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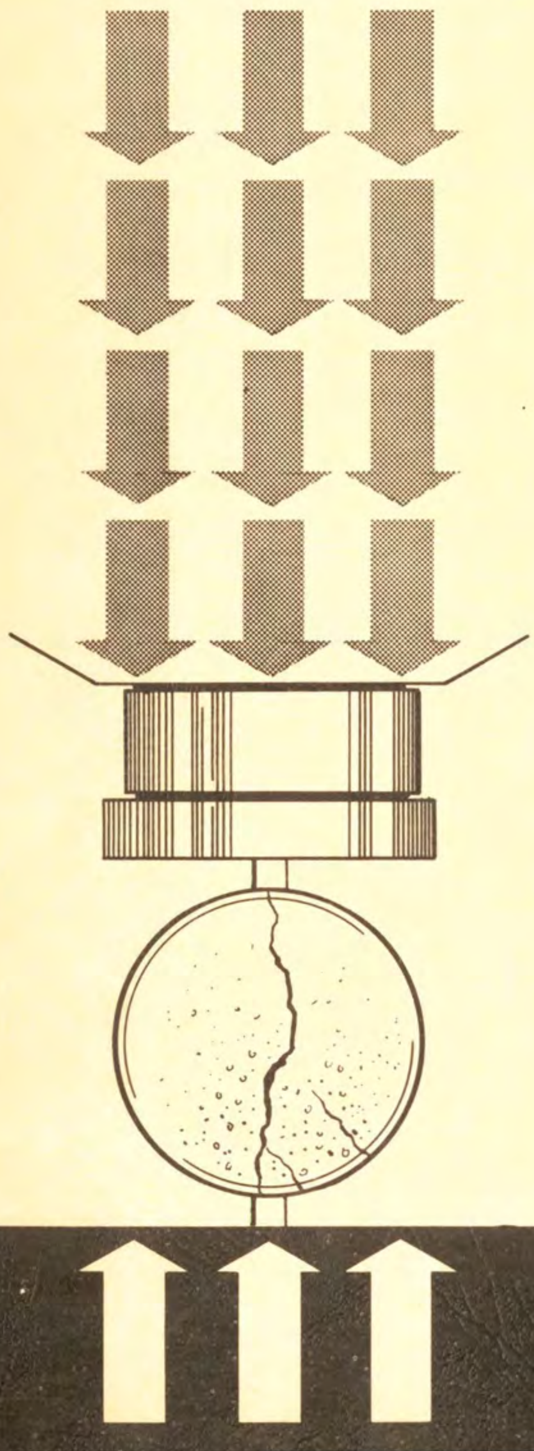

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FOR THE
MISSOURI SCHOOL OF MINES AND METALLURGY
IN COOPERATION WITH
THE MISSOURI STATE HIGHWAY COMMISSION
AND
THE BUREAU OF PUBLIC ROADS
JANUARY 1961

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SYNOPSIS

The exploratory investigation covered by this report included determination of strength and deformation properties in non-air-entrained (dense) concrete at ambient temperatures of 40, 70, and 100 F, and in air-entrained concrete at 70 F, from the earliest age at which tests could be made to 28 days.

Stress deformation and strength were determined on concrete cylinders in compression, and on beams under flexural loading for tension and compression. Tension strength was determined also on concrete cylinders loaded with concentrated line loads in a diametric plane.

Deformation properties in compression and tension were determined at each age from the cylinder and beam short-time tests. Tension strengths obtained in flexural and concrete splitting tests were compared in relation to other strength and deformation properties. Relations between the modulus of deformation and strengths were suggested for different temperatures.

From the influence of ambient temperatures upon strength values and deformation properties, relatively clear indications are given as to the earliest ages at which prestress could be applied without crushing bearing areas.

Ultimate strains in tension, as indicated by the short-time beam tests, were much lower at ages of one day or less than at mature age. For application to pavement construction the data suggest that more than usual care may be necessary in curing to prevent cracks due to temperature and moisture changes.

INTRODUCTION

Strength properties of concrete are inefficiently utilized in conventional concrete pavements. Stresses are limited to concrete's relatively low strength in bending. As a result, thick pavements are used for high wheel loads, with corresponding increase in pavement stiffness as well. Restraints of moisture warping and temperature curling combine with load stresses to limit slab lengths, or induce critical stresses and cracking. Joints between short slabs and cracks are points for moisture attack on the subgrade and progressive deterioration in some soils. Effective use of compressive prestress holds challenging possibilities for concrete pavements through use of much longer and thinner slabs.

The application of prestressing to concrete pavements involves many unknown variables. Prominent among them are problems of deformation and stresses in the concrete at early age, and deformations under prestress of thin slabs on subgrades. Many problems concerned with prestressed pavements cannot be answered without extensive field experiments and construction of actual pavements. Answers to some questions might be suggested by more modest experimental investigations.

The following problems were selected for exploratory investigations of prestressing as applied to pavements in a Missouri State Highway Commission cooperative research project at the Missouri School of Mines and Metallurgy at Rolla:

(A) Continuing length changes and deformations of simulated, relatively short, prestressed pavement slabs on a typical highway subgrade.

(B) Stress distribution and concrete failure determination near concentrated loads applied against an edge of a thin concrete slab, in the manner longitudinal prestressing forces might be applied against ends of long prestressed slabs.

(C) Physical properties of pavement concretes at early age and at different ambient temperatures, for determination of earliest age of prestressing, and possible pavement stresses prior to prestressing, under different seasonal highway construction conditions.

This report covers the last mentioned experimental investigation. The tests were intended to provide a clue to stresses in concrete pavements at early age. They also give information on the earliest age at which, for different construction temperatures, prestress can be imposed without excessive deformation. The tests were exploratory, limited to three specific temperatures, 100, 70, and 40 F, and to conventional data for laboratory tests. The test series for each temperature, and air-entrained concrete, were made as separate projects at different times, with concrete materials assembled beforehand to be representative for all. Information from the separate investigations has been combined in this report.

RESEARCH PROGRAM

The scope of research in this exploratory investigation covered short-time tests to failure of conventional cylinder and beam laboratory specimens, which were made and stored at typical cold, median, and high ambient construction temperatures, and which were tested at different ages from the earliest at which they could be handled and placed in the testing machine, up to 28 days. Immediate deformation with increasing stress was measured, in compression on both cylinders and beam, and in tension on the beams. The program included only normal pavement concrete mix as used on Missouri highways; air-entrained concrete was used only in one series at median temperature.

The research was planned to provide information on hardening and strength increase in pavement concrete during early age at different construction temperatures. It was intended, also, to give some indication of maximum stresses which might be expected in pavements due to length changes occasioned by shrinkage and temperature changes, of the ability of the concrete to sustain such length changes at different ages, and of slab shortening which might occur when subjecting the pavement to compressive prestress.

Repeated tests were not made; it is accordingly not possible to say how much of the deformations was elastic. Creep tests were not included; stresses based on deformations observed in the tests accordingly are the highest that could be expected, lower stresses or greater deformation without increase in stress could very well occur.

Materials

Cement was all Type I purchased from two manufacturers, in each case all from one burn. The cement was stored in sacks sufficient for all series and mixed equal parts from each manufacturer in all batches. For the 100 F series the cement had been in storage over six months, and was screened prior to use, discarding all material retained on #10 screen.

Sand was Meramec River sand with dry rodded weight per cubic foot, 109 pounds, bulk specific gravity 2.55, and 1.5% water absorption.

Coarse aggregate was crushed limestone with dry rodded weight per cubic foot, 92.5 pounds, bulk specific gravity 2.66, and 0.7% water absorption. The gradation used in all series was:

Sieve size	Retained total
1/2"	35%
#4	95%
#10	100%

Air-entrained concrete was used in one 70 F series, air-entrained agent

AD-AIRE mixed with the water at the rate of 13 1/2 grams per sack cement, which gave air content from 3.4 to 5.3%, average 4.4% for 18 batches of concrete, measured with pressure-type air meter.

Concrete Proportions

The basic mix was fixed by the Missouri State Highway Commission as 1:1.97:3.36 by solid volume, with 5.6 gallons water per sack cement, yielding 4.45 cubic feet of concrete. For the air-entrained concrete the mix was 1:1.72:3.36 with 4.47 cubic feet yield, with the sand adjusted for air content.

The mix for the 40 F specimens varied somewhat from the other series. Proportions by dry weight per 94 pound sack of cement for the different series were:

		Sand (#4 screen)	Stone #	Water gallons	Slump inches
Dense concrete,	100 F	229	295	5.6	1/4 to 3
Dense concrete,	70 F	232	295	5.6	-
Dense concrete,	40 F	245	248	5.1	1 1/4 to 2 3/4
Air-entrained concrete	70 F	203	295	5.6	1 to 4.25, average 2.2

The concrete was mixed in a 3 cubic foot mixer, with 2.2 to 3.0 cubic foot batch sizes, mixed not less than 2 minutes. Both cylinders and beam forms were filled and rodded according to A.S.T.M. Standard procedure.

Temperature Control

The concrete materials, and specimens up to the time of testing, were kept in a small temperature controlled room at substantially constant ambient temperatures selected for each series of tests. All materials, including the water were placed in the room not less than 72 hours prior to concrete mixing. Batches were weighed in the room and brought to the mixer just outside. As soon as possible after placement in the forms, the specimens were returned to the room, to remain until tested.

The room temperature and its variation for the different series, the humidity in the room as determined daily, and the maximum deviating concrete temperature during the short interval of mixing and placing in the forms outside of the room, were:

Investigation Series	Room Temperature	Room Humidity	Concrete Placement Temperature
Dense concrete	100 ± 2 F	73 to 82%	97 F
Dense concrete	70 ± 5 F	87 to 94%	-
Dense concrete	40 ± 2 F	87 to 92%	49 F
Air-entrained concrete	70 ± 5 F	89 to 94%	-

Identical preassembled materials, and the same facilities and equipment were used in all four investigations. The different series were scheduled as follows:

70 F dense concrete,	Summer	1956
70 F air-entrained concrete,	Fall	1956
40 F concrete,	Winter	1957
100 F concrete,	Spring	1957

Testing Schedule

As soon as the specimens could be handled and placed in the testing machine the earliest tests were made. These ages depended upon temperature; cylinder tests could be made somewhat earlier than beam tests, as shown below:

	Earliest testing age: hrs.	
	Cylinders	Beams
100 F series	3	6
70 F series	6	8
40 F series	12	24

Other tests were made at increasing age, a few hours apart during the first day, every 12 hours to three-day age, and a 7, 14 and 28 days. A few cylinders at 40 F were tested also between 3 and 7 days. A random schedule was arranged for the making of specimens for the different tests and ages in each series.

The specimens were cured in their forms until just before testing or to three-day age. The specimens for tests at greater age were stored in the temperature controlled room without further curing. Just before testing the individual specimen was taken to the testing machine in the laboratory at normal room temperature, instrumented and tested immediately. Generally the test was completed within 15 to 20 minutes. All tests were carried to failure.

Not less than three identical specimens were tested at each age. The average test values apply unless some test seemed to be definitely deficient. In the 70 F tests including dense and air-entrained concrete, a total of eight to 12 specimens have generally been averaged; however, many 100 F and 40 F values are based on only two tests. The total number of specimens in all series included about 190 compression cylinders, 175 tensile splitting test cylinders, and 165 beam tests.

Compression Tests

All compression specimens were 6 by 12 inch cylinders, cast in parafined paper molds with metal bottom.

For tests at the earliest ages the cylinders were not capped but were tested between fiber board sections in the testing machine. Plaster of paris capping was used for later tests, commencing with:

100 F cylinders at 12 hours
70 F dense concrete cylinders at 12 hours
70 F air-entrained concrete cylinders at 16 hours
40 F cylinders at 48 or 60 hours

Generally the cylinders were capped near the time of testing, but all 100 F cylinders for later tests were capped at twelve-hour age.

Deformations of the cylinders between fiber boards were measured with dial gages against the fiber boards; the measurements are not useable for determination of deformations in the concrete alone. Deformations in all capped cylinders were measured with a "Riehle compensating compressometer". An instrumented cylinder in the testing machine is shown in Figure 1. Deformation observations were continued to near failure loads in 8 to 12 equal increments of loading.

Deformations at early age were comparatively quite large and probably nearly all plastic. The plaster-of-paris capped cylinders generally gave stress-deformation curves as conventionally expected, with rates of deformation increasing with load. The fiber board capped cylinders seemed to deform at fairly constant rate, or at a diminishing rate with increasing loads less than 200 psi. Diminishing rates of deformation were observed also in the 40 F tests at 2-1/2, 3, and 4 days; accordingly, the behaviour cannot be said with certainty to have been due to consolidation in the fiber boards only.

To avoid confusion with conventional age concrete tests, in which a great part of the immediate length change is elastic, the relation between load and unit length change in these tests is referred to as modulus of deformation, rather than modulus of elasticity. The term also should not be confused with modulus of resistance, which term includes plastic deformation due to creep under load.

