# LOW-DENSITY STRUCTURAL MATERIALS FOR AIRCRAFT

A THESIS

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of Master of Science in Aeronautical Engineering

by

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Approved:

## Acknowledgments

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# Preface

## Meaning of Symbols Used

$A$ = Area in square inches.

$D$ = Maximum deflection at midspan in inches.

$e$ = Total elongation in inches.

$\epsilon$ = Unit elongation in inches per inch.

$E$ = Modulus of elasticity in pounds per square inch.

$f_b$ = Bending stress in pounds per square inch.

$f_c$ = Compressive stress in pounds per square inch.

$I$ = Moment of inertia of section in inches.

$\ell$ = Length of span in inches.

$M$ = Bending moment in inch-pounds.

$P$ = Applied load in pounds.

$\rho$ = Specific gravity.

$w$ = Unit weight pounds per cubic inch.

$y$ = Distance from neutral axis to position of desired stress in inches.

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# LOW-DENSITY STRUCTURAL MATERIALS FOR AIRCRAFT

## Summary

A brief history is given on the support of thin sheets in compression by a low-density core. This is followed by a discussion of three methods, i.e., casting, spraying, and plastering, used in forming a core of fibrous material. The results of each process and the various tests made on the low-density speciments are shown by photographs and tables. It is concluded that a continuous medium might provide satisfactory support for thin sheets in compression if an efficient bonding agent and a high-strength cement are developed.

## Introduction

The origin of many of the structural problems encountered in metal aircraft design is in making an efficient structure to carry compressive stresses. Because of the high density of steel and duralumin, the materials most used for structural parts, ordinary sections are so thin that they have to be supported laterally to prevent buckling under compression loads.

It is customary procedure in the United States to support the external skin of metal airplanes by extruded stiffeners of various forms riveted to the inner surface. It is possible, however, that a more efficient support might be furnished by bonding the thin high-strength skin to one or both sides of a continuous low-density material. The sheet would carry the high tension, compression, and shear loads present at one time or another in all the primary structural parts of an airplane. The continuous medium, or "continuum", as it has been called by J. D. North of England would then give lateral support in order to prevent buckling. Ordinarily the magnitude of this lateral support is small and should be easily provided by a low-density material. If the modulus of elasticity of the continuum is low, the load carried by it would be negligible when compared with that carried by the metal, so that high-strength in the medium is of secondary importance. Such a low-density material could also be used as a shear medium between two thin metal sheets subjected to bending loads.

Up to the present time very little has been published on the support of thin sheets by a continuous medium, but it is a subject that has been suggested by several outstanding engineers as worthy of investigation. The most complete investigation yet made on this subject is by Gough, Elam, and de Bruyne (Ref.1). A theoretical analysis of eight different combinations of skin and supporting material was made and of the eight cases analyzed three were the object of tests. The thin strips used in the experiments were spring steel, duralumin, magnesium alloy, and birch plywood, each supported by an expanded ebonite known as "Onazote". This material was used because it is obtainable in a range of specific gravity, $\rho$, from 0.04 to 0.15 and has an approximate linear variation of modulus of elasticity, E, as follows:

$$E = 27{,}100\,\rho \quad \text{lb/in}^2$$

The results obtained in the laboratory compared favorably, in general, with theory. The stresses actually carried by the test pieces were in some cases lower and in others higher than those predicted by theory. When the failing stresses were lower than the theoretical prediction, it was due to either poor adhesion of the cement used to attach the metal strip to the medium, or local failure of the ends of the specimen. Higher strength than that predicted by theory was caused by curvature along the axis of the metal strips, arising from non-uniform layers of cement or shrinkage of the cement while setting. This effect was most noticeable on the thin wide specimens, that is, those 0.05 inch thick and 1 inch wide.

## Procedure

The purpose of this investigation was to find a low-density substance of sufficient strength to provide lateral support for thin skin in compression and, at the same time, be inexpensive, readily available, and easy to apply to the metal.

Because of the high strength of wood fibers, their low weight, and the large available supply in this part of the United States, it was believed that a material built up of matted wood fibers would, if bonded properly, fulfill the above requirement. Once the wood fibers had been selected as the basis of the low-density medium, it was necessary to find some way of forming these fibers into the streamline shapes and compound curvatures of aircraft structures.

Two possible methods suggested themselves at once, first, casting in a plaster-of-Paris mold in a manner similar to that used in the ceramic industry for various types of ware, and second, spraying the material out of a gun. Both of these methods were tried with some success, although it was found later that plastering the fibers on with a trowel gave better results than either of the two other methods mentioned above.

## Casting Process

Until satisfactory wood fibers could be obtained, it was decided to make a preliminary investigation with paper. An ordinary newspaper was cut into two-inch squares and boiled for fifteen hours in a solution of sodium hydroxide, $NaOH$, in order to reduce the paper to a pulp. There was very little change in the paper during this time, however, except that it absorbed a large amount of water. After being boiled the paper pulp was thoroughly washed, poured into a plaster-of-Paris mold, and allowed to remain for twenty-four hours, at which time it was dry enough to be removed. The resulting specimen, Fig.1, was very light (specific gravity = 0.105) but had no other favorable properties; its surface was irregular and its strength poor. Although the product itself was of no value, it taught several lessons. First, a bonding substance of some sort was required if any strength was to be obtained, and second, the mixture should be more like a clay slip if satisfactory results from casting were desired.

Since clay slip is ordinarily ground in a ball mill before casting, it was decided to grind some tissue paper in order to learn if a substance suitable for casting could be obtained. Bentonite, a clay used in many cast ceramic products, was mixed with the tissue paper to furnish a bond and improve the casting properties. After several hours of grinding a mixture similar in appearance to clay slip was obtained. This mixture was then cast in a plaster-of-Paris mold whose shape was that of a spherical cup. After drying in the mold, the thin shell was dried more thoroughly in an oven, painted with shellac, and reheated to harden the shellac. The final result is shown in Fig. 2. The surface was tough and fairly smooth, with the inside more porous than the outside. Considering its constituents, the strength of this specimen was good, but this was due, to some extent at least, to the shape. Even though better than the first attempt, the result of this experiment was far from satisfactory. The weakness of this specimen was apparently due to the absence of all fibers. Whatever fibers the tissue paper had had in the beginning were all ground into particles in the ball mill.

With the lessons learned from the first two attempts in mind, the experiments were continued, but this time with the exploded wood or "Masonite" fibers shown in Fig.3. A mixture of 100 grams of fibers, 25 cubic centimeters of Bentonite and sufficient water was ground in the ball mill until the average fiber length was one-quarter of an inch. The result of casting this mixture in a plaster mold in shown in Fig.4, which was the best of all those samples yet obtained. Its surface was a tough reasonably smooth shell of high density surrounding an interior of lower density. The strength of this specimen was good and its specific gravity, 0.24, fairly low.

The results of the casting methods were improving, but, at the same time, it was becoming more and more apparent that such a procedure was impractical. First, the size of a plaster-of-Paris mold required to form a wing, for example, would be prohibitive, and second, the plaster would probably be rather fragile. Both of these reasons make plaster undesirable in a shop being used for mass production. The casting process was, therefore, abandoned at this point.

Spraying Process

A spraying process was thought to be advantageous because the material could be applied directly on the metal to be supported, a procedure which would be only one more step in the assembly of the airplane. Also, it might be added that with a spray gun by changing the spraying distances and pressures, the thickness and possibly the density of the medium could be varied at different places as required by the magnitude and type of load to be carried.

The primary problem, and one that never was completely solved, in spraying the Masonite fibers was the designing of a suitable spray gun. The ordinary type paint spray gun was too small for use with wood fibers, and the cost of the "Gunite" or cement spraying apparatus was prohibitive. Since no gun was readily obtained, it was decided to make one.

