

INVESTIGATION OF EPOXY RESINS FOR
USE IN PHOTOELASTICITY

by

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ABSTRACT

A cross-section of the various types of epoxies was investigated to determine the type best suited for photoelastic use. This included a casting and annealing procedure, as well as the determination of the photoelastic properties. The effect of strain rate on the photoelastic properties was also investigated, and the properties not dependent on strain rate such as transparency, machineability, and time-edge effect are mentioned. A method for comparing the optical creep of different photoelastic materials is introduced for conditions of both constant stress and constant strain loading.

CHAPTER I

INTRODUCTION

A large number of different types of epoxies have been used as photoelastic materials, and this presents a problem in deciding what type of epoxy to use for a given photoelastic test. There is a rather wide variation in properties among different epoxy systems, and the material best for one type of photoelastic test is not necessarily the best for a different type of test. For instance, one material might work well for a photoelastic test made using static loading, but have a large change in properties with strain rate making it undesirable for dynamic loading.

For this investigation it was decided to study a cross-section of epoxy resins and hardeners which showed promise of being good photoelastic materials. Materials which were reported in the literature to have poor photoelastic properties or handling properties were generally avoided. The investigation included a casting and annealing technique, determination of photoelastic properties, and the effect of strain rate on some of these photoelastic properties. Another consideration in choosing the epoxies to be tested was to use materials which are commercially available, either as pre-cast sheets or in a form which could readily be cast. All of the epoxies tested were cast by the investigator, but some of these materials, or their equivalent, are commercially available as pre-cast sheets. The purpose of the investigation was to determine which of these promising epoxies was the best over-all material for photoelastic use.

Although the material used for a photoelastic model is somewhat dependent on the type of test being made, certain desirable properties for any photoelastic material can be listed. According to Frocht [1]¹ the specifications for an ideal photoelastic material are as follows:

1. Transparency.
2. Machinability.--Unless the material is easily machinable the cost of the model will be high. This is the greatest disadvantage of glass as a model material.
3. High Optical Sensitivity.--If the optical sensitivity is low the accuracy will be poor, especially on thin models since it will take a large load to produce a suitable stress pattern.
4. Proper Hardness.--If the material is too hard it will be difficult to machine, and if it is too soft it will be easily distorted.
5. Absence of Undue Optical or Mechanical Creep.--For the stress pattern to depend only on the applied load, it is essential that the fringe order shall not change with time.
6. Freedom from Initial Stresses.
7. Isotropy.--For convenience and accuracy the material properties should be independent of the direction of loading.
8. Linear Stress-Strain and Linear Stress-Fringe Relations.
9. Rigidity.--It is important that the shape stay essentially constant during a photoelastic test.

¹Numbers in brackets refer to similarly numbered references at the end of the thesis.

10. Constancy of Properties During Moderate Temperature Changes.

11. Moderate Cost.

Frocht states that Bakelite, a material widely used in photoelasticity, most closely approaches the ideal requirements. Its greatest disadvantage is that it is only available with a rough surface finish and must be polished before it can be used.

Leven [2] has made an investigation of epoxy resins for photoelasticity in which he discusses casting, curing, and machining for phthalic anhydride, PA, cured epoxy resins, and has presented the physical and optical properties for this type of plastic, which he found to be the kind best suited for photoelastic use. According to Leven, this was due chiefly to PA's low exothermic reaction upon curing, which permits the curing of large castings without a large temperature rise, and the fact that PA cured resins are less susceptible to time-edge effects. However, most models used in two-dimensional photoelasticity are small, and a large casting is not necessary. Time-edge effect, characterized by a stress in the edge of the material under no load, can largely be overcome by machining the model immediately before it is used. Since small models are often used and time-edge effects can be overcome, this investigation also included the amine cured epoxy resins.

Photoelasticity is becoming increasingly important in dynamic stress analysis, and it is necessary to know if the properties of a photoelastic material are dependent on the loading rate. Clark and Sanford [3] have investigated a number of photoelastic materials

(primarily epoxy resins) and compared their dynamic and static properties. They tested the materials dynamically at a very high strain rate by firing a projectile into the end of a long, square bar of the material, giving a ratio of static to dynamic loading time of 1.5 million. The results of these tests indicated that there are several materials available which show little change in photoelastic properties with increased loading rate. This small change enables a material to be calibrated statically and then used in a dynamic experiment with fair accuracy even though the exact loading rate is not known. Since this is important, it was decided to test specimens at different intermediate strain rates and compare the properties with those obtained statically and those obtained at a very high strain rate.

One of the desirable optical properties of a photoelastic model listed by Frocht [1] is low optical creep. Optical creep in a photoelastic material is characterized by an increase in fringe order with respect to time in a constant strain test.

Optical creep is caused by relaxation effects in the material. According to Rosenthal [4] a property which can be expected of all substances on theoretical grounds is visco-elasticity: a transition from elastic to viscous behavior as a function of time. For example putty, when rolled into a spherical shape, bounces like a rubber ball. If left alone under the influence of gravity, it flattens out and spreads like a viscous liquid. Time is an essential characteristic in the transition from elastic to viscous behavior. This time factor, which depends on the material, is called the relaxation time.

In a plastic this transition takes place only in isolated regions, with the bulk of the material maintaining the properties of a solid [4]. This tendency of only parts of the material to flow is known as creep. In a photoelastic material this creep can cause an error in the experimental results as the relation between stress and fringe order changes with time.

Since a fringe is the result of strain in the material, optical creep should be related to creep in the material. According to Andrade [5] constant-stress creep is composed of two separate creep processes. The first component, transient creep, has a decreasing rate with time while the second component, called viscous creep, has a constant rate. Andrade found that creep could be represented by the empirical equation

$$L = L_0 (1 + \beta t^{1/3}) e^{Kt}, \quad (1)$$

where L is the length of the specimen at time t , β and K are empirically determined constants, and L_0 is the initial length just after the load is applied. The transient creep is represented by the constant β , and K represents a strain which proceeds at a constant rate. Since in photoelasticity results are obtained in a relatively short time after loading, the steady-state creep can be neglected. Replacing L by n , the fringe order, Equation 1 can be written

$$n = n_0 (1 + \beta t^{1/3}), \quad (2)$$

where n is the fringe order at time t , and n_0 is the fringe order just after the load is applied. β will be defined as the optical creep constant, having the unit $(\text{time})^{-1/3}$.

Constant stress photoelastic tests are probably the most widely used type, but some tests are made with constant strain loading. The fringe pattern does not change in constant strain loading, but the stresses will relax because of the visco-elastic behavior of the plastic. The material is given an initial strain which is all elastic at time equals zero. However, as time goes on, there is a decrease in the elastic strain in favor of viscous strain, and the material loses its resistance to the change in shape with a corresponding decrease in stress. This behavior can be characterized by the equation

$$\gamma = \gamma_0 e^{-t/\theta} \quad (3)$$

where γ is the stress at time t , γ_0 is the stress immediately after loading, and θ is the relaxation time. The smaller the relaxation time θ , the sooner the substance loses its resistance to a change in shape [4]. This relaxation of the stress at constant strain means that at some later time a fringe represents a lower stress than it did initially, therefore the stress should be determined immediately upon loading.

The optical creep constant and the relaxation time are valuable for comparing the optical creep between various photoelastic materials for constant stress and constant strain loading respectively. Test results to determine these two quantities for various materials are presented.

CHAPTER II

METHODS AND PROCEDURES

Selection of Epoxy Resins and Curing Agents

Three resins in combination with three hardeners were investigated. Araldite 502, 6010, and 6020, which are manufactured by the Ciba Corporation, were the resins chosen. Each resin was cured with Araldite hardener 950, 951, and either Araldite 901, or its equivalent, PH8 from Photoelastic, Inc. This combination gave a total of nine epoxy systems. These systems were thought to be a good cross-section of possible photoelastic materials. Many other types are available, but were eliminated because they were essentially the same as those used or were known to have some undesirable photoelastic property, such as a high material fringe value, or poor casting properties.

