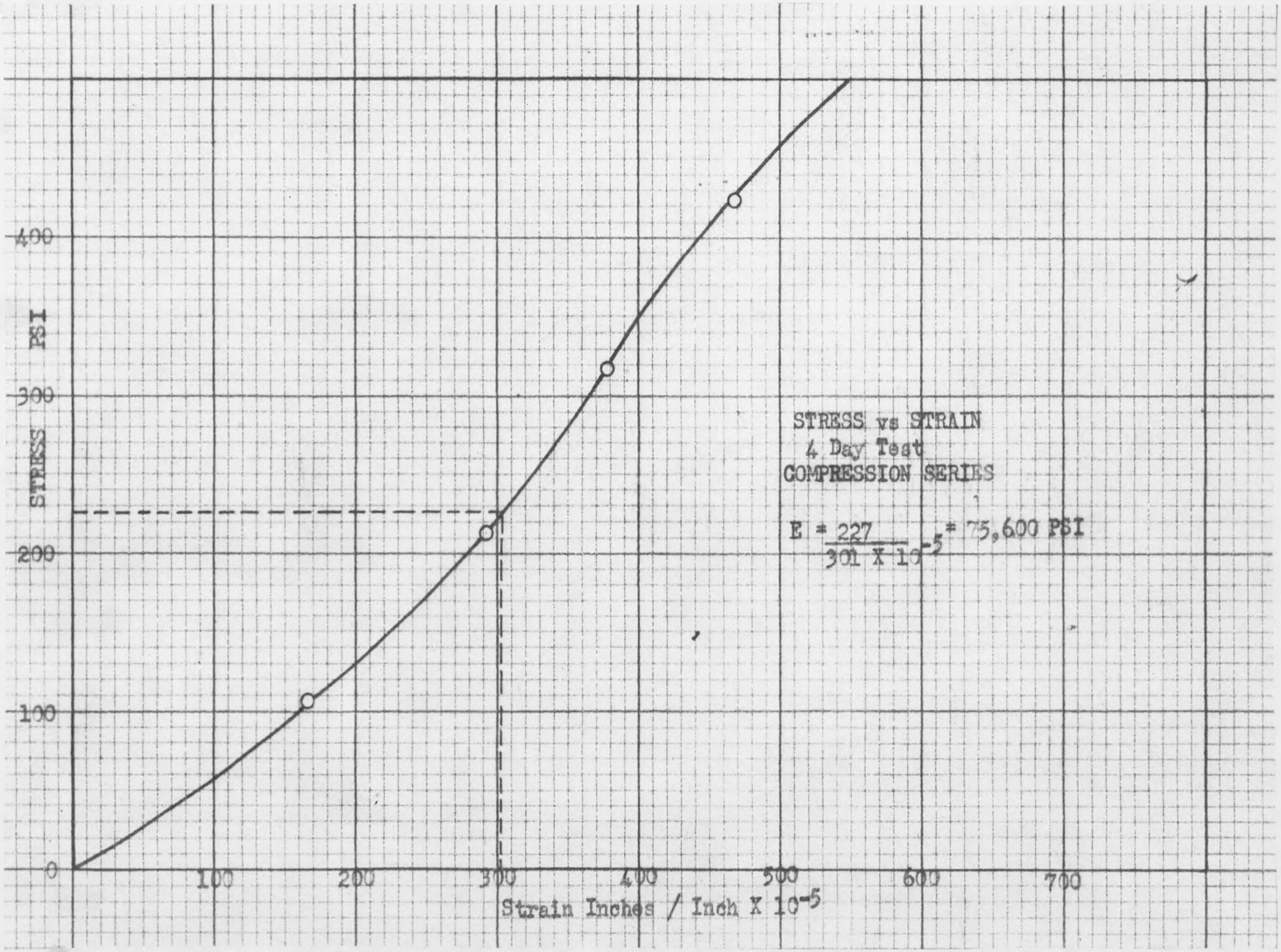
Although insufficient tests were conducted to accurately evaluate the properties of a concrete mixture under consolidation, the possible significance of these results may be inferred. Allowing construction equipment to operate over a highway section at the age of 36 hours might detrimentally affect the later age properties of the concrete; while such actinn at 48 hours, a mere 12 hour time differential, could be advantageous.