The first gun, Fig.5, was made from two pieces of quarter inch pipe brazed together as shown. The cylinder from a large grease gun was connected to the end of one pipe and a valve for regulating air pressure was connected to the end of the other pipe. The fibers to be sprayed were put in the cylinder and forced up the pipe by compressed air let in through a valve at the bottom. When the fibers reached the top of this pipe the stream of compressed air from the other pipe sprayed them onto a sheet metal mold. This gun operated poorly, was easily stopped up, and sprayed the mixture over too wide an area. Often, the operator was covered with as many sprayed fibers as the mold. A second gun, Fig.6, which was made of copper tubing was much more satisfactory than the first one. It sprayed in a much smaller cone so that the operator was in no danger of being covered with fibers. Although not as easily clogged as the first gun, this one still caused trouble.

After experimenting for some time a mixture of 100 grams of Masonite fibers and 1600 grams of water was found to be the most successful one used in the spray gun. These were ground together in the ball mill about twenty-four hours until the fibers had become fine particles. This ground mixture was strained through a 60 mesh screen to remove some of the water and the smaller particles, and then thoroughly mixed with 100 grams of dry unground Masonite fibers of one-half an inch average length. The unground fibers even when mixed with water, Bentonite, or shellac would not pass through the gun. Consequently, the finely ground fibers were necessary for successful spraying.

With the above mixture as a basis, the following were used as bonding agents: casein glue, shellac, Bentonite, and both shellac and Bentonite together. This last, shellac and Bentonite, gave the best results, one sample of which is shown in Fig.7. As is readily seen from this photograph the material warped and was very rough on the top surface.

Excessive warping could probably be prevented by reducing the amount of water in the mixture or by drying the specimen more slowly. The first method was in this case impossible because a mixture with less water would not flow easily through the gun. The increase in time of manufacture required by the second method makes it undesirable.

Two other disadvantages of this material were, one, the rough surface, and two, the material had to be sprayed in layers; because it did not have sufficient strength when wet to support a thick application. The rough surface could have been eliminated by smoothing with a trowel after each spraying operation. The second disadvantage might be removed entirely if a gun capable of spraying drier fibers could be developed. It is also apparent that with the fibers almost dry when sprayed, the drying time would be shortened.

Plastering Process

Because of the difficulty in getting the spray gun to operate successfully, a method of plastering the fibrous mixture on a form with a trowel was investigated. This process proved to be the best of all those attempted. Fig.8 and Fig.9 are two of the better specimens made by the plastering method. The one shown in Fig.8 is a mixture of Masonite fibers, Bentonite, and shellac plastered on a flat sheet metal mold. Immediately after molding the specimen, the outer surface was smoothed with a trowel. This caused the material to be more homogeneous on the inside as well as made the top surface smooth. The sample shown in Fig.9 is a mixture of Masonite fibers with a solution of gum arabic as the bonding agent. This specimen was stronger but heavier than the one containing shellac and Bentonite.

An interesting property of all the flat plastered samples was that the outside layer was of higher density than the core. Fig.10 shows one of the specimens made on a cylindrical mold. In these cylindrical samples, though, only the outer surface was of higher density, possibly because some of the bonding agent drained out of the material and down the sides of the vertical mold. The specific gravity, 0.11, of these was lower than that of all the other specimens made by the plastering process, because of drainage of the bonding substance from the fibers.

Load Tests

In order to have some basis for comparing the different materials developed, a series of compression and transverse bending tests were made.

The compression tests were used to find the modulus of elasticity of those materials tested, and the bending tests were used to find both the modulus of elasticity and the modulus of rupture. TABLE I, which is a schedule of the test specimens,gives the dimensions, specific gravities, and the type of test made upon each.

The bending tests were made on the samples of material formed by the plastering method and cut into pieces two inches wide and eight inches long. Other bending tests were made using the Celotex samples shown in Fig.11. The one on the left is plain Celotex; the center one is Celotex that has been shellaced; and the one on the right was soaked overnight in a dilute solution of shellac. A Riehle Universal Testing Machine (Fig. 12) was used to test the different samples. Deflections were measured by means of a dial gage placed between the platens of the machine. The transverse bending tests were made using the specimens as simple beams with a concentrated load at the center.

The compression tests were made on plain Celotex and one composite specimen of duralumin and Celotex. They were subjected as nearly as possible to pure axial compression. The purpose of the test upon the composite specimen was to learn how well the duralumin would be supported by the low-density material. It consisted of two pieces of duralumin .010 inch thick cemented to either side of a piece of Celotex one-half an inch thick, two inches wide, and four and one-quarter inches long. The cement used was "Plymax Plastic Glue" which is capable of gluing wood to metal.

The results of the tests are shown graphically in Figs.13 through 17 and tabulated in TABLE II. The materials are arranged in the table according to their unit weights. The values listed for spruce, duralumin, and steel are given for reference only.

The equationsused in calculating the values in the table are:

Bending $f_b = \frac{My}{I}$

$$E = \frac{P\ell^3}{48ID}$$

Compression $f_c = \frac{P}{A}$

$$E = \frac{P}{Ae} = \frac{f_c}{\epsilon}$$

Also, the strength-weight factor is defined by Shanley (Ref.2) for materials subject to "stability failure" as :

$$\frac{E}{w^2} .$$

## Discussion of Results

The curves in Fig.13 through Fig.17 should all pass through the origin, but because of the small loads imposed on the test specimens there was difficulty in getting accurate zero readings. The gaps in the various curves are probably due to static friction in the hydraulic piston of the testing machine.

Fig.13 is the load-deflection curve for bending tests upon samples made with Masonite fibers and gum arabic by the plastering method. The four encircled points to the right of the curves near the origin have the correct slope but are obviously out of position for the reasons given above.

Fig.14 is the curve for a similar test made on another sample of the plastering process, this one using Bentonite and shellac to bond the fibers. Neither the strength nor the strength-weight factor of this material is as good as that of Fig.13.

The curves of the bending tests on plain Celotex are given in Fig. 15; and from TABLE I it can be readily seen that this material is high among those compared both from the point of view of specific gravity and strength-weight factor.

Fig.16 is the load-deflection curve for the shellac-painted and shellac-soaked Celotex specimens shown in Fig.11. The slope of the curve is approximately the same for both, but the load carried by the painted specimen is greater than that carried by the impregnated one. Since only one specimen of each was tested, these results may not be as reliable as some of the others.

Fig.17 shows the stress-strain curves for plain Celotex in compression. The slope of all the curves are practically identical, and give the same modulus of elasticity as obtained in bending.

The stress-strain for the composite specimen is given in Fig.18. Here again only one test was made so that inaccuracies may be present. As the load on the specimen was increased, the duralumin developed a series of waves and failed by pulling away from the Celotex. The cement held, but the tensile strength of the Celotex was not great enough to prevent the metal from tearing away. The load carried by this specimen, using only the area of the duralumin, was 24 per cent of the block compression load for duralumin.

The development of the waves in the metal skin is dependent upon the relation between the modulus of elasticity of the metal and that of the low-density medium. Therefore, the Masonite and gum arabic material, because of its higher modulus of elasticity (see TABLE II), would support the metal sheet better than any other of the materials tested. However, the specimens made of this material had such a rough surface that it was difficult to cement metal to it, therefore, the composite specimen using Celotex was substituted.

## Suggestions for Future Study

The results of the preceding investigation break down, in the writer's opinion, into two basic problems which should be solved in some future investigation. The first is the development of a bonding agent that will furnish high strength between the fibers without too great an increase in density; the second is to obtain a cement that will give a high-strength bond between the metal and the fibers.

There are also several other problems that ought to be solved in order to have a positive proof of the value of the low-density material as a supporting substance for metallic sheets. However, these problems, because of lack of time, were not studied during this investigation. All wood fibers are subject to fungus growth and tend to absorb water; both of these properties should be eliminated as much as possible from materials used on aircraft. A thorough study should be made with different thicknesses of the low-density medium so that the proper thickness for a given design could be computed. And last, a comparison between the weight of a metal skin supported by a low-density material and that of an identical section supported by extruded stiffeners should also be made, so that the relative value of the two supporting systems can be learned.