Araldite 502 resin was chosen because it is recommended by the Ciba Corporation, and also because it was decided that at least one modified resin should be investigated. It is a light straw colored resin, with the modification increasing the resilience of the cured resin [6]. It has a viscosity of 2,100 to 3,600 centipoises at 25°C, and a weight per epoxide of 232 to 250.

Araldite 6010 and 6020 resins are both unmodified epoxy resins. They, or resins with similar properties, have been widely used in photoelastic materials. Araldite 6010 has a viscosity of 12,000 to 16,000 centipoises and an epoxide equivalent of 185 to 196. There is some variation between resins made by different companies, but

Araldite 6010 generally corresponds to resins such as Bakelite ERL-2774 from the Bakelite Company, DER 331 from Dow Chemical Company, and Epi-Rez 510 from the Jones-Dabney Company [7]. Araldite 6020 has a viscosity of 16,000 to 20,000 centipoises and an epoxide equivalent of 196 to 208. It is similar to Araldite 6010, but has a slightly higher molecular weight and viscosity.

Araldite hardeners 950 and 951 are both polyamines and are used for room temperature curing systems. Araldite 950 is a diethylene-triamine hardener, DETA, which is a highly reactive polyamine having a molecular weight of 103 [7]. Its viscosity is seven centipoises at room temperature. The stoichiometric ratio of DETA to resin is approximately ten to eleven pph (parts per hundred by weight) which reduces the initial viscosity of the resin mix to about 3,000 centipoises. DETA cured resins have vigorous exotherms, and will set hard within a short time. Araldite 951 is a triethylenetetramine hardener, TETA, and is also a reactive polyamine. TETA has similar properties to DETA, being slightly less reactive and more viscous. These amines are widely used as general purpose curing agents. Araldite 502 resin cured with TETA is the epoxy recommended by the Ciba Corporation as a photoelastic material [6].

Both Araldite 901 and PH8 are trade designations for phthalic anhydride hardener. Phthalic anhydride, PA, is a powdery white solid having a molecular weight of 148 [7]. PA, which melts at 128° C, gives low exotherms and a long pot life. According to Lee and Neville about 0.6 to 0.9 equivalent PA is used per epoxy group, while Leven uses an equivalent of approximately one. For Araldite

6020 with an epoxide equivalent of around 200, or an epoxy value of 0.5, the ratio of PA to resin will be fifty per cent. This ratio is for an equivalent value of unity, and was the value used in this investigation. When casting PA cured systems the resin must be heated to dissolve the hardener, and, to prevent the PA from precipitating out of solution, the mold must be held at about 200°F until the casting has gelled.

Since epoxy resins are cured by a crosslinking process, there is a stoichiometric ratio of curing agent necessary for complete consumption of the reactive groups in the resin [7]. If too little curing agent is added to the resin the cure will be inadequate, whereas if too much curing agent is added it tends to stop chain building at low molecular weights and embrittle the resin. The customary method is to allow for one epoxy group for each active hydrogen of the curing agent, or as previously stated, an equivalent of one per epoxy group. This stoichiometric ratio of hardener to resin was used for all the resin-hardener systems of this investigation.

Casting Procedures

The casting procedures were of two types: the procedure used for the amine cured systems and that used for the anhydride cured systems. The molds used were constructed by clamping glass plates on either side of 3/16 inch thick steel bars which were glued into a "U" shape. The glass plates used for the amine cured systems were seven inches square, and those used for the PA cured epoxy measured fourteen inches square. Cardboard gaskets were used between the

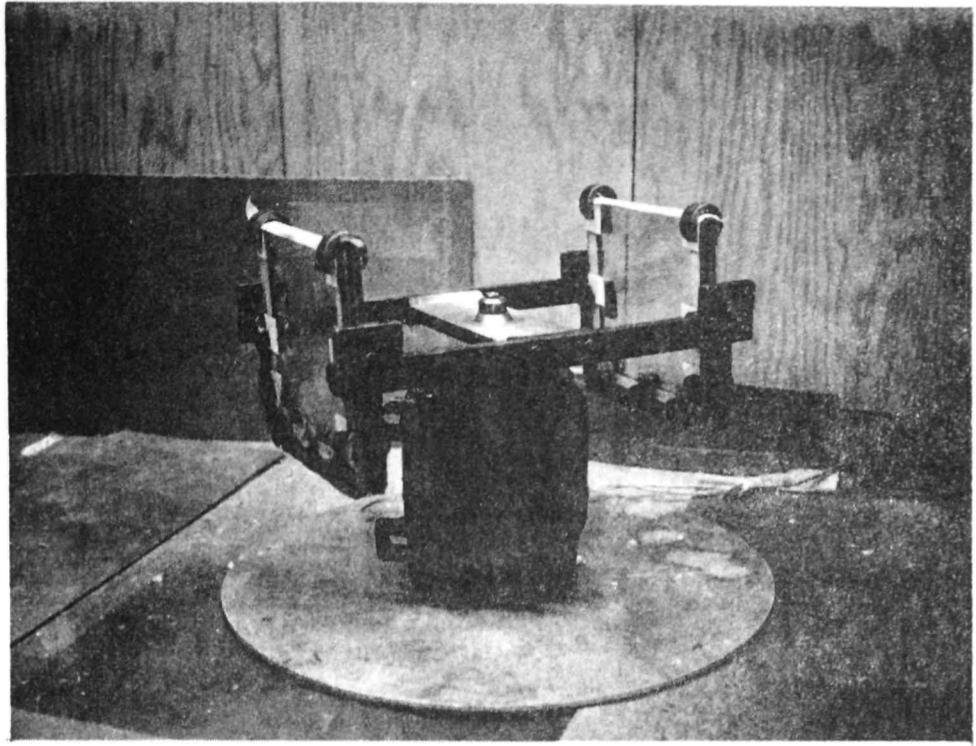
steel bars and the glass to prevent leakage, thereby increasing the thickness of the epoxy sheets to approximately 0.225 inches. The epoxy was poured with the mold in a vertical position.

It was necessary to centrifuge the amine cured epoxies to remove the air bubbles introduced in the mixing process. Since these systems set rapidly, it was decided to construct a centrifuge which would spin the entire mold. This method of centrifuging eliminated the possibility of the epoxy gelling before it was poured, and also avoided the problem of trapping air bubbles during the pouring process. The PA cured epoxy did not have to be centrifuged since it was held at an elevated temperature, and the viscosity was so low the air bubbles rose to the surface before gellation occurred. Since the mold for the PA cured epoxy was not centrifuged, it was made larger than the mold for the amine cured epoxy. The centrifuge used is shown in Figure 1.

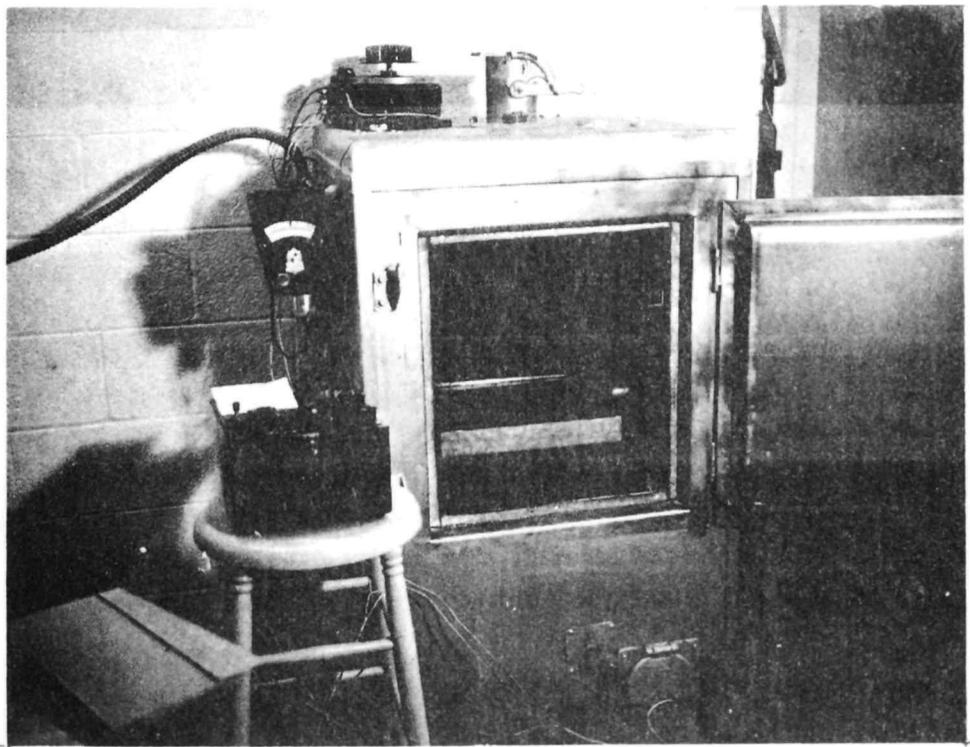
The summary of the casting procedure listed next is for the equipment and mold sizes used in this investigation. It is fairly general however, and can be adapted to other equipment.

