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EFFECTS OF MOLDING PRESSURE ON THE STRENGTH PROPERTIES OF SEVERAL TYPES OF GLASS-FIBER REINFORCED PLASTICS

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FOREWORD

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This report covers work conducted from May 1953 to August 1955.

ABSTRACT

An investigation was made to determine the effects of molding pressure on the mechanical properties of glass-fiber reinforced laminates fabricated from a polyester resin reinforced with woven glass fabric or with 2 oz. or 8 oz unoriented glass fiber mat.

The laminates were fabricated in an open mold at molding pressures of 1, 10, and 100 lb/in^2, and in a closed mold at 10, 100, and 500 lb/in^2. The resin content of the free-edge panels varied with the molding pressure, while that of the closed-edge panels was maintained at a constant value for each type of reinforcement.

Flexural, tensile and compressive strengths and flexural and tensile moduli of elasticity were determined for dry specimens as well as for specimens that had been immersed in water at 73.5 °F(23°C) for thirty days. Specific gravity, resin content, and voids content were also determined.

The test results indicate that the properties of laminates fabricated in the closed mold do not vary appreciably with changes in molding pressure. However, the flexural and tensile properties of panels molded in the open mold increase as the pressure increases from 1 to 10 lb/in^2 but do not change appreciably at higher molding pressure. Compressive strength shows a tendency to decrease with increasing molding pressure.

The results obtained for the closed-mold panels were in close agreement with those of the open-mold panels having the same reinforcement and similar resin content.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
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1. INTRODUCTION

The importance of glass-fiber reinforced plastic laminates has assumed major proportions in the aircraft industry. However, the development of the full potential of these materials cannot be realized until a major problem confronting their use can be overcome. This is the need for improved methods of quality control and fabrication techniques during the manufacturing processes of the basic materials as well as the finished products. In view of this fact, numerous investigations have been conducted in an effort to achieve such improvements.

A series of investigations dealing with the effects of fabrication variables on the strength and other related properties of glass-fiber reinforced plastics have been conducted at the National Bureau of Standards, in conjunction with the National Advisory Committee for Aeronautics and the Materials Laboratory, Wright Air Development Center (References 1-4). The last prior phase of these studies (Reference 4) was concerned with the effects of laminating pressure on the strength properties of glass-fabric reinforced polyester laminates in which several types of polyester resins were used.

This report is a summary of another phase of these investigations in which the effects of molding pressures on several types of glass-fiber reinforcing materials were studied. To reduce the variables to a minimum, only one of the previously used polyester resins (Reference 4) was used in these experiments.

2. MATERIALS

The materials used in this investigation were typical examples of commercially available resin and glass-fiber reinforcements and conform to one of the following military specifications: 1) Resin, MIL-R-7575A; 2) Glass fabric, MIL-F-9084 ; 3) Glass mat, MIL-M-15617A. The materials used were as follows:

A. Reinforcements:

1.) Glass fabric; 181 glass fabric with Volan A fiber finish, produced by the Hess, Goldsmith Company.

2.) Glass mat: The mechanically bonded, unoriented glass fiber mat with Volan A fiber finish was obtained in two weights, 2 oz and 8 oz/ft^2 from the Bigelow Fiber Glass Products Division of the Bigelow-Sanford Carpet Company.

The basic glass fibers used in all the reinforcing materials were produced by the Pittsburgh Plate Glass Company. The Volan finish is produced by E. I. duPont de Nemours & Co., Inc.

B. Resin:

Selectron 5003, an unsaturated polyester resin adaptable for laminating at low pressure, produced by the Pittsburgh Plate Glass Company.

C. Catalyst:

Luperco ATC, 50 percent benzoyl peroxide and 50 percent tricresyl phosphate, produced by the Lucidol Division of Wallace and Tiernan, Inc.

D. Mold Release:

Sylphrap 600 P-2-L, cellophane sheet, produced by the Sylvania Division of the American Viscose Corporation.

3. EQUIPMENT

3.1 Description of the Mold

The steel mold used in fabricating the laminates is shown in Figures 1 and 2, disassembled and partly closed, respectively. It consists of the following parts:

1.) A lower platen, 1/2 by 12 by 12 inches.
2.) An upper platen, 1 1/8 by 12 by 12 inches.
3.) A chase 15 inches square made of bars 1 1/2 inches square to enclose the platens.

The chase was machined to enclose the platens loosely to prevent loss of molding pressure from friction, and was used only when making laminates in the closed mold. Neither the chase nor molding stops were used when molding free-edge.

3.2 Description of the Press

A fifty-ton hydraulic press, fitted with steam-heating and water -cooling systems, was used to mold the laminates. The press was operated under its own power when molding at 100 and 500 lb/in^2. The lower molding pressures of 1 and 10 lb/in^2 were obtained by the use of two hydraulic jacks connected in series and placed under the movable press platen.

4. MOLDING PROCEDURES

4.1 Preparation of Reinforcements

Approximately thirty-six yards of glass cloth were cut into 11 3/4 inch squares. The pieces were randomized and divided into thirty groups of eleven plies each. Eighteen such groups were needed for the experimental work; the rest were held in reserve for the preparation of duplicate panels where necessary.

Sixteen yards of 2 oz glass mat, obtained in equal amounts from two rolls of material , were cut into 11 3/4 inch squares, randomized, and assembled into thirty-six groups of four plies each.

Four yards of 8 oz glass mat were cut to the same size, randomized, and assembled into thirty-six groups of one ply each. As with the glass fabric, only eighteen groups of each type of mat were actually needed for test purposes.

4.2 Preparation of the Mold

The mold was wrapped in the cellophane release agent and the lower platen and chase were assembled. When fabricating panels in a closed mold, thin strips of unvulcanized natural rubber used as the gasket material were placed along the periphery of the lower platen, in contact with the chase. The gasket was continuous when molding at 100 and 500 lb/in^2 to prevent leakage of resin, but was broken at the corners of the mold when laminating at 10 lb/in^2 to allow air to escape. Gasket material was not used for free-edge molding since the chase was removed as soon as the resin coating process was completed, just prior to placing the mold in the press.

4.3 Preparation of the Wet Lay-up

The glass fiber reinforcement was weighed to the nearest 0.1 gram and placed in a constant temperature drying oven for one hour at 230°F (110°C) to remove any traces of moisture.

The amount of resin needed was calculated from the weight of glass fiber to be used in a laminate. The resin was removed from the refrigerator, warmed to room temperature, weighed, and catalyzed by the addition of two percent Luperco ATC by weight of resin. The catalyzed resin was spread in an even layer over the entire surface of the lower platen. The glass reinforcement was removed from the oven, one ply at a time, and laid in the resin. When more than one ply of reinforcement was used, as with the glass fabric and 2 oz mat, the alternate plies were rotated ninety degrees with respect to the roll direction of the material to cross-laminate the reinforcement and thereby reduce the directional effects. For glass fabric the "warp" side was always up and the "fill" side down, for glass mat the "loop" side was up and the "chopped strand" side down. The upper platen was set into place, the chase then being removed if a panel were to be molded free-edge.

4.4 Curing Cycle

The uncured laminate was placed in the press and presqueezed for 15 minutes. The purpose of the presqueeze was to allow the resin to thoroughly coat the glass fibers. Wet lay-ups of glass mat laminates molded at a pressure of 1 lb/in^2 were not presqueezed at the molding pressure. Preliminary experiments indicated that the glass mat panels presqueezed and cured at 1 lb/in^2 had a high voids content and were too thick to be tested according to the conditions specified in the flexural test method. It was found that a presqueeze pressure of approximately 5 lb/in^2 was necessary to reduce the voids and thickness of these laminates adequately. At the end of the fifteen minute presqueeze period the pressure was allowed to decrease slowly to 1 lb/in^2 before the heating cycle was started. All other laminates, including those reinforced with glass fabric and molded at 1 lb/in^2, were presqueezed at the molding pressure. Preliminary studies also indicated that the strength properties were more closely related to the presqueeze pressure than to the molding pressure if the former were the higher of the two Also, if the presqueeze pressure were the higher, there was a tendency for the voids content to increase. This was probably due to the entrance of air into the liquid resin as the pressure was decreased to that used for curing the panels.

The remainder of the curing cycle consisted of raising the temperature of the wet lay-up to 225°F (107°C) in 15 to 20 minutes, followed by a 25 minute cure at that temperature. The mold was cooled to room temperature and the laminate was removed.

Panels fabricated in the open mold were molded at pressures of 1, 10, or 100 lb/in^2. Closed mold panels were made at molding pressures of 10, 100, or 500 lb/in^2.

4.5 Sequence of Fabrication

Three replicate series of laminates were fabricated. Each series consisted of one laminate molded at each condition of molding pressure, mold type, and glass fiber reinforcement, making a total of eighteen laminates. The sequence of fabrication was randomized within each series and differed with each series. All of the laminates in a series were completed before those in a succeeding series were begun.

5. DETERMINATION OF OPTIMUM RESIN CONTENTS

The resin content of panels fabricated in the open mold varied with the molding pressure used. However, it was necessary to use an excess amount of resin in the wet lay-up to insure complete coating of the glass fibers. The amount of resin necessary was determined experimentally. Several laminates were molded using various amounts of resin. After these laminates were cured, resin content determinations were made and the results compared with the initial amount of resin used. Resin in excess of 60, 80, or 85 percent in the wet lay-up with glass fabric, 8 oz mat, or 2 oz mat, respectively, raised the resin content of the cured laminate by less than one percent. The percentages listed were the minimum amounts that could be used at the 1 lb/in^2 molding pressure without the occurrence of dry spots in the laminate. To minimize the variables, all glass fabric panels molded free-edge contained 60 percent resin by weight initially, while all free-edge panels reinforced with glass mat contained 85 percent resin.

It was also necessary to determine the amount of resin to be used in the closed mold laminates reinforced with glass mat. It was desirable to use the same weight percent of resin for both types of mat to keep the molding variables at a minimum. A number of free-edge laminates were made at various molding pressures from 1 to 30 lb/in^2 to determine the resin content which results in maximum strength properties. Data obtained from these laminates, shown in Figures 3 and 4, indicated that maximum strength properties were attained in 2 oz mat laminates having a resin content of 45 to 55 percent, and in 8 oz mat laminates when the resin content was approximately 50 percent. As the resin content was increased further, a decrease in the strength properties was observed in both cases. The best common resin content was approximately 50 percent.

The application of the information obtained from the free-edge panels to the laminates fabricated in the closed mold was not successful in the case of the 2 oz mat laminates molded at 10 lb/in^2. Apparently, the 10 lb/in^2 molding pressure was not sufficient to reduce the apparent volume of the four plies of mat to a point where all of the glass fiber could be impregnated with the resin. Therefore, a resin content of 55 percent was selected for the mat laminates to be made in the closed mold so that both the 2 oz and 8 oz mat would contain the same weight percentage of resin. Alternative methods of resin impregnation were considered, such as the use of higher presqueeze pressures, dip coating with solvent-thinned resin , and the use of excess resin in the wet lay-up which would be presqueezed in the open mold prior to transfer to the closed mold for the curing cycle. However, it was believed that these methods would increase the fabrication variables and decrease the control of resin content. The only undesirable feature of using 55 percent resin was that the strength properties of the 8 oz mat laminates would be expected to be somewhat below the maximum obtainable values.

6. DETERMINATION OF THE WEIGHT VARIABILITY OF THE GLASS MAT

The resin content of glass fabric reinforced laminates fabricated in the closed mold had been established as 39 ± 1.5 percent, the small range allowing for minor variations in molding technique from panel to panel. In the preliminary work it was extremely difficult to mold glass mat reinforced laminates having average resin contents falling within the range of the calculated resin content plus or minus 1.5 percent. Wide ranges in resin content for specimens within a single panel were observed for glass mat laminates but not for glass fabric laminates molded by the same techniques. Therefore, a study was made of the weight variability of the glass mat, particularly with respect to small areas of the size of resin content specimens.

A number of pieces of both 2 oz and 8 oz mat, 11.75 inches square, previously cut out for use in the preparation of test panels, were weighed and measured. The average weight of twenty pieces of 2 oz mat was 1.80 oz/ft^2, and of eighteen pieces of 8 oz mat 6.84 oz/ft^2. The respective standard deviations for these determinations were 0.2 and 0.3.

Five additional one-foot-square pieces of 2 oz mat and three of 8 oz mat were randomly cut from the respective 125-yard rolls. These pieces were weighed and measured. The average weights were 1.81 and 7.06 oz/ft^2 for the 2 oz and 8 oz mat, respectively. The respective standard deviations were 0.2 and 0.4. Six lengthwise and six crosswise specimens were then cut from each of these eight pieces of mat by means of a strip tensile die, 0.5 by 5 inches, and the specimens were weighed. Specimen-to-specimen variability was calculated, as well as panel-to-panel variability based on the average values obtained for each group of twelve specimens.

The average weight of the materials was calculated to be 1.82 and 7.19 oz/ft^2, with standard deviations of 0.2 and 0.4, respectively. A statistical analysis of the data obtained on the 0.5-by-5-inch specimens indicated a coefficient of variation within a panel of 11.5 percent and 6.6 percent for the 2 oz and 8 oz mat, respectively. Since a 1 in^2 specimen is required for resin content determination, a reduction in specimen size from 2.5 to 1.0 in^2 would result in a specimen-to-specimen coefficient of variation of 18.2 and 10.4 percent for 2 oz and 8 oz mat, respectively.

Calculations made from the coefficients of variation, to determine the effect of glass variability on the variation in resin content, were simplified by assuming that each unit area of the laminate absorbed the same weight of resin.

This assumption was later verified by an analysis of the resin content data obtained from the panels used in the final tests. For a resin content of 55 percent, coefficients of variation of 18.2 and 10.4 percent in the glass weight correspond to coefficients of variation in the resin of 8.2 and 4.7 percent, respectively. Thus the range in variability in resin content due to the variability of the glass mat is ± 9.0 percent for the 2 oz mat and ± 5.2 percent for the 8 oz mat, at the 95 percent confidence level. Since four plies of mat are used in the 2 oz laminates, the range is reduced to ± 4.5 percent. Adding the normally allotted range of ± 1.5 percent for variation in resin content due to molding variables, the allowable ranges in resin content would be 55 ± 6.0 percent and 55 ± 6.7 percent for the 2 oz mat and 8 oz mat laminates, respectively. Actually, to minimize the spread in the physical test data, the criterion used for a satisfactory test panel was that the average resin content be within the range of 55 ± 4 percent, and that the range of five specimens within a panel be of the order of 10 percent or less. Additional panels were made to obtain the requisite number with resin contents within this limit.

7. TESTING PROCEDURES

7.1 Specimen Sampling

Figure 5 shows the sampling pattern used to obtain specimens from a nine-inch-square test area in each laminated panel. Each panel was cut into 8 flexural, 4 compression, and 4 tensile strength specimens, and 5 specimens for the determination of resin content, specific gravity, and voids content. The specimen blanks cut from the test area were machined to the dimensions specified in each test method. One half of the flexure and compression specimens were cut from the lengthwise direction and half from the crosswise direction. Tensile specimens could not be obtained from both directions in a single panel. Lengthwise tensile specimens were obtained from the first and third series of panels, with respect to the sequence of molding, while crosswise specimens were obtained from the second series of panels. Specimen direction was identified with the lengthwise and crosswise direction of the roll of material as applied to the bottom ply of reinforcement in the laminate.

7.2 Specimen Conditioning

The odd-numbered specimens shown in Figure 5 were tested dry and the even-numbered specimens were tested wet, with the exception of the resin content specimens, labeled "R". The conditioning period for dry specimens was a minimum of four days at 73.5°F (23°C) and 50 percent relative humidity. The wet specimens were immersed in distilled water for 30 days at 73.5°F (23°C) prior to testing. All tests were conducted at 73.5°F (23°C) and 50 percent relative humidity.

7.3 Sequence of Testing

All of the specimens for a given type of strength test were randomized, the wet specimens being randomized prior to immersion in water. The sequence of testing consisted of alternately testing a dry and a wet specimen. The wet specimens were removed from the water, blotted dry with absorbent tissue, and tested immediately.

8. TEST METHODS

8.1 Flexural Properties

Flexural strength and modulus of elasticity were determined in accordance with Method 1031 of Federal Specification L-P-406b (Reference 5). The specimens were approximently 4.1 inches long and were machined to a width of 0.500 inch. The span-depth ratio was 16:1 for most specimens, giving a span length of approximately 2 inches. When the thickness of the laminate was less than 0.100 inch, the limitations of the flexural test jig prevented the use of a span-depth ratio as small as 16:1 and an arbitrary span length of 1.600 inches was used, to simplify the calculations. Specimens falling in this category were obtained from glass fabric and from 8 oz mat reinforced panels molded free-edge at 10 lb/in^2, and from all panels molded free-edge at 100 lb/in^2. A rate of crosshead motion of 0.05 inch per minute was used. Load-deflection data were obtained by the use of an automatic recording deflectometer.

All of the flexural specimens were tested by applying the load to the surface which had been in contact with the upper platen of the mold.

8.2 Tensile Properties

Tensile strength and modulus of elasticity were determined according to Method 1011 of Federal Specification L-P-406b(Reference 5). A nine-inch-long Type 1 specimen was used, having a reduced section of 0.500 inch. A rate of head separation of 0.05 inch per minute was used. Load-deformation curves were obtained by use of a recording extensometer. The tensile modulus of elasticity was calculated for the initial straight portion of the stress-strain curves.

8.3 Compressive Strength

The compressive strength tests were conducted according to the procedure outlined in Method 1021 of Federal Specification L-P-406b (Reference 5), using a supporting jig. The specimens were 0.500 inch wide and 3.000 or 3.100 inches long depending on the thickness of the specimen. The testing machine head was operated at a speed of 0.05 inch per minute.

8.4 Resin and Fiber Finish Content Determination

The resin content was determined in accordance with the method outlined in Paragraph 4.2.2.1.2 of Military Specification MIL-P-8013A (Reference 6). This method requires the ignition of a one-inch-square specimen at 1000 to 1100°F (538 to 593°C) until all of the resinous constituents have been volatilized. The resin content is reported as the weight percent of the original specimen lost on ignition corrected for weight of volatilized fiber finish.

The fiber finish on the reinforcements used in these experiments was also volatilized at the ignition temperature used in resin content determinations. The amount of fiber finish volatilized, whether all or part of that present on the glass fiber, was sufficiently high to cause a considerable error in the actual resin content. Since it was impossible to determine the amount of volatile fiber finish in a test specimen of the laminate, values were obtained on randomly selected specimens of the reinforcing materials. These specimens were approximately the same weight as the glass fiber contained in a resin content specimen from a cured laminate. The fiber finish content was calculated in the same manner as the resin content. Values for the amount of fiber finish volatilized were 0.2, 1.4, and 1.0 percent of the original weight of glass fiber for the samples of glass fabric, 2 oz mat, and 8 oz mat, respectively. For the voids content determination it was assumed that these values represented all of the fiber finish present on the glass fibers.