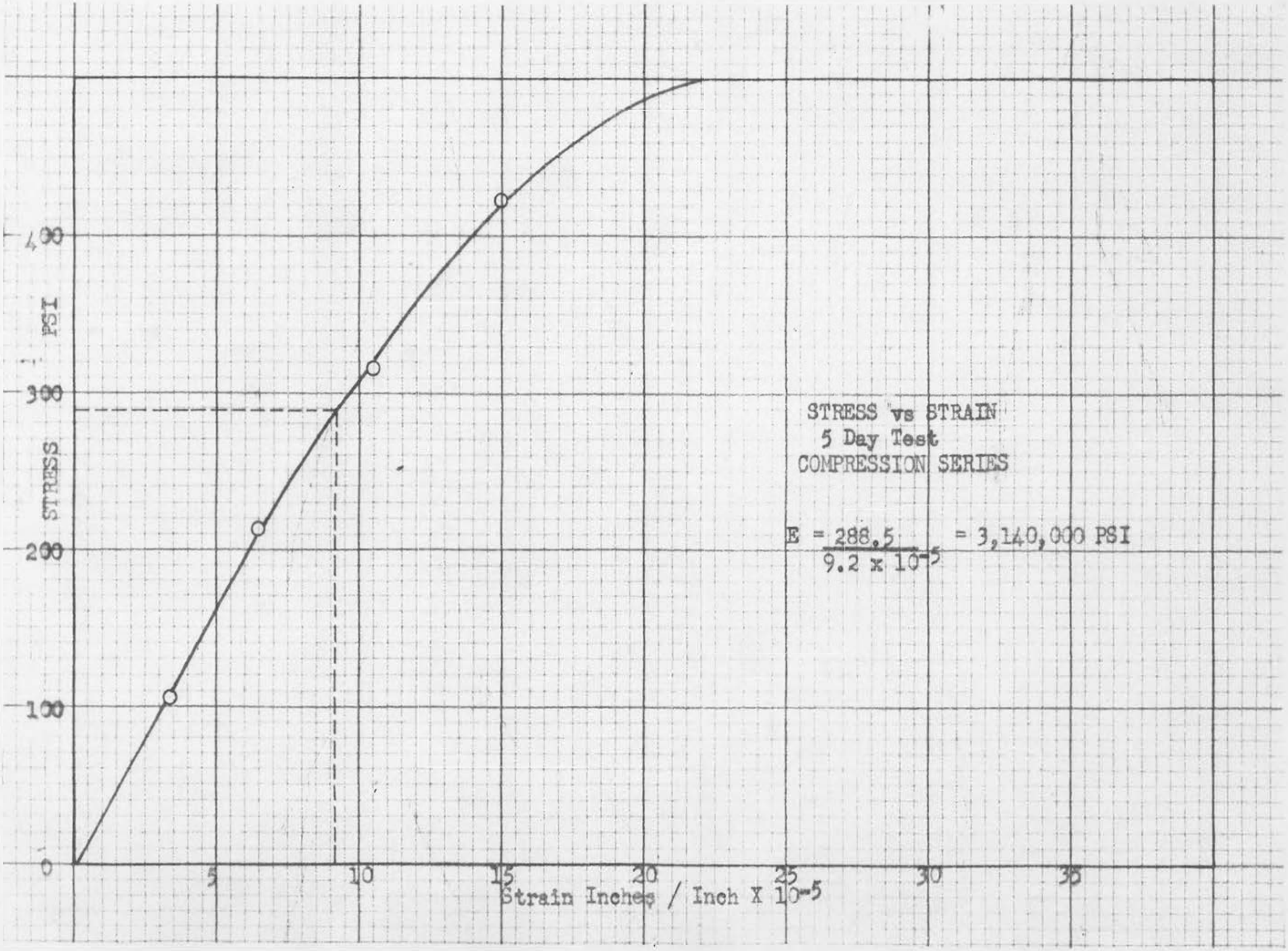
It is strongly urged that an attempt be made to further study the physical properties of concrete, particularly at the very early ages. Perhaps we have the opportunity to better utilize this most important construction material; certainly additional information would be helpful in some manner.