Room Temperature Cure

1. Clean the glass plates and metal spacer bars; Bon Ami cleanser worked well for cleaning these items.
2. Put mold release on the glass and on the metal bars. Allow the mold release to dry and then buff. Two coats of mold release on the glass seemed to improve the results. It is not necessary to buff the metal bars.



CENTRIFUGE



OVEN

Fig. 1.--Casting and Annealing Equipment

3. Fasten the metal bars into a "U" shape. Rubber cement is satisfactory for holding the bars together.

4. Cut "U" shaped cardboard gaskets to fit over the metal bars.

5. Put the mold together and place it in the centrifuge. It is advisable to place cardboard squares between the glass and the clamps, to help prevent glass breakage. A strip of masking tape over the top of the mold will prevent dust from entering the mold before the epoxy is poured.

6. Weigh a sufficient amount of resin to fill the molds in a container or containers. As an estimate, about seventeen to eighteen grams per cubic inch of mold will suffice. Tin cans make good containers, since they can be discarded after being used.

7. Weigh the hardener in a separate container. In this investigation a separate container was used for both the resin and hardener for each mold.

8. Add the hardener to the resin and mix thoroughly. A propeller type mixer in a drill press gives good mixing results.

9. Pour the mixture into the mold and start the centrifuge. If it is not possible to centrifuge the mold, the mixture can be centrifuged and then carefully poured into the mold.

10. When the bubbles are removed, stop the centrifuge and let the epoxy set until it is hard, after which it can be removed from the mold.

High Temperature Cure

1. Clean the glass plates and metal spacer bars.

2. Put mold release on the glass and metal bars. Do not buff the glass or bars. Two coats of Hysol AC 4-4368 mold release were used.

3. Fasten the metal bars into a "U" shape with epoxy glue and let it dry for several hours. Rubber cement will not withstand the curing temperature used for this mold.

4. Cut cardboard gaskets to fit over the metal bars.

5. Assemble the mold as before, except that the mold is clamped with small C clamps, again using small cardboard squares between the clamps and the glass plates.

6. With the mold in the oven, raise the temperature to approximately 200°F.

7. Weigh out in a container, a sufficient amount of resin to fill the mold; fourteen grams of resin per cubic inch of mold volume is sufficient to completely fill the mold when the hardener is added. In a separate container weigh out the necessary amount of phthalic anhydride hardener in the correct ratio for the resin being used. For the resins used in this investigation the amount of PA hardener used for each resin was as follows:

42 pph for Araldite 502
50 pph for Araldite 6020
55 pph for Araldite 6010

8. Heat the resin to 240°F to 250°F and slowly stir in the hardener while maintaining the temperature. Stir the mixture until the hardener is completely dissolved.

9. Take the mold from the oven and pour the epoxy into the mold as rapidly as possible, immediately returning the mold to the oven,

since the hardener will precipitate out if the temperature drops much below 200°F.

10. Hold the mold at approximately 200-210°F until the epoxy is firm enough to remove from the mold. This hardening will take from one to three days.

11. When the plastic sheet is firm, take the mold from the oven and remove the casting. It can be removed while the mold is still warm.

Annealing Procedure

The purpose of annealing is twofold; to complete the cure of the epoxy resin, and to relieve the initial stresses. Annealing is always done on the sheets of epoxy and never on a finished model. This precaution is necessary since time-edge effects will form at the edges of the epoxy within a few hours. These edge effects show up as fringes around the edge of the material, and they are not removed by annealing.

The epoxy sheets are placed on a flat plate of glass during annealing since they are relatively soft at the annealing temperature, and the glass will prevent the epoxy from deforming. The glass is placed in a pan, and the pan is filled with transformer oil or Dowtherm to keep the temperature as uniform as possible during the annealing process. Annealing can also be done in air, but the results are generally not as good.

The oven used for annealing was the same one used for casting the PA cured epoxy. The temperature was controlled by regulating

the voltage to the electric heating element with a variable transformer. A fan in the oven circulated the air and helped to maintain a uniform temperature. The temperature was determined by suspending a thermocouple in the pan of oil in which the epoxy was annealed. The oven is also shown in Figure 1.

The general annealing procedure listed here is from Frocht [1], and is the same for both the amine and PA cured systems, except that the PA cured epoxy is annealed at a higher temperature. The procedure is as follows:

1. Trim the edges around the casting. These edges contain the worst initial stresses, and their removal will aid the annealing process.

2. Place the casting on a plate of glass which is suspended above the bottom of a metal pan. Fill the pan with oil until the oil is well above the epoxy sheet.

3. Slowly heat the oil bath to approximately 215°F for the amine cured epoxy and to about 250°F for the PA cured plastic. A heating rate of around 10°F per hour gives satisfactory results.

4. Hold the oven at the annealing temperature for two to eight hours.

5. Cool the oven to room temperature. The cooling rate should be adjusted to require at least twenty-four hours to reach room temperature.

Equipment Used for Variable Strain Rate Tests

As stated previously it was decided to test the epoxy specimens at variable strain rates. This testing was done by using a variable speed motor to drive a Dillon Tensile Testing Machine. The shaft of the motor was connected to the shaft of the testing machine with a chain and sprockets, and the speed of the testing machine shaft was determined with an electronic counter. Since it took 320 revolutions to move the screw of the testing machine one inch, the strain rate could easily be determined. Once the strain rate was set, a tensile specimen was inserted and the test was conducted.

The data was recorded on a recording oscillograph that was driven by the shaft of the testing machine. Since the speed of the shaft determined the strain rate in the specimen, the paper speed in the oscillograph was proportional to the strain rate in the tensile specimen. The load was sensed by a load cell located just above the specimen. The load cell, shown in Figure 2, which was an aluminum bar with strain gages attached, was connected to a carrier amplifier and then to the recording oscillograph. It was calibrated such that a 500 pound load gave a full scale deflection on the oscillograph. Since the recording paper was driven at a speed proportional to the strain rate, a load, or stress, versus strain diagram was recorded on the paper for the material being tested. The gearing ratio between the testing machine and the oscillograph was such that a plastic with a modulus of elasticity of 450,000 pounds per square inch would give a trace at approximately a thirty degree angle on the recording paper.

To determine the material fringe value, a fringe counter was constructed by passing a thin beam of polarized light through the specimen and onto a photocell. The photocell was one leg of a Wheatstone bridge, which was also connected to the carrier amplifier and to the oscillograph. The bridge was balanced with the light beam on and no-load on the specimen. When a load was applied, a fringe would pass across the specimen and change the intensity of the light impinging on the photocell. This would unbalance the bridge and cause a signal which would make a blip on the recording paper. This fringe counter can also be seen in Figure 2. A standard or crossed circular polariscope was used to polarize the light beam in the counter. The polariscope was made using sheet polaroid for the polarizer and analyzer, and cellophane for the quarter-wave plates. A Wratten No. 57B filter was also inserted in the light beam to make the fringe more distinct. Without the filter the fringe counter was sensitive to any change in color, which made it difficult to determine exactly when the same fringe order appeared. The fringe counter was calibrated using CR-39 plastic for which the material fringe value was already known [8]. By comparing the fringe and corresponding load on the recording paper, the material fringe value could easily be determined. The equipment for the variable strain rate tests is shown in Figure 2.