Some estimates were made to determine the effects of variation in fiber finish on the accuracy of the resin content. Specimens obtained from panels fabricated in the closed mold were used, consisting of glass fabric specimens containing 39 percent resin and glass mat specimens containing 55 percent resin. It was estimated that an uncorrected resin content would be in error by the following ranges: 0.1 to 0.2, 0.3 to 1.1, and 0.4 to 0.6 percent when using glass fabric, 2 oz mat, and 8 oz mat, respectively. Similarly, the corrected resin content was estimated to be accurate to ± 0.02, ± 0.20, and ± 0.09 percent for the three respective forms of glass fiber products. The relatively small range in the uncorrected resin content of glass fabric reinforced panels is due to the small range in fiber finish content probably resulting from a more even distribution of fiber finish on this material. In those free-edge panels where the resin content was lower than that of the corresponding closed mold panels, the accuracy of the corrected resin content was decreased. In addition, a corresponding increase in the range of the uncorrected resin content was evident.

8.5 Specific Gravity Determination

The specific gravity was measured by the displacement of water technique in Method 5011 of Federal Specification L-P-406b (Reference 5).

8.6 Voids Content Determination

The actual voids content of a specimen is equivalent to the measured volume of the specimen less the calculated volume. The measured volume was obtained by multiplying the specific gravity of the laminate specimen by 0.9976 gm/cm^3, the density of water at 73.5°F (23°C), to obtain the specimen density. The weight of the specimen in air divided by the density was equal to the measured volume of the specimen. The calculated volume was the summation of the volumes of resin, glass fiber, and fiber finish, obtained by dividing the respective densities into the weight of each component as obtained from the resin content determination. The density values for cast resin, glass fiber, and fiber finish as supplied by the respective manufacturers, were 1.22, 2.57, and 1.03 gm/cm^3, respectively.

The voids content is expressed in the tables as percent of the measured volume and was derived as follows:

$$\text{Voids content} = \frac{Vm - Vc}{Vm} \times 100$$

where Vm = measured volume of the specimen
Vc = calculated volume of the materials in the specimen.

9. TEST RESULTS AND DISCUSSION

9.1 Statistical Analysis

The results obtained were statistically analyzed to evaluate the effects of type of mold, molding pressure, specimen direction, set-to-set and panel-to-panel variability. A separate analysis was made for each property for laminates reinforced with each type of glass fiber and molded in each of the two types of mold.

The standard errors were calculated from the variabilities in duplicate measurements without regard to specimen direction for both dry and wet flexural and tensile strength and modulus from both mold types.

Since duplicate specimens for compressive strength could not be obtained from the test areas of the panels, the standard errors for those values were calculated from the variabilities of the specimens obtained from the sets of three replicate panels at each molding pressure and for each mold type, assuming that there was no significant directional effect. The standard errors for resin content, specific gravity, and voids content were calculated from the variabilities between panel averages for each molding pressure and mold type.

9.2 Effects of Molding Pressure on Glass-Fabric Reinforced Laminates

The results obtained for the flexural, tensile, and compressive properties of glass fabric laminates are given in Tables 1, 2, and 3 and summarized in Tables 13, 14, and 15. Other physical properties are given in Table 4. Figures 6 and 7 show the effect of molding pressure on flexural strength and modulus of elasticity, respectively; Figures 8 and 9, the effect on tensile strength and modulus; and Figure 10, the effect on compressive strength. The effect of pressure on the resin content of free-edge panels is shown in Figure 21. Figures 22 and 23 indicate effects of pressure on specific gravity and voids content, respectively.

There was little, if any, effect of pressure on the strength properties of laminates fabricated in the closed mold.

The strength properties of panels fabricated in the open mold were, in general, affected significantly by the variation in molding pressure. The flexural and tensile properties increased significantly as the molding pressure increased from 1 to 10 lb/in^2. However, these properties changed little as the molding pressure increased from 10 to 100 lb/in^2. With regard to compressive strength, the values obtained for panels molded at 1 lb/in^2 were approximately 25 percent higher than those obtained for panels molded at 10 and at 100 lb/in^2 when tested dry and approximately 30 to 50 percent higher when tested wet. The statistical significance of these differences could not be determined because duplicate compression specimens were not provided for in the sampling pattern, due to the physical limitation of the size of each test panel.

In general, the average values obtained for the strength properties of laminates fabricated in the closed mold were between the values obtained in the open mold at 1 and 10 lb/in^2, and they were usually closer to those obtained at 1 lb/in^2.

Directional effects were not pronounced in the tensile and compressive properties of the glass fabric laminates. However, there were pronounced directional effects in the flexural properties except for the dry flexural strength of closed-edge panels. The interpretation of the directional effects observed is not clear, since the panels were cross-laminated as described previously in the molding procedure.

The loss of strength due to immersion in water was appreciable and generally independent of the molding pressure for closed-mold laminates. In free-edge panels, there was some indication of increased loss in strength with increased molding pressure. Water immersion had little effect on the modulus of elasticity. Although the values obtained for the wet flexural modulus of panels molded at 1 and 100 lb/in^2 were higher than those for the corresponding dry modulus, the differences were not significant. As was the case with strength properties, the average value for loss in strength of the closed mold laminates was most similar to that obtained for the open mold panels laminated at 1 lb/in^2. The values obtained for loss in strength indicated that the tensile strength was least affected by immersion in water, and that the flexural strength was affected less than the compressive strength.

There were no significant variations in the strength properties of the panels molded under the same conditions in the three series of laminates. However, there was a small, but significant, variation in resin content between like panels in the three series. For glass fabric laminates this variation was most pronounced for the three panels molded free-edge at 1 lb/in^2. Since similar variations were not found for the strength properties it was assumed that the resin content variations were too small to affect the strength of the materials.

The results of this investigation on the effects of laminating pressure on strength properties do not correlate completely with those obtained in a previous investigation under Purchase Order 33(038)50-1463-E (Reference 4). A common laminating pressure of 10 lb/in^2 was included in both investigations since it was suspected that the results of the two studies might not agree exactly. The lack of agreement in the results is attributed to five differences in the experimental work.

First, the data shows that there is a difference in voids content. At the beginning of the present investigation, a study was made to find a fabrication technique that would give a very low voids content. It had been observed in previous studies that the highest mechanical properties and the best resistance to water of glass fiber plastic laminates were usually obtained when the voids content was very low. Second, as a result of this effort to reduce voids content to a very low value, a different fabrication technique was used in the two investigations.

Third, different lots of Selectron 5003 resin were used. The second lot was made about 2 years after the first one. Fourth, the periods and conditions of storage between the synthesis of the resin and the fabrication of the laminates and thus the chemical age of the two lots of resin were different.

Fifth, two different lots of glass fabric were used. In the first study (Reference 4), the glass fiber and fabric were made and treated with an acrylic finish (114) by the Owens-Corning Fiberglas Corporation. In the present study, the glass fiber was made by the Pittsburgh Plate Glass Company, and the fabric woven and treated with a different acrylic finish (Volan A) by the Hess, Goldsmith & Company, Inc.

The resin content, specific gravity, and voids content of closed mold laminates were not affected significantly by differences in molding pressure. The volume percent of voids was below the level of 2 percent previously reported (Reference 4) as the point at which good correlation between increased voids content and decreased strength begins. In the open mold laminates, the resin content decreased and the specific gravity increased significantly with increased molding pressure. The increases in specific gravity with molding pressure were nearly proportional to the corresponding decreases in resin content. The voids content showed a tendency to increase slightly with increasing molding pressures. For all three properties, the average values obtained for the closed mold laminates were most similar to those obtained for the open mold panels laminated at 1 lb/in^2. This probably accounts for the previously reported similar relationships observed for the strength properties.

9.3 Effects of Molding Pressure on 2 oz Glass Mat Reinforced Laminates

The results obtained for the strength properties of 2 oz mat laminates are given in Tables 5, 6, and 7, and are summarized in Tables 13, 14, and 15 for flexural, tensile, and compressive properties, respectively. The other physical properties including thickness, resin content, specific gravity, and voids content are given in Table 8. Figures 11 and 12 show the effect of molding pressure on flexural strength and modulus of elasticity; Figures 13 and 14, the effect on tensile strength and modulus; and Figure 15, the effect on compressive strength. The effect of pressure on the resin content of free-edge panels, and on the specific gravity and voids content of all panels are shown in Figures 21, 22, and 23, respectively.

There was little, if any, effect of pressure on the tensile, flexural, and compressive properties of laminates fabricated in the closed mold.

Generally, the strength and related properties of panels fabricated in the open mold were significantly affected by the variation in molding pressure.

The flexural and tensile properties increased significantly as the molding pressure increased from 1 to 10 lb/in^2. There were no significant differences observed for the flexural and tensile properties between laminates molded at 10 and 100 lb/in^2 except for dry flexural modulus and dry tensile strength. In these cases, the properties increased with increased molding pressure. Since duplicate compression test specimens were not obtained from each panel, the significance of the variations in compression data cannot be definitely stated. Nevertheless, it may be noted that the values obtained for the panels molded at 1 and 10 lb/in^2 were approximately the same both for the wet tests and for the dry tests. These values in turn were approximately 25 percent higher than those obtained in the respective tests for the panels molded at 100 lb/in^2.

The average values obtained for the strength properties of the panels molded closed-edge were, in general, approximately equal to those values obtained in free-edge laminates molded at 10 lb/in^2. There was no consistent indication of directional effects in the strength tests except for the flexural modulus of elasticity.

The loss in strength due to immersion in water was generally independent of molding pressure for the panels fabricated in the closed mold. The loss in strength observed in the tensile and flexural tests of the free-edge molded panels was not appreciably different for molding pressures of 1 and 10 lb/in^2 but was considerably higher for the panels molded at 100 lb/in^2 than for the other two molding pressures. The average losses observed for these two tests in the closed mold panels were similar to those observed at the lower molding pressures in the open-mold panels. The losses in strength due to immersion were somewhat erratic in the compression tests. The losses observed in the tensile tests were generally lower than those observed in the flexural tests, which in turn were lower than those for the compression tests.

No significant variation between replicate panels was found for the strength properties. The resin content of triplicate panels molded under the same conditions in the three series varied slightly. This effect was most pronounced for the panels molded at 1 lb/in^2 in the open mold, and at 10 lb/in^2 in the closed mold.

The resin content and specific gravity were not affected by variations in molding pressure when using the closed mold. The voids content of these laminates, however, appeared to decrease as the pressure increased from 10 to 100 lb/in^2 but did not decrease further with increased molding pressure. The higher voids content apparently did not affect the strength of the panels molded at 10 lb/in^2.

For free-edge panels, the resin content decreased significantly as the pressure increased. A comparable significant increase was observed for the specific gravity of these laminates. The voids content could not be correlated to any effect of molding pressure. The resin content and specific gravity of panels molded free-edge at 10 lb/in^2 were most similar to the average values obtained for the closed-mold panels.

9.4 Effects of Molding Pressure on 8 oz Glass Mat Reinforced Laminates

The results obtained for the strength properties of 8 oz. mat laminates are given in Tables 9, 10, and 11, and summarized in Tables 13, 14, and 15 for flexural, tensile, and compressive properties, respectively. The other physical properties of these laminates are given in Table 12. Figures 16 and 17, respectively, indicate the effect of molding pressure on the flexural strength and modulus of elasticity; Figures 18 and 19, show the effect on tensile strength and modulus; and Figure 20 the effect on compressive strength. The effect of pressure on the resin content of free-edge panels, and on the specific gravity and voids content of all panels is shown in Figures 21, 22, and 23, respectively.

Molding pressure did not affect the strength properties of the closed-mold laminates appreciably.

In most cases, significant effects of molding pressure were observed on the strength properties of laminates fabricated in the open mold. In general, the tensile and flexural properties increased as the molding pressure increased from 1 to 10 lb/in^2, but the results between 10 and 100 lb/in^2 were not consistent for most properties. The moduli, however, showed a tendency to increase with increasing molding pressure. The compressive strength did not change appreciably as the molding pressure increased from 1 to 10 lb/in^2 for both the dry and the wet tests, but decreased approximately 25 percent in the dry tests and 40 percent in the wet tests as the molding pressure increased to 100 lb/in^2.

The average values obtained in the tensile and flexural tests of the closed-mold panels were, in general, between the values obtained at 1 and 10 lb/in^2 in the open mold, and usually were most similar to the values obtained at 1 lb/in^2. The compressive strengths obtained in the closed mold were higher than those obtained in the open mold.

There were no pronounced directional effects observed in the strength tests of the 8 oz mat laminates.

The loss in strength after immersion in water was independent of the molding pressure in the closed mold for all three types of tests. The loss in strength of free-edge molded panels increased, in general, as the molding pressure increased. The average losses observed for the closed mold panels were most similar to those observed for the panels molded at 1 and 10 lb/in^2 in the open mold.

The strength properties of replicate panels did not vary significantly and were not affected by the small, significant variation in resin content observed in groups of triplicate panels. The resin content variation was most pronounced for those panels molded free-edge at 100 lb/in^2 and closed-edge at 10 lb/in^2.

No effect of molding pressure was observed for the resin content and specific gravity of the laminates fabricated in the closed mold. The voids content showed a tendency to decrease slightly with increased pressure.

The resin content of free-edge molded panels decreased with an increase in molding pressure and the specific gravity increased under the same conditions. The increase in specific gravity with increase in molding pressure was approximately proportional to the corresponding decrease in resin content. The voids content showed a tendency to decrease slightly with increased molding pressure. The resin content and specific gravity of the closed mold laminates were most similar to the properties of the open mold laminates fabricated at 1 lb/in^2.

9.5 Comparison of Reinforcing Materials

The averages of the strength properties of the various materials are given in Tables 13 to 15. The averages were calculated for the three sets without reference to specimen direction. The directional effects were not pronounced in most cases. In addition, no significant set-to-set variability was observed, indicating that the resin was stable over the two month molding period.

The molding pressure had little, if any, effect on the strength properties of the materials laminated in the closed mold.

In most cases, the flexural and tensile properties of panels molded free-edge increased as the molding pressure increased from 1 to 10 lb/in^2 but did not change significantly as the pressure increased to 100 lb/in^2. The compressive strength showed a tendency to decrease with increased pressure for all three materials. The decrease was most pronounced between molding pressures of 1 and 10 lb/in^2 for glass fabric, and between 10 and 100 lb/in^2 for glass mat.

In most cases, the strength properties of the closed mold panels were close to those of the open mold panels with the same reinforcement and similar resin content. In general, the resin content of the closed mold panels was most similar to that of the open mold panels molded at 1 lb/in^2 for glass fabric and 8 oz glass mat, and at 10 lb/in^2 for 2 oz glass mat. Actually, higher strength values were obtained in the open mold panels than in the closed mold panels, except for compressive strength. The maximum strengths were attained in open mold panels having relatively low resin contents. These resin contents, however, were lower than the minimum amounts necessary for the fabrication of satisfactory panels in the closed mold at 10 lb/in^2 and therefore were not used in these tests. However, satisfactory panels could probably be made at 100 and 500 lb/in^2 in the closed mold using these same low resin contents, with strength properties similar to the highest obtained in the open mold.

The strength properties of the glass fabric reinforced laminates were usually 2 to 3 times as great as those of the glass mat panels molded and tested under similar conditions. Greater differences were observed in the wet tests than in the dry tests. There was no consistent superiority of one type of mat over the other when considering all molding pressures and both types of molds. In the closed mold panels, there were indications that the flexural properties of the 2 oz glass mat laminates were superior to those of the 8 oz glass mat laminates and the tensile modulus of the 8 oz laminates was superior to that of the 2 oz laminates. In the open mold panels, the modulus values for the 8 oz mat appeared to be higher than those for the 2 oz mat, but the compressive strength of the 2 oz laminates appeared to be higher than that of the 8 oz laminates.

The flexural and tensile properties of the 8 oz mat laminates molded at 1 and 10 lb/in^2 in the open mold were consistently higher than those of the corresponding 2 oz mat laminates by at least 10 percent in most cases. The maximum strength values were obtained at a molding pressure of 10 lb/in^2 in each case, where the resin content was 56.1 and 50.4 percent for the 2 oz and 8 oz mats, respectively. These data are consistent with results obtained in the preliminary experiments in which the optimum resin contents were found to be approximately 55 and 50 percent for the 2 oz and 8 oz mats, respectively. However, as stated previously, the resin content of 55 percent was used for both types of mat in the closed mold to minimize fabrication variables. Thus the results obtained for the 8 oz mat in the open mold indicate that higher strength properties could be obtained in the closed mold with this type of mat by decreasing the resin content to 50 percent.

In most cases, the loss in strength due to immersion in water was approximately the same for both types of mat for any given test. The percent loss for the glass fabric laminates was less than that for the glass mat laminates and on the average was approximately half as great. In general, the percent loss was independent of pressure in the closed mold but showed a tendency to increase with increasing molding pressure in the open mold. For all materials, the tensile strength appeared to be least affected by water immersion, and the flexural strength less affected than the compressive strength.

For panels laminated in the closed mold, the specific gravity and voids content as shown in Figures 22 and 23 did not vary appreciably with molding pressure; the resin content was maintained at a fixed value in the closed mold. The voids content, however, did show a tendency to decrease slightly with increased molding pressure for the mat laminates.

In the free-edge panels, the resin content decreased, shown in Figure 21, and the specific gravity increased, shown in Figure 22, with increased molding pressure. The voids content, shown in Figure 23, did not change appreciably with pressure for any of the materials.

10. CONCLUSIONS

The results of this study indicate that the following conclusions concerning the effects of molding pressure on properties of polyester laminates reinforced with glass fabric, and 2 oz and 8 oz glass mat can be made for laminates properly fabricated under the conditions investigated:

1. Molding pressure has no appreciable effect on flexural, tensile or compressive properties, or resin content, specific gravity, or voids content of panels fabricated in a closed mold.

2. For laminates fabricated in an open mold, flexural and tensile properties increase as the molding pressure is increased from 1 to 10 lb/in^2, but there is no appreciable change in these properties as the pressure increases

further. The compressive strength shows a tendency to decrease with increasing molding pressure. In addition, the resin content decreases, the specific gravity increases, and the voids content does not change appreciably with increasing molding pressure.

3. The strength properties of panels fabricated in the closed mold are similar to those of the open mold panels having similar resin contents. In conjunction with the other results observed, this can be interpreted as indicating that for panels of a given resin content which are properly fabricated from the same materials with good resin distribution and low voids content, the physical properties are not affected appreciably by the molding pressure or type of mold. The properties are a function primarily of resin content.

4. The strength properties of glass fabric reinforced panels are usually two to three times as great as those of 2 oz or 8 oz glass mat panels fabricated under similar conditions. There is no consistent superiority of one type of mat over the other. However, there are indications that if the resin content of the 8 oz mat laminates prepared in the closed mold were reduced, the properties would be slightly superior to those of the 2 oz mat laminates.

5. The strength properties of the laminates decrease as a result of immersion in water for 30 days at 73.5°F (23°C). The percentage loss in strength is independent of pressure in the closed mold laminates and shows a tendency to increase with increasing molding pressure in the open mold laminates. The loss in strength is approximately the same for panels reinforced with either type of glass mat and molded under similar conditions. On the average, the loss in strength of the glass fabric laminates is approximately half that of the glass mat laminates. For all

materials, the loss in strength is least for the tensile properties, and less for the flexural properties than for the compressive properties.