Beams

All flexural test specimens measured 6 by 8 by 32 inches, tested with the 8 inch dimension vertical, and loaded at the third points of a 27 inch span. The beam forms were 3/4 inch plywood with the sides held in grooves and clamped. The bottom was hinged 4 inches from each end so that the early-age beams could be placed on the supports in the testing machine while still mainly supported by the bottom form.

The beam tests were made in a 10,000 pound Tinius Olsen Beam Testing Machine. Huggenberger 8 or 7 inch tensometers were attached for strain measurements 1 inch below the top and 1 inch above the bottom on one side of the beam at center span between the two loads. Figure 2 shows a beam under test. The beam testing machine was zeroed after positioning of the beam and loading rig. Stresses in this report include 12 psi due to 140 pound beam weight and about 80 pound loading rig weight. The 40 F and

70 F beam tests were made with half-round centering bars at the loading points, introducing an unknown quantity in those tests due to possible friction at the load points. In the 100 F tests round bars were used at both load points. No capped pads were used at the loads; however, as the beam failures undoubtedly all began at the beam bottom, any slight load concentration at the top surface would be of minor influence. No strains were recorded in the tests on air-entrained concrete beams.

FLEXURAL ANALYSIS

In analyses of beam strains it is assumed that the stresses do not change on beam sections over the 7 or 8 inch gage lengths between the two load points 9 inches apart, also that strains vary linearly from top to bottom, and are constant across the beam at each level. Generally the observed strains near top and bottom both increased in nearly linear relation to the load, with about 10 equal load increments before removal of the tensometers at 1/2 to 3/4 of the failure loads. Accordingly, stresses in compression and tension have been assumed proportionate to strain up to failure in the beam tests, with substantially triangular distribution of tension and compression stresses below and above the neutral axis.

If no friction forces were present at the supports and at the load point the total compression and tension above and below the neutral axis would be equal. Such conditions were not strictly observed in the tests; however, they were more nearly approached in the 100 F series, with round bars at the loading points. If friction were present at the load points the horizontal resistance to flexure would serve to decrease the compression above the neutral axis an equivalent amount. In the 70 F and 40 F tests, with half-round bars at the loading points, the neutral axis was apparently in all cases above beam center.

The edge strains in compression e_c and tension e_t (both positive) and the location of the neutral axis can be deduced from the observed strains e_a and e_b 1 inch from the compression and tension edges. The numerical compression edge strain e_c would be $(7e_a + e_b)/6$, the tension edge strain e_t would be $(7e_b + e_a)/6$. The neutral axis would be $(7e_a + e_b)/(e_a + e_b)$ below the compression edge. In analyzing the test results the edge strains e_c and e_t are of primary interest, for which the neutral axis is $8e_c/(e_c + e_t)$ below the compression edge.

The edge stresses in tension f_t and compression f_c , and relation between stress and strain can be computed using above assumptions.

a) No Friction At Load Points. The edge stresses are obtained directly from the triangular stress areas; the internal couple with a moment arm of 5-1/3 inch equals the external moment M on the 6 inch wide beam section.

We obtain:

$$f_t = \frac{M}{5\text{-}1/3 \cdot 6 \cdot \dfrac{8e_t}{2 \cdot (e_c + e_t)}} = \frac{M}{128} \cdot \frac{e_c + e_t}{e_t} \qquad (1)$$

$$f_c = \frac{M}{128} \quad \frac{e_c + e_t}{e_c} \qquad (2)$$

For equal edge strains in compression and tension, the formulas give the modulus of rupture values. For unequal edge strains the modulus of deformation in tension F_t is f_t / e_t , and in compression F_c is f_c / e_c.

b) <u>Friction At Load Points</u>. In that case the internal resisting couple to the moment M consists of two terms, the compressive stress area force C with a moment arm of 5-1/3 inch to the centroid of the tension stress area force T , and the horizontal friction force at the top edge loading level, with a moment arm $[8 - 8e_t / 3 (e_c + e_t)]$. The magnitude of the horizontal friction force could not be greater than (T-C). The edge stresses in this case cannot be determined independently; however, if the moduli of deformation in tension and compression are assumed equal, the forces C and T are related as the stress areas, and the modulus of deformation in flexure F_t and the stresses can be determined, as follows:

$$T = \frac{6 \cdot 8e_t^{\;2}}{2\,(e_c + e_b)} \cdot F_f$$

$$C = \frac{6 \cdot 8e_c}{2\,(e_c + e_t)} \cdot F_f$$

$$M = 5\text{-}1/3\ C + (T\text{-}C)\ (8 - \frac{8e_t}{3(e_c + e_t)})$$

from which:

$$F_f = \frac{M}{64} \quad \frac{1}{(2e_t - e_c \quad)} \qquad (3)$$

$$f_t = F_f \cdot e_t \qquad (4)$$

$$f_c = F_f \cdot e_c \qquad (5)$$

The friction force (T-C) at each load point would be related to the vertical loading and the manner of support. The amount of the friction force (T-C) would be $24\ F_f\ (e_t - e_c)$ or $24\ (f_t - f_c)$.

It can be assumed that the beams failed in tension. The modulus of deformation in compression should be in reasonable agreement with values obtained in cylinder tests up to the same stress. This criterion gives a measure of comparison to determine whether or not friction affected the beam tests seriously. Stresses and deformation moduli computed from the beam tests are sensitive to numerical differences between compression and tension strains with attendant shift in neutral axis and large difference in stress areas; only values showing reasonable agreement with compression cylinder deformations can be considered reliable.

Tensile Splitting Tests

Cylinder splitting tests were made at the same ages as the cylinder compression tests. The cylinders were split by two diametrically opposed line loads applied through metal loading strips and 1/2 inch wide 12 inch long plywood pads. Figure 3 shows a test immediately after failure.

The indirect tension test, or tensile splitting test, was introduced independently in Brazil by Carneiro and in Japan by Akazawa. Substantial information, references, and discussion have been provided by Thaulow (1). For a concrete cylinder of diameter D loaded by opposed concentrated loads p per unit of length, the tensile splitting strength f_d is taken as:

$$f_d = \frac{2}{\pi} \quad \frac{P}{D} = 0.64\ P/D \tag{6}$$

The formula gives the true tension stress only for isotropic elastic materials and concentrated line loads. The horizontal component of radial distribution force on each side of the diametric plane, P/π at each of the two loads, is balanced by the evenly distributed tension on the vertical diametric plane in line with the loads. If the force is distributed over a narrow (substantially straight) bearing dimension b the peripheral compression immediately under the load is p/b ; beyond a depth b that compression would have diminished to insignificant values, and the tension on the diametric plane would be substantially the same as for true line load, formula (6).

If, however, plastic readjustment (shear wedge failure) occurred near the load points, the tension on the diametric plane would be increased, because only the section below the shear wedge would be effective for tension reaction to the horizontal component of radial distribution force. Assuming shear wedge depth w , the average tension stress f_t on the remainder of the section would be:

$$f_t = \frac{2}{\pi} \quad \frac{P}{(D - 2w)} = 0.64 \quad \frac{P}{D - 2w} \tag{7}$$

The depth of a shear wedge at failure is probably not less than the width of loading b , and might be greater. For shear wedge depth equal to bearing strip dimension $D/12$ formula (7) would give diametric section

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(1) Thaulow, Sven - "Tensile Splitting Test and High Strength Concrete Test Cylinders", Journal ACI, January 1957, Vol. 28, No. 7, with Discussion. Journal, Part 2, December 1957, Vol. 29, No. 6.

stress 20% higher than formula (6). Tension stress concentration near the shear wedge may result in even higher local tension stress. At early age concrete tension strength appears to be higher in relation to compressive strength than at later age and local crushing (shear wedge failure) is to be expected. Tensile splitting strength f_d is then only indicative, with probable concrete tension strength f_t at least 20% higher, due to the plastic readjustments near the loads. Such probable deviation at failure must be considered in appraising tensile splitting resistance computed by formula (6).

TEST DATA

In this presentation of test data emphasis is given to early-age development of strength and to relations between strength and deformation for compressive and tensile stresses. An attempt has been made to present the data so as to facilitate comparisons between compression-deformation and tension-deformation.

It is not possible to determine from the tests the extent to which measured "strains" were elastic; accordingly, all unit length change measurements have been termed deformation. Especially at early age large unit deformation occurred which may have been almost entirely plastic.

Dense and air-entrained concrete tests at 70 F were not significantly different; the average values of all tests at 70 F have been shown in illustrations of data comparing the different ambient temperatures.

Compression Tests

Typical stress-deformation diagrams from compressometer measurements on compression cylinders at early age are shown in Figure 4 for all three temperatures. A sufficient number of specimens were tested at 70 F to indicate representative stress-deformation relationships; however, 100 F and 40 F relationships are at most for only three specimens, one of which was often omitted from consideration if radically different from the other two. The 4, 5, and 6 day tests at 40 F are for single specimens.

Figure 4 shows that 40 F concrete had very little resistance to deformation prior to four-day age, but between four and seven-day age the resistance increased to values in the range of 70 and 100 F specimens. The compressive strengths, and approximate deformations at 50% of compressive strength at different ages for 100 F, 70 F and 40 F cylinders are shown in Table 1. The close agreement between the two 70 F series is evident. At fourteen and twenty-eight-day age there was no significant difference in resistance to deformation between concretes of the three temperatures.

In Figure 5 the secant moduli of deformation for increasing stresses to 1500 psi at different ages are shown for the three temperatures. For the 70 F series with nine or more cylinders of dense and air-entrained concrete the averages show clear trends. In the 100 F and 40 F series only 2 or 3 cylinders were tested at each age; the curves are therefore less reliable; in the 100 F tests deformation measurements were not made for low loads in the range of flexural stresses. The 28 day values at 100 F probably are not representative.

Beam Tests

The diagrams in Figure 6 show typical relations between applied loads (equally divided between the third points) and compression edge and tension edge strains for 100 F and 70 F dense concrete beams at twenty-four hour age, and for 40 F beams at seventy-two hour age. Figure 6 shows also the change in location of the neutral axis with increasing load for the three series computed from the observed strains. Figure 7 shows the same data for 14 day beams of all three temperatures. Table 2 shows the average top and bottom edge strains at 50% of the failure loads prorated from observed strains in the individual tests. No strain data were reported for 70 F air-entrained concrete beams.

In the 100 F beams the tension strains were generally lower than the compression strain at early age, and the two approach about the same value at ages of one week or more. In the 70 F and 40 F tests the observed tension strains were substantially higher than the compression strains at all ages. It seems likely that the difference in testing arrangement between the 100 F and the other tests could have been a primary cause for the lower neutral axis in the 100 F tests; however, such a conclusion is not supported by some test observations, and it cannot be assumed to explain the difference.

In accordance with the typical load - "strain" curves in Figure 6 and 7 the observed tension strains increased at nearly constant rate with loading. Only a few tests evidenced any appreciable non-linearity between load and observed deformation, the 6 and 12 hour and the 14 day tests (shown in Figure 7) at 100 F, and the 24 and 48 hour tests at 40 F.

In Table 3 the average failure moments in the beams at different ages are listed for the three temperatures, together with ultimate strains at the top and bottom edges, prorated and extrapolated from the observed average "strains" at lower loads. The failure moments include the effects of beam weight and rig load. Reliable values of "strains" could not be obtained at earlier ages than included in Table 3. The average location of the neutral axis at failure, indicated by the average for all ages in Table 3, was

4.1 inches from the top in the 100 F tests
3.3 inches from the top in the 70 F tests
3.2 inches from the top in the 40 F tests

Four of the eight 100 F tests, Table 3, and all 70 F and 40 F tests showed the neutral axis location above center depth.

The 100 F tests have been analyzed for failure stresses and deformation modulus on the assumption of equal compression and tension above and below the neutral axis, Table 4A. The 70 F and 40 F tests have been analyzed on the same assumption in Table 4A; they have been studied also on

TABLE 1

COMPRESSIVE STRENGTH OF 6 BY 12 INCH CYLINDERS AND COMPRESSIVE DEFORMATION AT 50% OF COMPRESSIVE STRENGTH, FOR 100 F, 70 F, AND 40 F CONCRETE AT DIFFERENT AGES.

Age at Test	100 F		70 F Normal Weight		70 F Air-entrained		40 F	
	Compression strength psi.	Deformation at 50% 10^{-6}in. per.in.	Compression strength psi.	Deformation at 50% 10^{-6}in. per.in.	Compression strength psi.	Deformation at 50% 10^{-6}in. per.in.	Compression strength psi.	Deformation at 50% 10^{-6}in. per.in.
8 hr.			30	(7200)	25	(7400)		
9 hr.	420	(9500)						
12 hr.	780	300	90	120	90	(10,000)	6	
16 hr.			220	90	220	70	9	
24 hr.	1410	300	660	100	590	110	18	
36 hr.			1140	170	1070	180	44	
48 hr.	1700	180	1410	210	1380	190	83	(8000)
60 hr.			1690	240	1660	220	250	5800
3 day	1960	280	1810	230	1790	240	400	7100
7 day	2410	300	2510	260	2490	330	1270	200
14 day	2400	350	2950	340	3100	320	2480	380
28 day	2410	390	3220	340	3340	360	2550	320

Note: Fiber board capping was used in tests at:

100 F, 9 hours,

70 F dense concrete, 8 hours,

70 F air-entrained concrete, 8 and 12 hours,

40 F, 48 hours.

Deformations were measured between fiber boards and do not apply for concrete alone.