After several initial tests it became apparent that the strain in the equipment and ends of the tensile specimen was not negligible. In other words, a serious error was introduced by assuming that the total strain was all located in the reduced section of the tensile

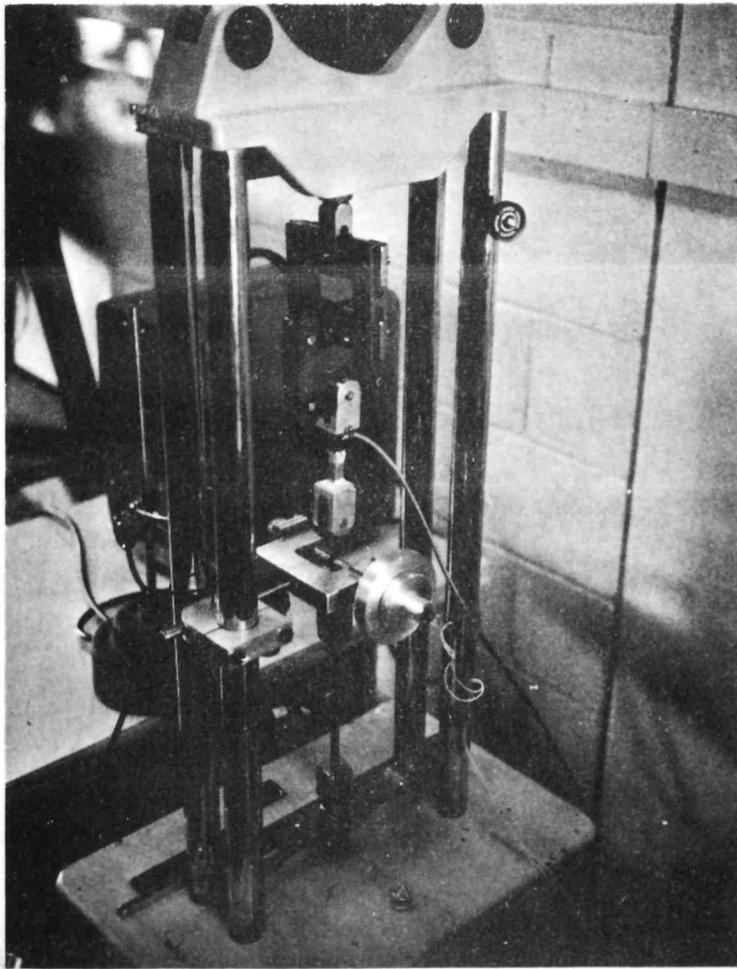
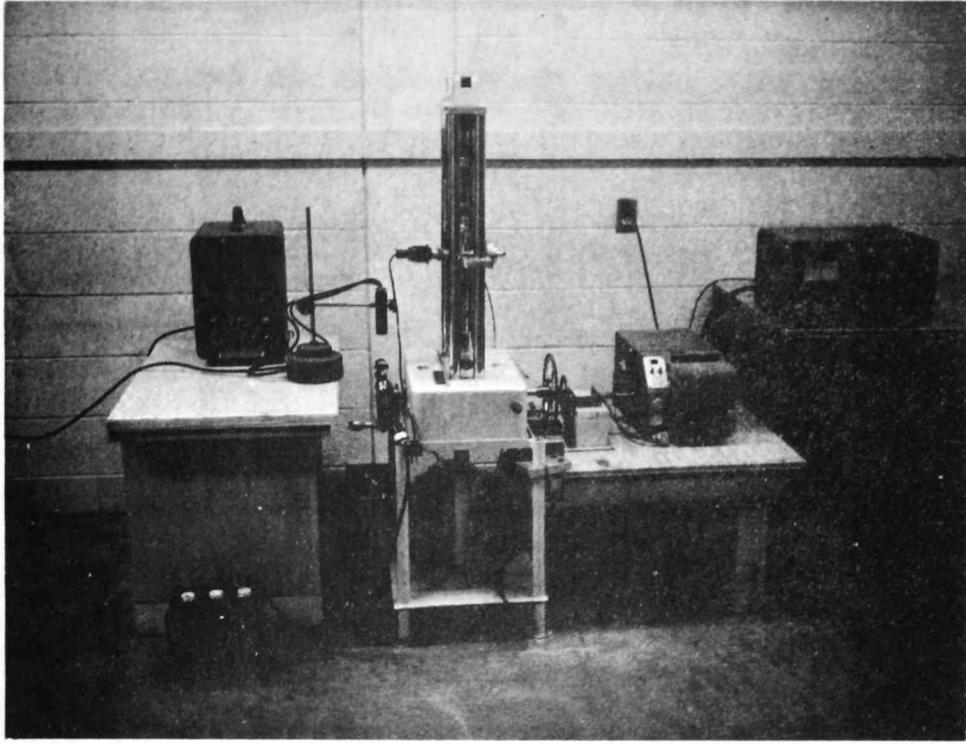


Fig. 2.--Equipment for Variable Strain Rate Tests

specimen. To correct for this error, a stub specimen of each material was also loaded at each strain rate. The stub specimen was simply a tensile specimen without the reduced section. By taking the difference in strain at equal stresses in the tensile and stub specimens, a corrected value for the modulus of elasticity and strain rate were obtained. Both a tensile specimen and a stub specimen are shown in Figure 3.

Originally it was intended to use the fringe counter to determine the linear stress-retardation curve for the various materials. However, with the white light, the colors became faint as the load increased, and the change in intensity was not great enough to cause a deflection on the recording paper. Instead, the specimens were loaded by hand in a standard polariscope using a mercury vapor lamp, which gives a monochromatic light with a wavelength of 5461 \AA . The load corresponding to each fringe was taken, and, since the specimen had been measured with a micrometer, and results could be plotted as a stress-fringe order curve. Actually the stress-fringe order curve and the stress-strain curve for a given material should be linear to the same value of stress since a fringe is apparently caused by shear strain in the material.

Optical Creep

To determine the optical creep in each of the materials used, a tensile specimen was loaded in a standard circular polariscope, again using the mercury vapor lamp, and the fringe order was determined at different intervals of time using Tardy compensation to