11. SUMMARY

A study was made of the effects of molding pressure on the strength and related properties of laminates reinforced with 181 glass fabric and with 2 oz or 8 oz unoriented glass fiber mat. An unsaturated polyester resin was used as the bonding medium for the glass fiber reinforcement. Laminates were fabricated in a closed mold at molding pressures of 10, 100, and 500 lb/in^2, and at each pressure panels were prepared containing the following percentages of resin, by weight: 39 ± 1.5 percent, and 55 ± 4.0 percent for glass fabric and glass mat, respectively. Panels were also molded in an open mold at pressures of 1, 10, and 100 lb/in^2 in which case the resin content varied with the molding pressure.

Tests were conducted to determine the effects of molding pressure on flexural strength and modulus of elasticity, tensile strength and modulus, and compressive strength. The tests were made on dry specimens and on wet specimens after thirty days' immersion in water at 73.5°F (23°C). Specific gravity, resin content, and voids content determinations were also made on each laminate.

There was no significant effect of molding pressure on the mechanical properties of closed mold panels for any of the reinforcements. For panels molded in the open mold, the flexural and tensile properties increased as the molding pressure increased from 1 to 10 lb/in^2 but did not change appreciably as the pressure increased to 100 lb/in^2. The compressive strength showed a tendency to decrease with increased molding pressure.

The strength properties of the closed mold panels were usually close to those of the open mold panels with the same reinforcement and similar resin content. The closed mold panels were most similar to the open mold panels molded at 1 lb/in^2 for the glass fabric

and 8 oz mat, and at 10 lb/in^2 for the 2 oz mat.

In most cases, there were no significant directional effects observed in the laminates.

The glass fabric laminates were usually two to three times as strong as the corresponding glass mat laminates. There was no consistent superiority of one type of mat over the other when considering all tests and molding conditions.

In general, the percentage loss in strength due to immersion in water was independent of molding pressure in the closed mold but showed a tendency to increase with increased molding pressure in the open mold. The loss in strength was approximately the same, in most cases, for laminates made from either type of mat, and was, on the average, twice as great as that for the glass fabric laminates. The tensile properties were affected the least by water immersion, and the flexural properties less than compressive properties.

The results obtained concerning the effects of laminating pressure on strength properties do not correlate completely with those obtained in a previous study because of differences in (1) voids content, (2) fabrication technique, (3) lot of resin, (4) age of resin, and (5) glass fabric and finish.

The resin content and specific gravity of panels fabricated in the closed mold did not vary appreciably with molding pressure. For free-edge panels, however, the resin content decreased and the specific gravity increased with increased molding pressure. The voids content did not change appreciably with pressure for either type of mold.

12. References

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5. Federal Specification L-P 406b for Plastics, Organic: General Specifications, Test Methods. Federal Standard Stock Catalog Section IV, Part 5. Item L-P 406b, (27 September 1951).

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Table 1. Flexural Properties of Glass-Fabric Reinforced Polyester Laminates[a]

Molding Pressure lb/in^2	Open Dry 1[b]	Open Dry c[b]	Open Wet 1	Open Wet c	Closed Dry 1	Closed Dry c	Closed Wet 1	Closed Wet c
	Flexural Strength, 10^3 lb/in^2							
1	58.4	62.0	52.6	55.8	-	-	-	-
10	68.0	76.2	54.4	59.5	65.6	65.3	57.2	60.4
100	66.1	71.9	51.4	54.5	65.1	65.0	53.2	58.8
500	-	-	-	-	65.9	65.2	58.0	58.9
Standard Error[c]		±0.8		±0.9		±0.4		±0.5
	Flexural Modulus of Elasticity, 10^6 lb/in^2							
1	3.61	3.61	3.91	3.72	-	-	-	-
10	5.23	5.12	5.42	4.44	4.17	4.09	3.73	3.73[d]
100	5.50	4.84	5.65	5.22	4.22	3.90	4.23	3.81[d]
500	-	-	-	-	3.96	4.09	3.97	3.74
Standard Error[c]		±0.13		±0.14		±0.08		±0.08
	Loss of Flexural Strength Due to Immersion in Water, Percent							
1	9.9	9.7			-	-		
10	20.1	22.0			12.7	7.4		
100	22.1	24.2			18.2	9.4		
500	-	-			11.8	9.4		

a. Each value is the average of six specimens, two from each of three panels, unless otherwise noted.
b. 1 = lengthwise direction; c = crosswise direction.
c. Based on differences between duplicates in both directions.
d. Average of five specimens.

Table 2. Tensile Properties of Glass-Fabric Reinforced Polyester Laminates

Molding Pressure lb/in²	Open Dry l[a]	Open Dry c[b]	Open Wet l	Open Wet c	Closed Dry l	Closed Dry c	Closed Wet l	Closed Wet c
	Tensile Strength, 10^3 lb/in²							
1	41.9	45.1	39.7	43.0	-	-	-	-
10	54.6	54.4	47.7	50.0	46.2	46.4	43.9	43.0
100	58.0	55.6	49.4	50.5	45.1	47.2	41.9	42.2
500	-	-	-	-	45.5	47.6	41.1	43.9
Standard Error[c]		±0.6		±0.6		±0.4		±0.3
	Tensile Modulus of Elasticity, 10^6 lb/in²							
1	3.12	3.33[d]	2.71	2.92	-	-	-	-
10	3.75	5.00	3.75	4.16	3.75	3.33	3.33[e]	3.33
100	4.58	4.16	4.58	4.16	3.54	2.92	2.92	2.92
500	-	-	-	-	3.33	4.16	3.33	2.92
Standard Error[c]		±0.26		±0.22		±0.15		±0.13
	Loss of Tensile Strength Due to Immersion in Water, Percent							
1	5.1	4.8			-	-		
10	12.6	8.2			4.8	7.4		
100	14.7	8.9			7.1	10.4		
500	-	-			9.5	7.8		

a. Each value for the lengthwise direction is the average of four specimens, two from each of two panels, unless otherwise noted.
b. Each value for the crosswise direction is the average of two specimens from one panel, unless otherwise noted.
c. Based on differences between duplicates in both directions.
d. Result for one specimen.
e. Average of three specimens.

Table 3. Compressive Strength of Glass-Fabric Reinforced Polyester Laminates[a]

Molding Pressure lb/in^2	Open: l[b]	Open: c[b]	Open: Standard Error[c]	Closed: l	Closed: c	Closed: Standard Error
	Compressive Strength, Dry, 10^3 lb/in^2					
1	43.4	42.7	0.8	-	-	-
10	35.4	32.8	2.7	44.5	44.8	1.9
100	34.7	33.9	2.7	39.5	44.1	2.0
500	-	-	-	44.3	42.0	1.9
	Compressive Strength, Wet, 10^3 lb/in^2					
1	36.7	34.5	1.4	-	-	-
10	25.5	28.2	1.2	38.4	35.7	1.0
100	24.5	22.5	2.1	38.1	37.1	0.8
500	-	-	-	37.5	35.7	2.5
	Loss of Compressive Strength Due to Immersion in Water, Percent					
1	15.5	19.1		-	-	
10	28.0	10.5		13.2	20.1	
100	27.5	30.5		2.8	15.8	
500	-	-		15.2	15.6	

a. Each value is the average of three specimens, one from each of three panels.
b. l = lengthwise direction; c = crosswise direction.
c. Based on residual in analysis of variance.

Table 4. Physical Properties of Glass-Fabric Reinforced Polyester Laminates

Molding Pressure	Open Average	Open Range	Open Standard Error[a]	Closed Average	Closed Range	Closed Standard Error[a]
lb/in²	Panel Thickness, Inches[b]					
1	.130	.121-.137	.004	-	-	-
10	.095	.092-.097	.001	.121	.115-.123	>.001
100	.088	.084-.091	<.001	.123	.118-.128	.001
500	-	-	-	.121	.110-.128	.001
	Resin Content, Weight Percent[c]					
1	41.9	38.5-43.7	1.4	-	-	-
10	28.4	27.1-29.0	0.1	38.8	38.0-39.9	0.3
100	24.5	23.2-25.3	0.1	39.4	38.1-40.3	0.1
500	-	-	-	39.1	37.0-40.7	0.3
	Specific Gravity[c]					
1	1.75	1.73-1.80	.02	-	-	-
10	1.94	1.94-1.97	<.01	1.79	1.79-1.80	.00
100	2.00	1.98-2.02	<.01	1.78	1.74-1.80	>.01
500	-	-	-	1.79	1.77-1.82	.01
	Voids Content, Volume Percent[c]					
1	0.5	0.3-0.6	0.1	-	-	-
10	0.6	0.5-0.8	< 0.1	0.4	-0.1-0.8	0.1
100	1.2	0.8-1.4	0.1	0.7	0.4-2.8	0.2
500	-	-	-	0.4	-0.3-0.6	0.1

a. Based on the variabilities of the panel averages.
b. Each value is the average for 48 measurements, 16 from each of three panels.
c. Each value is the average for 15 specimens, five from each of three panels.

Table 5. Flexural Properties of 2 oz Glass Mat Reinforced Polyester Laminates[a]

Molding Pressure lb/in²	Open Dry l[b]	Open Dry c[b]	Open Wet l	Open Wet c	Closed Dry l	Closed Dry c	Closed Wet l	Closed Wet c
	Flexural Strength, 10^3 lb/in²							
1	24.2	24.3	18.1	18.8	-	-	-	-
10	29.8	29.6	23.2	22.6	30.0	28.5	22.8	22.6
100	33.9	31.8	21.6	21.0	32.2	32.2	23.7	22.2
500	-	-	-	-	30.1	29.0	26.3	23.2
Standard Error[c]		±1.0		±0.6		±0.6		±0.3
	Flexural Modulus of Elasticity, 10^6 lb/in²							
1	1.70	1.72	1.16	1.24	-	-	-	-
10	1.90	2.00	1.50	1.65	1.94	1.98	1.42	1.58
100	2.24	2.36	1.59	1.81	1.94	2.22	1.56	1.58
500	-	-	-	-	1.97	2.01	1.69	1.61
Standard Error[c]		±0.06		±0.03		±0.03		±0.02
	Loss of Flexural Strength Due to Immersion in Water, Percent							
1	24.6	22.6			-	-		
10	21.9	22.4			23.3	20.6		
100	35.7	33.7			25.6	30.8		
500	-	-			12.1	18.8		

a. Each value is the average of six specimens, two from each of three panels, unless otherwise noted.
b. l = lengthwise direction; c = crosswise direction.
c. Based on differences between duplicates in both directions.

Table 6. Tensile Properties of 2 oz Glass Mat Reinforced Polyester Laminates

Molding Pressure lb/in²	Open Dry l[a]	Open Dry c[b]	Open Wet l	Open Wet c	Closed Dry l	Closed Dry c	Closed Wet l	Closed Wet c
	Tensile Strength, 10^3 lb/in²							
1	12.5	11.0	10.3	9.7	-	-	-	-
10	15.4	16.4	12.7	14.0	15.5	15.6	12.6	13.2
100	19.0	19.4	12.5	13.6	14.8	16.4	12.8	12.4
500	-	-	-	-	16.4	15.2	13.0	13.5
Standard Error[c]		±0.6		±0.4		±0.4		±0.2
	Tensile Modulus of Elasticity, 10^6 lb/in²							
1	1.37[d]	1.25	0.96	0.91	-	-	-	-
10	1.49	1.72	1.08	1.11	1.49	1.55	1.08	1.06
100	1.75	1.55	1.22	1.18	1.55	1.67	1.08	1.11
500	-	-	-	-	1.55	1.55	1.12	1.12
Standard Error[c]		±0.04		±0.03		±0.02		±0.01
	Loss of Tensile Strength Due to Immersion in Water, Percent							
1	16.7	10.4			-	-		
10	17.0	14.0			18.7	15.8		
100	34.4	29.6			13.2	24.2		
500	-	-			20.9	11.0		

a. Each value for the lengthwise direction is the average of four specimens, two from each of two panels.
b. Each value for the crosswise direction is the average of two specimens from one panel.
c. Based on differences between duplicates in both directions.
d. Average of five specimens.

Table 7. Compressive Strength of 2 oz Glass Mat Reinforced Polyester Laminates[a]

Molding Pressure lb/in^2	Open: l[b]	Open: c[b]	Open: Standard Error[c]	Closed: l	Closed: c	Closed: Standard Error
	Compressive Strength, Dry, 10^3 lb/in^2					
1	25.0	24.8	0.8	-	-	-
10	25.7	25.9	0.4	23.7	22.1	1.0
100	20.0	19.7	0.9	27.3	25.5	0.7
500	-	-	-	26.2	26.5	0.5
	Compressive Strength, Wet, 10^3 lb/in^2					
1	16.5	16.8	0.3	-	-	-
10	15.5	15.1	0.4	14.2	13.2	0.8
100	11.2	13.3	0.5	15.1	16.1	0.6
500	-	-	-	16.4	16.4	0.4
	Loss of Compressive Strength Due to Immersion in Water, Percent					
1	33.6	31.6		-	-	
10	39.6	41.7		40.2	40.3	
100	43.1	31.3		44.6	36.5	
500	-	-		37.2	38.2	

a. Each value is the average of three specimens, one from each of three panels.
b. l = lengthwise direction; c = crosswise direction.
c. Based on residual in analysis of variance.

Table 8. Physical Properties of 2 oz Glass Mat Reinforced Polyester Laminates

Molding Pressure lb/in^2	Open: Average	Open: Range	Open: Standard Error[a]	Closed: Average	Closed: Range	Closed: Standard Error[a]
	Panel Thickness, Inches[b]					
1	.156	.150-.161	.002	-	-	-
10	.128	.124-.131	.001	.131	.126-.134	.001
100	.095	.087-.103	.003	.128	.118-.134	.003
500	-	-	-	.126	.110-.138	.005
	Resin Content, Weight Percent[c]					
1	63.6	58.6-69.4	1.4	-	-	-
10	56.1	50.1-61.3	0.5	55.7	50.2-60.2	1.0
100	45.7	41.1-48.7	0.8	55.9	52.0-59.7	0.8
500	-	-	-	56.4	50.1-59.9	0.5
	Specific Gravity[c]					
1	1.48	1.44-1.53	0.01	-	-	-
10	1.57	1.52-1.63	0.01	1.55	1.53-1.60	0.01
100	1.67	1.64-1.73	0.01	1.58	1.54-1.64	0.01
500	-	-	-	1.57	1.54-1.64	0.01
	Voids Content, Volume Percent[c]					
1	1.8	-0.8-5.7	0.7	-	-	-
10	0.9	0.7-1.3	0.1	2.4	0.7-6.2	1.0
100	1.5	1.1-2.2	<0.1	0.4	-0.9-0.7	0.1
500	-	-	-	0.4	0.4-0.5	<0.1

a. Based on the variabilities of the panel averages.
b. Each value is the average for 48 measurements, 16 from each of three panels.
c. Each value is the average for 15 specimens, five from each of three panels.

Table 9. Flexural Properties of 8 oz Glass Mat Reinforced Polyester Laminates[a]

Molding Pressure lb/in²	Open Dry l[b]	Open Dry c[b]	Open Wet l	Open Wet c	Closed Dry l	Closed Dry c	Closed Wet l	Closed Wet c
	Flexural Strength, 10^3 lb/in²							
1	26.6	27.7	20.2	21.2	-	-	-	-
10	31.7	32.6	24.2	23.3	26.4	27.9	21.8	20.6
100	31.6	28.7	20.1	16.1	26.6	24.8	20.5	20.3
500	-	-	-	-	29.3	27.9	22.3	22.2
Standard Error[c]		±0.9		±0.6		±0.5		±0.4
	Flexural Modulus of Elasticity, 10^6 lb/in²							
1	1.88	1.93	1.41[d]	1.40	-	-	-	-
10	2.28	2.34	1.71	1.56	1.77	1.90	1.43	1.30
100	2.62	2.38	2.03	1.78	1.74	1.68	1.44	1.32
500	-	-	-	-	1.94	1.91	1.47	1.42
Standard Error[c]		±0.06		±0.04		±0.03		±0.02
	Loss of Flexural Strength Due to Immersion in Water, Percent							
1	24.1	21.2			-	-		
10	22.6	28.2			16.3	25.1		
100	35.8	44.0			22.6	17.6		
500	-	-			22.6	20.2		

a. Each value is the average of six specimens, two from each of three panels, unless otherwise noted.
b. l = lengthwise direction; c = crosswise direction.
c. Based on differences between duplicates in both directions.
d. Average of five specimens.

Table 10. Tensile Properties of 8 oz Glass Mat Reinforced Polyester Laminates

Molding Pressure lb/in²	Type of Mold: Open, Dry, l[a]	Open, Dry, c[b]	Open, Wet, l	Open, Wet, c	Closed, Dry, l	Closed, Dry, c	Closed, Wet, l	Closed, Wet, c
	Tensile Strength, 10^3 lb/in²							
1	14.3	13.8	12.6	12.4	-	-	-	-
10	17.7	17.8	14.9	13.0	15.8	16.2	12.8	12.8
100	20.7	15.9	12.6	11.8	14.8	15.8	11.5	12.8
500	-	-	-	-	15.8	16.0	14.0	13.4
Standard Error[c]		±0.8		±0.5		±0.4		±0.3
	Tensile Modulus of Elasticity, 10^6 lb/in²							
1	1.61	1.67	1.22	1.25[d]	-	-	-	-
10	1.78[e]	1.67	1.34	1.43	1.61	1.55	1.25	1.34
100	1.92	1.55	1.38	1.43	1.61	1.84	1.19	1.27
500	-	-	--	-	1.67	1.84	1.30	1.34
Standard Error[c]		±0.05		±0.05		±0.03		±0.03
	Loss of Tensile Strength Due to Immersion in Water, Percent							
1	11.1	9.8			-	-		
10	15.0	26.3			18.2	21.4		
100	39.0	25.2			21.7	18.6		
500	-	-			11.0	15.2		

a. Each value for the lengthwise direction is the average of four specimens, two from each of two panels, unless otherwise noted.
b. Each value for the crosswise direction is the average of two specimens from one panel, unless otherwise noted.
c. Based on differences between duplicates in both directions.
d. Result for one specimen.
e. Average of three specimens.

Table 11. Compressive Strength of 8 oz Glass Mat Reinforced Polyester Laminates[a]

Molding Pressure lb/in²	Type of Mold: Open			Closed		
	1[b]	c[b]	Standard Error[c]	1	c	Standard Error
	Compressive Strength, Dry, 10^3 lb/in²					
1	22.6	23.3	0.5	-	-	-
10	22.5	20.5	1.3	25.6	24.7	1.0
100	15.4	15.8	1.8	26.5	24.5	1.3
500	-	-	-	27.7	27.5	0.8
	Compressive Strength, Wet, 10^3 lb/in²					
1	14.1	12.8	0.6	-	-	-
10	13.3	12.5	0.6	14.3	13.7	0.5
100	7.7	7.3	0.7	15.1	15.2	0.4
500	-	-	-	15.6	15.7	0.3
	Loss of Compressive Strength Due to Immersion in Water, Percent					
1	37.7	45.0		-	-	
10	39.7	38.0		44.0	44.4	
100	47.5	53.9		42.8	36.5	
500	-	-		43.5	42.8	

a. Each value is the average of three specimens, one from each of three panels.
b. l = lengthwise direction; c = crosswise direction.
c. Based on residual in analysis of variance.

Table 12. Physical Properties of 8 oz Glass Mat Reinforced Polyester Laminates.