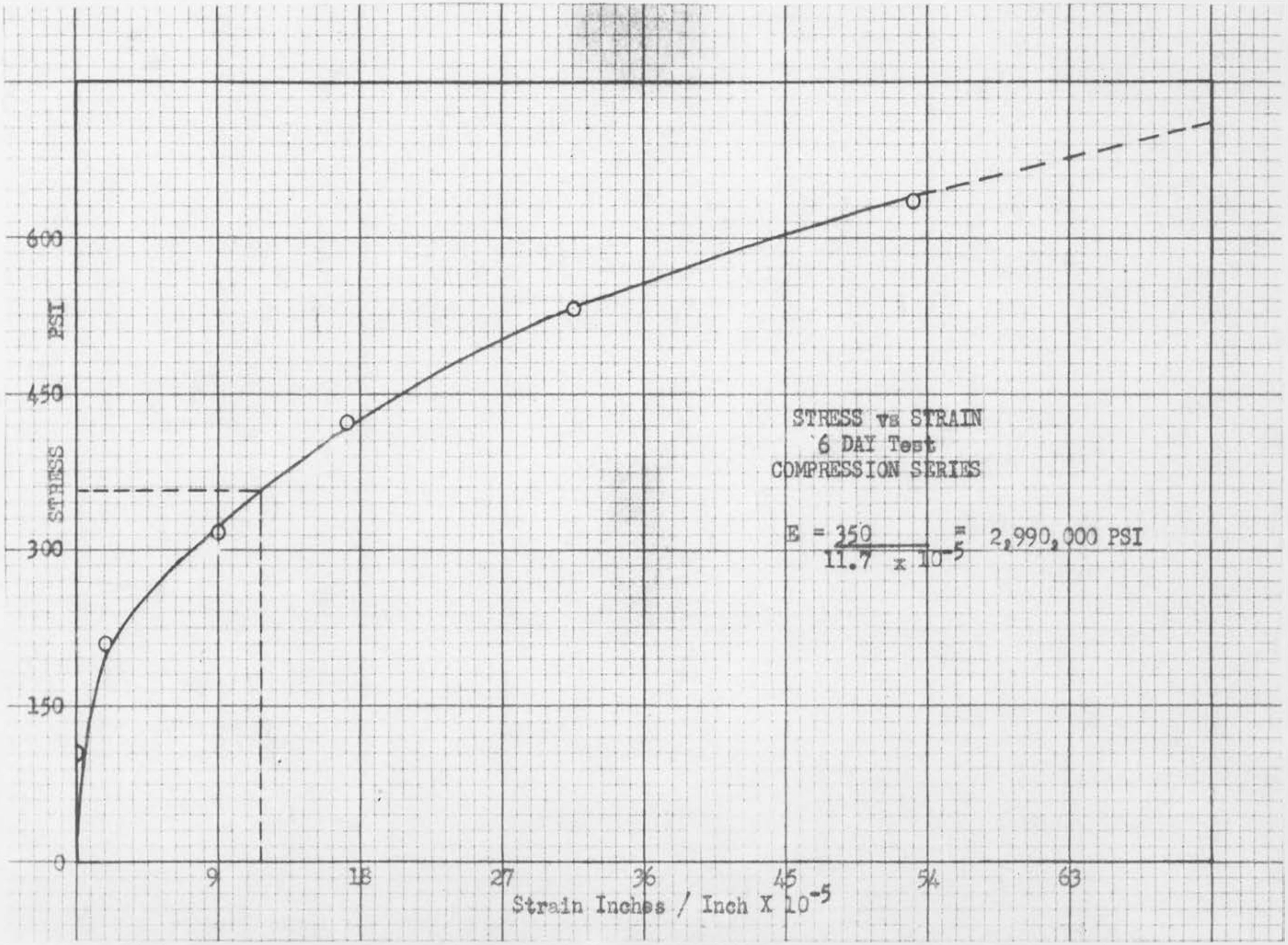
It is also suggested that methods of analysis related to the soil mechanics field might be adapted and used as tools in the interpretation of the action of concrete under load.