## Conclusions

From the results of this investigation the following conclusions were reached:

1. The process of forming a low-density material by casting wood fibers in a plaster-of-Paris mold was tried but appears to be impractical.

2. The spraying process apparently has possibilities if a gun capable of spraying the coarse fibers is developed.

3. The plastering process is the best one of the three at present, but a more efficient bonding agent is required before it can be used to any extent.

4. The material made of Masonite fibers with gum arabic as a bonding agent was the best one developed by this investigation.

5. The tests made indicate that thin metal sheets in compression can be supported laterally by a low-density medium, but that an efficient bonding agent and a high-strength cement are needed before this method of support can be of practical value.

References

1. Gough, G.S., Elam, C.F., and de Bruyne, N.A.: "The Stabilisation of a Thin Sheet by a Continuous Supporting Medium," The Journal of the Royal Aeronautical Society, No.349, Vol. XLIV, January, 1940, p.12.

2. Shanley, F.R.: "Pounds or Pounds Per Square Inch," Aviation November, 1936, p.27.

TABLE I

TEST SPECIMEN SCHEDULE

| Material | Specimen Number | Thickness in Inches | Width in Inches | Length in Inches | Specific Gravity | Type of Test |
|---|---|---|---|---|---|---|
| Masonite and Gum Arabic | 1 | 0.513 | 2.15 | 8.9 | .4345 | Bending |
| | 2 | 0.533 | 2.22 | 8.75 | .4287 | Bending |
| | 3 | 0.535 | 2.16 | 8.78 | .4298 | Bending |
| Masonite Bentonite and Shellac | 4 | .514 | 2.15 | 8.9 | .361 | Bending |
| | 5 | .472 | 2.22 | 7.4 | .341 | Bending |
| Plain Celotex | 6 | 1 | 1.965 | 7.68 | .2205 | Bending |
| | 7 | 1 | 1.965 | 7.64 | .218 | Bending |
| | 8 | 1 | 1.965 | 7.64 | .219 | Bending |
| Shellacked Celotex | 9 | 1 | 1.965 | 7.69 | .252 | Bending |
| Soaked Celotex | 10 | 1 | 1.965 | 7.72 | .273 | Bending |
| Plain Celotex | 11 | 1 | 2 | 3.25 | .22 | Compression |
| | 12 | 1 | 2 | 3.25 | .22 | Compression |
| | 13 | 1 | 2 | 3.25 | .22 | Compression |
| | 14 | 1 | 2 | 3.25 | .22 | Compression |
| Composite | 15 | .520 | 2 | 4.25 | .344 | Compression |

TABLE II

STRENGTH-WEIGHT COMPARISONS [1]

| Specimen | $w = lbs/in^3$ | Modulus of Elasticity E | Strength-Wt. Factor $\frac{E}{w^2}$ | Modulus of Rupture |
|---|---|---|---|---|
| Cast Newspaper | 0.0038 | -- | -- | -- |
| Plain Celotex | 0.00795 | 10,300 | $163x10^6$ | $168\ lbs/in^2$ |
| Cast Masonite and Bentonite | 0.00867 | -- | -- | -- |
| Celotex Painted with Shellac | 0.00903 | 11,250 | $138x10^6$ | 369 |
| Celotex Soaked in Shellac | 0.00975 | 11,250 | $118.5x10^6$ | 315 |
| Composite | 0.0124 | 3,280,000 | $2140x10^6$ | -- |
| Masonite, Bentonite and Shellac (Plastered) | 0.0126 | 13,280 | $83.3x10^6$ | 180 |
| Masonite and Gum Arabic (Plastered) | 0.0155 | 46,300 | $192x10^6$ | 316 |
| Spruce | 0.0162 | 1,500,000 | $5720x10^6$ | 9,400 |
| Duralumin | 0.10 | 10,000,000 | $1000x10^6$ | 55,000 |
| Steel | 0.283 | 30,000,000 | $370x10^6$ | 90,000 |

[1] Specimens are arranged in the Table according to their densities.

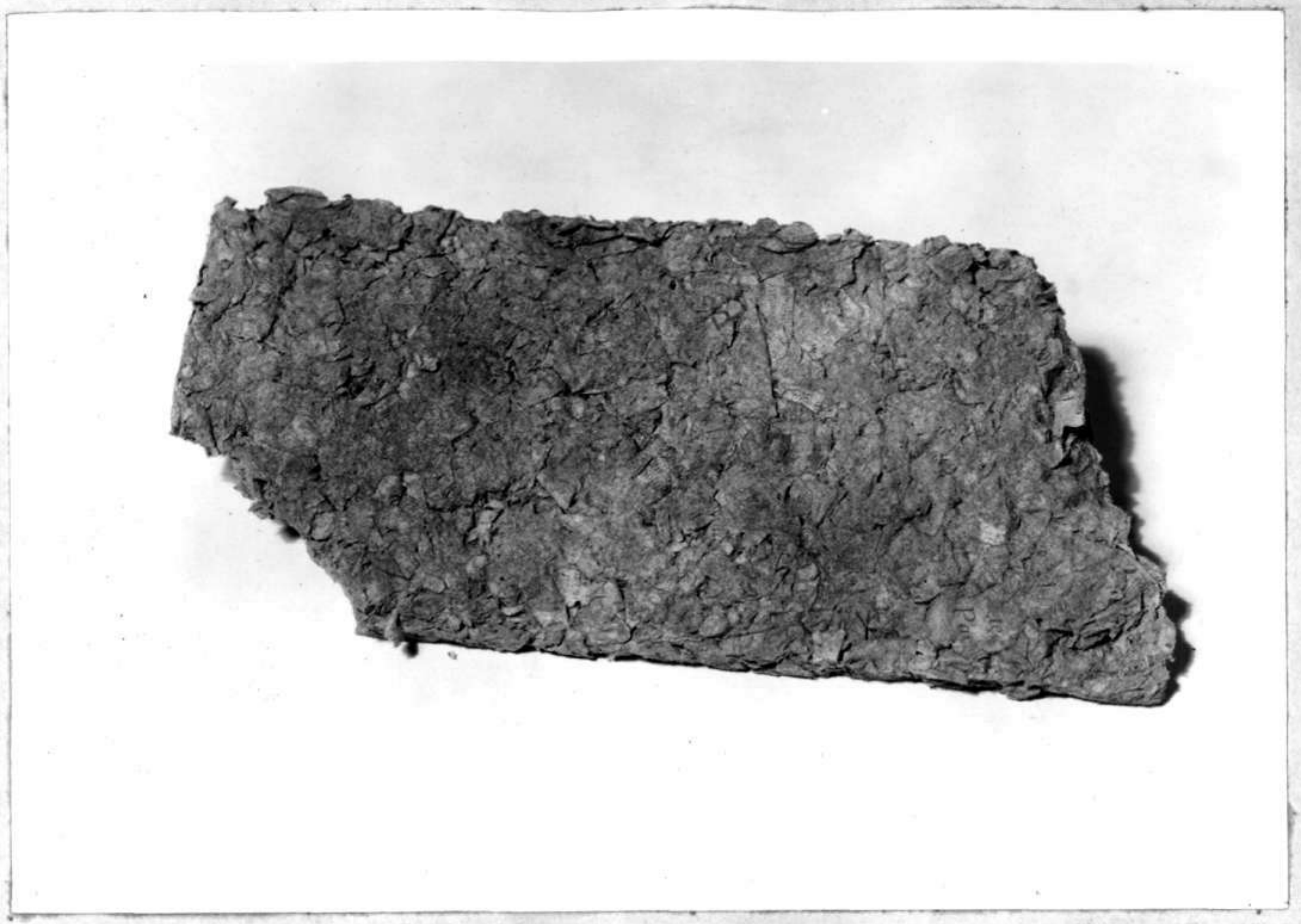


Fig. 1 Cast Newspaper Specimen.