TABLE 2

FAILURE LOADS ON 6 BY 8 INCH BEAMS LOADED AT THIRD POINTS OF 27 INCH SPAN, AND TOP AND BOTTOM EDGE STRAINS FOR 50% OF FAILURE LOADS, AT 100 F, 70 F, AND 40 F TEMPERATURES.

Age at Test	100 F			70 F			40 F		
	Failure load lb.	Edge strain at 50% 10^{-6}in./in. Top	Bot.	Failure load lb.	Edge strain at 50% 10^{-6}in./in. Top	Bot.	Failure load lb.	Edge strain at 50% 10^{-6}in./in. Top	Bot.
10 hr.	740	-14	+19						
12 hr.	2180	-26	+18	580	-19	+24			
16 hr.				1660	-28	+38			
24 hr.	4890	-47	+38	3030	-24	+42	180	- 6	+10
36 hr.				5160	-38	+52	620	-21	+34
48 hr.	5000	-37	+29	5330	-27	+50	1280	- 9	+24
60 hr.				5580	-28	+48	2330	-16	+24
3 day	5560	-36	+38	5920	-39	+52	3090	-14	+21
7 day	5820	-40	+45	7220	-36	+58	5500	-19	+33
14 day	6130	-33	+30	7200	-33	+57	7350	-17	+36
28 day	7100	-46	+47	8410	-40	+63	8210	-43	+58

Note: The failure load is the load applied by the testing machine exclusive of beam weight of 140 and rigload of about 80 lb.

TABLE 3

MAXIMUM MOMENTS AT FAILURE OF BEAMS, EDGE STRAINS AT FAILURE EXTRAPOLATED FROM OBSERVED STRAINS, AND PRORATED LOCATION OF NEUTRAL AXIS AT FAILURE.

Age at Test	100 F				70 F				40 F			
	Failure moment in. kip	Edge Strain 10^{-6}in./in.		Neutral Axis, in. from top	Failure moment in. kip.	Edge Strain 10^{-6}in./in.		Neutral Axis, in. from top	Failure moment in. kip	Edge Strain 10^{-6}in./in.		Neutral Axis, in. from top
		Top	Bot.			Top	Bot.			Top	Bot.	
10 hr.	4.0	-41	+ 47	3.7								
12 hr.	10.5	-55	+ 43	4.5	3.3	-59	+ 74	3.6				
16 hr.					8.2	-72	+ 89	3.6				
24 hr.	22.7	-94	+ 78	4.4	14.4	-59	+ 93	3.1	1.5	-34	+ 52	3.2
36 hr.					23.9	-80	+105	3.5	3.3	-40	+ 68	3.0
48 hr.	23.2	-68	+ 57	4.4	24.7	-68	+111	3.0	6.5	-27	+ 45	3.2
60 hr.					25.8	-66	+102	3.1	11.2	-41	+ 51	3.6
3 day	25.7	-74	+ 78	3.8	27.4	-84	+108	3.5	14.6	-35	+ 50	3.3
7 day	26.9	-88	+ 98	3.8	33.2	-85	+122	3.3	25.4	-41	+ 62	3.2
14 day	28.3	-82	+ 80	4.1	33.1	-72	+120	3.0	33.8	-38	+ 72	2.8
28 day	32.7	-85	+ 89	3.9	38.6	-90	+140	3.2	37.6	-95	+120	3.5

Note: The failure moment includes moment of beam weight and rigload.

TABLE 4A

ULTIMATE BEAM BENDING STRESSES AND MODULI OF DEFORMATION IN COMPRESSION AND TENSION, ASSUMING TRUE FLEXURE WITHOUT FRICTION AT LOAD POINTS.

Age at Test	100 F				70 F				40 F			
	Edge Stress		Modulus of Deformation 10^6 psi.		Edge Stress		Modulus of Deformation 10^6 psi.		Edge Stress		Modulus of Deformation 10^6 psi.	
	Top psi.	Bot. psi.	Com-pression	Tension	Top psi.	Bot. psi.	Com-pression	Tension	Top psi.	Bot. psi.	Com-pression	Tension
10 hr.	-65	+ 60	1.6	1.2								
12 hr.	-145	+185	2.6	4.4	-60	+ 35	1.0	0.5				
16 hr.					-145	+115	2.0	1.3				
24 hr.	-325	+390	3.4	5.0	-290	+185	4.9	2.0	- 30	+ 20	0.9	0.4
36 hr.					-430	+330	5.4	3.2	- 70	+ 40	1.8	0.6
48 hr.	-335	+395	4.9	7.0	-510	+310	7.5	2.8	-135	+ 80	5.0	1.8
60 hr.					-510	+330	7.8	3.2	-195	+155	4.7	3.0
3 day	-410	+390	5.5	5.0	-490	+380	5.8	3.5	-275	+195	7.9	3.9
7 day	-445	+400	5.0	4.1	-630	+440	7.4	3.6	-500	+330	12.2	5.3
14 day	-435	+445	5.3	5.6	-630	+385	8.8	3.3	-765	+405	20.1	5.6
28 day	-520	+500	6.1	5.6	-760	+495	8.4	3.6	-675	+520	7.2	4.2

Notes: Stresses, and modulus based on failure moments, top edge strains and bottom edge strains as shown in Table 3.

Top compression stress per Equation (2)

Bottom tension stress per Equation (1)

<u>TABLE 4B</u>

ULTIMATE BEAM BENDING STRESSES AND MODULUS OF DEFORMATION IN FLEXURE FOR 70 F AND 40 F TESTS ASSUMING FRICTION AT LOAD POINTS EQUAL TO DIFFERENCE BETWEEN FLEXURAL COMPRESSION AND TENSION.

Age at Test	70 F					40 F				
	Modulus of Deformation	Edge Stress		Load Point Friction		Modulus of Deformation	Edge Stress		Load Point Friction	
	10^6 psi.	Top psi.	Bot. psi.	Force lb.	% of load	10^6 psi.	Top psi.	Bot. psi.	Force lb.	% of Load
12 hr.	0.6	- 35	+ 45	220	60					
16 hr.	1.2	- 85	+110	500	55					
24 hr.	1.8	-105	+165	1440	90	0.3	- 12	+ 18	210	120
36 hr.	2.9	-230	+300	1700	64	0.5	- 22	+ 37	360	92
48 hr.	2.5	-170	+280	2590	95	1.6	- 44	+ 73	700	97
60 hr.	2.9	-195	+300	2560	89	2.9	-120	+150	940	75
3 day	3.2	-275	+350	1880	62	3.5	-120	+180	1270	78
7 day	3.3	-280	+400	2930	79	4.8	-200	+300	2420	85
14 day	3.2	-240	+370	3210	87	5.0	-190	+360	4080	110
28 day	3.3	-300	+450	3760	88	3.9	-370	+480	2740	66

Notes: The ultimate moment is based on Table 3.
Top and bottom edge stresses are proportionate to strains in Table 3, computed by Equations (4) and (5).
Load point friction is the maximum possible for the entire difference between tension and compression at center span.

TABLE 5

TENSILE SPLITTING LOADS AND ULTIMATE AVERAGE TENSION STRESS ON THE DIAMETRIC PLANE OF 6-IN. CYLINDERS AT INCREASING AGE FOR 100 F, 70 F AND 40 F CONCRETE.

Age at Test	100 F			70 F regular, dense			70 F air-entrained			40 F		
	Split. load	Tensile Stress		Split. load	Tensile Stress		Split. load	Tensile Stress		Split. load	Tensile Stress	
	lb./in.	Eq.(6) psi.	% of Compr. Strength	lb./in.	Eq.(6) psi.	% of Compr. Strength	lb./in.	Eq.(6) psi.	% of Compr. Strength	lb./in.	Eq.(6) psi.	% of Compr. Strength
3 hr.	25	+ 3	25									
5 hr.	105	+ 11	20									
6 hr.				8	+ 1	6	10	+ 1	8			
7 hr.	305	+ 33	19									
8 hr.				23	+ 2	8	30	+ 3	13			
9 hr.	725	+ 75	18									
12 hr.	1120	+ 120	15	100	+ 11	12	115	+ 12	13	8	1	14
16 hr.				225	+ 24	11	285	+ 30	14	10	1	12
24 hr.	1730	+ 185	13	640	+ 70	10	695	+ 75	13	18	2	11
36 hr.	2210	+ 235		1090	+ 115	10	1310	+ 140	13	92	10	22
48 hr.	2330	+ 250	15	1540	+ 165	12	1400	+ 150	11	145	15	18
60 hr.				1670	+ 180	11	1800	+ 190	12	300	32	13
3 days	2120	+ 225	12	1860	+ 200	11	2000	+ 215	12	470	50	12
7 days	3240	+ 350	14	2480	+ 265	11	2150	+ 230	9	1530	165	13
14 days	3000	+ 320	13	2760	+ 295	10	2670	+ 285	9	2140	230	9
28 days	2950	+ 315	13	3150	+ 335	10	3040	+ 325	10	2870	305	12

the assumption that friction at the load took up a compression corresponding to the difference in strain areas, with results shown in Table 4B.

Table 4A, assuming equal compression and tension on the cross section, shows the computed values of flexural stresses at top and bottom edges at failure, and the modulus of deformation - or modulus of elasticity - corresponding to the failure stress in both compression and tension. The over-all average values of the modulus of deformation in the 100 F tests were

in compression	4,300,000 psi
in tension	4,700,000 psi

Considering the small and variable number of tests, the small difference is without significance; there is no difference in the average modulus in compression and tension for 48 hour and older concrete.

For the 70 F and 40 F beams, Table 4A, the computed values of modulus of deformation in compression are very much higher than in tension; for the 40 F tests at 7 and 14 days even improbable. The over-all average values of compression and tension stresses at beam failure, and modulus of deformation, for the 70 F tests on 36 hour and older concrete, and for the 40 F tests on 48, 69, 72 hour and 28 day concrete, but excluding 7 and 14 day tests, were as follows:

	70 F	40 F
Number of tests:	7	4
Tension failure stress, psi	+ 380	+ 240
Compression stress, psi	- 570	- 320
Modulus of Deformation		
in tension	3,300,000	3,200,000
in compression	7,300,000	6,100,000

Considering the 70 F and 40 F tests on the assumption of friction at the load point, and equal modulus of deformation in flexural tension and compression, Table 4B, the over-all average values of stresses and modulus for the same seven 70 F and four 40 F tests were:

	70 F Concrete	40 F Concrete
Average tension failure stress, psi	+ 350	+ 220
Average compression stress, psi	- 240	- 164
Modulus of deformation, psi	3,050,000	3,000,000

Tension failure stresses deduced from strain distribution, and modulus of deformation in tension and in flexure, as shown by comparing above listings, are not significantly different whether or not friction is present at the load points.

Tensile Splitting Tests

No deformation measurements are included in the indirect tension tests, which indicates values of the ultimate tension stress on the diametric loaded plane at splitting, which generally occurred suddenly.

In Table 5 the splitting loads are given, also "tension stress" computed in accordance with Equation (6) for the different ages, average of at least three cylinders tested at each age. The Table shows also the computed splitting stress in percent of compressive strength at the same age. The average splitting stress in relation to compression strength for all ages was

for 100 F	16% of compression strength
for 70 F dense concrete	10% of compression strength
for 70 F air concrete	11% of compression strength
for 40 F	14% of compression strength

The lower relative values for the 70 F series may have been due to less perfect linear support near the ends of the cylinders in those tests (the head in the testing machine somewhat shorter than the 12 inch cylinder length).

TEST CORRELATIONS

These exploratory tests included concrete properties observed by more than one method of testing, as follows:

(a) Concrete deformations in compression were observed both on the cylinders and in the beam tests.

(b) Tension strengths were indicated by the tensile splitting test as well as by the beam tests.

A comparison of observations obtained by different methods gives an indication of the more reliable test observations. Considering the small number of specimens in the 100 F and 40 F series, and questions concerning test methods, especially the substantial observed differences in apparent location of the neutral axis between the 100 F and other beam series, a comparison of properties obtained by different methods is desirable.

Compression Deformations in Cylinders and Beams

Secant modulus of deformation for the cylinder tests to varying stresses are shown in Figure 5. Computed maximum compression stresses in the beam tests and corresponding modulus of deformation, based on beam strains, are given in Table 4A, assuming cross sectional equilibrium, and in Table 4B assuming frictional resistance at the load points.