Molding Pressure lb/in^2	Type of Mold: Open			Closed		
	Average	Range	Standard Error[a]	Average	Range	Standard Error[a]
Panel Thickness, Inches[b]						
1	.120	.111-.127	.004	-	-	-
10	.093	.081-.100	.003	.122	.110-.134	.005
100	.075	.069-.082	.001	.122	.114-.127	.001
500	-	-	-	.126	.115-.137	.004
Resin Content, Weight Percent[c]						
1	54.8	51.3-60.1	0.1	-	-	-
10	50.4	45.8-53.4	0.5	55.4	48.1-59.8	1.1
100	38.2	33.7-44.6	1.7	56.5	50.4-59.1	0.5
500	-	-	-	56.5	51.9-60.1	0.8
Specific Gravity[c]						
1	1.56	1.51-1.59	<0.01	-	-	-
10	1.63	1.59-1.67	<0.01	1.56	1.49-1.65	0.01
100	1.78	1.71-1.84	0.02	1.56	1.52-1.63	0.01
500	-	-	-	1.57	1.53-1.62	0.01
Voids Content, Volume Percent[c]						
1	2.2	1.5-2.8	0.3	-	-	-
10	1.2	0.6-2.1	0.1	1.6	0.8-4.1	0.5
100	1.0	0.6-1.4	0.1	0.8	0.4-2.2	0.3
500	-	-	-	0.5	0.3-0.7	0.1

a. Based on the variabilities of the panel averages.
b. Each value is the average for 48 measurements, 16 from each of three panels.
c. Each value is the average for 15 specimens, five from each of three panels.

Table 13. Summary of Flexural Properties of Glass-Fiber Reinforced Polyester Laminates[a]

Molding Pressure lb/in^2	Open: Glass Fabric	Open: 2 oz Mat	Open: 8 oz Mat	Closed: Glass Fabric	Closed: 2 oz Mat	Closed: 8 oz Mat
	Flexural Strength, Dry, 10^3 lb/in^2					
1	60.2	24.3	27.2	-	-	-
10	72.1	29.7	32.2	65.4	29.2	27.2
100	69.0	32.8	30.2	65.0	32.2	25.7
500	-	-	-	65.5	29.6	28.6
Average	-	-	-	65.3	30.3	27.2
	Flexural Strength, Wet, 10^3 lb/in^2					
1	54.2	18.4	20.7	-	-	-
10	56.9	22.9	23.8	58.8	22.8	21.2
100	53.0	21.3	18.1	56.0	22.9	20.4
500	-	-	-	58.5	24.8	22.2
Average	-	-	-	57.8	23.5	21.3
	Flexural Modulus of Elasticity, Dry, 10^6 lb/in^2					
1	3.61	1.71	1.90	-	-	-
10	5.18	1.95	2.31	4.13	1.96	1.84
100	5.17	2.30	2.50	4.06	2.08	1.71
500	-	-	-	4.02	1.99	1.92
Average	-	-	-	4.07	2.01	1.82
	Flexural Modulus of Elasticity, Wet, 10^6 lb/in^2					
1	3.82	1.20	1.41[b]	-	-	-
10	4.93	1.58	1.63	3.73[b]	1.50	1.36
100	5.44	1.70	1.90	4.04[b]	1.57	1.38
500	-	-	-	3.86	1.65	1.44
Average	-	-	-	3.87	1.57	1.40
	Loss of Flexural Strength Due to Immersion in Water, Percent					
1	9.8	23.6	22.6	-	-	-
10	21.0	22.1	25.4	10.0	21.9	20.7
100	23.2	34.7	39.9	13.8	28.2	20.1
500	-	-	-	10.6	15.4	21.4

a. Each value is the average of twelve specimens, four from each of three panels, unless otherwise noted.
b. Average of eleven specimens.

Table 14. Summary of Tensile Properties of Glass-Fiber Reinforced Polyester Laminates[a]

Molding Pressure lb/in²	Open: Glass Fabric	Open: 2 oz Mat	Open: 8 oz Mat	Closed: Glass Fabric	Closed: 2 oz Mat	Closed: 8 oz Mat
Tensile Strength, Dry, 10^3 lb/in²						
1	43.0	12.0	14.1	-	-	-
10	54.5	15.7	17.7	46.3	15.6	15.9
100	57.2	19.1	19.1	45.8	15.4	15.1
500	-	-	-	46.2	16.0	15.8
Average	-	-	-	46.1	15.6	15.6
Tensile Strength, Wet, 10^3 lb/in²						
1	40.8	10.1	12.6	-	-	-
10	48.4	13.2	14.2	43.6	12.8	12.8
100	49.8	12.8	12.3	42.0	12.7	12.0
500	-	-	-	42.0	13.2	13.8
Average	-	-	-	42.6	12.9	12.8
Tensile Modulus of Elasticity, Dry, 10^6 lb/in²						
1	3.16[b]	1.32[b]	1.63	-	-	-
10	4.16	1.56	1.74[b]	3.61	1.51	1.59
100	4.44	1.68	1.80	3.33	1.59	1.68
500	-	-	-	3.61	1.55	1.72
Average	-	-	-	3.52	1.55	1.67
Tensile Modulus of Elasticity, Wet, 10^6 lb/in²						
1	2.78	0.94	1.23[b]	-	-	-
10	3.89	1.09	1.37	3.33[b]	1.07	1.28
100	4.44	1.20	1.40	2.92	1.09	1.22
500	-	-	-	3.19	1.12	1.31
Average	-	-	-	3.14	1.10	1.27
Loss of Tensile Strength Due to Immersion in Water, Percent						
1	5.0	14.6	10.6	-	-	-
10	11.1	16.0	18.7	5.7	17.8	19.2
100	12.8	32.8	34.4	8.2	16.8	20.6
500	-	-	-	8.9	17.6	12.4

a. Each value is the average of six specimens, including two lengthwise specimens from each of two panels and two crosswise specimens from a third panel, unless, otherwise noted.

b. Average of five specimens.

Table 15. Summary of the Compressive Strength of Glass-Fiber Reinforced Polyester Laminates[a]

Molding Pressure lb/in^2	Type of Mold: Open			Closed		
	Glass Fabric	2 oz Mat	8 oz Mat	Glass Fabric	2 oz Mat	8 oz Mat
	Compressive Strength, Dry, 10^3 lb/in^2					
1	43.0	24.9	23.0	-	-	-
10	34.1	25.8	21.5	44.7	22.9	25.2
100	34.3	19.8	15.6	41.8	26.4	25.5
500	-	-	-	43.1	26.4	27.6
Average	-	-	-	43.2	25.2	26.1
	Compressive Strength, Wet, 10^3 lb/in^2					
1	35.6	16.7	13.4	-	-	-
10	26.8	15.3	12.9	37.1	13.7	14.0
100	23.5	12.3	7.5	37.6	15.6	15.2
500	-	-	-	36.6	16.4	15.7
Average	-	-	-	37.1	15.2	14.9
	Loss of Compressive Strength Due to Immersion in Water, Percent					
1	17.3	32.6	41.3	-	-	-
10	19.2	40.6	39.9	16.7	40.3	44.2
100	29.0	37.2	50.7	9.3	40.5	38.6
500	-	-	-	15.4	37.7	43.1

a. Each value is the average of six specimens, two from each of three panels.

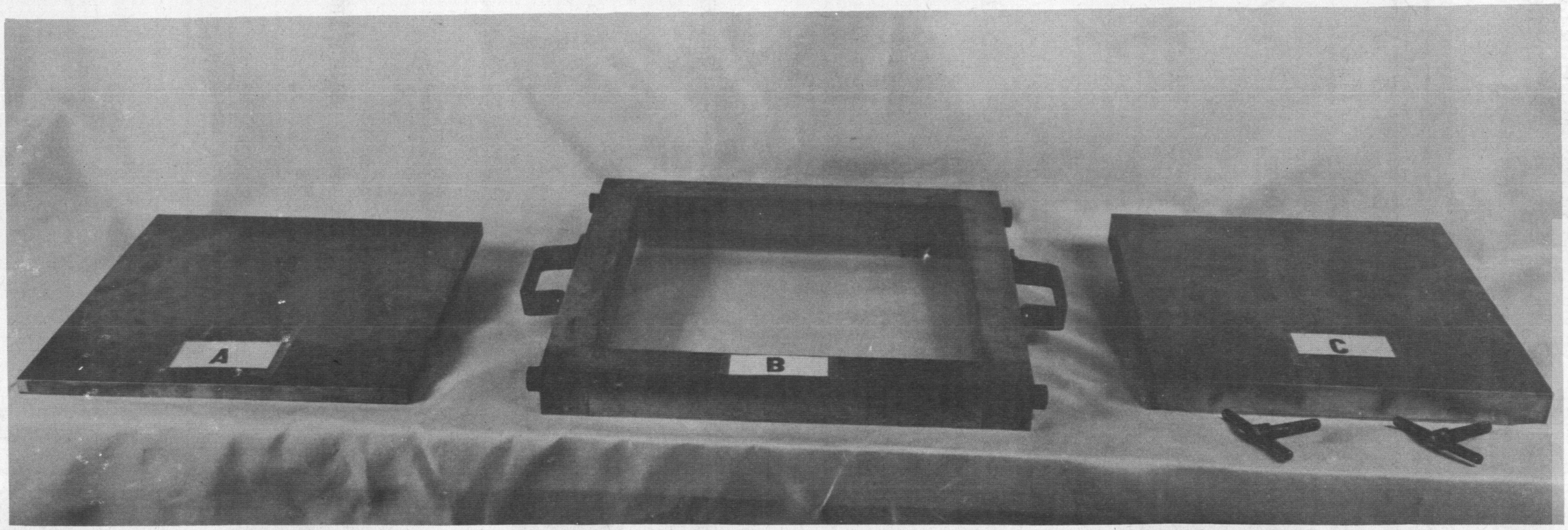


FIGURE 1. LAMINATING MOLD, DISASSEMBLED

Three parts of the mold are:

A - Lower platen
B - Chase
C - Upper platen

The T-shaped rods in front of the upper platen are threaded handles used to facilitate handling of the platens.

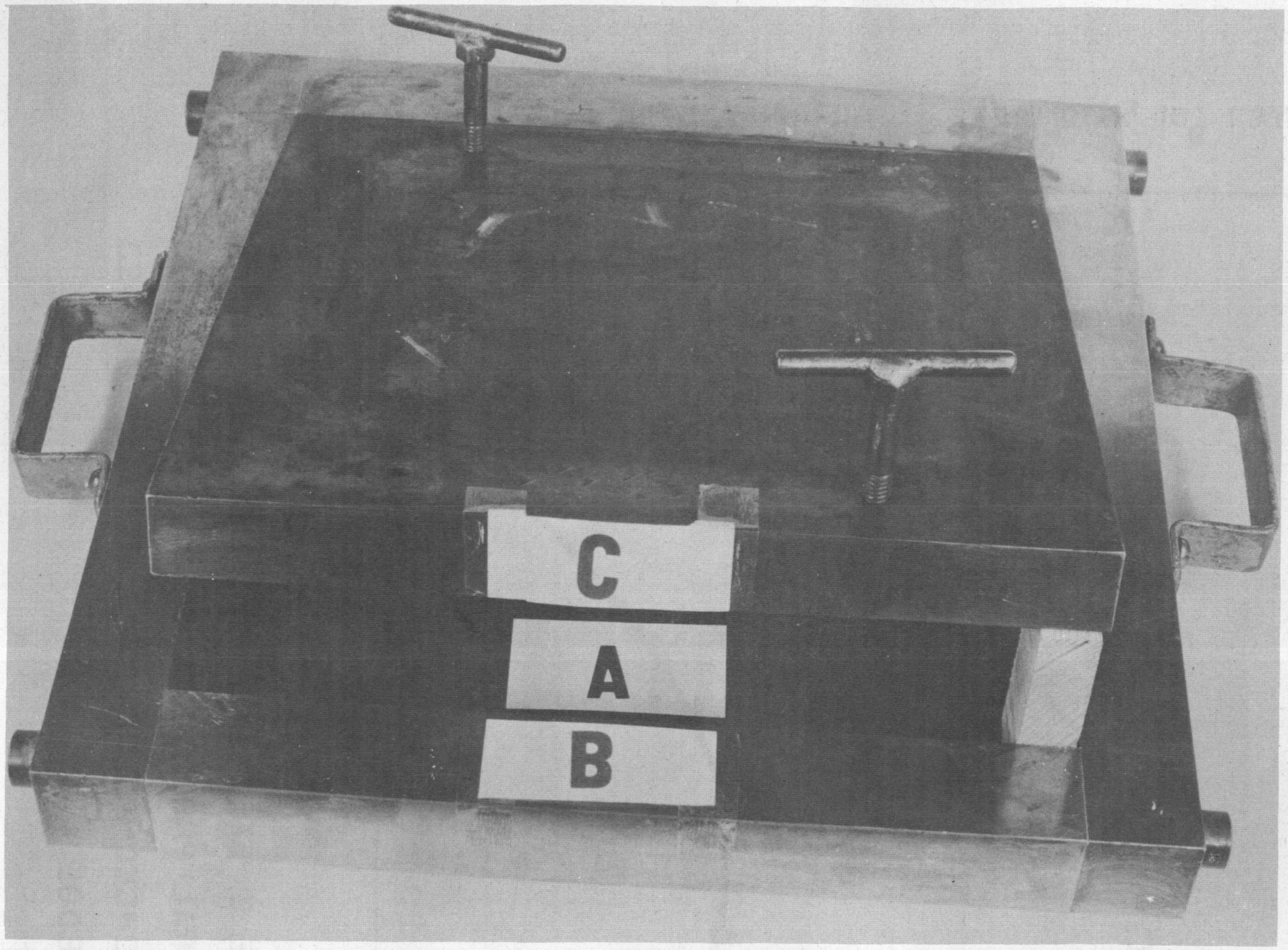


FIGURE 2. LAMINATING MOLD, PARTLY CLOSED

The lower platen, A, and the chase, B, are shown assembled as used. The upper platen, C, was raised up for photographic purposes. During molding operations, the upper platen is parallel to the lower platen. The handles in the upper platen are shown in the position in which they are used. They are removed before the mold is placed in the press.

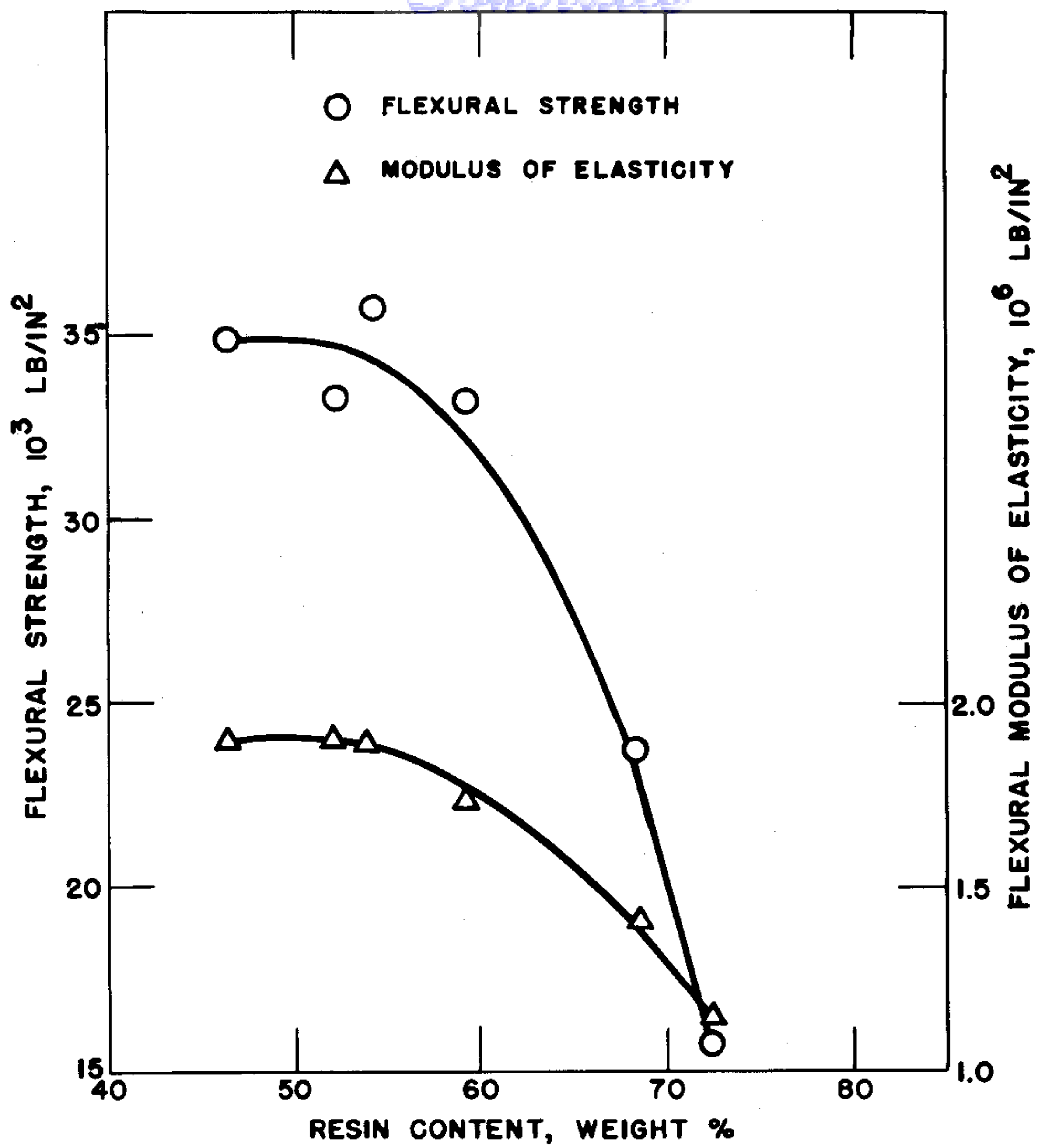


FIGURE 3. EFFECT OF RESIN CONTENT ON THE FLEXURAL PROPERTIES OF 2 OZ GLASS MAT REINFORCED POLYESTER LAMINATES MOLDED FREE-EDGE