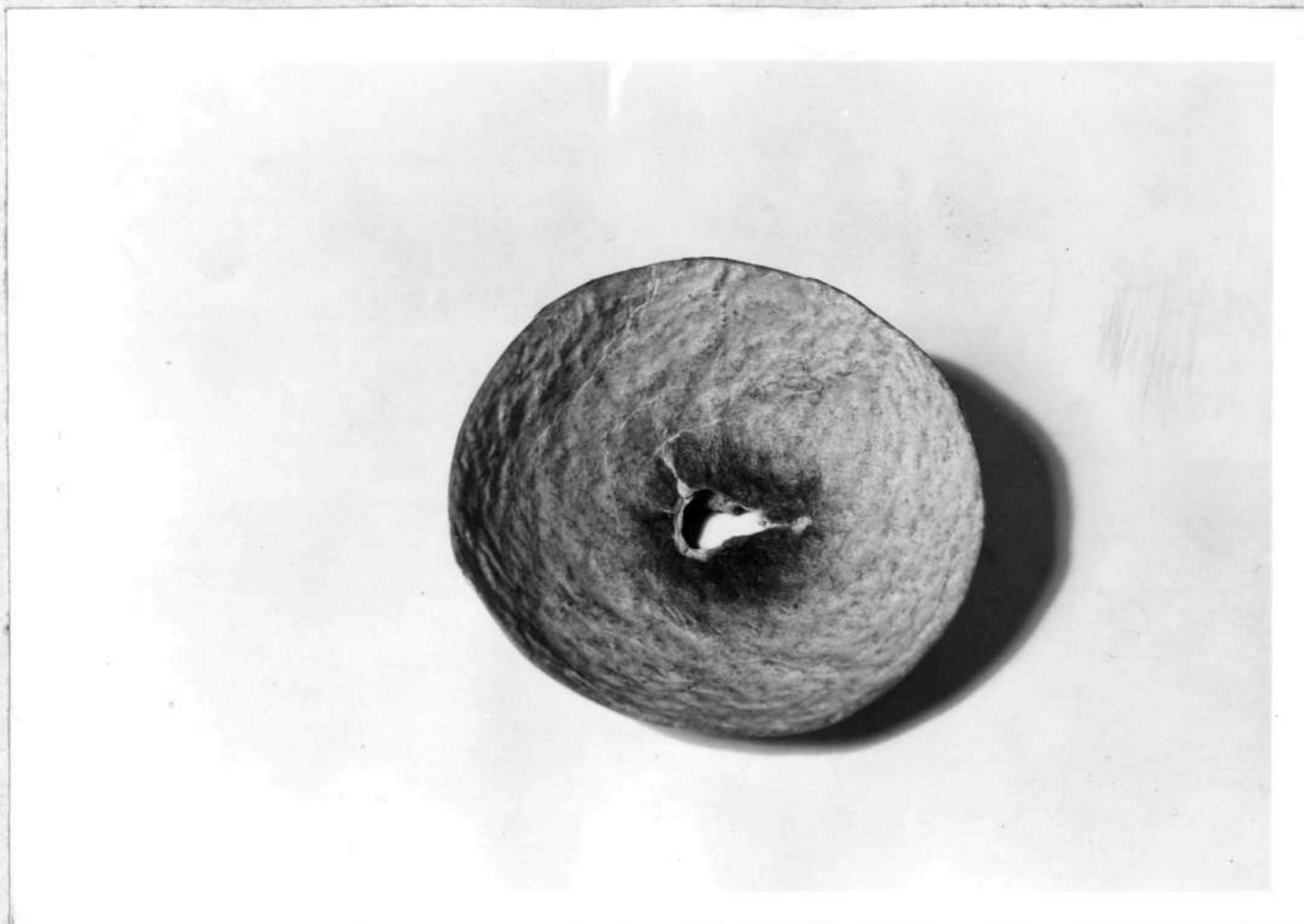


Fig. 2 Cast Tissue Paper.

Fig. 3. Natural Masonite Fibers.

Fig. 4. Cast Masonite.

Fig. 5. Original Spray Gun.

Fig. 6. Improved Spray Gun.

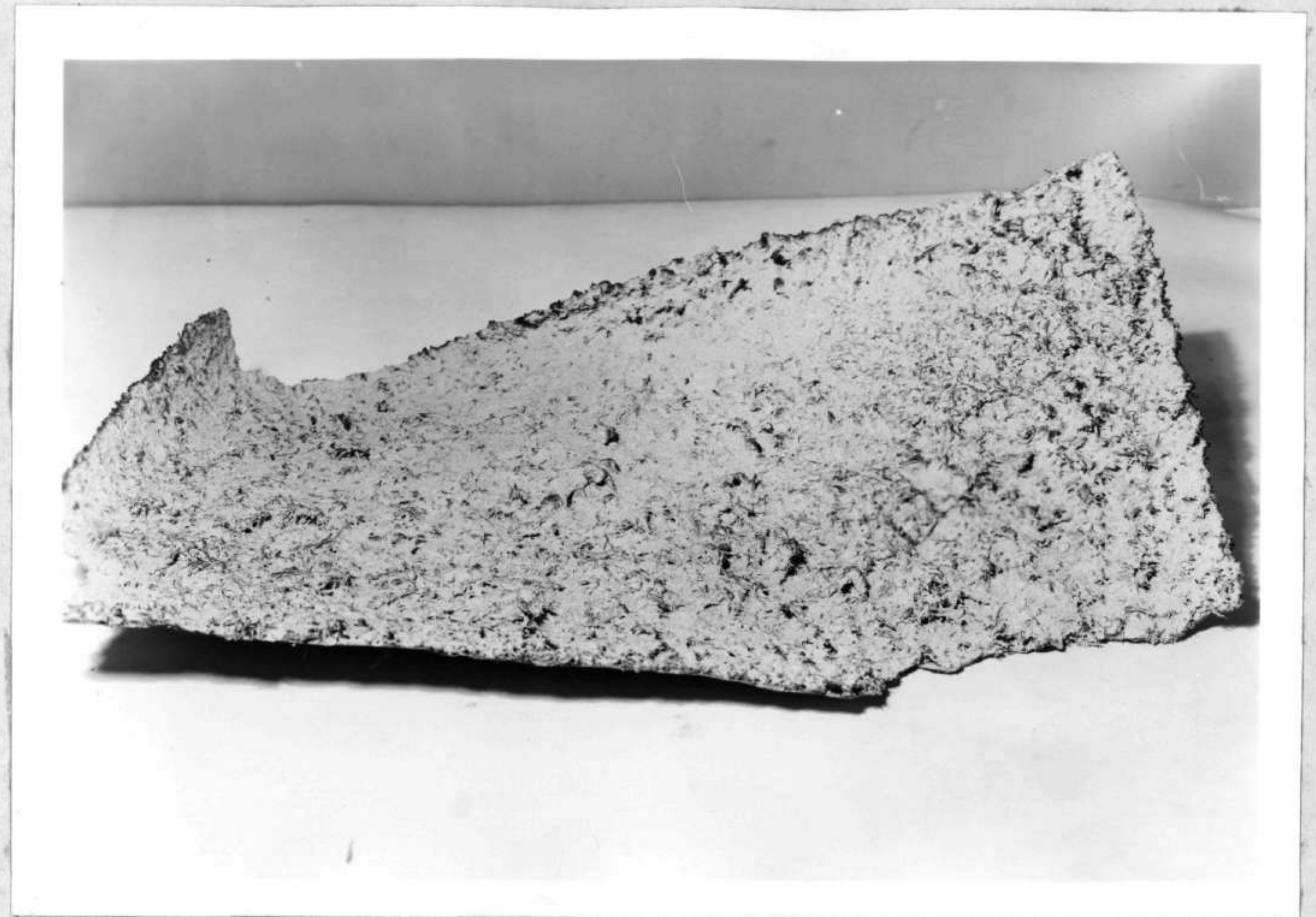


Fig. 7. Sprayed Masonite Specimen.