For 100 F concrete applicable comparative values of modulus of deformation from beams, Table 4A, and from cylinders to equal compression stress are listed below:

Age	Beam Edge Stress psi	Modulus of Deformation Beam Test 10^6 psi	Modulus of Deformation Cylinders 10^6 psi
24 hours	- 325	3.4	3.2
48 hours	- 335	4.9	6
3 days	- 410	5.5	4
7 days	- 445	5.0	4
14 days	- 435	5.3	5
24 days	- 520	6.1	4
	Average	5.0	4.4

As listed above the modulus values obtained on beams and cylinders are not radically different for the 100 F tests.

For 70 F beams, values of compression stress and modulus of deformation could be taken either from Table 4A, assuming true flexure, or from Table 4B, assuming friction at the load points as the cause for the upward shift of the neutral axis. For the real condition reasonable comparison with cylinder strains should be possible; for the two alternatives the following data apply:

Age	Table 4A Correlation			Table 4B Correlation		
	Edge Stress psi	Modulus Beams (millions psi)	Modulus Cylinders (millions psi)	Edge Stress psi	Modulus Beams (millions psi)	Modulus Cylinders (millions psi)
12 hours	- 60	1.0	0.2	- 35	0.6	0.3
16 hours	- 140	2.0	1.0	- 90	1.2	1.5
24 hours	- 290	4.9	4.5	- 105	1.8	6
36 hours	- 430	5.4	4.5	- 230	2.9	6
48 hours	- 510	7.5	5	- 170	2.5	8
60 hours	- 510	7.8	5	- 190	2.9	8
3 days	- 490	5.8	5.5	- 270	3.2	6
7 days	- 630	7.4	8	- 280	3.3	8
14 days	- 630	8.8	7	- 240	3.2	8
28 days	- 760	8.4	7	- 300	3.3	8
Average:		5.9	4.8		2.5	6.0

As shown above the agreement between cylinder strain and beam strain for Table 4A is much better than Table 4B correlation. The data indicated that stress and modulus values shown in Table 4A are more representative than those in Table 4B; Table 4A data accordingly are used, neglecting any partial stress relief by reason of friction at the load points.

For 40 F concrete a similar comparison could not be made because of questionable deformation data for the cylinders and too few specimens for representative deformation values in all but the 28 day test. Except for obviously questionable compression moduli, Table 4A data appear to be more representative also for 40 F concrete in flexure.

Figure 5 illustrates the difference between 100 F and 70 F concrete. Whereas, for 70 F concrete, rather high secant modulus of deformation values are indicated for low stress, in agreement with the beam tests, the modulus values for 100 F concrete are appreciably lower and do not show nearly as large variation with stress. The average modulus of deformation values in millions psi for 24 hour and older concrete (Table 4A) were:

for 100 F concrete, in compression 5.0, in tension 5.4
for 70 F concrete, in compression 7.0, in tension 3.2

Compression stresses reached in beam tests are small compared to stresses for which modulus of elasticity is generally given. High compression modulus at low stress and lower comparative tension modulus does not appear to be inconsistent with expected material behavior. The lower compression modulus and the higher modulus of deformation in tension of the 100 F compared to 70 F concrete cannot be explained by this investigation; however, considering the few 100 F tests, and variations in test arrangements, additional tests would be necessary to give a complete comparison.

In the 40 F beam tests, Table 4A, beam tension strengths to and including forty-eight hour age were equal to the compression strengths obtained in the cylinder tests. The compression stresses at beam failure are indicated about 2/3 higher than the cylinder compression strengths; however, non-linear compressive stress distribution could account for this variation, reliable stress-strain data in compression were not obtained.

Tensile Splitting Resistance and Beam Tension Strength

The tests do not indicate close or uniform relation between the tension stresses computed from the cylinder splitting tests and the beam tension strengths, Table 4A. Except for tests before 12 hours, and a few 40 F tests, the tensile splitting resistance seems to be more uniformly related to compression than to beam strength. Figure 8 shows cylinder splitting resistance in relation to cylinder compression strength, Figure 9, in relation to beam tension strength.

For 100 F concrete, Figure 8, the splitting resistance at very early age is high in relation to compression strength and remains relatively high and uniform at about 14% after the first day. Except for the earliest comparison at 10 hours 100 F concrete, Figure 9, shows also more uniform relation to beam tension strength, between 48 and 85%.

For 70 F concrete the splitting resistance is lower in relation to compression strength, 11% after the first day, and more variable in relation to beam strength, from 20 to 75%. For 40 F concrete the splitting resistance values do not show consistent trend in relation to compression strength at 36 and 48 hours, Figure 8, but otherwise are not out of range at 12% of compressive strength. In relation to beam tension strength their trend is more consistent, with gradual increase from about 10 to 60% of the beam tension strength.

With exception for the isolated 40 F values, Figure 8, reasonable estimates of tensile splitting resistance in percent of compressive strength can be made from less than one-day age for each temperature, in percent of beam strength, however, only after several days' age for 70 F and 40 F concrete.

In the tensile splitting test critical tension stresses occur in the interior of the cylinder, and at failure are distributed more or less evenly over a central dimension, influenced by the depth to which plastic readjustments (shear wedge) occur under the narrow "line" surface loading. Bearing stress under the narrow strips at splitting was generally not less than twice the compression strength. While compression strengths are low, plastic readjustment penetrates some distance into the cylinder, a smaller central section resists the splitting, and equation (6) indicates too low tension resistance computed on the diameter. After mature strength has been reached plastic readjustment is shallow, a greater section resists splitting, and relatively higher tension resistance is indicated. The relationships between tensile splitting resistance and beam tension strength are in general accord with above explanation.

In the beam test, on the other hand, critical tension stress occurs at the bottom edge, compression stresses are relatively low, and location of neutral axis is well defined, so that stress distribution can be computed with reasonable accuracy, provided flexural strains are observed. The beam tests, accordingly, are believed to indicate tension strengths closer than the cylinder splitting tests at early age.

At mature age tensile splitting resistance is fairly uniform, average 65% of the beam tension strength. The actual average tension stress in the splitting test would equal the tension strength obtained in the beam tests if the shear wedge depth w under each loading strip equalled 1 inch, computed using Equation (7). Such plastic conditions near failure could very possibly occur.

Series Comparison

The 70 F concrete tests which included both dense and air-entrained concrete, combined in this report, comprise an adequate number of specimens to assure representative data. Possible errors concern testing arrangement only.

The 100 F tests included only 3 specimens at each age. Many test values, average of only 2 observations, are insufficient except for rough indications. At 100 F high strengths were reached quickly and the data have a greater number of reasonable high strength values, normal for mature concrete properties and testing.

The 40 F tests, on the other hand, at early age show unexpected behavior, quite different results in cylinder tests and beam tests, comparatively very large deformations, and low strengths even at three days. They included few tests during the period indicating rapid change from very low to mature strengths. Generally, only three specimens were tested for each test value. Some of the test results are questionable. Accordingly, the indications of the 40 F concrete tests are most tentative and limited.

TEST INDICATIONS

While exploratory tests are not intended to establish definite conclusions, with respect to strength values at least these investigations have given rather clear indication of the influence of ambient temperatures for the particular concrete materials and mix.

AMBIENT TEMPERATURE AND CONCRETE STRENGTH

Conventional strength properties, as represented by cylinder compression strength and tensile splitting resistance, and modulus of rupture, for 100 F, 70 F and 40 F to mature age are shown in Figure 10. Actual tension strengths indicated by flexural strain observations on the beams are shown in Figure 11. Tension strengths indicated by the beam tests at different ages are shown in Figure 12, expressed as percent of cylinder compression strength at the same age. The very great influence of ambient temperatures on concrete strength values is clearly evident in these illustrations.

Tension Strengths. The relations between ambient temperature and tension strength, and between tension and compression strengths, are of special value in judging the severity of pavement stresses at early age. The data in Figure 12 indicate that tension strength develops much more rapidly than compression strength, except possibly at very early age before 12 hours. Near one day age the ratio between tension and compression strength is twice as great as the same ratio at mature age for 100 F concrete, three times as great for 70 F concrete, and several fold as great for 40 F concrete, Figure 12. The actual beam tension strengths indicated by strains reached about equal value at twenty-eight day age irrespective of the test temperatures, Figure 11, a condition which is not clearly shown by the modulus of rupture values in Figure 10. Prior to two days 40 F concrete had very low compressive strength, and small bending strength, which however, seemed to be in the same range as compressive strength. In 100 F concrete substantially mature compression strength was reached in three days, mature tension strength even in less than two days.

Strength Prognostications. Figure 13 shows the ages at which various selected values of strengths in compression and in tension - as determined from beam tests - could be expected to be reached at different ambient temperatures for the particular concrete. Prognostications above 2000 psi compressive strength, at seven-day and greater age are subject to question, considering that continued curing of the test specimens was less than adequate especially for high temperature. In the graph for tension strength, Figure 13, the age for 400 and 500 psi modulus of rupture have been indicated as well. Tension strength is of primary interest in relation to shrinkage and contraction at early age, but bending resistance is equally pertinent for warping and curling considerations.

DEFORMATION PROPERTIES AT VARYING AMBIENT TEMPERATURE

Concrete's resistance to deformation determines the restraint stresses to length changes at early age. A low modulus of deformation means small maximum restraint stress; high modulus means greater likelihood of critical stresses. The test data have direct bearing only on immediate response to stress, and may have much less relation to restraints to slowly developing length changes. Nevertheless, deformation properties found in the tests may give some indication of maximum restraints if no plastic readjustment were to take place. The deformation properties most pertinent to pavements are those which apply for tension stresses and the corresponding low compression stresses, with possible pertinence also of modulus of deformation in compression for evaluation of restraints to expansion in pavements without expansion facilities.

Figure 14 shows moduli of deformation in compression and in tension for increasing age, in compression based on compressometer measurements and beam strains, and in tension based on beam strains at failure, Table 4A, for 100 F and 70 F concrete. Conventional modulus values at 50% of compression strength are shown as well. Data for 40 F concrete have not been included in the graphical illustration as beams and cylinders gave no good apparent correlation. In Figure 15 modulus of deformation values in tension and in compression have been shown in terms of tension and compression strength, respectively, for compression the modulus at 50% of compressive strength, for tension at tensile strength (modulus in tension did not vary appreciably with stress). Modulus of "elasticity" in compression from two-day age on was for 100 F concrete about 1800, for 70 F concrete 1900 times the cylinder strength, average nearly equal for both temperatures and decreasing slowly with age. Whereas, accordingly, for the particular concrete at these two temperatures, the modulus of elasticity was relatively constant multiple of compressive strength, the modulus of elasticity in tension was not a constant multiple of tension strength with respect to temperature.

Because of the difference between tensile and compressive modulus of deformation the two-day and older beams of 70 F concrete carried greater load than corresponding 100 F beams, in spite of the fact that the tension strengths in the 100 F concrete were higher. Neither modulus of rupture as shown in Figure 10, nor modulus of elasticity in flexure, nor beam deflections, would indicate these conditions adequately because of the shifts in neutral axis for different modulus values in compression and tension.

Ultimate Strains

Compression. Before the concrete begins to gain strength it has very little resistance to deformation. Although Table 1 shows very high deformation under compressive stress at the earliest ages, fiber board capping of some or all of those cylinders preclude deductions from those earliest compression tests. Taking the strain values in Table 1 the least ultimate strains might be expected at 48 hours in 100 F, 16 hours in 70 F, and near seven-day age in 40 F concrete, from 200 to 400 microin per inch extrapolated values.

Tension. Ultimate strains in tension are of more direct interest. Table 3 shows ultimate strains in tension for 100 F, 70 F and 40 F concrete at increasing age. They increase gradually from the earliest age tested to one week and beyond in 100 F, and to beyond twenty-eight-day age in 70 F concrete. In 40 F concrete ultimate strains at two to three-day age may be lower than at earlier ages, but they increased rapidly thereafter. The early-age ultimate tension strain range indicated by the tests is:

for 100 F, from 50 microin / inch before 1 day to 100 microin / inch after 1 week
for 70 F, from 80 microin / inch before 1 day to 140 microin / inch after 2 days
for 40 F, from 50 microin / inch at 2 or 3 days to 120 microin /inch after 28 days

Considering possible improvement in strain capacity by continued curing, the ultimate tension strains in flexure at mature age which can be predicted from these tests are:

for 100 F concrete, 100 microin / inch
for 70 F and 40 F concrete, 150 microin / inch

APPLICATION OF TEST INDICATIONS TO PAVEMENTS

Minimum Age at Prestressing

The tests gave relatively clear indications concerning the earliest age at which prestress could be applied without crushing. For design purposes, the prestress imposed in pavements may range from 200 to 500 psi which might be applied when concrete strength is 500 and 1000 psi, respectively. The earliest age at which such strengths are reached is indicated to be:

Ambient Temperatures :	100 F	70 F	40 F
200 psi prestress	10 hours	24 hours	4 days
500 psi prestress	15 hours	36 hours	7 days

Figure 13 could be used for intermediate temperatures. It would not appear difficult to protect pavements of any length from cracking through proper curing up to the minimum age for prestressing.