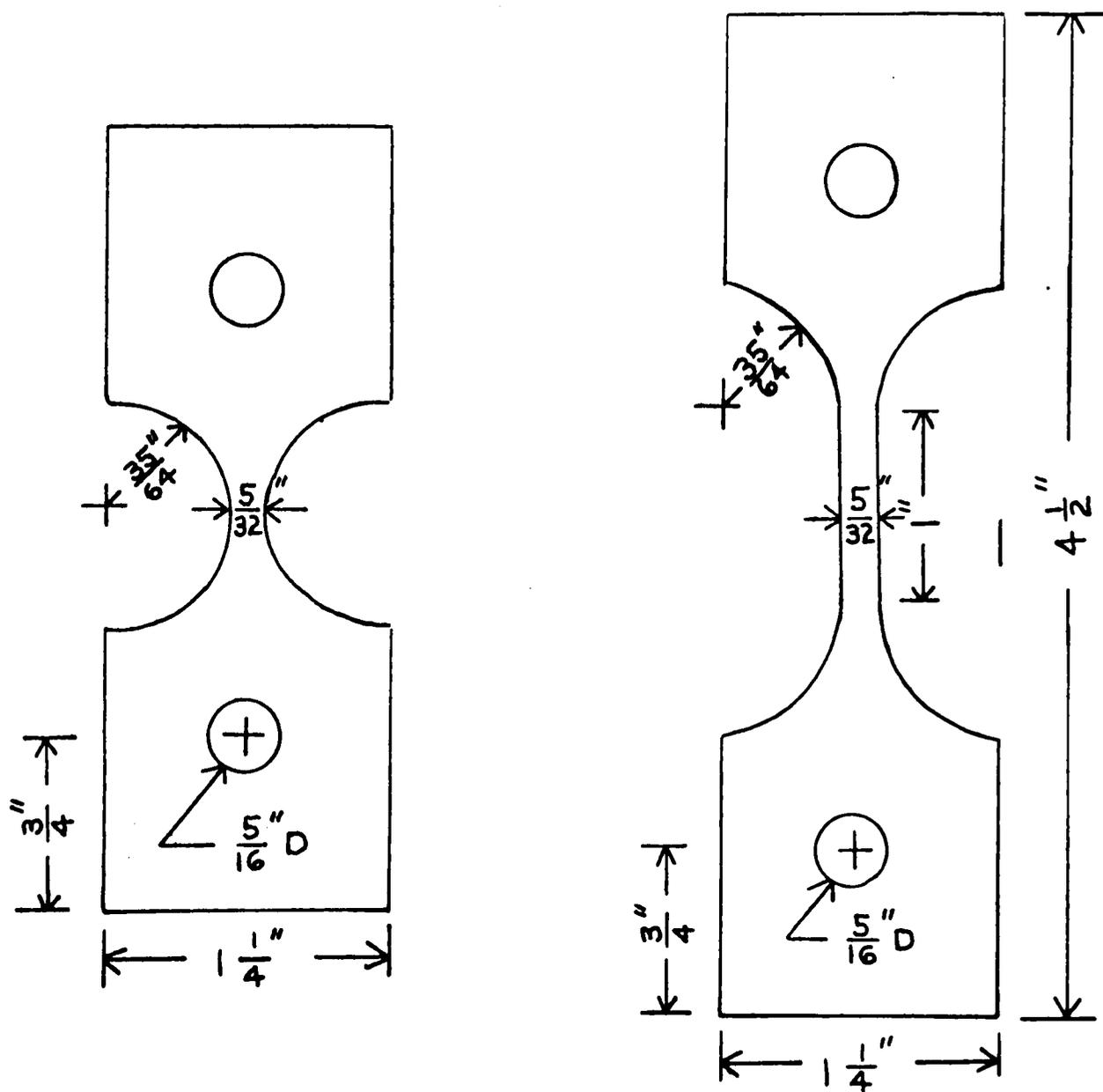


Fig. 3.--Stub and Tensile Specimens

determine the fractional fringe order. By plotting the fringe order versus time, the optical creep for a given material can be determined, and the optical creep constant can be calculated using Equation 2. In the test each specimen was loaded to approximately five fringes, and the exact fringe order was determined initially and after 5, 10, 15, 30, 60, and 120 minutes.

To determine the stress relaxation time, Araldite 502 resin cured with each of the three hardeners was loaded at constant strain in a standard circular polariscope, again using the monochromatic light source. Each specimen was loaded to approximately twelve fringes, and the load was determined initially and after 5, 10, 15, 30, 60, and 120 minutes. Since the area of each specimen was known, a plot of stress versus time could be made, and the stress relaxation time could be determined using Equation 3.

Method Used to Machine Specimens

The tensile and stub specimens were both made by sawing the rough outline of a specimen from a sheet of epoxy, and then finishing up around the edge with a rotary carbide cutter. In using the rotary cutter, a rough-cut specimen was fastened with jiggling tape to a steel template that had been machined to the proper shape. The template was then used as a guide for the cutter.

The rotary cutter used had a speed of 45,000 rpm, which goes along with the general recommendation that high rotating speeds and slow feeds be used to prevent chipping at the edges and to minimize machining stresses [1]. After each specimen was machined around the

edges, the loading holes were drilled on a drill press, again using the steel template as a guide.

CHAPTER III

FINDINGS AND INTERPRETATIONS

Results of Casting and Annealing

It is difficult to cast good sheets of epoxy resin in the laboratory. The greatest problem is to obtain a casting that is bubble-free and has a good surface finish.

There is a considerable variation in ease of casting between the different types of epoxy investigated, which can be expected because of the differences in viscosity. Of the amine cured systems, the DETA cured epoxies had lower viscosities than the TETA cured epoxies, which made them easier to mix and to cast bubble-free. However, the 6010 and 6020 resins cured with DETA were more brittle than the TETA cured resins, and were difficult to remove from the mold in one piece.

It was virtually impossible to remove the bubbles from the 6010 and 6020 resins cured with TETA at the centrifuge speed used because they were so viscous. They could be centrifuged at a higher speed, but this can cause a problem when the mold is being centrifuged since higher speeds tend to break the glass mold. Other disadvantages of the amine cured epoxies were that they tended to be streaked, and that the mold size was limited since the mold was centrifuged.

Air bubbles were no problem on the PA cured epoxies. They were held at an elevated temperature, and the viscosity was low enough that the bubbles could rise to the surface before the epoxy gelled.

The main problem encountered in casting the phthalic anhydride cured epoxies was finding a suitable mold release. The higher temperature had an adverse effect on all mold releases tried. Hysol AC4-4368 was the one finally used, and it gave satisfactory results only when it was put on the glass and not buffed. This left a rough surface finish on the epoxy, and it had to be polished before it could be used. Another disadvantage of the PA cured systems is that it takes from one to three days for the epoxy to set firmly enough to be removed from the mold. Added to the annealing time, this means that from three to five days are required before the material is ready for use, excluding the time required to prepare a mold.

The annealing process did not show one type of epoxy to have a distinct advantage over any other type in removal of initial stresses. The PA and DETA cured epoxies did have one advantage in that they did not change color as much as the TETA cured epoxies during annealing. The 6010 resin cured with DETA remained exceptionally clear, and the 502 resin and TETA hardened epoxy turned a relatively dark amber color. The other epoxies did not show much variation in color, and all fell between the two extremes.

Machinability

All the materials tested in this investigation had surprisingly good machining characteristics. None of them tended to chip at the edges, even when sawed. Some of the epoxies were easier to machine, since there seemed to be some difference in hardness. The PA cured epoxies and the epoxies with Araldite 502 resin were the best from a

machinability standpoint. The group with slightly poorer machinability contained the Araldite 6010 and 6020 resins cured with DETA and TETA hardeners.

Photoelastic Properties

The data taken in the variable strain rate test are shown in Tables 1, 2, and 3. The results shown are the average values of either two or three specimens of each type of epoxy loaded to failure at each loading speed. All tests were made at room temperature, which varied from approximately 70°F to 80°F.

There is a considerable variation in tensile strength among the different types of epoxies. The PA cured systems had greater tensile strengths, and also had a larger linear stress-strain region. The Araldite 502 epoxy resin was weaker in every case than the Araldite 6010 and 6020 resins. Apparently the plasticizer in the 502 resin improves the machinability, but at the expense of the strength properties. The tensile strength and linear stress-strain region generally increased with increasing strain rate.

None of the materials proved superior to another as far as material fringe value is concerned. All the epoxies were sensitive in that they had low material fringe values; also, there was little variation in this property among the different types. This property is very important for a material to be used for dynamic investigation, and a graph of material fringe value versus strain rate is shown in Figures 4, 5, and 6. Although all the epoxies are sensitive, the PA

TABLE 1

RESULTS OF VARIABLE STRAIN RATE TESTS FOR ARALDITE 502

Material	Strain Rate $\frac{\text{in.}}{\text{min.in.}}$	Tensile Strength $\frac{\text{lb.}}{\text{in.}^2}$	Modulus of Elas. $\frac{\text{lb.}}{\text{in.}^2} \times 10^5$	Linear Stress Strain Region $\frac{\text{lb.}}{\text{in.}^2}$	Fringe Value $\frac{\text{lb.}}{\text{in.fr.}}$
502-10pph TETA	.006	8125	3.16	4210	68.2
	.033	8613	2.93	4130	70.6
	.226	10911	2.59	5980	77.6
	.404	10380	2.99	5920	81.1
502-10pph DETA	.012	8455	1.67	4505	67.1
	.050	9710	2.21	5191	76.0
	.167	9950	2.72	6155	76.8
	.510	10625	2.33	6210	79.2
502-42pph PA	.006	10385	3.85	5230	69.9
	.064	8980	1.60	4905	65.1
	.320	9030	2.06	6235	74.4
	.680	10485	1.80	5480	68.7
502-10pph TETA cured 4 hours at 215°F					
502-10pph DETA cured 6 hours at 215°F					
502-42pph PA cured 4 hours at 250°F					