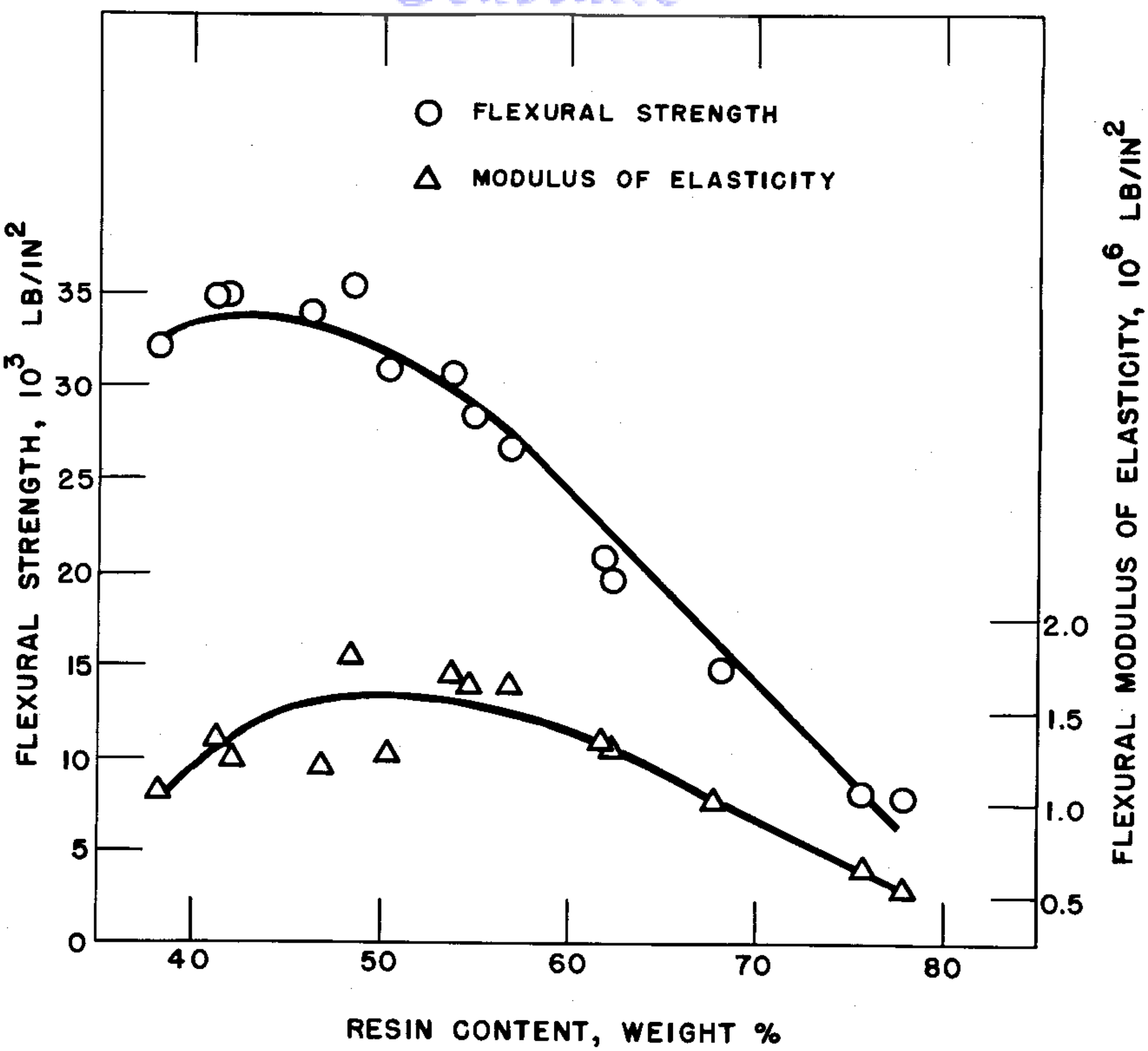
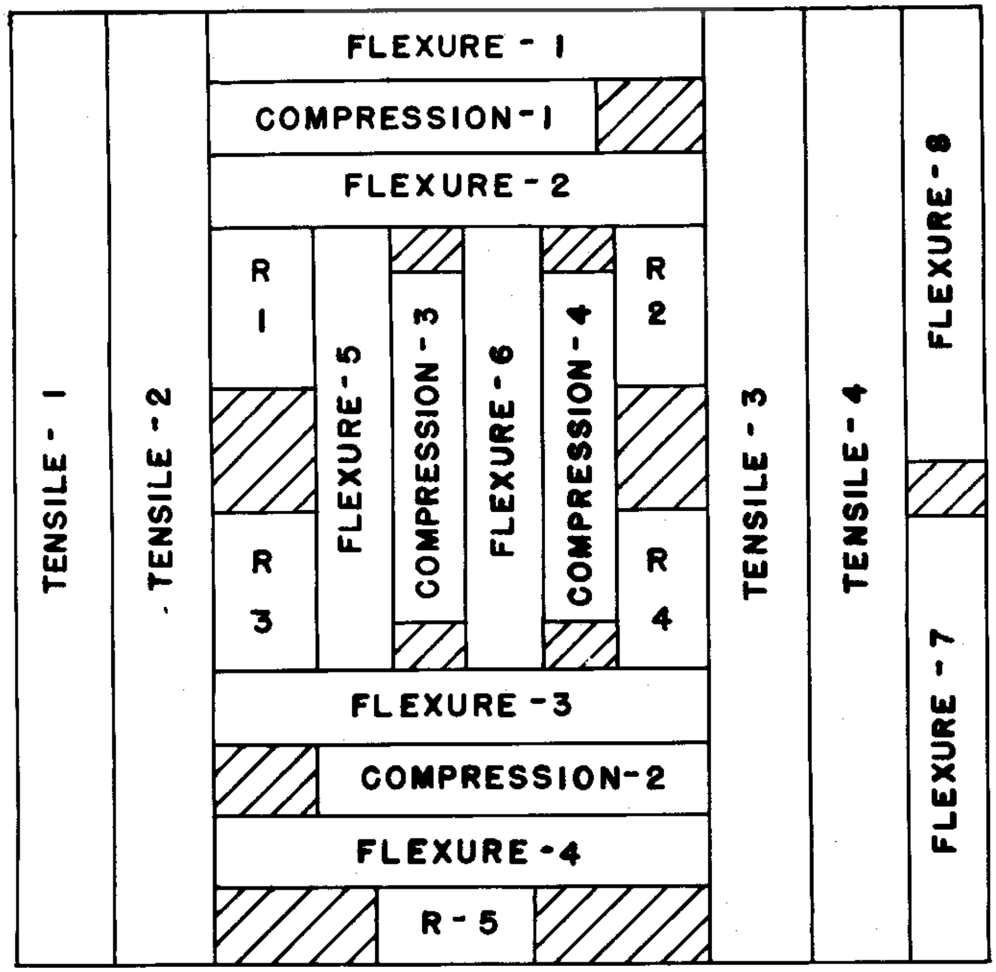


FIGURE 4. EFFECT OF RESIN CONTENT ON THE FLEXURAL PROPERTIES OF 8 OZ GLASS MAT REINFORCED POLYESTER LAMINATES MOLDED FREE-EDGE



R - SPECIFIC GRAVITY, RESIN CONTENT AND VOIDS CONTENT

FIGURE 5. SAMPLING PATTERN FOR GLASS-FIBER REINFORCED POLYESTER LAMINATES

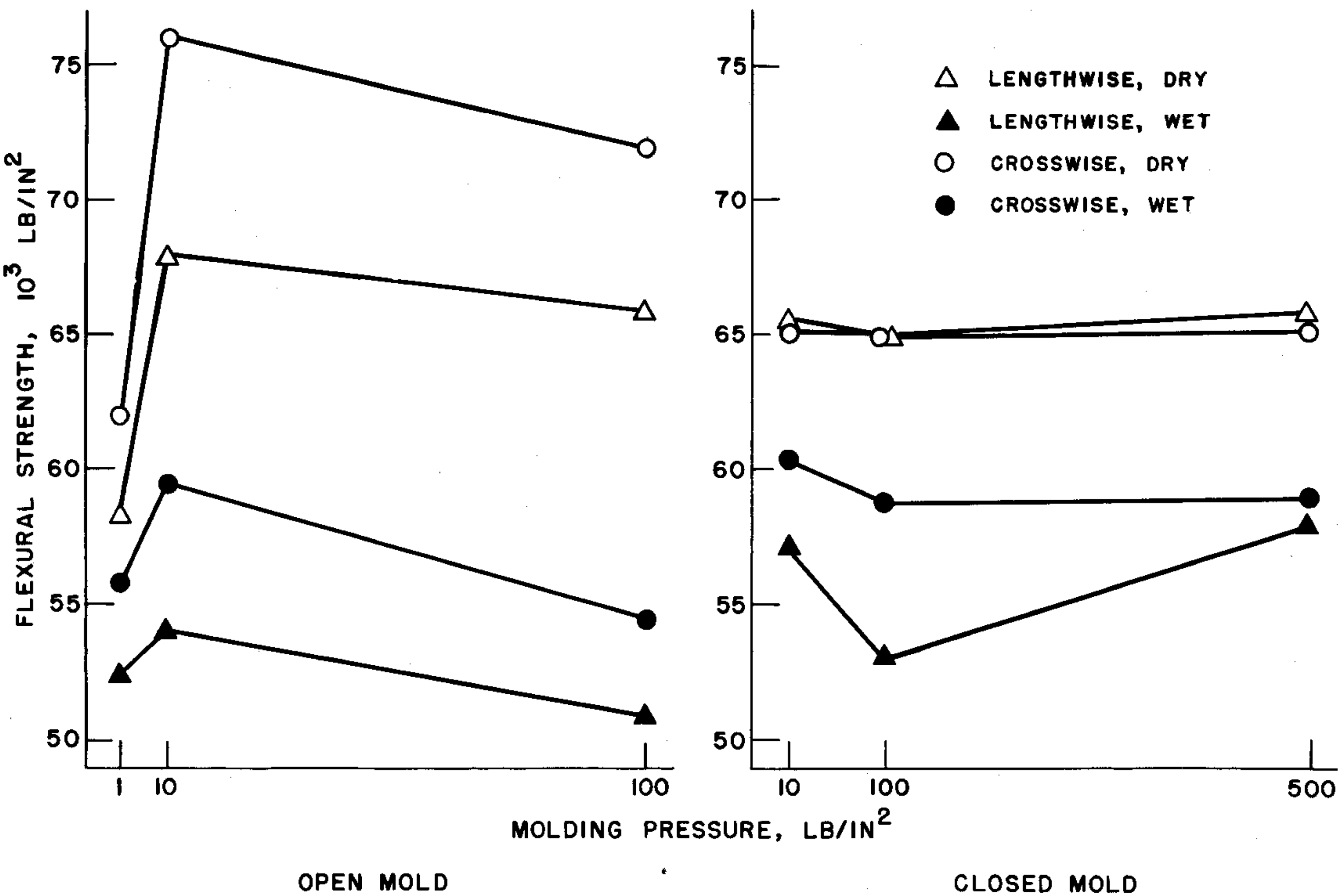


FIGURE 6. EFFECT OF MOLDING PRESSURE ON THE FLEXURAL STRENGTH OF GLASS-FABRIC REINFORCED POLYESTER LAMINATES

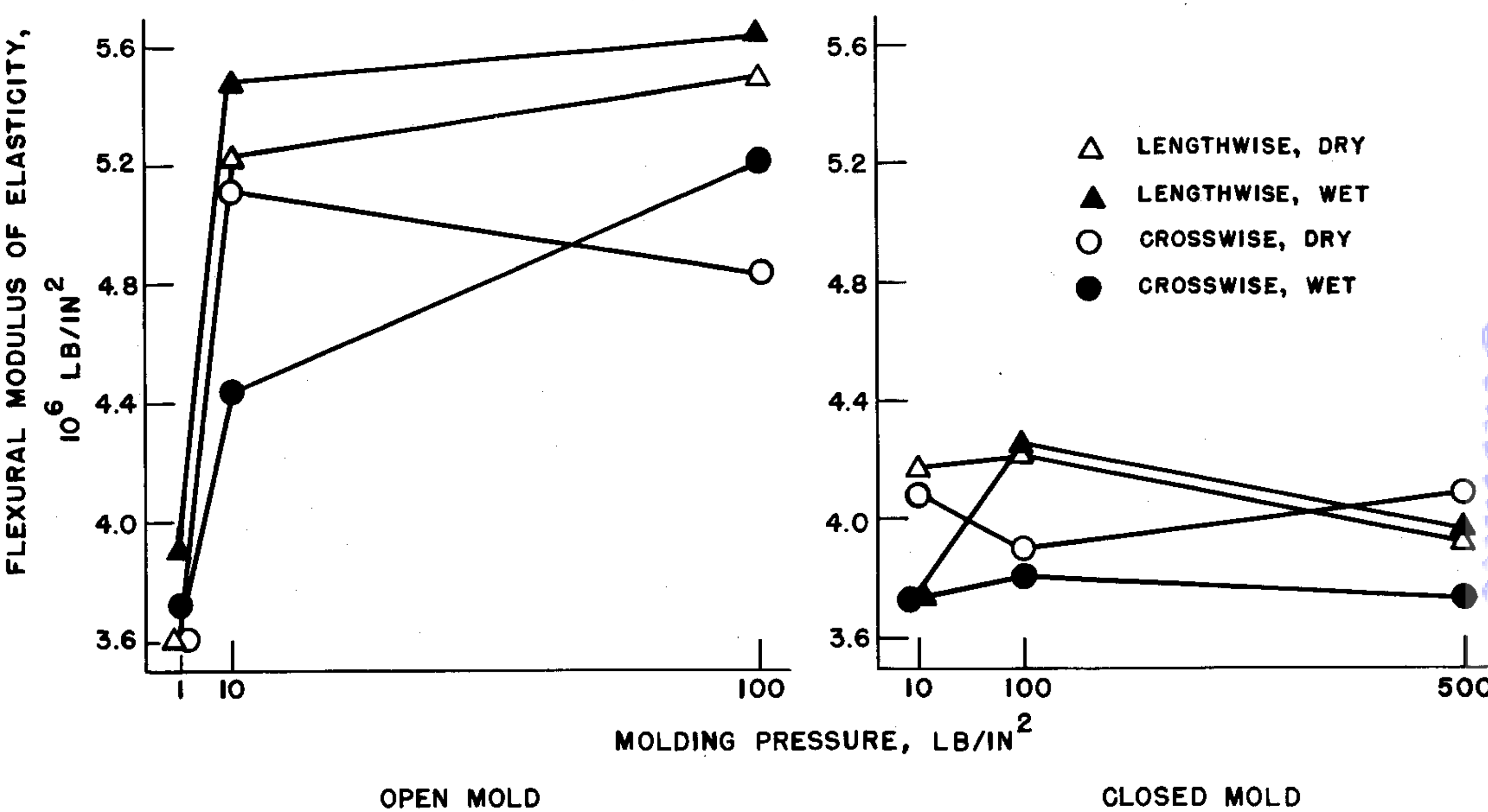


FIGURE 7. EFFECT OF MOLDING PRESSURE ON THE FLEXURAL MODULUS OF ELASTICITY OF GLASS-FABRIC REINFORCED POLYESTER LAMINATES