Prestressing Deformation.

It is necessary also to be assured against excessive shortening at the time of prestressing. The modulus of deformation indicates the immediate stress deformation. Following the earliest age at which prestress could be safely applied, shortening at prestressing for different probable modulus values in million psi, would approximate: (shortening expressed as inches per 100 foot of pavement length)

For prestress of:	200 psi		500 psi	
	Modulus	Shortening	Modulus	Shortening
At 100 F ambient temperature:				
10 hours	1.5	0.16"	-	-
15 hours	2.5	0.10"	2.0	0.30"
24 hours	4.0	0.06"	3.0	0.20"
At 70 F ambient temperature:				
24 hours	5.0	0.05"	-	-
36 hours	5.5	0.045"	3.0	0.20"
48 hours	6.0	0.04"	4.0	0.15"
At 40 F ambient temperature:				
4 days	0.1	2.4"	-	-
5 days	3.0	0.08"	2.0	0.30"
7 days	4.0	0.06"	3.5	0.17"

Probable deformations, rather than stress, would determine the earliest age at which prestressing could be applied, particularly at low temperature and for prestress much over 200 psi in very long slabs.

Critical Strains before Prestressing

One purpose of prestressed pavements is the elimination of transverse cracks and most joints. It is desirable to prevent transverse cracks prior to prestressing as well, particularly as prestressed pavements economically should not be designed to be entirely free from tension stresses under service loads. The investigation gave some indications to advisable precautions for prevention of cracks in long slabs, prior to prestressing, by adequate and careful curing methods.

The critical tension strains indicated by the short-time tests varied from 50 to 80 microin per inch at critical early age, and 100 to 150 microin per inch at mature age. The lower critical strains occurred at high temperature and at an age reached during the first night after concrete placing, but at low concrete temperature possibly not before two or three-day age.

Pavement Strains. The principal sources of stress in pavements at early age are restraints to temperature contraction and concrete shrinkage, also to curling and warping by reason of temperature gradient or moisture differential from top to bottom of the pavement. Of the two causes temperature and moisture, temperature effects have been investigated most adequately. Some data on moisture effects as well have been obtained in this research program, project (a).

Shrinkage. Shrinkage in pavements at early age occurs predominantely near the top surface resulting in warping, lifting the pavement ends and edges up from the subgrade with full restraint stress a short distance away. The experimental data for length and warping of 222 inch long slabs on subgrades in research project (a) indicate that warping and shrinkage was virtually nonexistent in 5-1/2 and 8 inch slabs during the curing period. Measurable shrinkage commenced after the wet burlap curing period, but it developed slowly and even in the driest weather was less than 10 microin per inch per day, average 2-1/2 microin per inch per day. Moisture warping and shrinkage therefore are indicated to be insignificant as a source of pavement stress during the critical early curing period. Being progressive, after curing or with some curing methods even earlier, shrinkage may become a serious source of stress after a week or more. Precuring cracks in too rapidly drying plastic concrete are outside of the scope of investigation.

Temperature Restraints and Curing. Temperature variations appear to be a more important source of early critical strains. Restraint stresses to temperature contraction increase slowly from pavement ends, but full restraint can be assumed to exist more than 50 to 100 feet from the ends in long slabs intended for prestressed pavements. Temperature curling stresses, on the other hand, increase rapidly from pavement ends and edges with full restraint a few feet away at early age. During nightly temperature loss the curling restraint flexural stress is top tension, additive to shrinkage and warping stress, during sun-heat temperature rise, the curling restraint stress is bottom tension and top compression. On the day of construction the temperature rise due to sun heat on concrete placed in early morning, if effective curing is delayed, could be sufficient to cause noticeable plastic consolidation near the surface, or critical tension strains near bottom if the surface concrete should harden rapidly. Thereafter, the data indicate tension strains near the pavement surface to be most critical in long slabs at early age.

The temperature restraint stresses are directly proportional to the coefficient of thermal expansion of the concrete. Greater cracking risks exist with concrete aggregates with high coefficient, as observed in highway crack surveys generally. For this study a coefficient of thermal contraction of 5 microin per inch per degree F is assumed.

For a normal design maximum air temperature cycle of 30 F per day, the average temperature variation in concrete pavements, which determines contraction and expansion, would approximate 20 F to 25 F in 6 inch slabs, about 18 F in 8 inch slabs, and 10 F to 15 F in 12 inch slabs. The corresponding average strain in fully restrained portions of 6 or 8 inch slabs setting at high temperature would be about 100 microin per inch, which is more than the ultimate strains in the short-time tests at early critical age. At the surface the tension strains would be still greater because of the temperature gradient.

For the 5-1/2 and 8 inch slabs on subgrade in project (a) of this research program, the daily cycles of average concrete temperature for air temperature daily cycles between 30 and 35 F following curing, and during the curing period, were as follows:

	in 5-1/2 inch Slabs	in 8 inch Slabs
First month after curing	26 F	18 F
Under wet burlap curing	8-1/2 F	7 F

The temperature gradients observed in the experimental 5-1/2 and 8 inch slabs were equally influenced by the curing method. During the first month following curing the average maximum temperature gradients, expressed as degrees temperature change per vertical inch, were:

	for daytime	for nighttime
5-1/2 inch slabs	+ 3.8 F	- 2.0 F
8 inch slabs	+ 3.3 F	- 1.8 F

By comparison, the maximum temperature gradients observed on the second day of curing under wet burlap were:

	for daytime	for nighttime
5-1/2 inch slabs	+ 1.7 F	- 0.5 F
8 inch slabs	+ 1.6 F	- 0.5 F

Without insulating curing cover, surface temperatures much higher than the air temperature can be reached on the day of construction in the concrete placed during forenoon. Such concrete could undergo substantially the same temperature drop, and approach the same temperature gradients as those observed in the experimental slabs after the curing period, with restraint tension strains during the first night computed to be: (thermal coefficient 0.000005)

	Average strain	Curling strain	Total strain at surface
	(Strains in microin per inch)		
in 5-1/2 inch slab	+ 130	+ 28	158
in 8 inch slab	+ 90	+ 36	126

These surface strains exceed the short-time ultimate strains in both 100 F and 70 F concrete.

With effective wet burlap curing the maximum temperature on the day of construction and the first night temperature gradient are much lower. The comparative full restraint tension strains the first night would be:

	Average Strain	Curling Strain	Total Strain at Surface
	(Strains in microin per inch)		
in 5-1/2 inch Slabs	+ 43	+ 7	+ 50
in 8 inch Slabs	+ 35	+ 10	+ 45

These strains are less than the ultimate strains for the short-time tests in either 100 F or 70 F concrete. Adequate curing, which protects the concrete against temperature extremes as well as moisture loss, could accordingly be expected to protect a pavement of any length against cracking during the curing period of even daily air temperature cycles, until such time as prestressing can be applied.

While the stresses in full restraint to temperature contraction and curling are relieved some uncertain amount by creep (plastic flow), the surface strains possible during the first night, in slabs without insulating curing cover, are so much in excess of the 50 to 80 microin per inch capacity as to make immediate cracking or distress leading to later cracking probable. It seems evident that a curing method should be preferred which provides effective insulation especially against the extreme sun heat, which is the primary reason for large daily concrete temperature cycles.

After the curing period critical strains at mature age probably would not be reached by temperature curling restraint alone, but they could well be exceeded away from ends in combination with a cold-spell temperature drop greater than the normal night temperature drop. Curing should continue up to the time of prestressing. Prestressing application should not be delayed beyond normal curing time.

ACKNOWLEDGEMENTS

The investigations covered by this report are part of a cooperative research project between the U. S. Bureau of Public Roads, the Missouri State Highway Commission, and the University of Missouri at its School of Mines and Metallurgy, Rolla, to study the effects of prestressing upon thin concrete pavement slabs, and the properties of concrete pertinent to such slabs.

General direction of the work, from its inception in the highway department throughout planning, execution, and interpretation, has been the responsibility of F. V. Reagel. E. W. Carlton directed and supervised the investigations for the University. The experimental work and data compilations of this investigation were done as part of work for degrees of Master of Science in Civil Engineering, and are contained in Theses by the four authors, as follows: 100 F concrete properties by K. H. Dunn, 70 F non-air-entrained concrete properties by P. G. Hansen, 70 F air-entrained concrete properties by J. A. Spilman, and 40 F concrete properties by C. E. Weddle, Jr.

For the Missouri Highway Department, E. O. Axon supervised material selection and proportioning. Bengt F. Friberg, Consulting Engineer, St. Louis was engaged to assist in planning and programming the investigations, and for combination and condensation of the test data from the theses, their correlation application, and appraisal in this report.

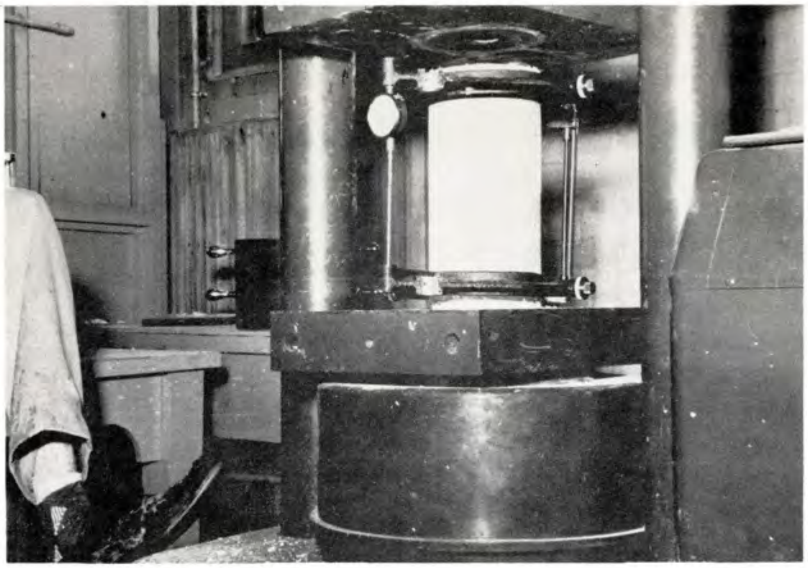


Figure 1

Compression Cylinder with Riehle Compensating compressometer in place in the testing machine.

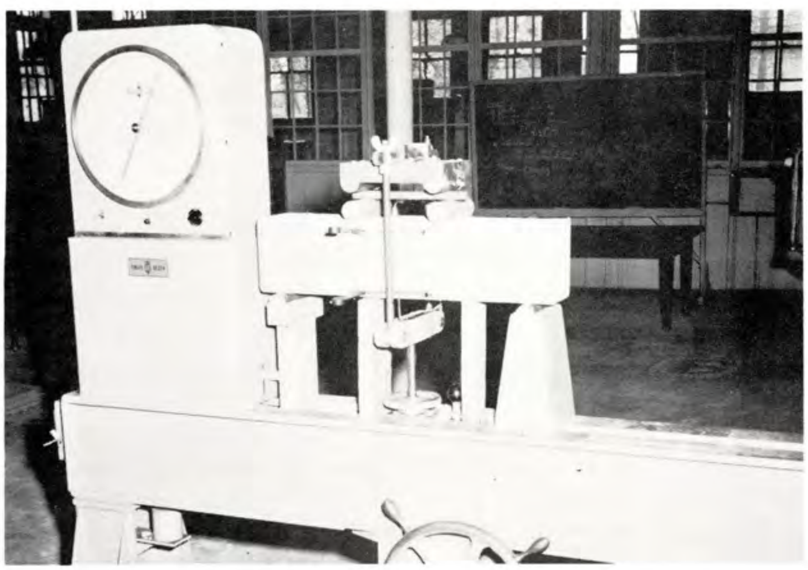
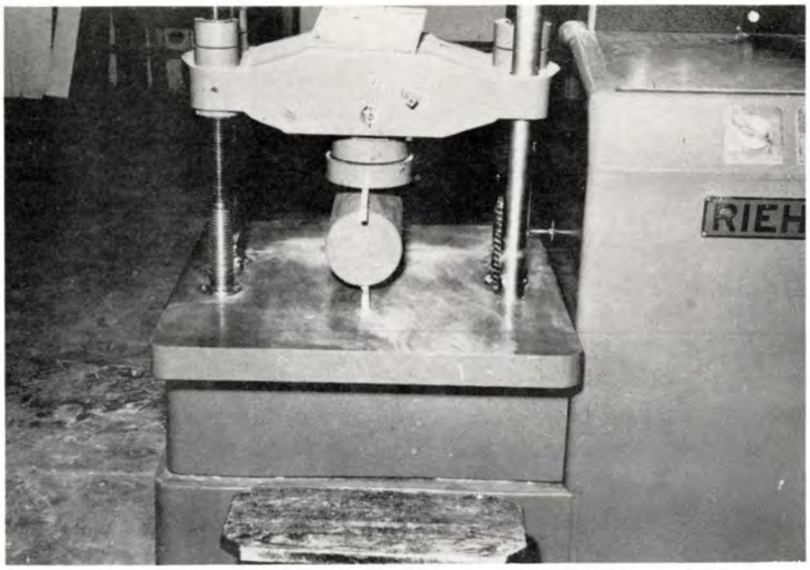


Figure 2

Beam with loading rig and Huggenberger tensometer gages attached in place in beam testing machine. Beam of 100F series shown; beams in other series had half round bars at the load points.