TABLE 2

RESULTS OF VARIABLE STRAIN RATE TEST FOR ARALDITE 6010

Material	Strain Rate $\frac{\text{in.}}{\text{min.in.}}$	Tensile Strength $\frac{\text{lb.}}{\text{in.}^2}$	Modulus of Elas. $\frac{\text{lb.}}{\text{in.}^2} \times 10^5$	Linear Stress Strain Region $\frac{\text{lb.}}{\text{in.}^2}$	Fringe Value $\frac{\text{lb.}}{\text{in.fr.}}$
6010-10pph TETA	.010	11575	2.38	6120	66.9
	.039	10675	3.13	5275	63.7
	.295	12640	2.20	6630	72.1
	.371	11700	3.18	7150	71.0
6010-10pph DETA	.008	11875	3.02	5785	71.3
	.042	8085	1.91	5270	57.7
	.221	12043	2.73	6770	72.6
	.280	12140	4.03	6750	73.8
6010-55pph PA	.008	11175	3.27	7640	72.0
	.040	13900	2.26	8370	67.0
	.195	14400	3.12	8655	69.1
	.448	12235	3.39	9640	73.1
6010-10pph TETA cured 6 hours at 215°F					
6010-10pph DETA cured 4 hours at 215°F					
6010-55pph PA cured 4 hours at 250°F					

TABLE 3

RESULTS OF VARIABLE STRAIN RATE TEST FOR ARALDITE 6020

Material	Strain Rate $\frac{\text{in.}}{\text{min.in.}}$	Tensile Strength $\frac{\text{lb.}}{\text{in.}^2}$	Modulus of Elas. $\frac{\text{lb.}}{\text{in.}^2} \times 10^5$	Linear Stress Strain Region $\frac{\text{lb.}}{\text{in.}^2}$	Fringe Value $\frac{\text{lb.}}{\text{in.fr.}}$
6020-12pph TETA	.009	10510	2.33	5090	74.0
	.045	12350	2.60	6465	78.0
	2.30	12840	2.64	5770	77.5
	.410	12950	2.72	6000	72.6
6020-12pph DETA	.008	10510	2.56	4615	70.4
	.047	11360	2.45	5290	72.5
	.229	12373	2.87	6370	72.2
	.478	11366	2.59	6200	77.8
6020-50pph PA	.006	12350	4.06	7350	77.3
	.017	12400	4.13	8000	77.7
	.146	13500	4.19	8665	78.0
	.342	12400	4.24	9175	81.0
6020-12pph TETA cured 6 hours at 215°F					
6020-12pph DETA cured 6 hours at 215°F					
6020-50pph PA cured 4 hours at 250°F					

cured material has the advantage of less change in material fringe value with different strain rates.

The values for the modulus of elasticity proved to be rather erratic. There was even a considerable variation among different specimens of the same material tested at the same strain rate. However, the modulus of elasticity did show a general tendency to increase with increasing strain rate. This increase was expected because at higher strain rates the material does not have time to relax and the stress corresponding to a given strain is higher.

The plot showing material fringe value versus strain rate agrees closely with data obtained by Clark and Sanford [3]. For instance, they show an increase in material fringe value from 79 lb./in.fr. with static loading to 97 lb./in.fr. at a very high strain rate for Araldite 502 resin cured with ten pph TETA. This change represents an increase in material fringe value of 22.8 per cent as the strain rate increased by a factor of 1,500,000. The results of this investigation gave an increase from approximately 67.5 lb/in.fr. to 82 lb./in.fr. as the strain rate went from a static load to 0.5 in/in./min. This change represented an increase of 21.5 per cent in the material fringe value. The difference in material fringe value with static loading was probably due to the difference in cure. Clark and Sanford used a room temperature cure, whereas the 502 resin cured with TETA used in this investigation was cured for four hours at 215°F. Similar results were obtained for Araldite 6020 cured with PA. Clark and Sanford obtained an 8.1 per cent increase using 45 pph PA, and the results of this investigation gave an increase of approximately

5.2 per cent using fifty pph PA. Both values are over the same respective strain rates as the values for the 502 resin cured with TETA.

The comparison in per cent increase with strain rate indicates that most of the change in material fringe value with strain rate occurs at relatively low values of strain rate. It can be seen from Figures 4, 5, and 6 that the curve flattens out as the strain rate increases and that above a strain rate of about 0.5 in/in./min. the change in material fringe value becomes negligible.

The optical creep constant, β , for each of the epoxies tested is given in Table 4. These values were obtained from the data of Figures 7, 8, and 9 which show fringe order versus time at constant stress. The optical creep constant was checked by computing its value at different values of time, and it proved to give very consistent results. Coolidge [7] shows graphs of fringe order versus time at different values of constant stress for CR-39. The optical creep constant was calculated for each of these curves, and the results consistently gave a value of β of approximately $0.18 \text{ (min.)}^{-1/3}$

Probably the greatest contribution of the optical creep constant is that it gives a definite comparison of optical creep between different photoelastic materials. The optical creep properties of a material are often given in a relative way by stating that the optical creep is high or low. The optical creep constant will actually assign a number to this property. It can also be used to correct the stress-fringe relation after optical creep has occurred. When a material is calibrated it is usually done rather rapidly, and optical