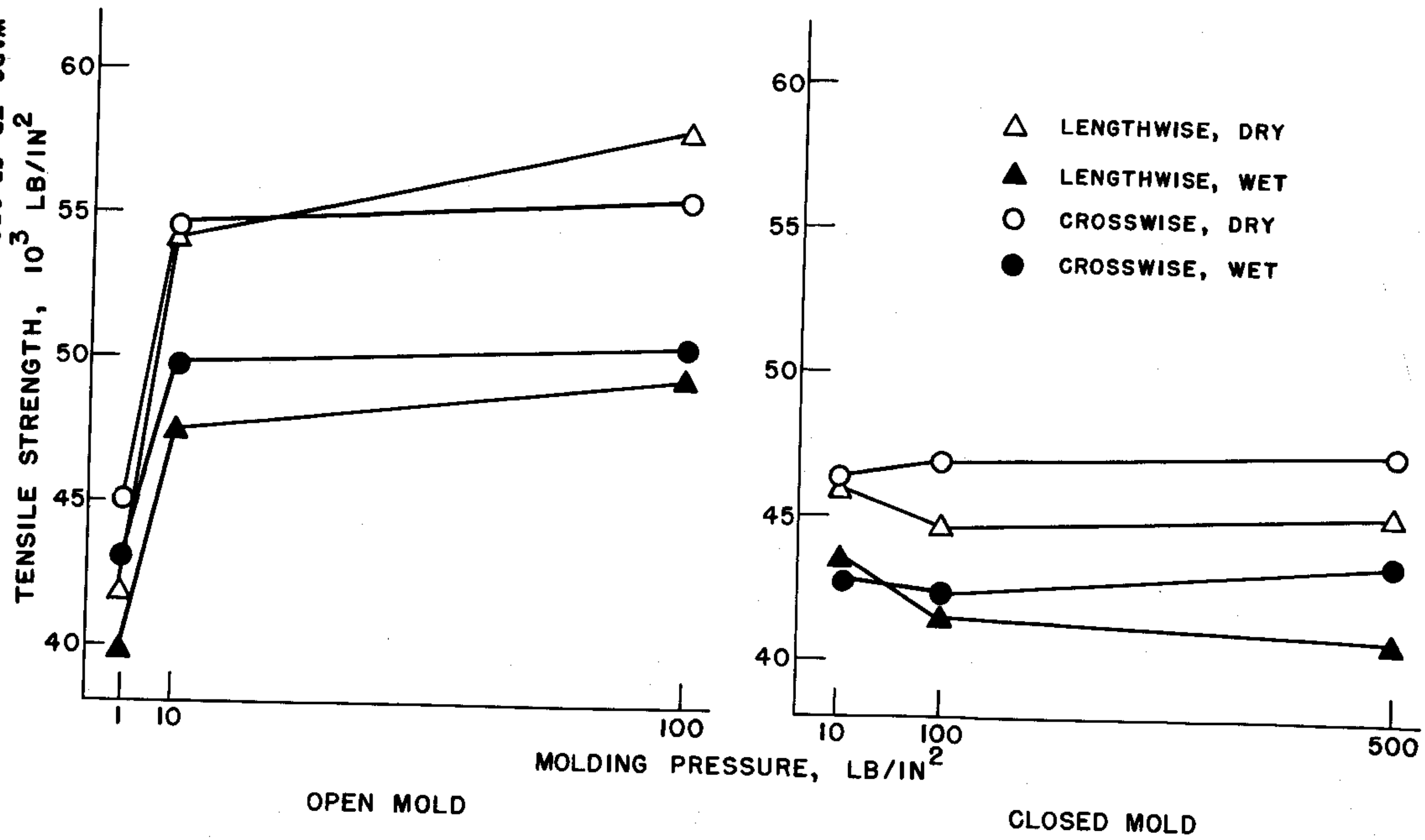


FIGURE 8. EFFECT OF MOLDING PRESSURE ON THE TENSILE STRENGTH OF GLASS-FABRIC REINFORCED POLYESTER LAMINATES

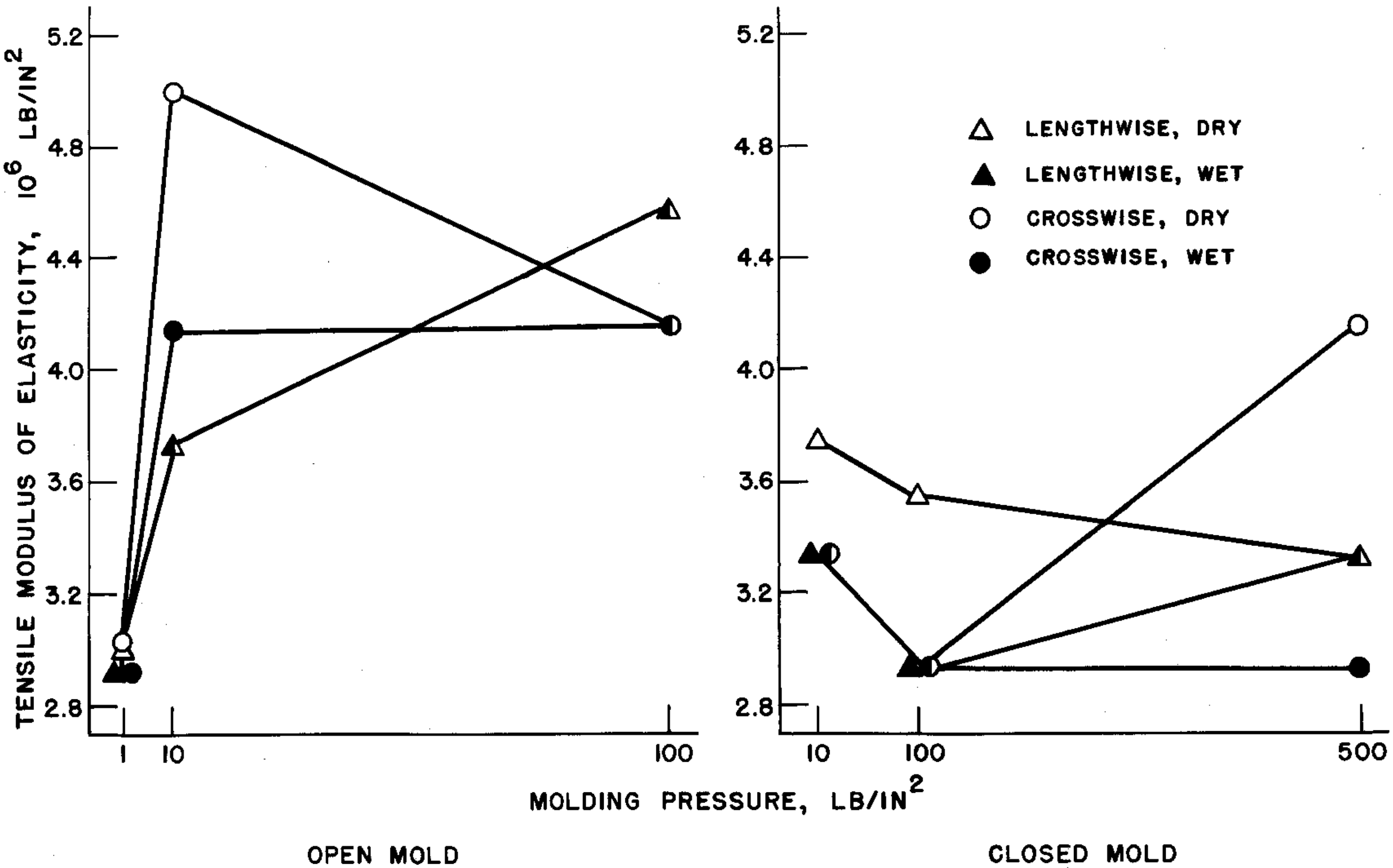


FIGURE 9. EFFECT OF MOLDING PRESSURE ON THE TENSILE MODULUS OF ELASTICITY OF GLASS-FABRIC REINFORCED POLYESTER LAMINATES

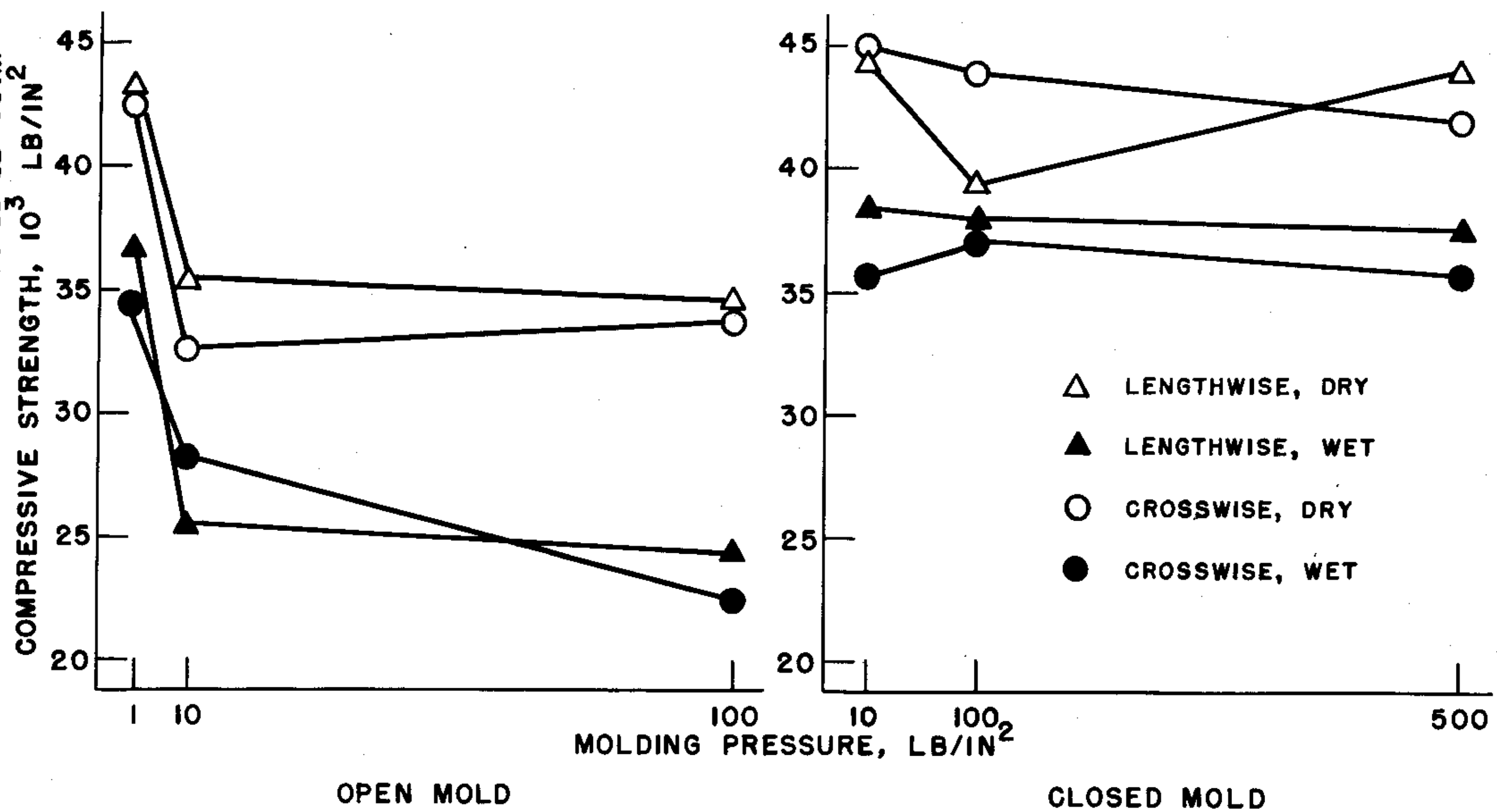


FIGURE 10. EFFECT OF MOLDING PRESSURE ON THE COMPRESSIVE STRENGTH OF GLASS-FABRIC REINFORCED POLYESTER LAMINATES

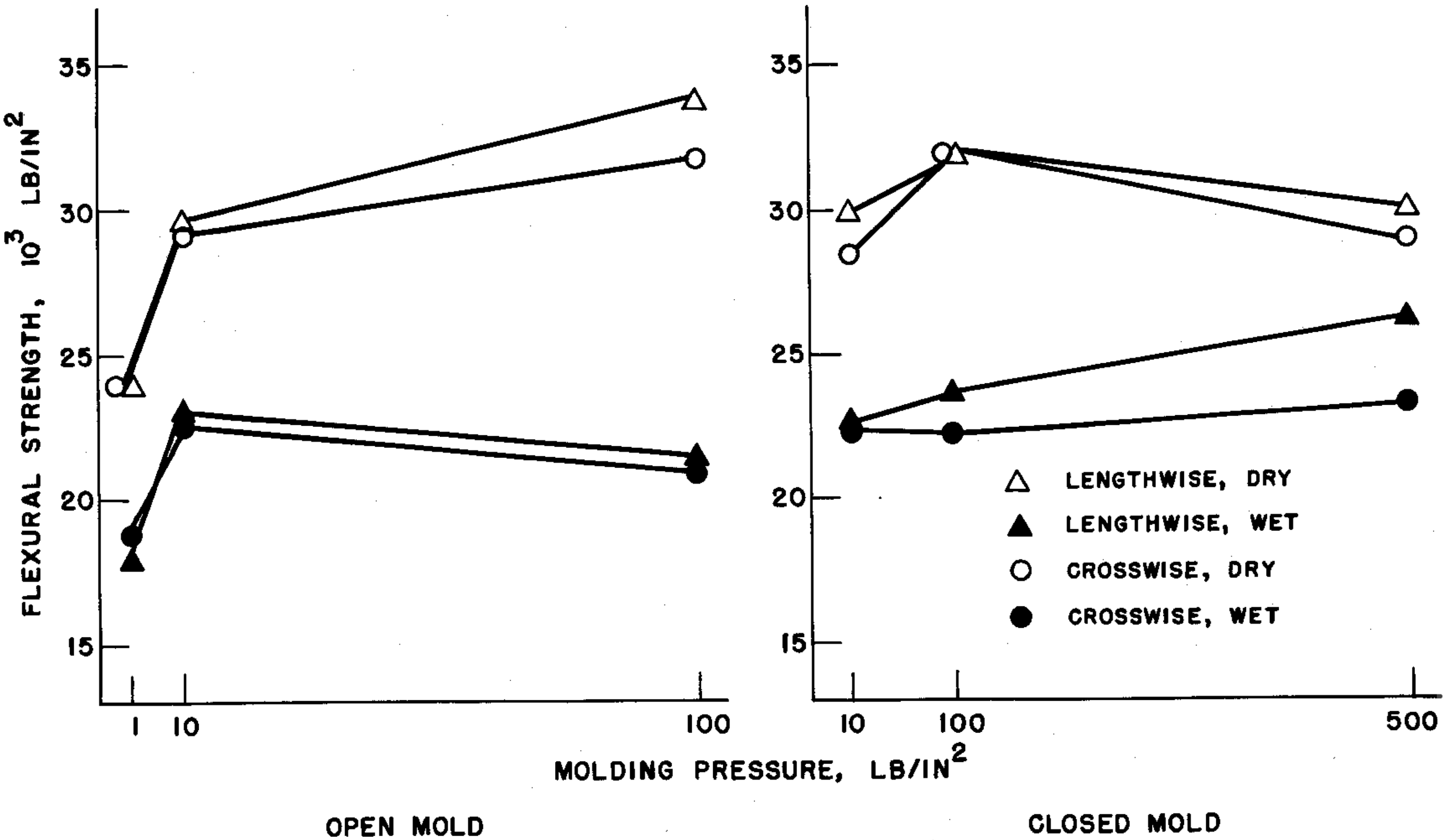


FIGURE 11. EFFECT OF MOLDING PRESSURE ON THE FLEXURAL STRENGTH OF 2 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

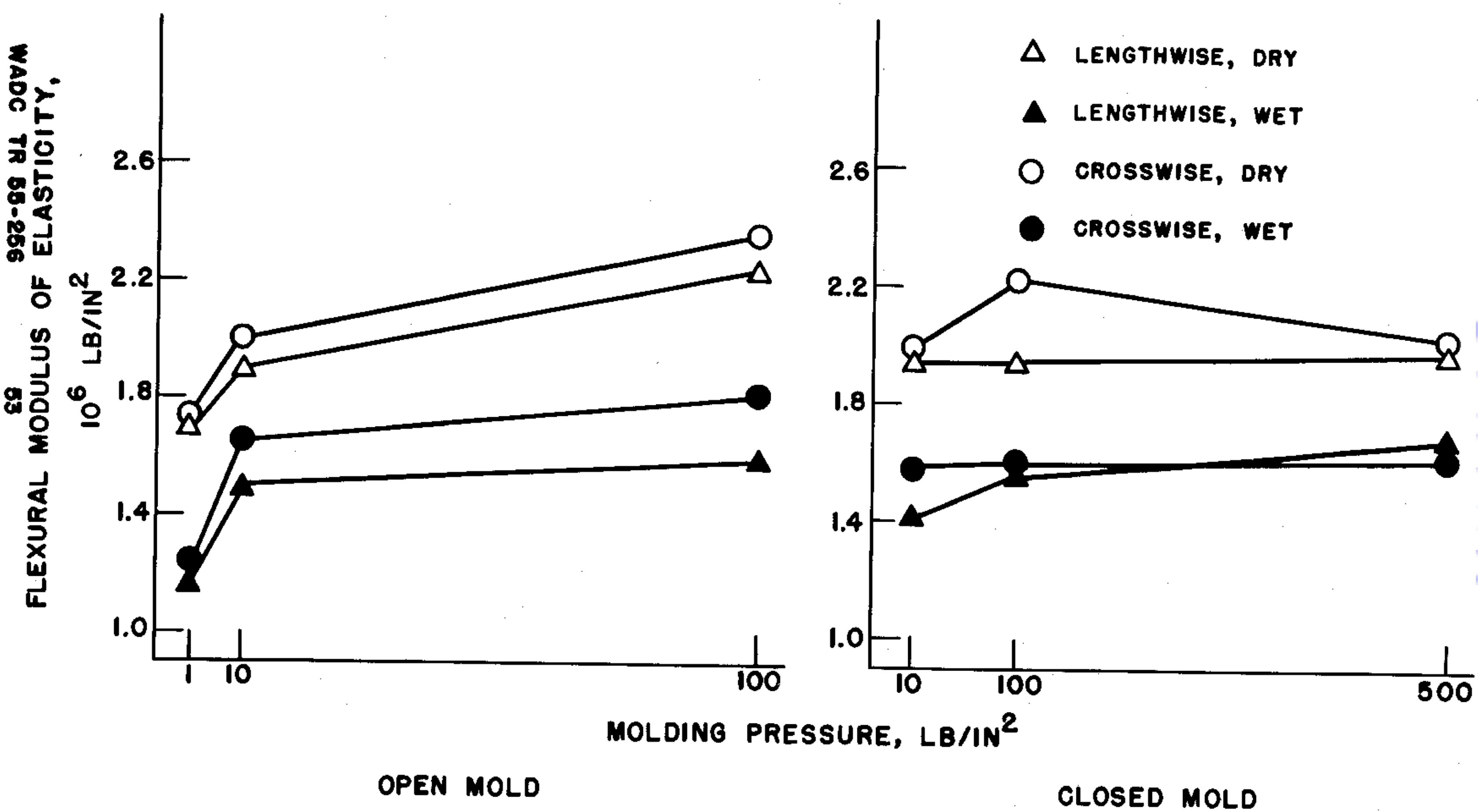


FIGURE 12. EFFECT OF MOLDING PRESSURE ON THE FLEXURAL MODULUS OF ELASTICITY OF 2 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