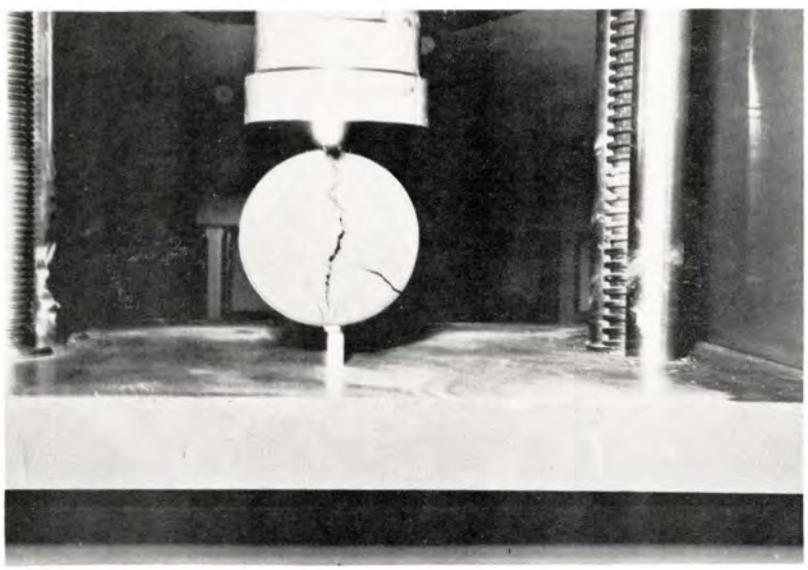


Figure 3

Tensile splitting test. Cylinder in place in the testing machine (upper) and immediately after splitting failure (lower).

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Figure 4

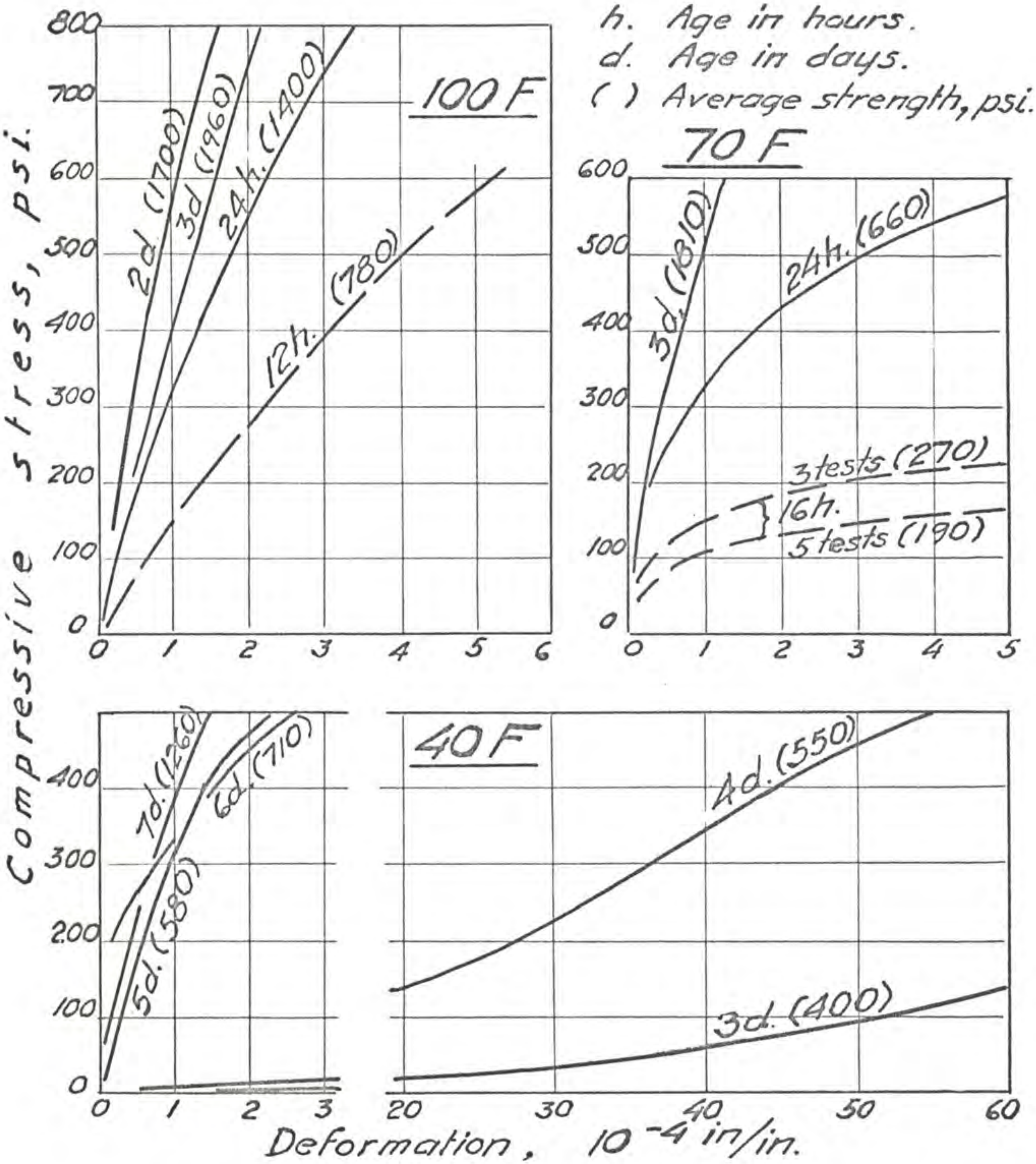

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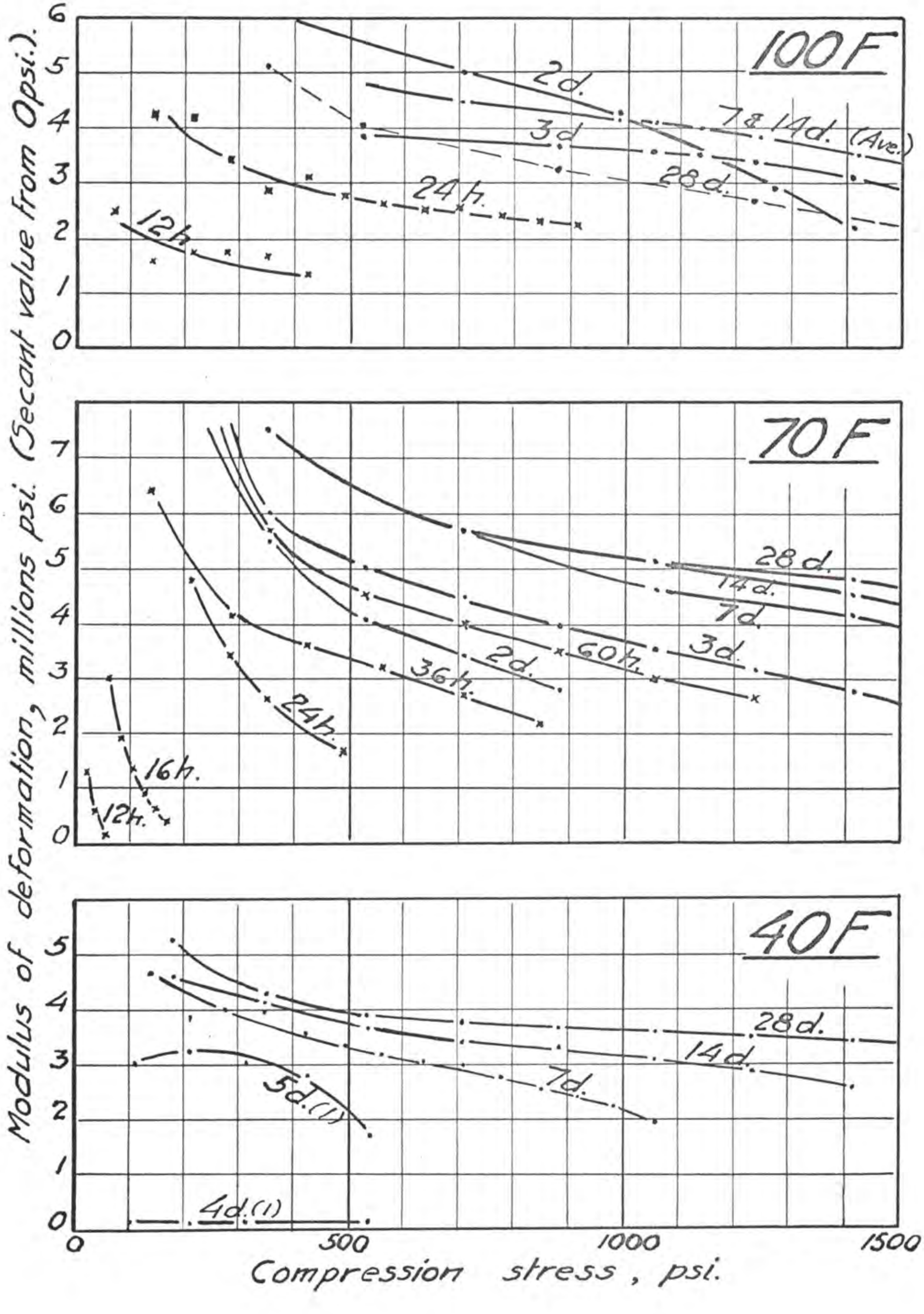
Figure 5