Fig. 8. Plastered Masonite with Shellac and Bentonite as Bonding Agents.

Fig. 9. Plastered Masonite with Gum Arabic as Bonding Agent.

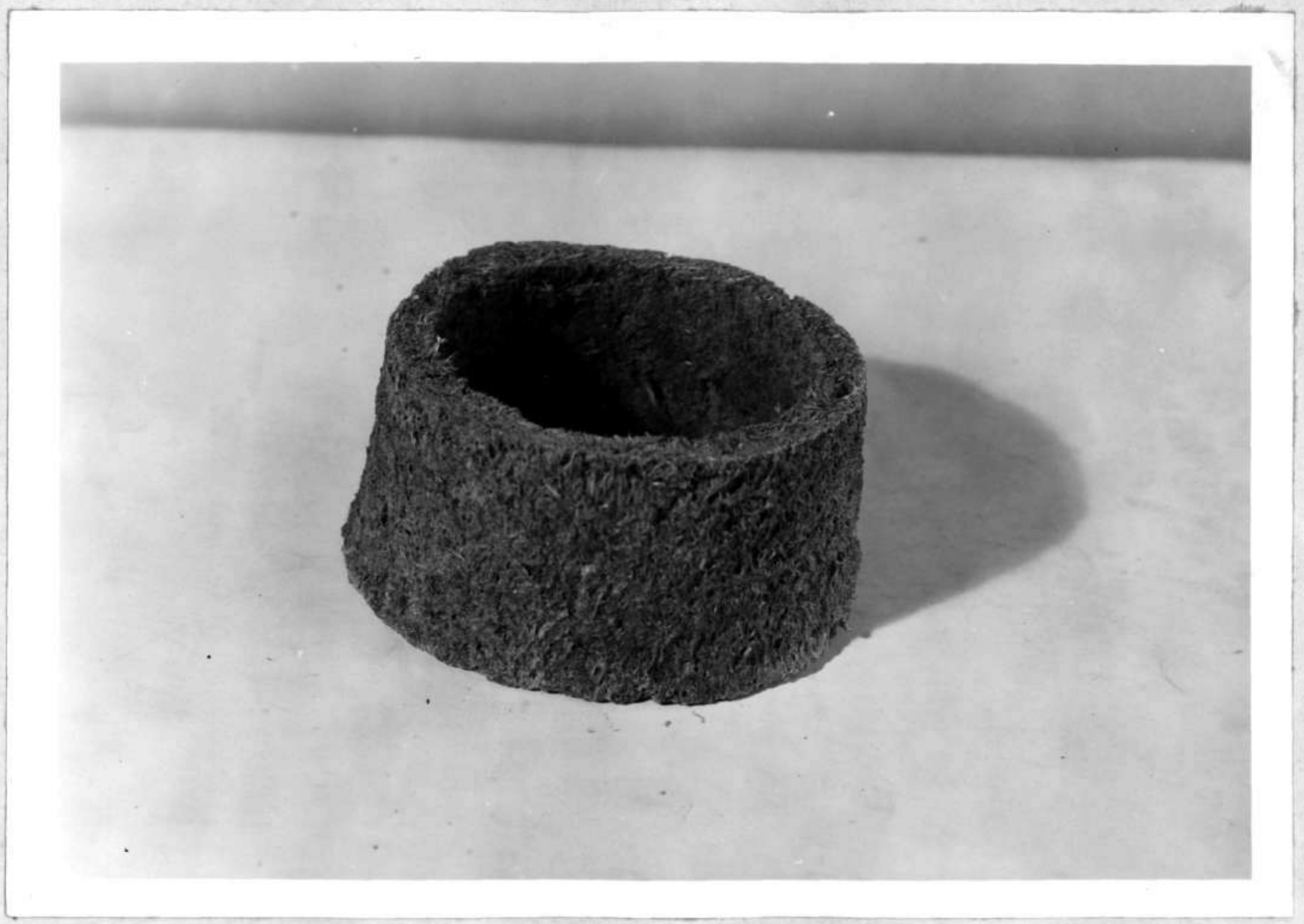


Fig. 10. Masonite Plastered on Cylindrical Mold.

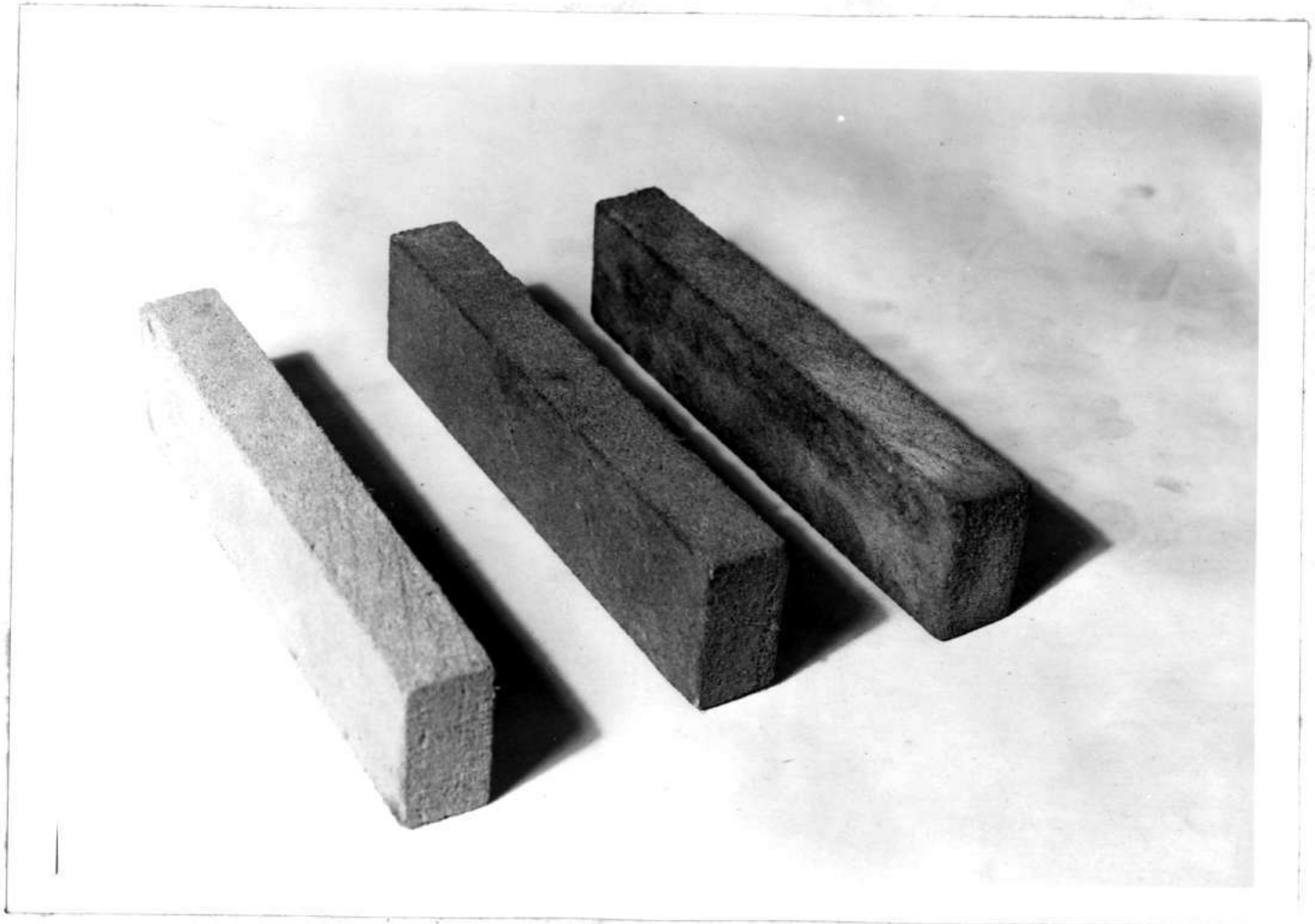


Fig. 11. Plain and Shellacked Celotex.