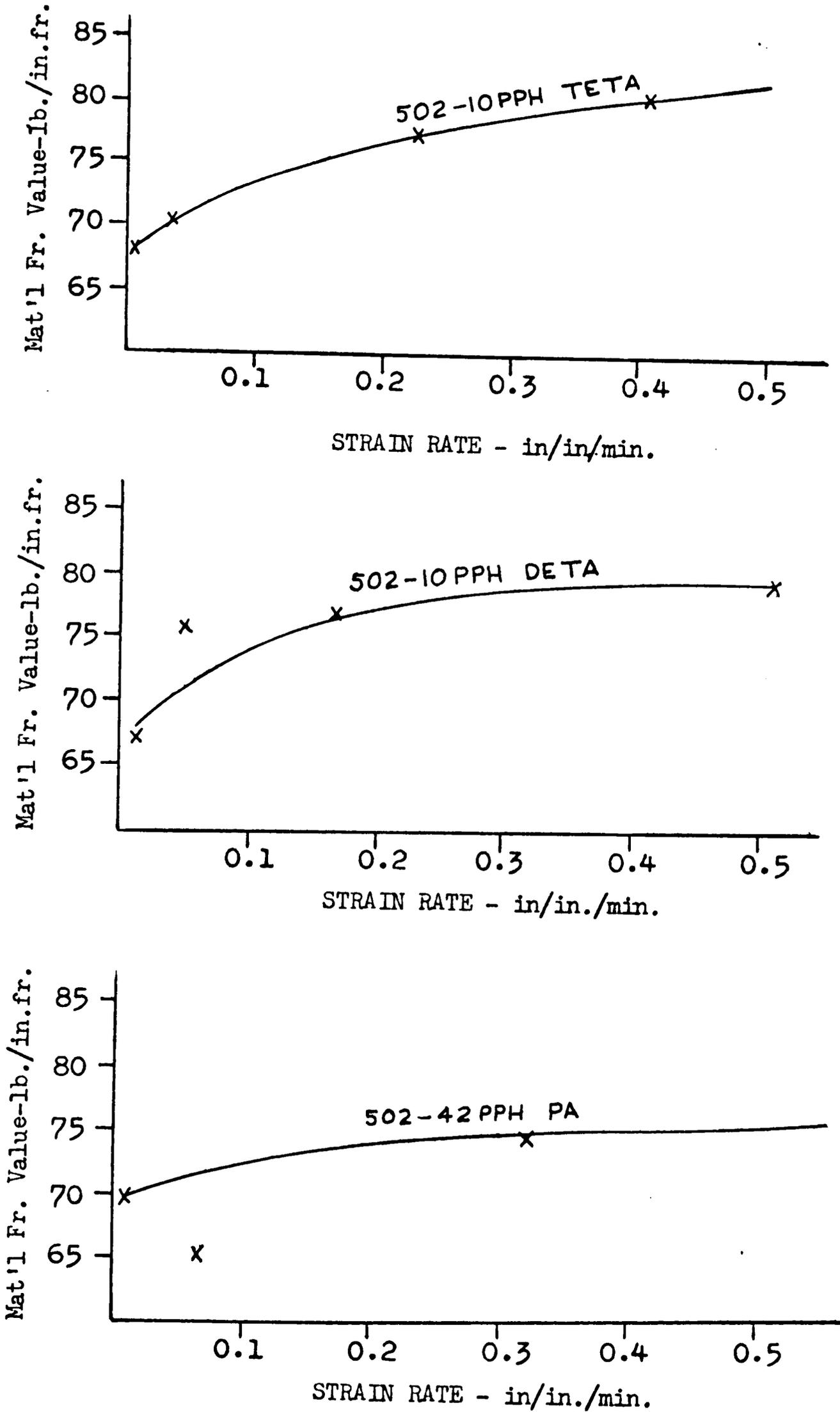


Fig. 4.--Material Fringe Value vs Strain Rate for Araldite 502

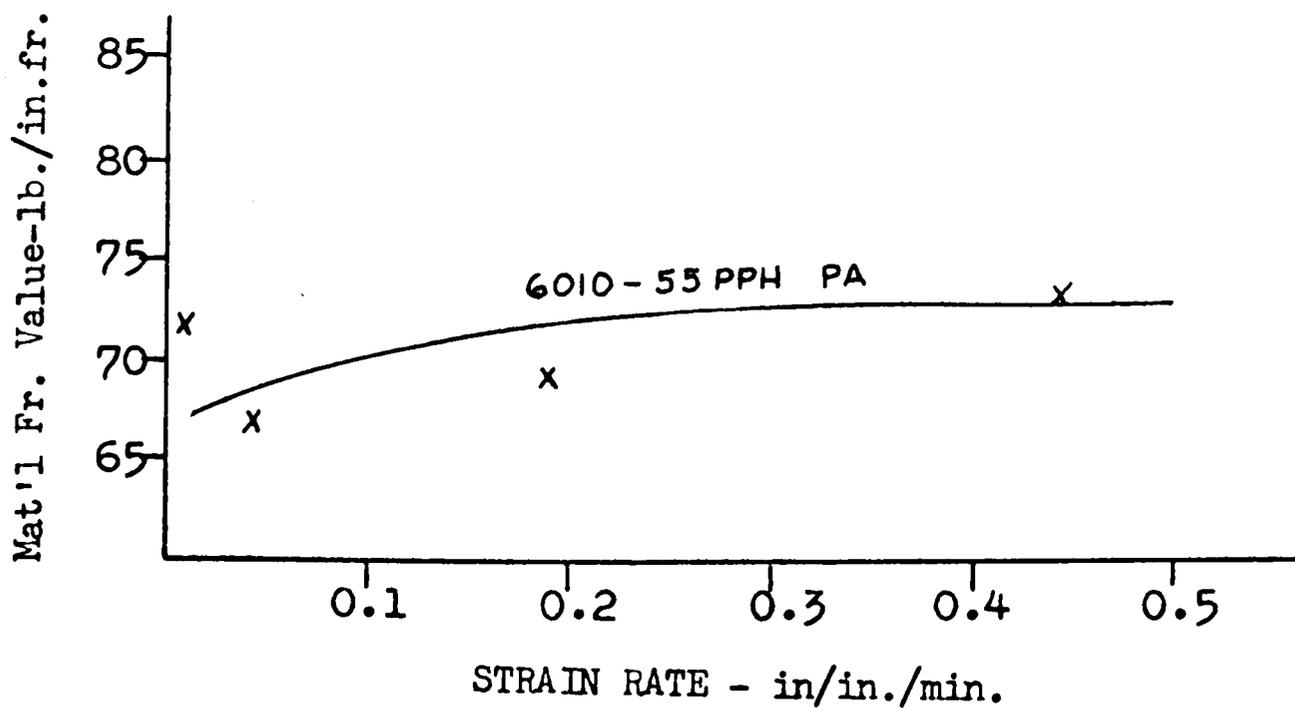
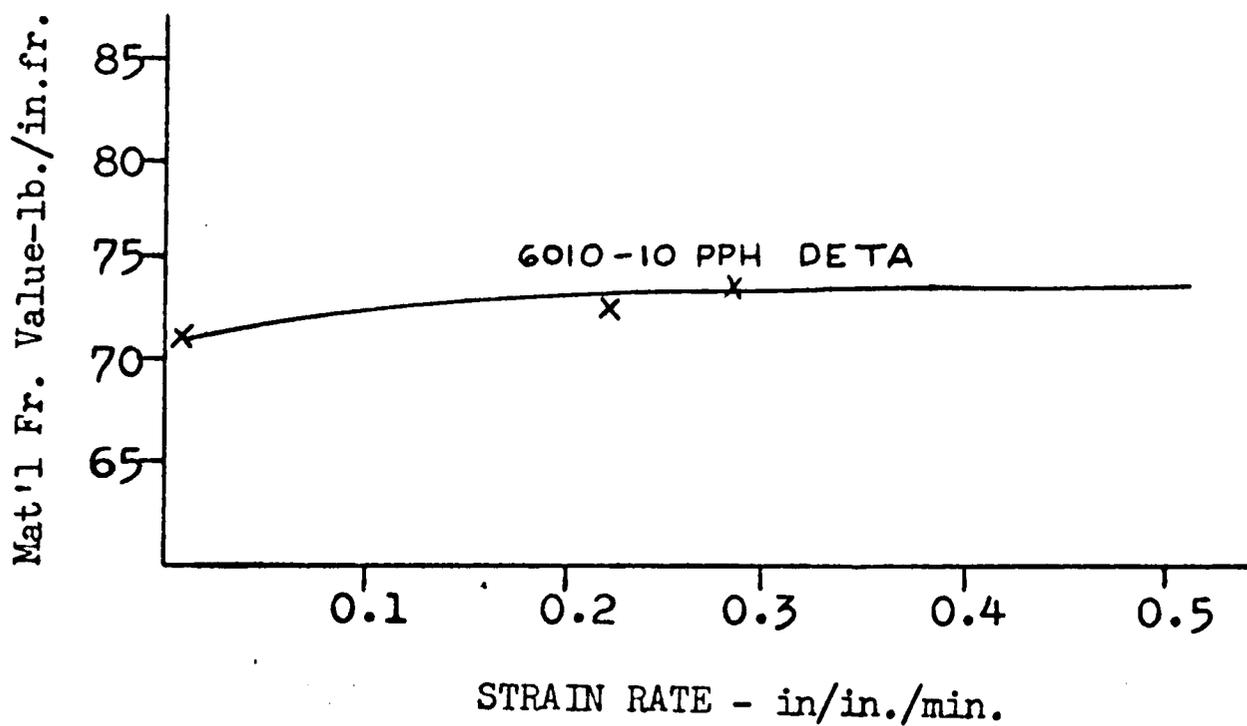
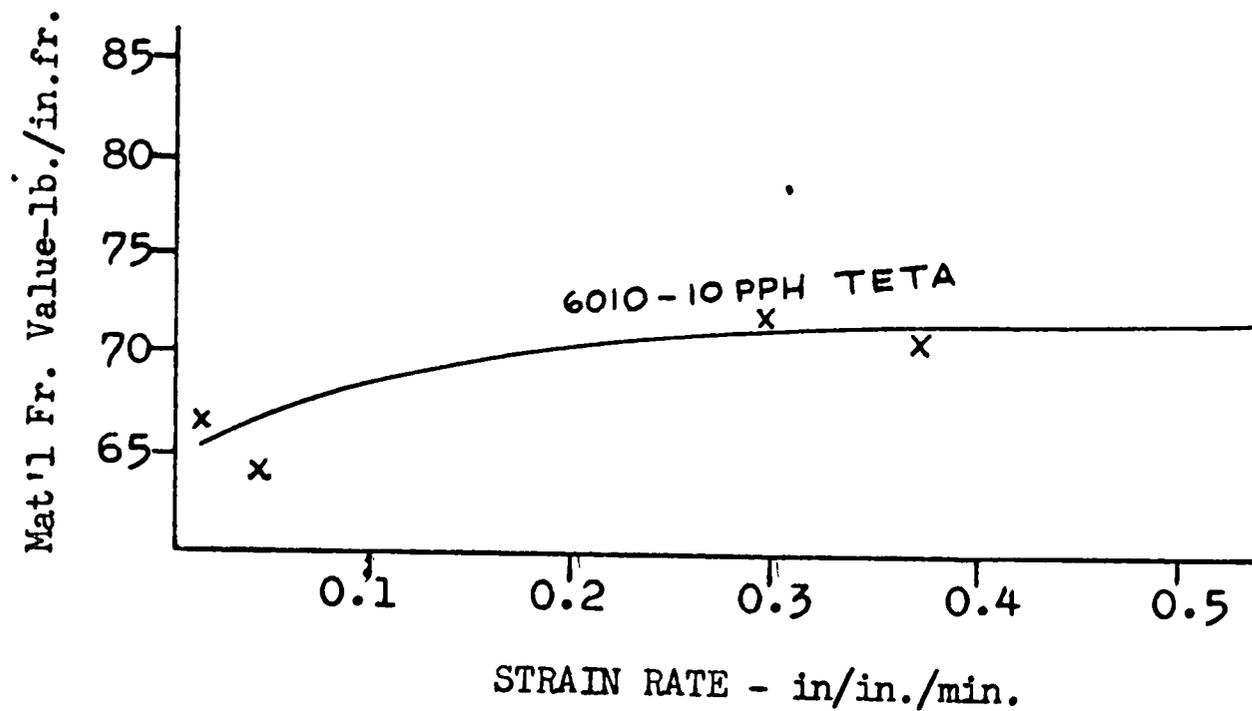