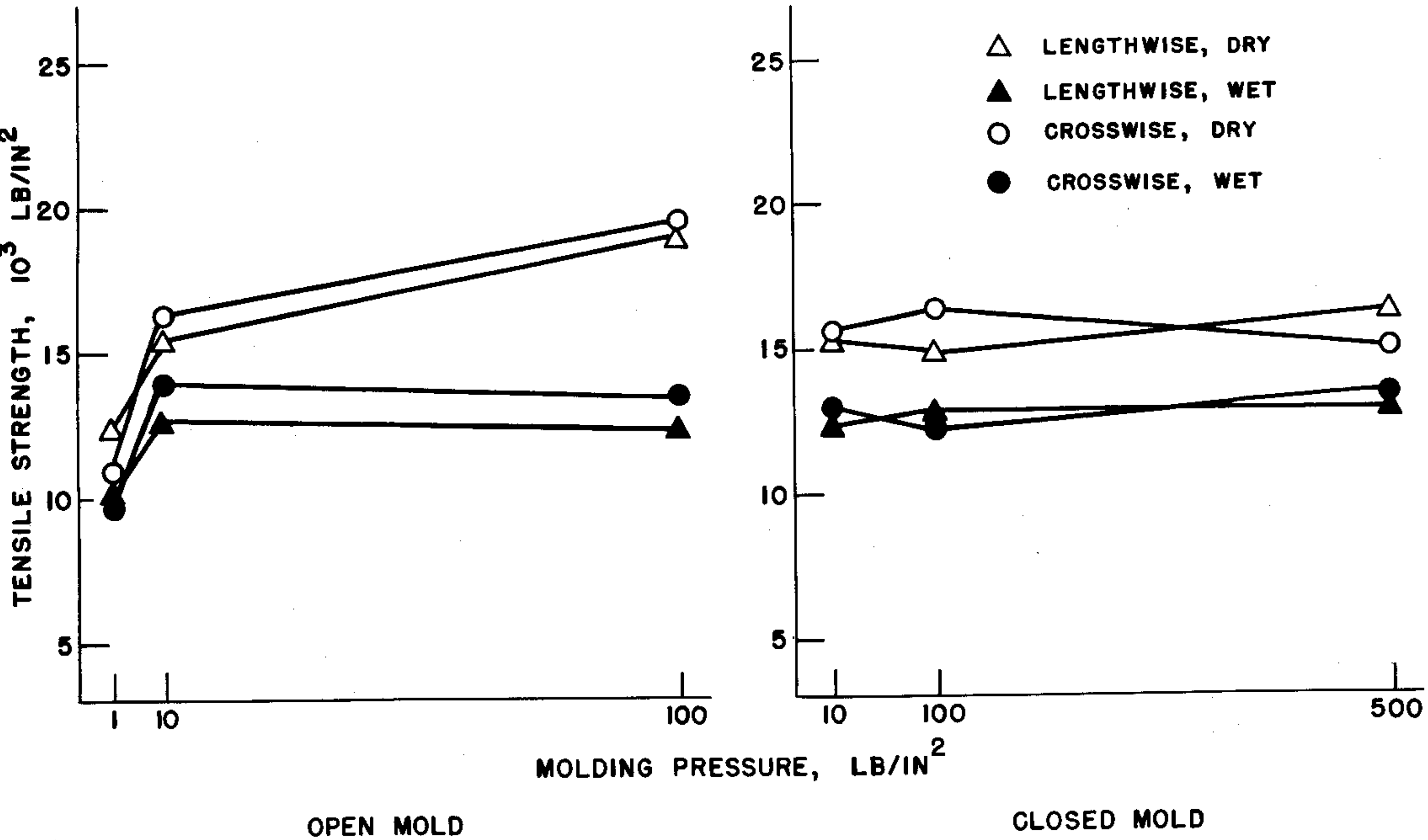


FIGURE 13. EFFECT OF MOLDING PRESSURE ON THE TENSILE STRENGTH OF 2 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

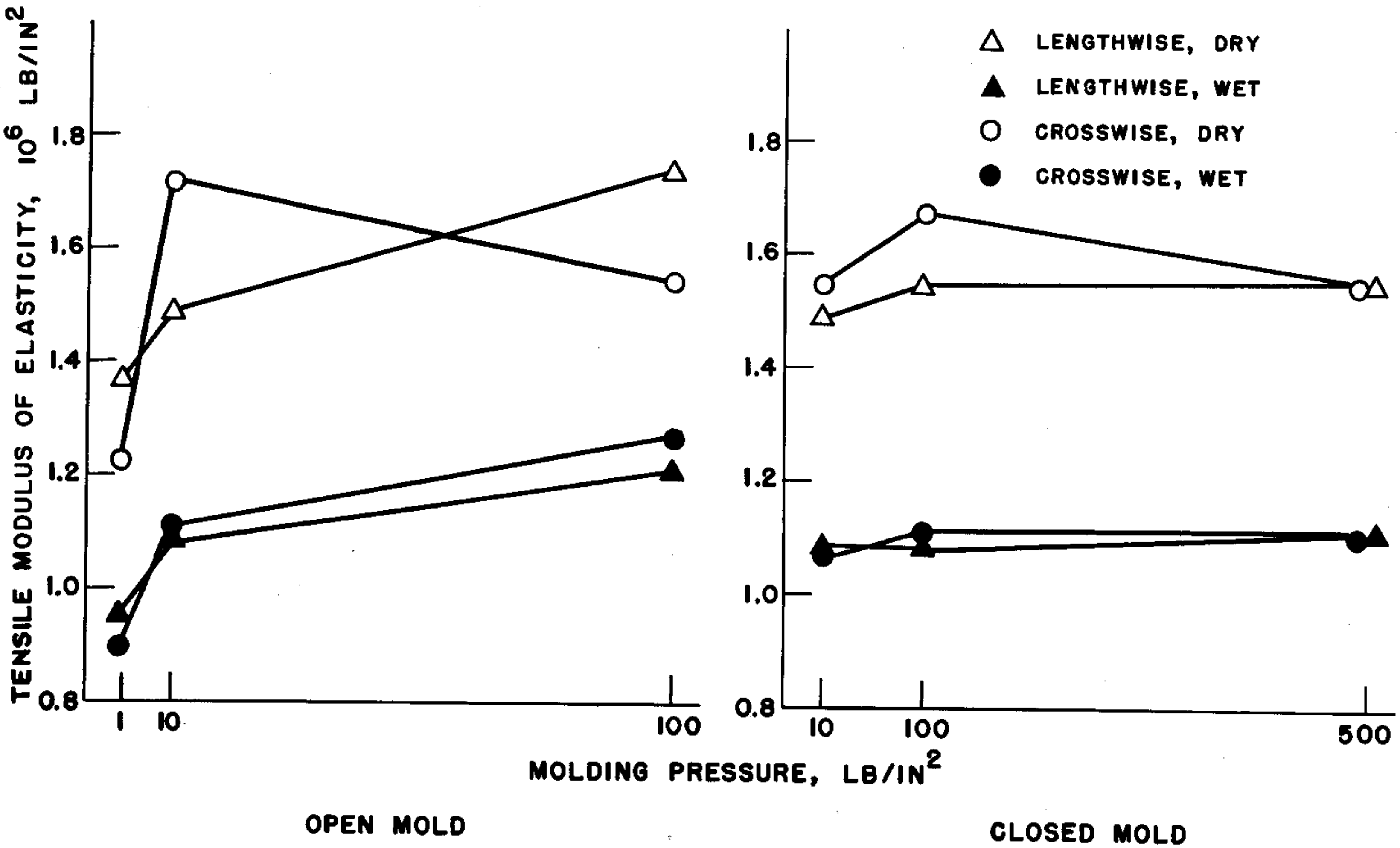


FIGURE 14. EFFECT OF MOLDING PRESSURE ON THE TENSILE MODULUS OF ELASTICITY OF 2 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

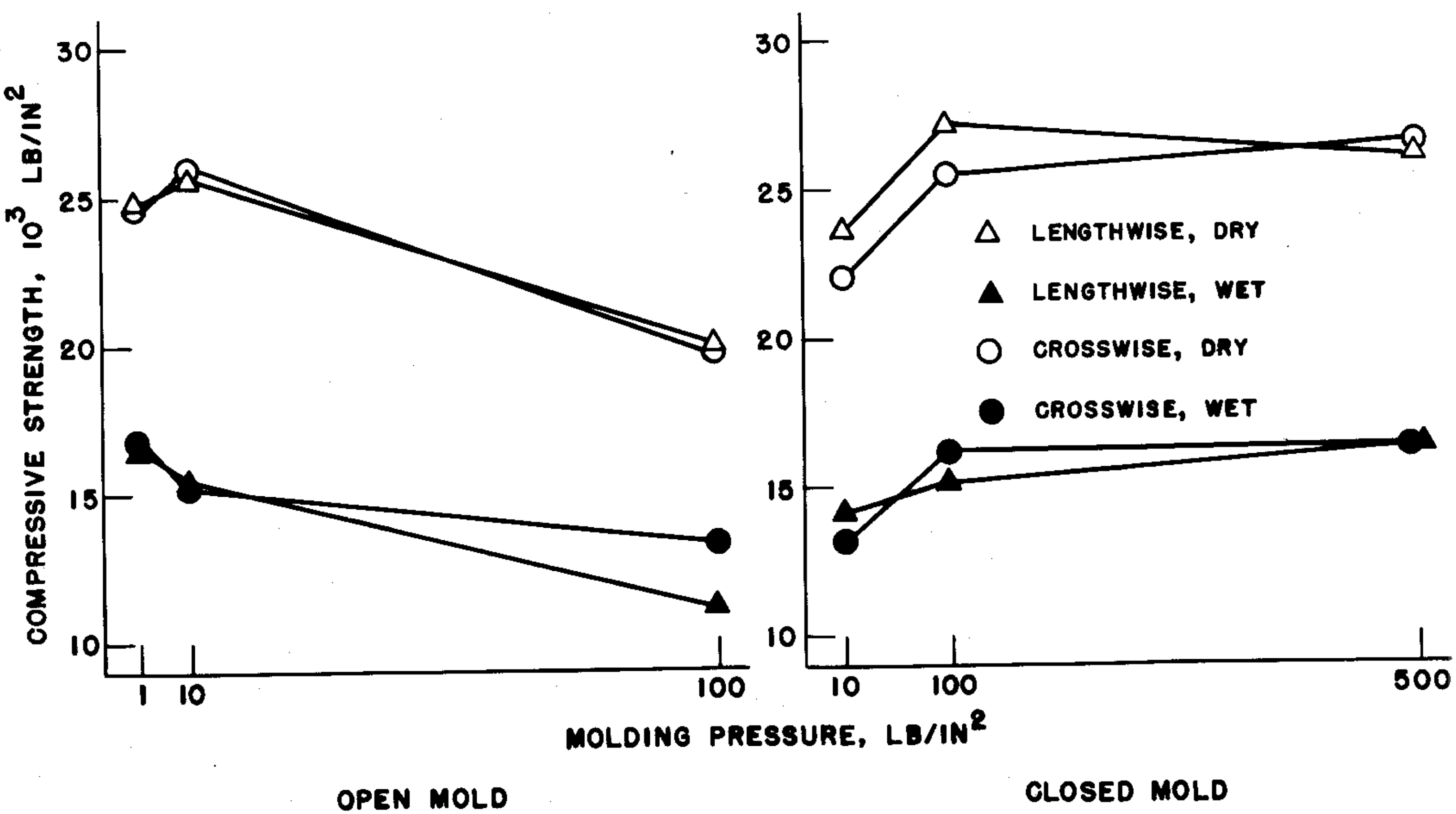


FIGURE 15. EFFECT OF MOLDING PRESSURE ON THE COMPRESSIVE STRENGTH OF 2 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

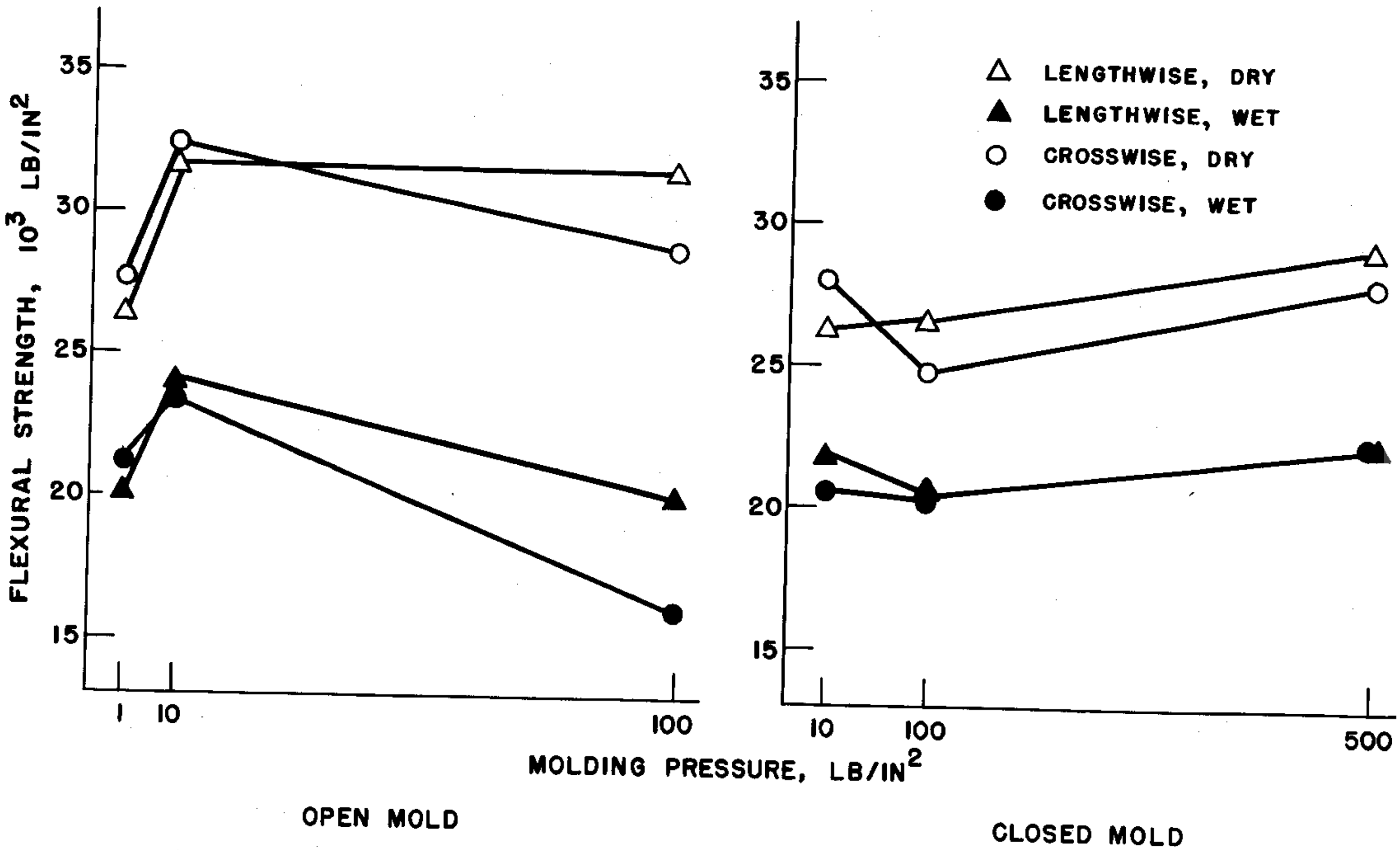


FIGURE 16. EFFECT OF MOLDING PRESSURE ON THE FLEXURAL STRENGTH OF 8 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

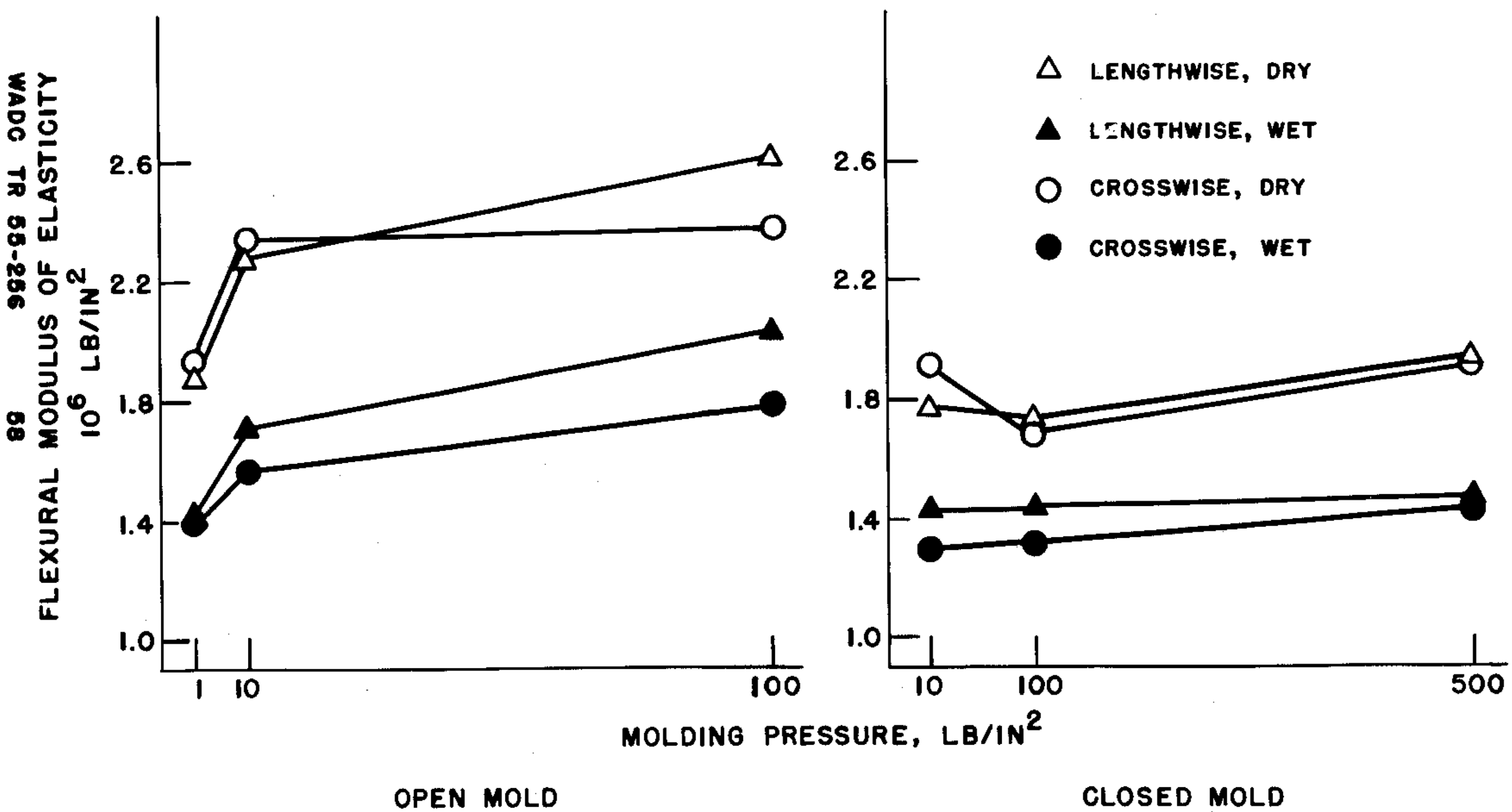


FIGURE 17. EFFECT OF MOLDING PRESSURE ON THE FLEXURAL MODULUS OF ELASTICITY OF 8 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