COMPRESSION SERIES STRESS VS. STRAIN MEASUREMENT 6" x 12" CONCRETE CYLINDERS -- AGES 4, 5, 6 DAYS

STRESS PSI	4 DAY	5 DAY	6 DAY
	STRAIN IN/IN x 10^{-5}		
106	166	3.5	0.0
212	291	6.5	1.8
318	379	10.5	9.0
424	469	15.0	17.2
530	583	31.5	31.5
636			53.1
714			
ULTIMATE	554	577	714


STRESS vs STRAIN
4 Day Test
COMPRESSION SERIES
$E = \frac{227}{301 \times 10^{-5}} = 75{,}600$ PSI
STRESS PSI
0
100
200
300
400
Strain Inches / Inch X 10^{-5}
100
200
300
400
500
600
700


STRESS vs STRAIN
5 Day Test
COMPRESSION SERIES
$E = \frac{288.5}{9.2 \times 10^{-5}} = 3,140,000$ PSI
STRESS PSI
0
100
200
300
400
5
10
15
20
25
30
35
Strain Inches / Inch X 10^{-5}

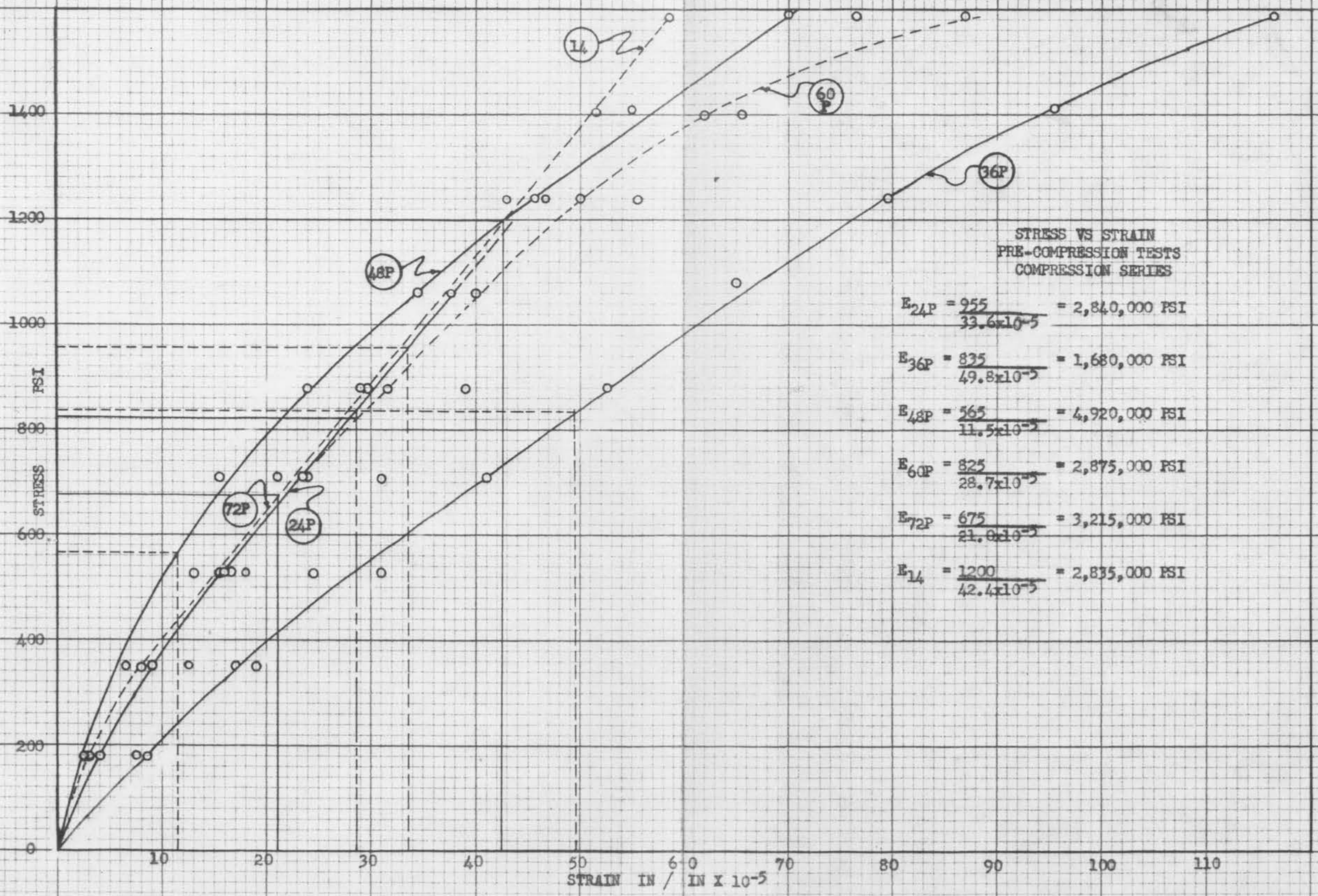


STRESS vs STRAIN
6 DAY Test
COMPRESSION SERIES

$E = \frac{350}{11.7 \times 10^{-5}} = 2{,}990{,}000$ PSI

COMPRESSION SERIES - LIST
STRESS AND STRAIN MEASUREMENTS ON 6"x 12"
SPECIMEN PRE-COMPRESSED TO A STRAIN OF 600 X 10^{-5} INCHES / INCH
TESTED AT 14 DAYS

STRESS	STRAIN IN / IN X 10^{-5}						
PSI	24P	36P	48P	60P	72P	14D	14D
180	4.0	8.5	2.5	3.0	2.5	10.0	4.5
350	9.0	19.0	6.5	9.0	8.0	17.0	8.0
530	16.0	31.0	13.0	16.5	15.5	24.5	11.5
710	23.5	41.0	15.5	23.5	21.0	31.0	16.5
880	29.0	52.5	24.0	31.5	29.6	39.0	21.0
1060	37.5	65.0	34.5	40.0	37.5	----	25.0
1240	45.5	79.5		50.0	46.5	55.5	31.0
1410	55.0	95.5		62.0		66.5	36.0
1590	70.0	116.5		87.0		76.5	40.5
1770						90.0	45.0
Ultimate	1910	1670	1130	1650	1350	2280	2520



STRESS VS STRAIN
PRE-COMPRESSION TESTS
COMPRESSION SERIES

$$E_{24P} = \frac{955}{33.6\times10^{-5}} = 2{,}840{,}000 \text{ PSI}$$

$$E_{36P} = \frac{835}{49.8\times10^{-5}} = 1{,}680{,}000 \text{ PSI}$$