AUG 1 1960 Figure 6

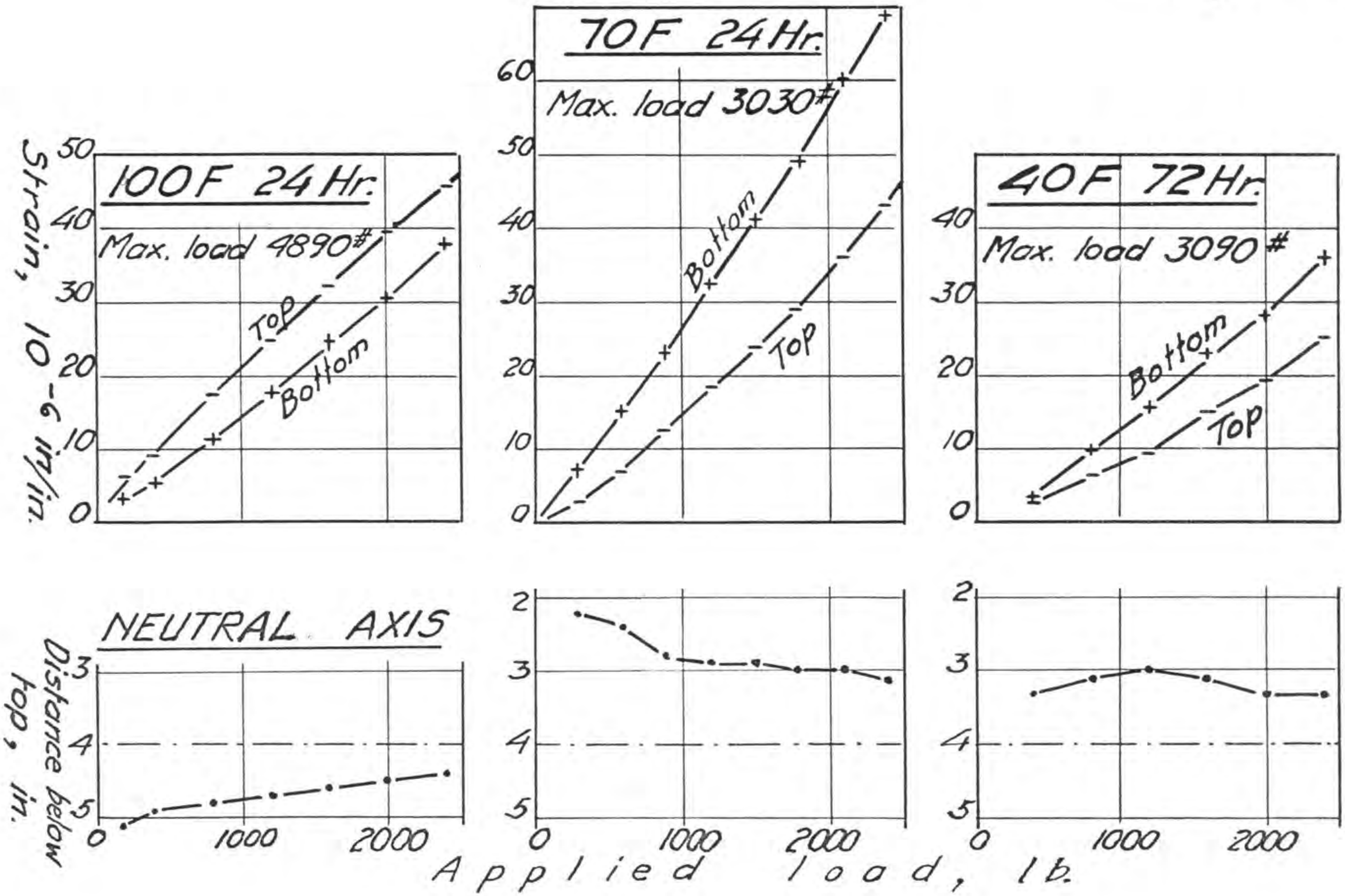


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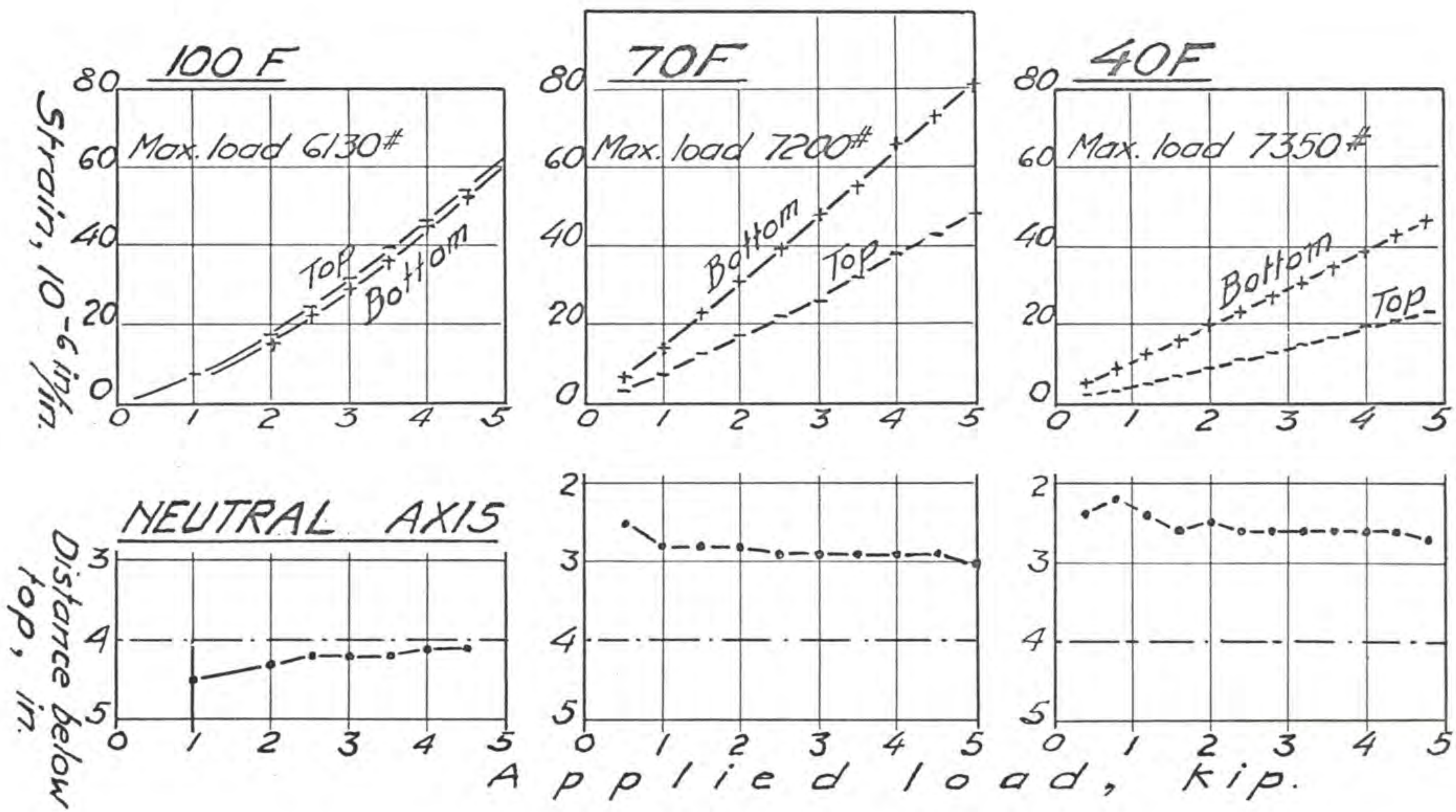
Figure 7



100 F
70F
40F
Max. load 6130#
Max. load 7200#
Max. load 7350#
Top
Bottom
Strain, 10-6 in/in.
NEUTRAL AXIS
Distance below top, in.
Applied load, kip.

AUG 1 1960

Figure 8

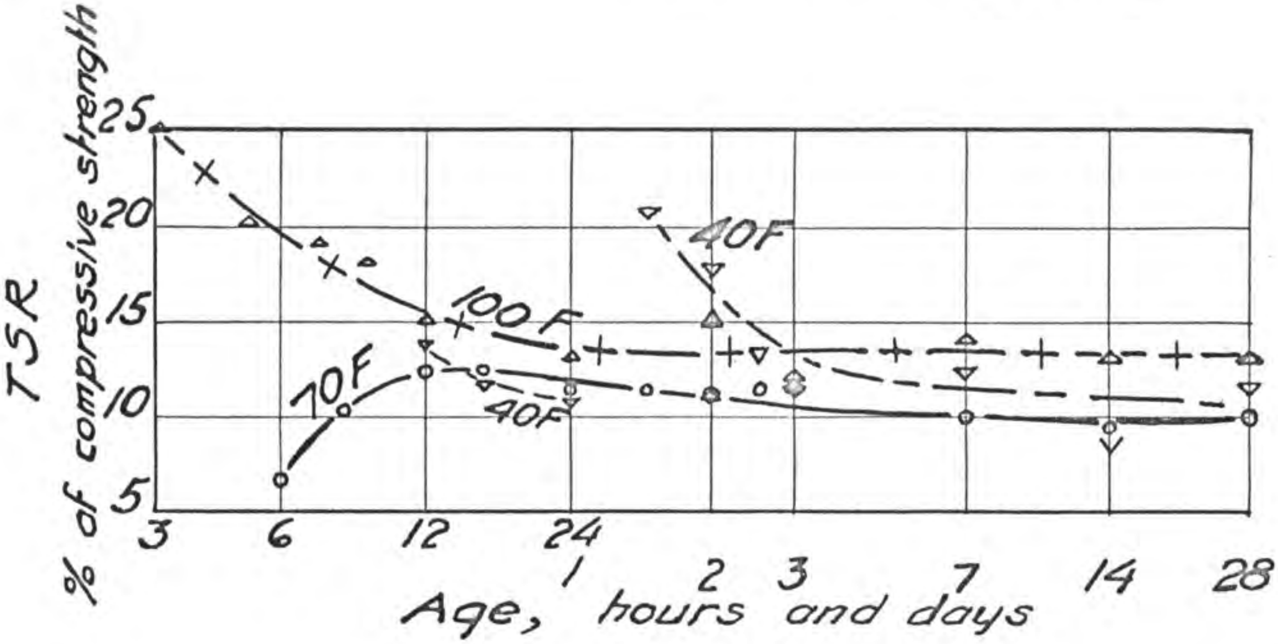


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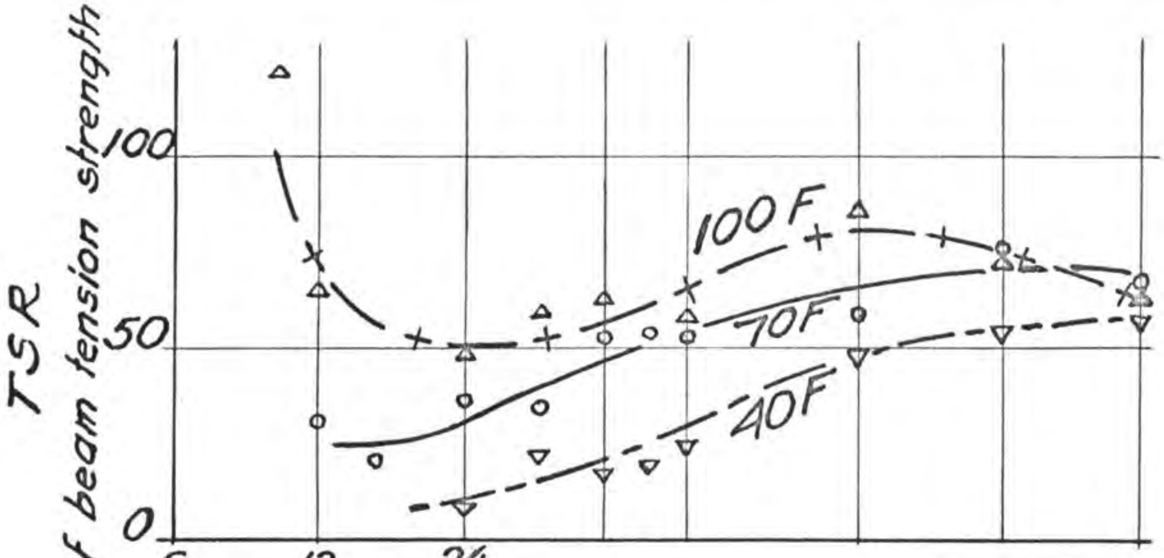
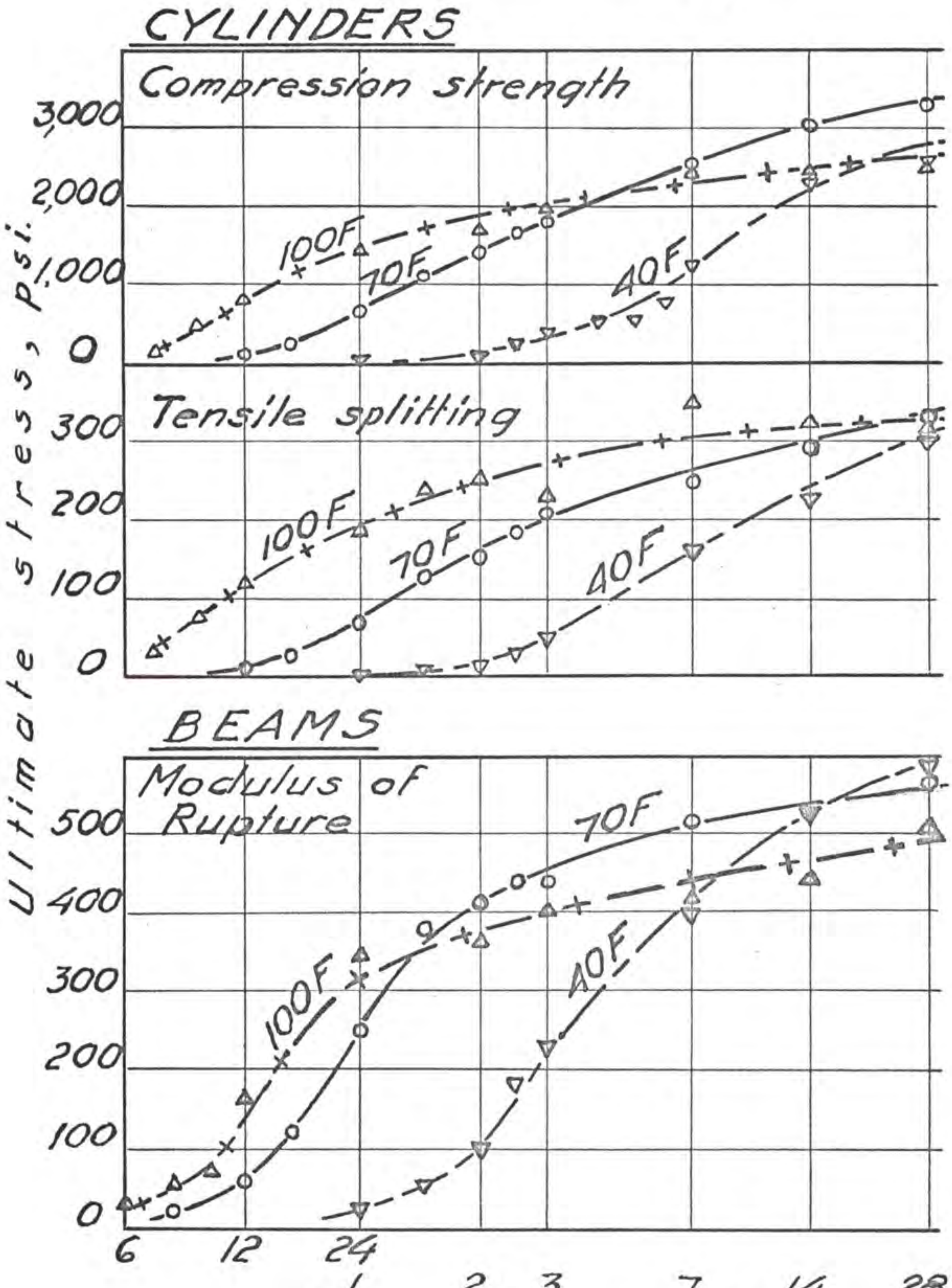
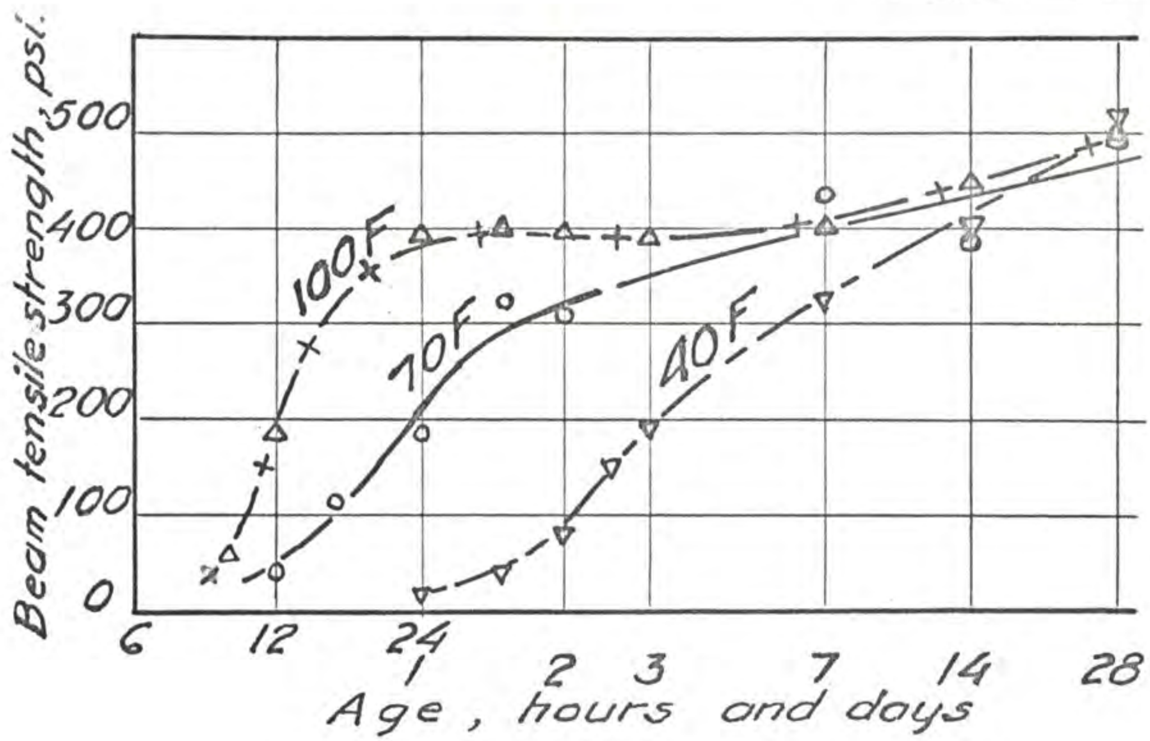
Figure 9