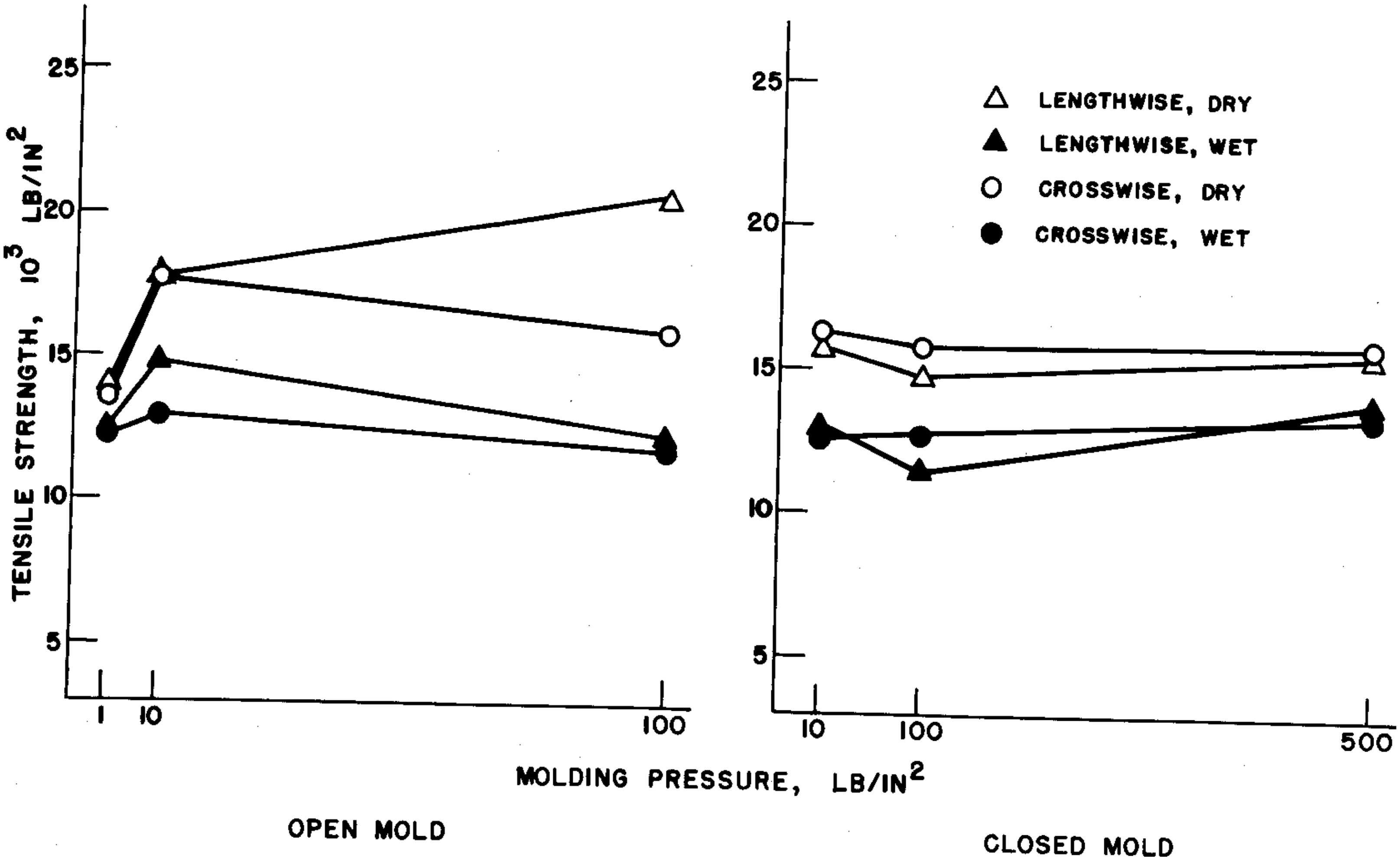


FIGURE 18. EFFECT OF MOLDING PRESSURE ON THE TENSILE STRENGTH OF 8 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

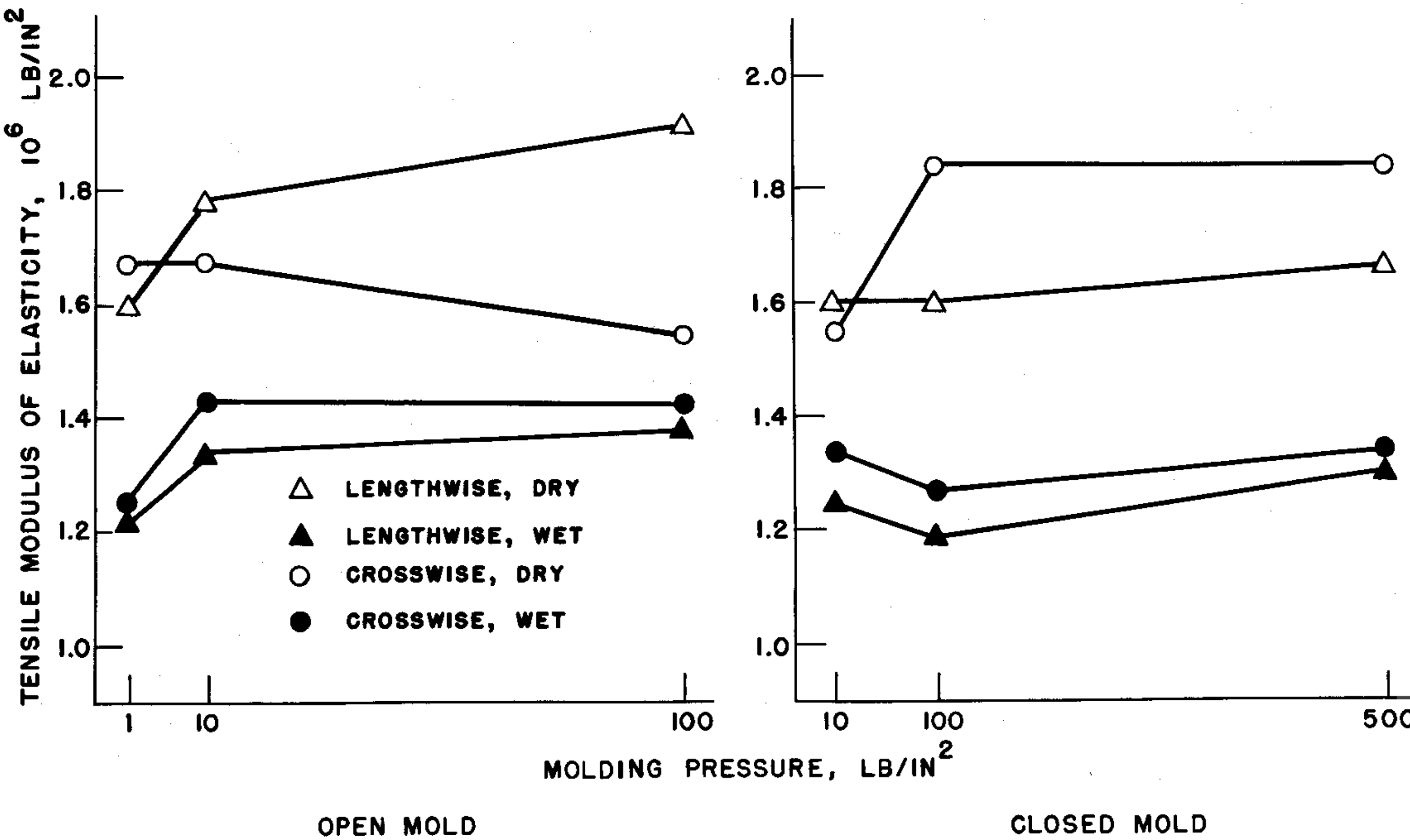
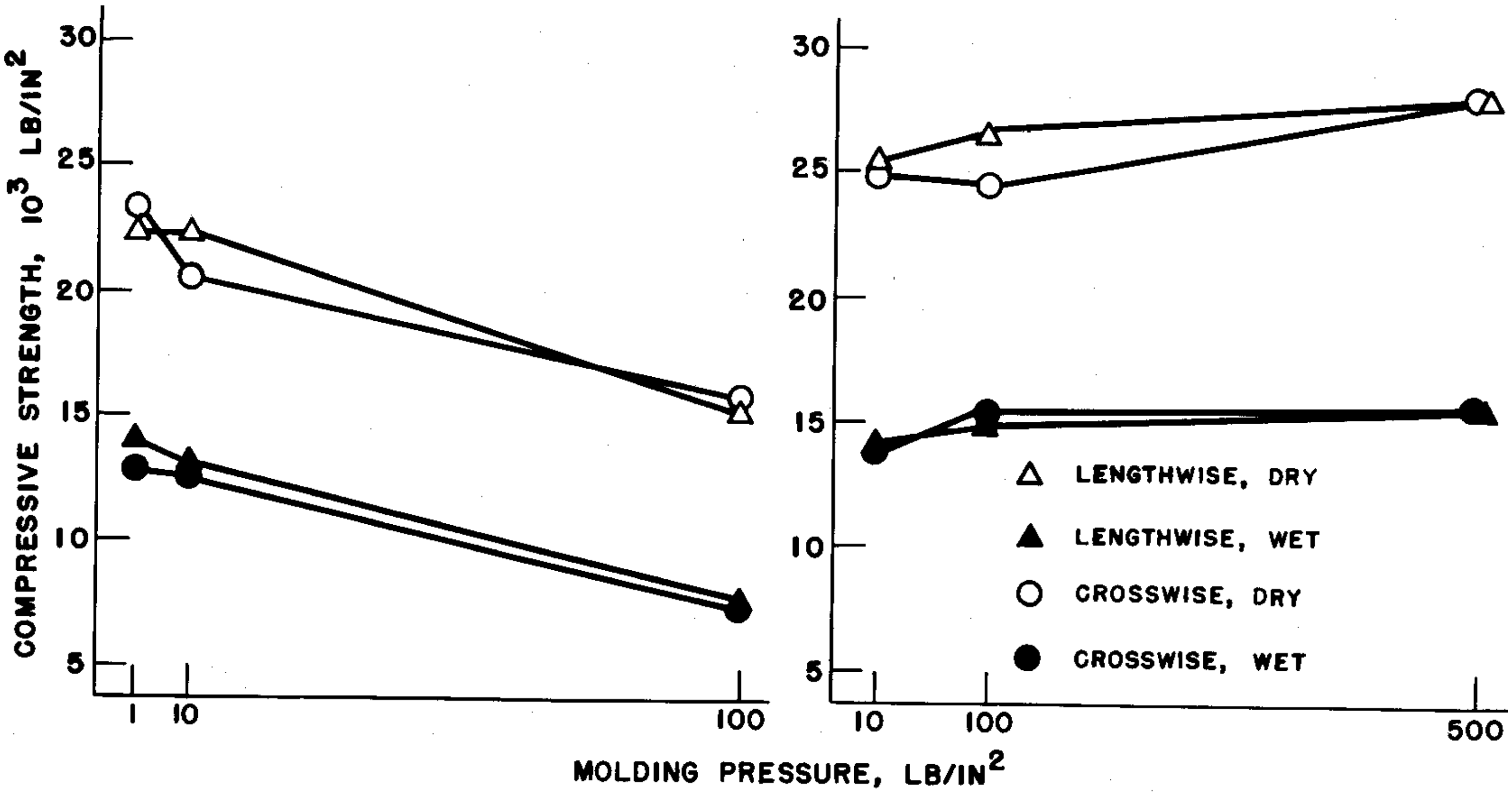


FIGURE 19. EFFECT OF MOLDING PRESSURE ON THE TENSILE MODULUS OF ELASTICITY OF 8 OZ GLASS MAT REINFORCED POLYESTER LAMINATES



OPEN MOLD CLOSED MOLD

FIGURE 20. EFFECT OF MOLDING PRESSURE ON THE COMPRESSIVE STRENGTH OF 8 OZ GLASS MAT REINFORCED POLYESTER LAMINATES

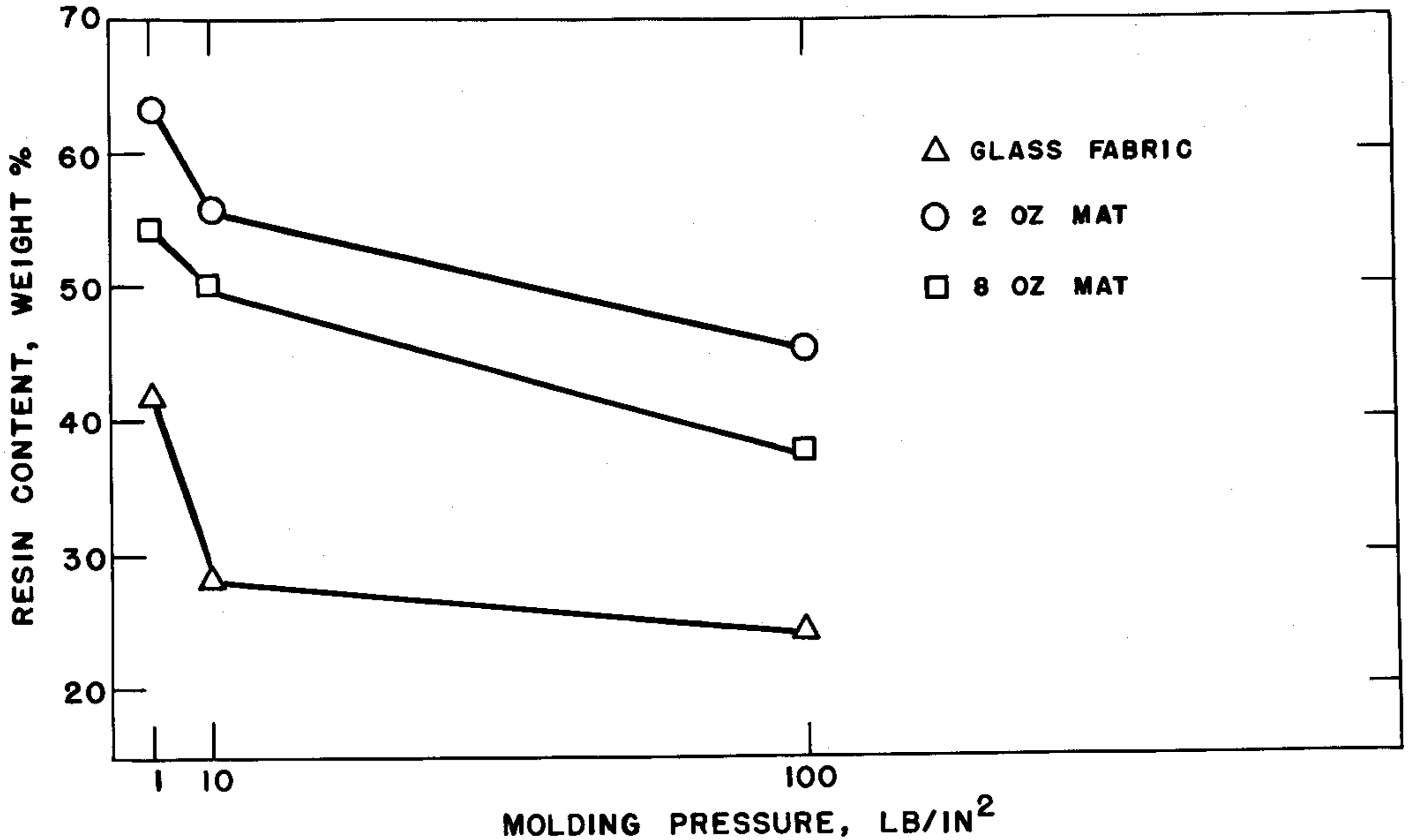


FIGURE 21. EFFECT OF MOLDING PRESSURE ON THE RESIN CONTENT OF GLASS-FIBER REINFORCED POLYESTER LAMINATES MOLDED FREE-EDGE

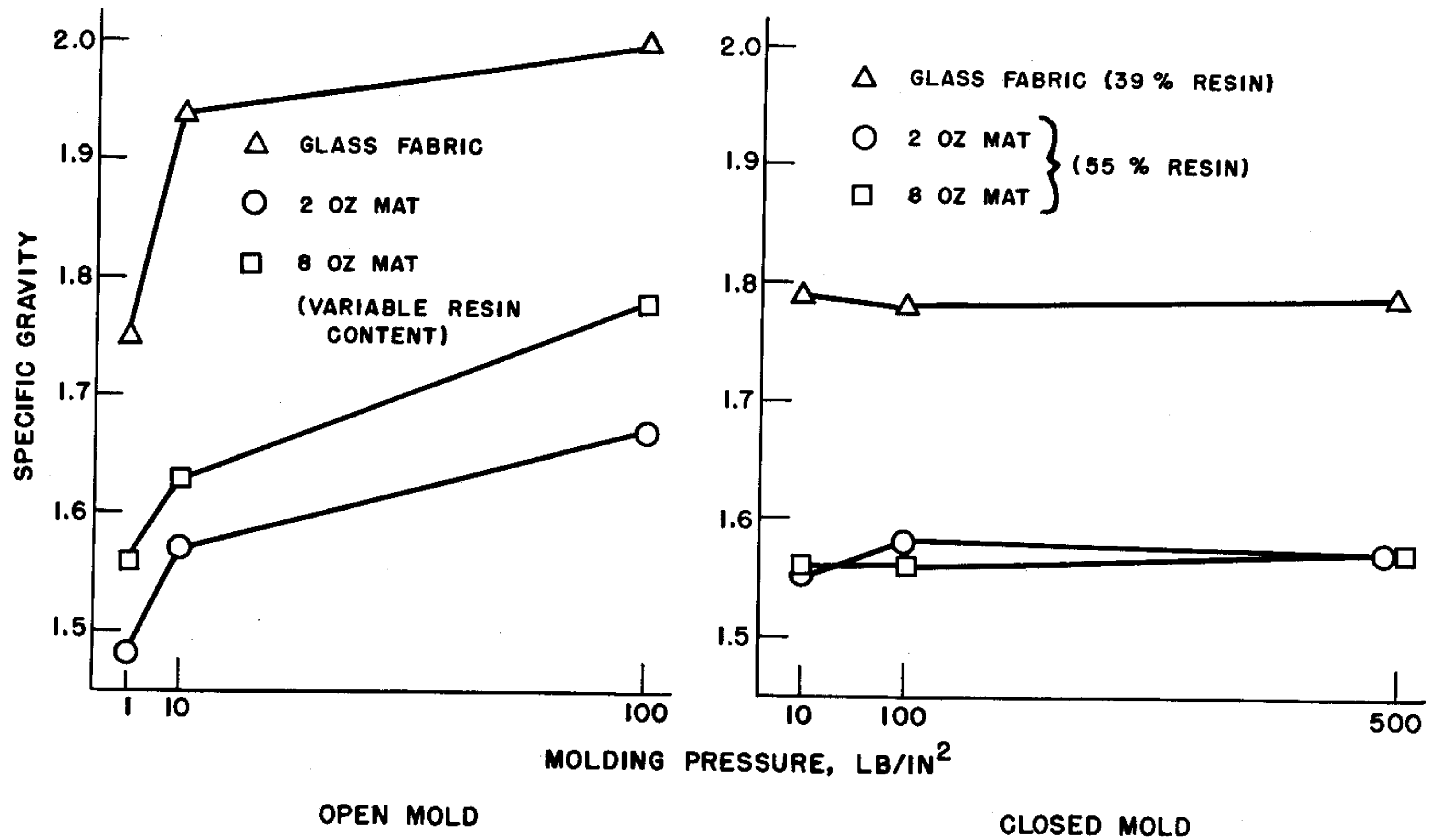


FIGURE 22. EFFECT OF MOLDING PRESSURE ON THE SPECIFIC GRAVITY OF GLASS-FIBER REINFORCED POLYESTER LAMINATES

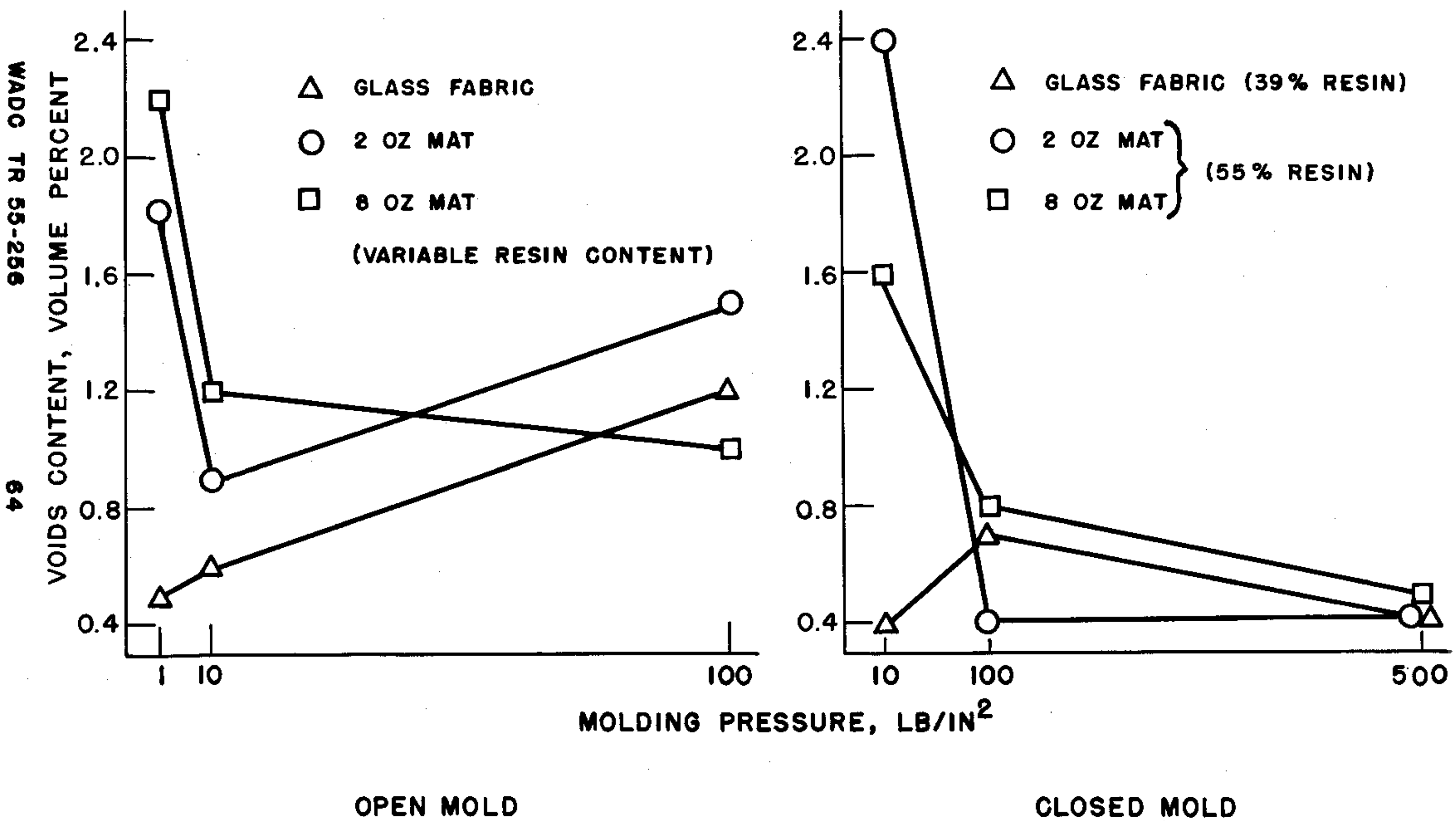


FIGURE 23. EFFECT OF MOLDING PRESSURE ON THE VOIDS CONTENT OF GLASS-FIBER REINFORCED POLYESTER LAMINATES