$$E_{48P} = \frac{565}{11.5\times10^{-5}} = 4{,}920{,}000 \text{ PSI}$$

$$E_{60P} = \frac{825}{28.7\times10^{-5}} = 2{,}875{,}000 \text{ PSI}$$

$$E_{72P} = \frac{675}{21.0\times10^{-5}} = 3{,}215{,}000 \text{ PSI}$$

$$E_{14} = \frac{1200}{42.4\times10^{-5}} = 2{,}835{,}000 \text{ PSI}$$

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VITA

Curtis Eugene Weddle, Jr. was born on July 28, 1928 near Independence, Missouri, the son of Mr. and Mrs. Curtis E. Weddle, Sr.

He received his grade school education at Rock Creek School and his high school education in the public school system of Independence.

He received the degree of Bachelor of Science in Civil Engineering in May, 1955 from the Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma, after attendance at Southwestern University, Georgetown, Texas, the University of Idaho and the University of Missouri.

His service time was spent as a student pilot in the United States Navy Flight Training Program.

His experience was gained by full-time and summer employment with a number of organizations among which are: General Motors Corporation, Standard Oil Company, Westinghouse Electric Corporation, Chicago, Burlington and Quincy Railroad, The City of St. Louis-MacArthur Bridge Commission, the United States Bureau of Reclamation and Consumer's Power Company.

In April, 1955 he was married to Miss Patsy R. McLemore of McAlester, Oklahoma and they now have one son, Curtis E. Weddle, III.

Appointed as Instructor in Civil Engineering at the Missouri School of Mines in June, 1955, he has served in that capacity to date.