Fig. 12. Riehle Universal Testing Machine.

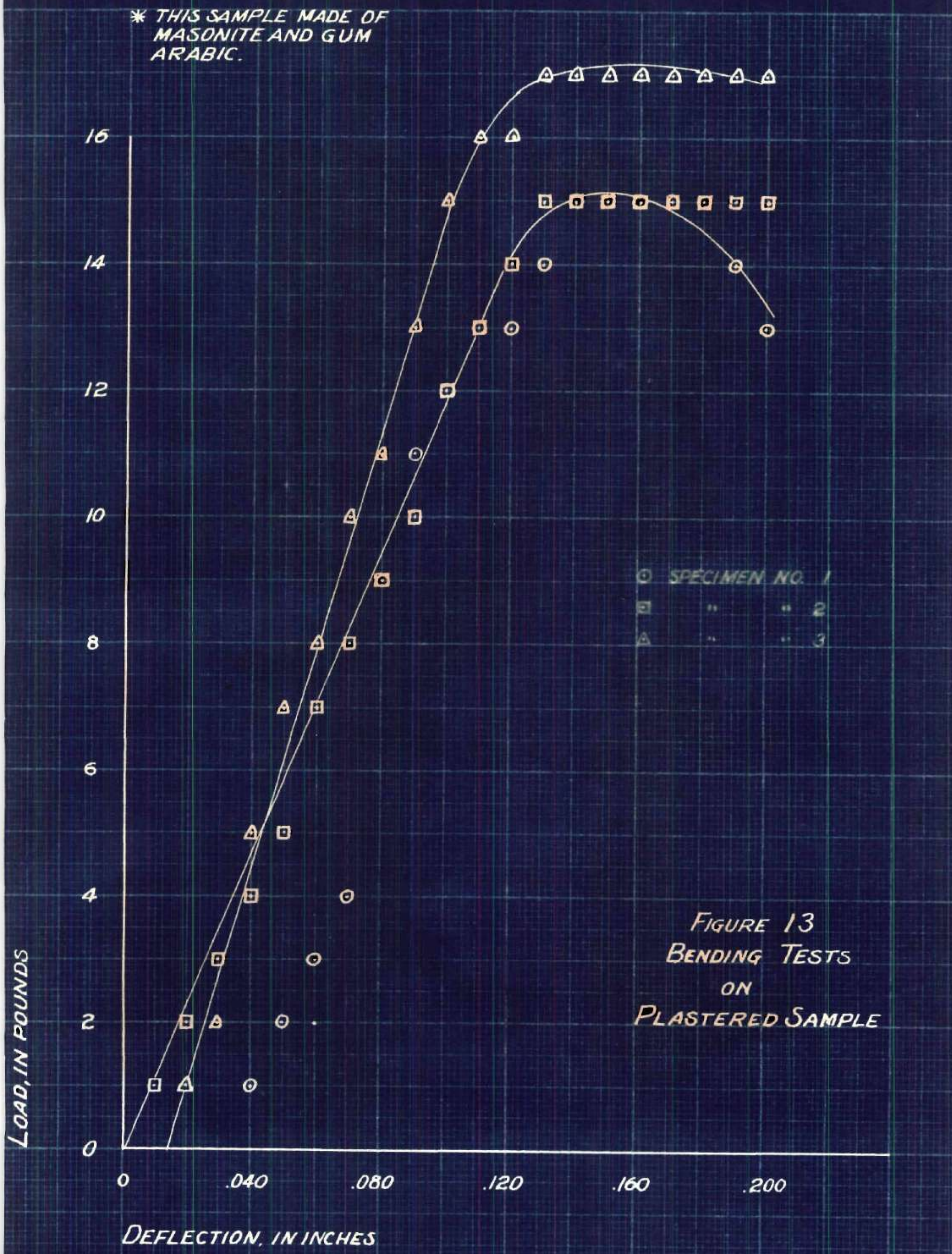



FIGURE 13
BENDING TESTS
ON
PLASTERED SAMPLE

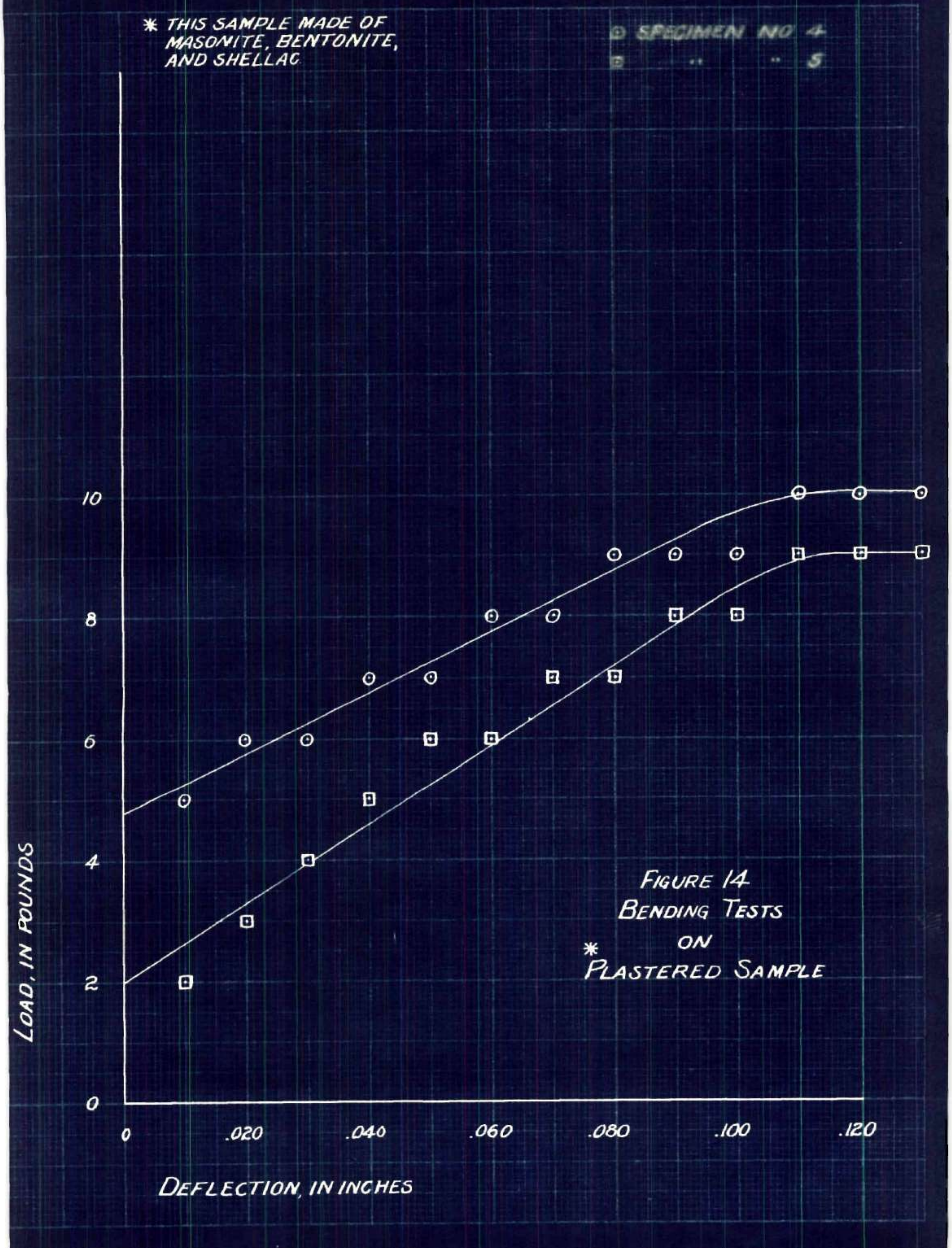



FIGURE 14
BENDING TESTS
ON
* PLASTERED SAMPLE