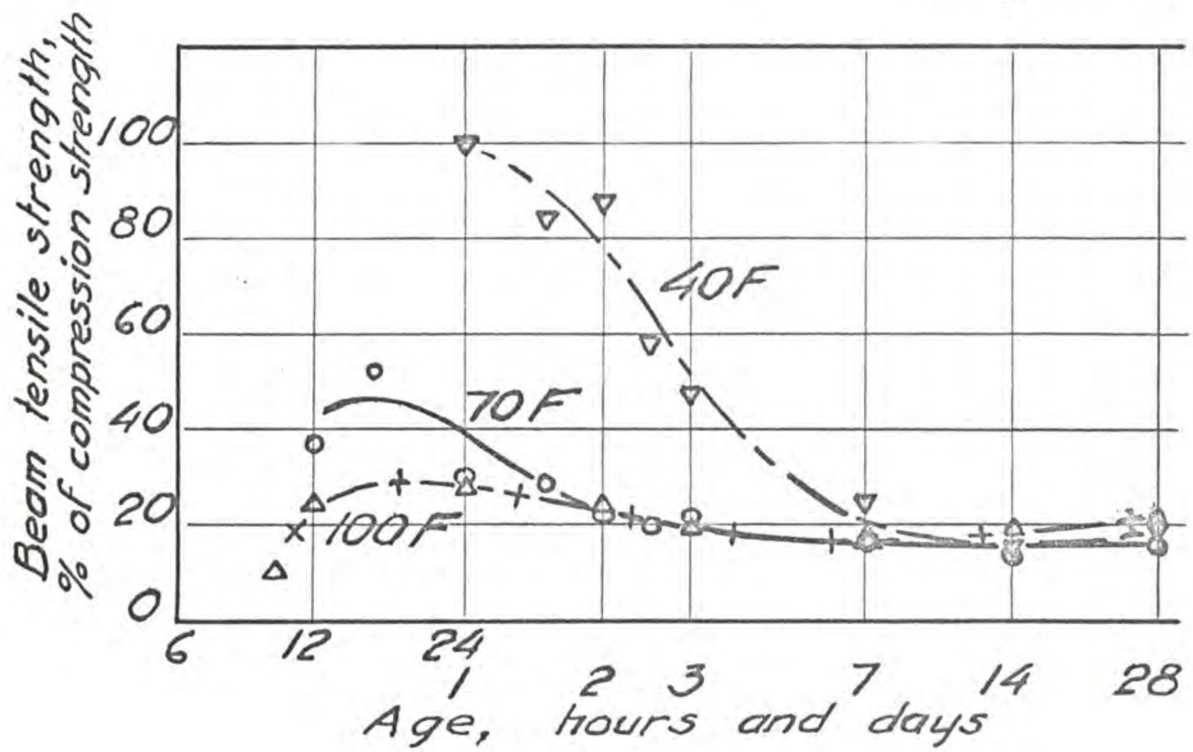
AUG 1 1960 Figure 10



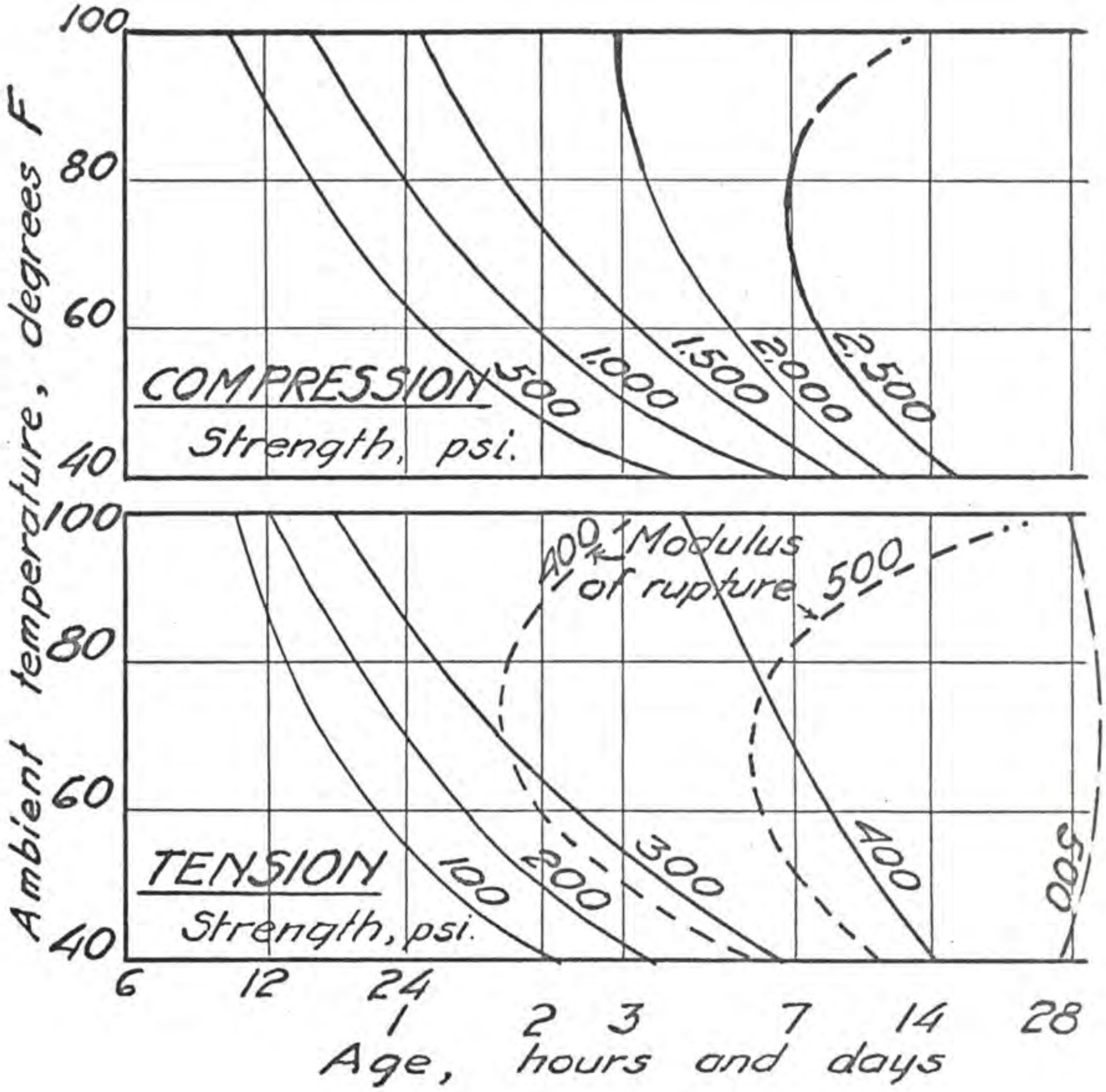
AUG 1 1960 Figure 11



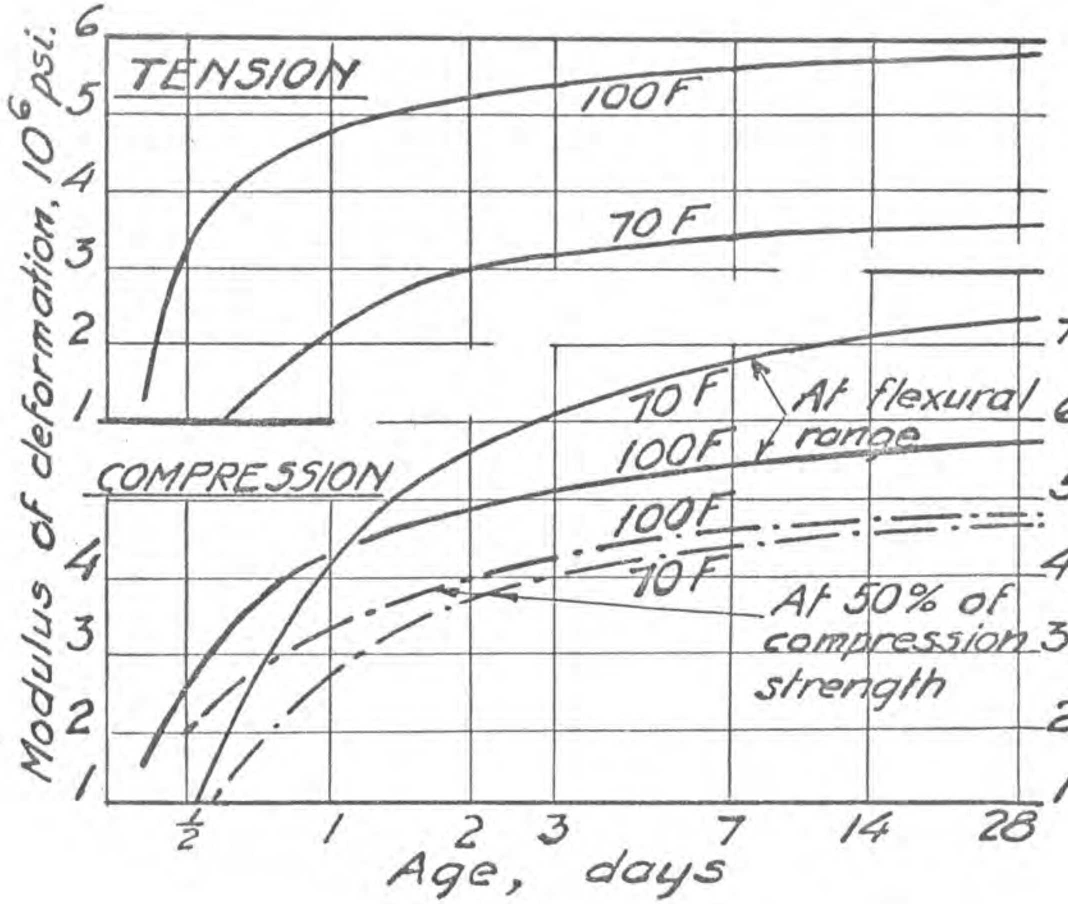
AUG 1 1960 Figure 12



AUG 1 1960 *Figure 13*



AUG 1 1960 Figure 14



AUG 1 1960 Figure 15