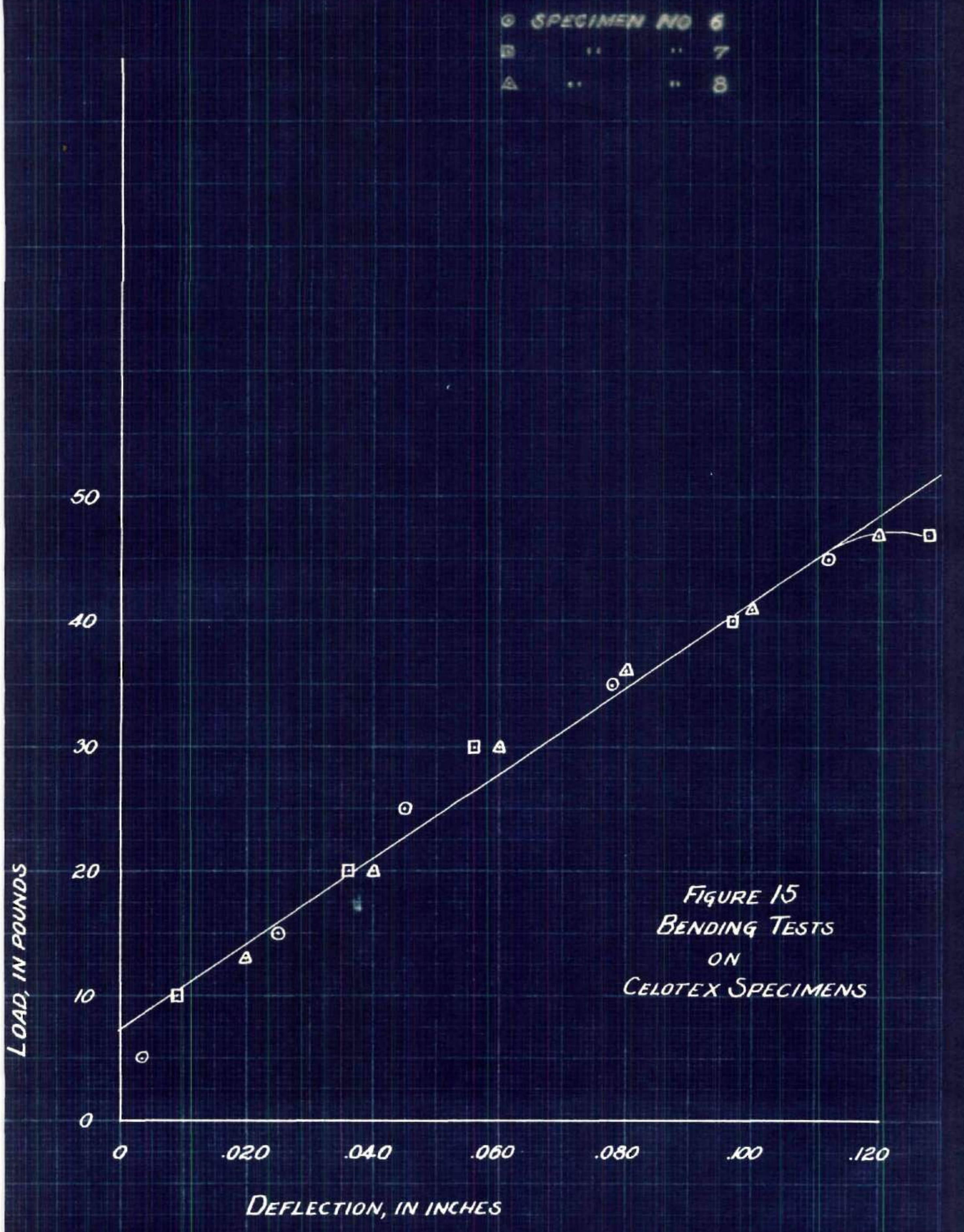



FIGURE 15
BENDING TESTS
ON
CELOTEX SPECIMENS

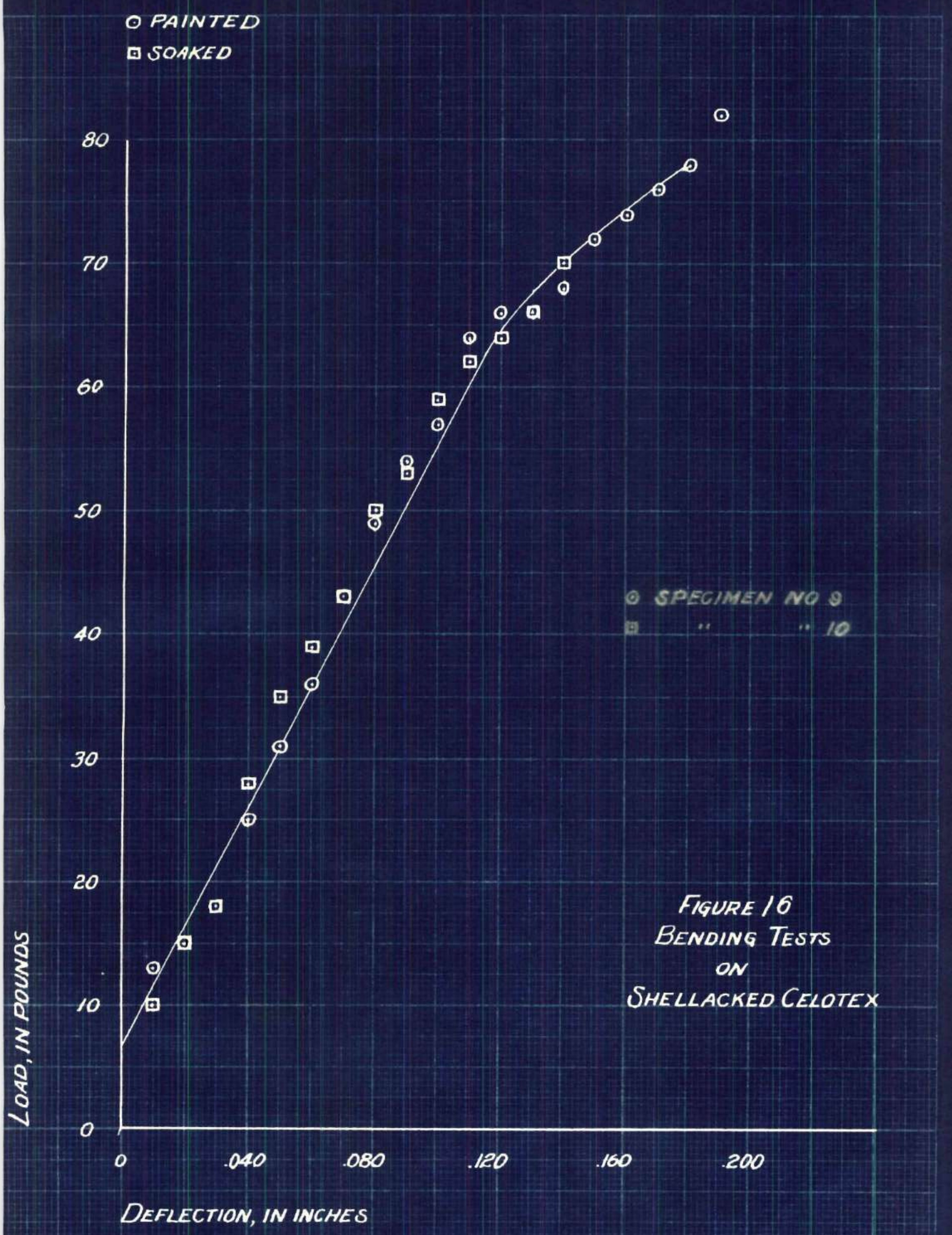



FIGURE 16
BENDING TESTS
ON
SHELLACKED CELOTEX

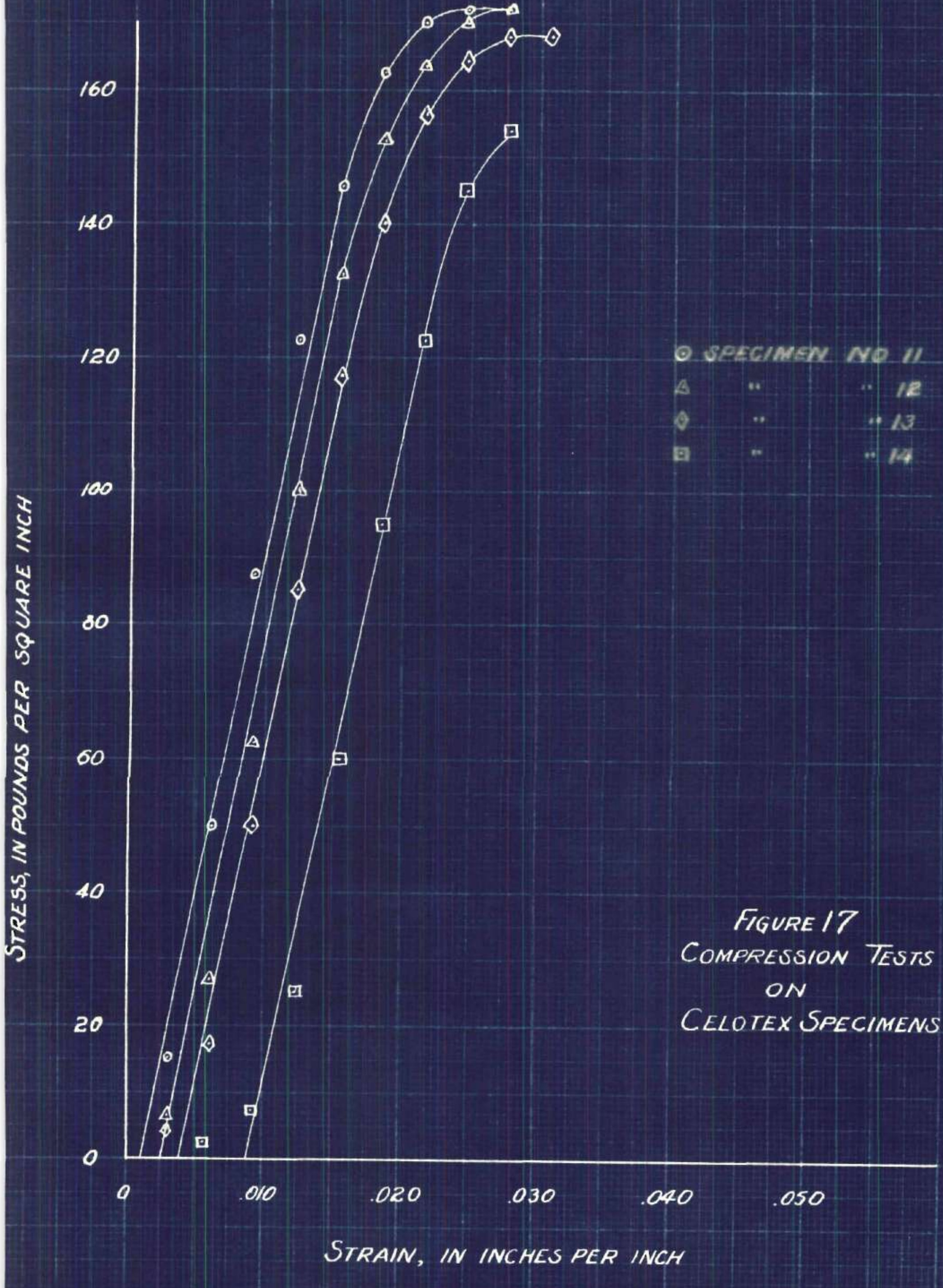
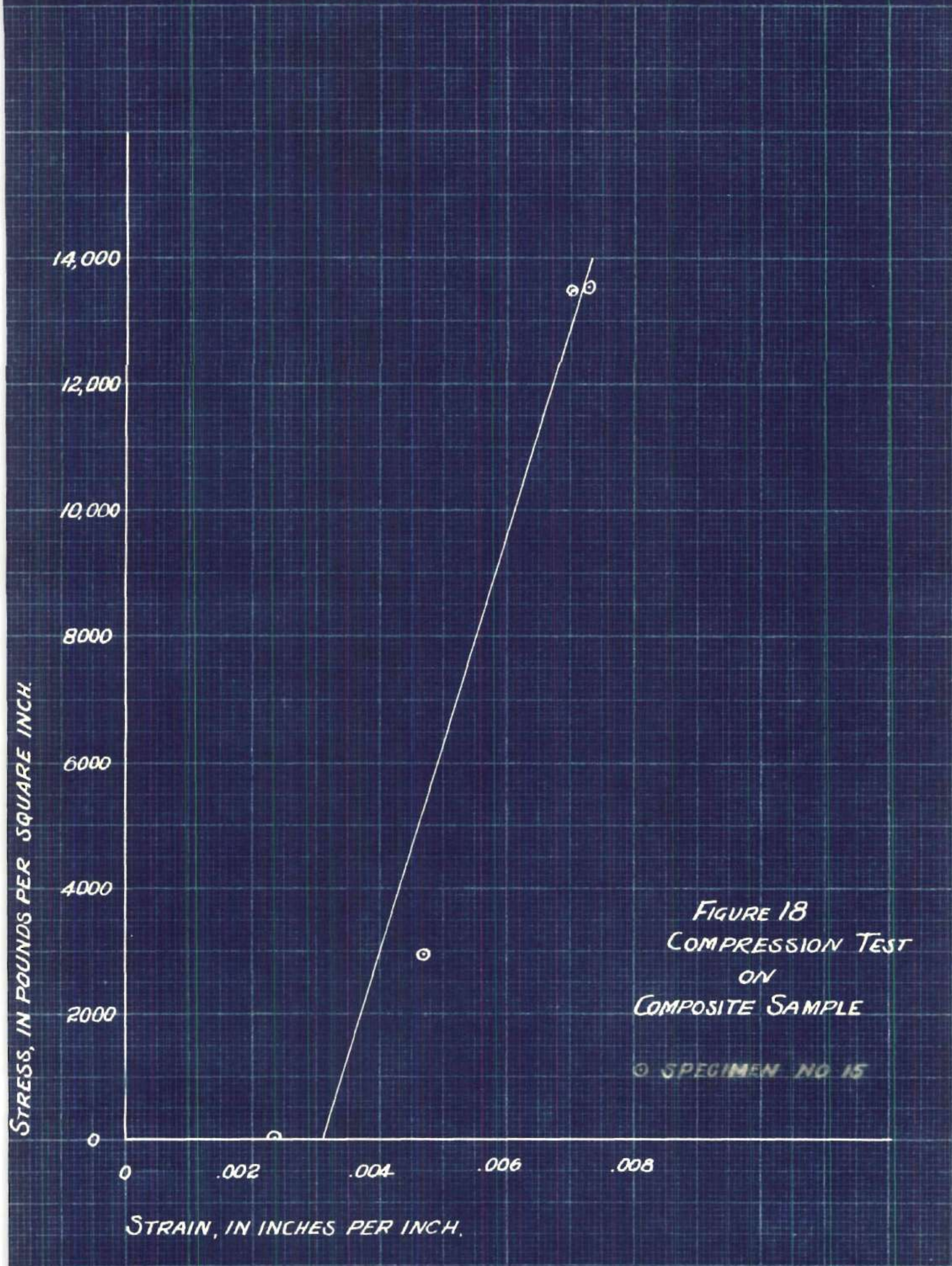



FIGURE 17
COMPRESSION TESTS
ON
CELOTEX SPECIMENS



14,000
12,000
10,000
8000
6000
4000
2000
0
STRESS, IN POUNDS PER SQUARE INCH.
0
.002
.004
.006
.008
STRAIN, IN INCHES PER INCH.
FIGURE 18
COMPRESSION TEST
ON
COMPOSITE SAMPLE
⊙ SPECIMEN NO 15