Fig. 5.--Material Fringe Value vs Strain Rate for Araldite 6010

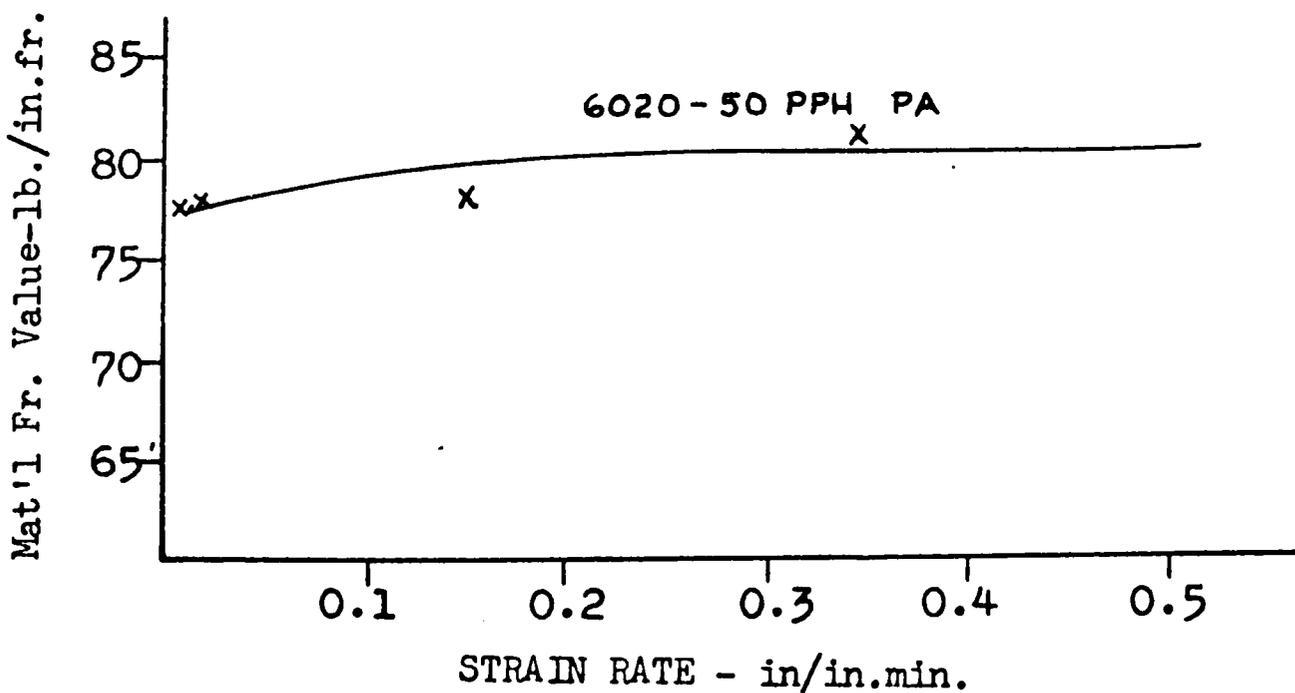
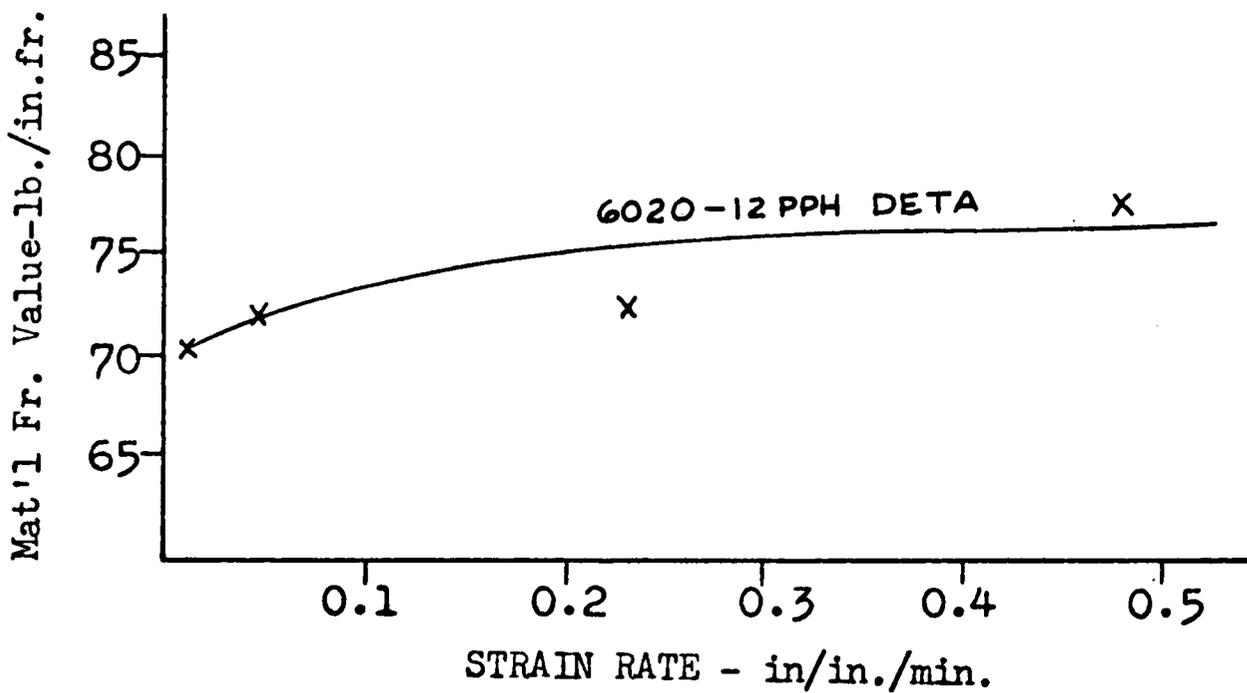
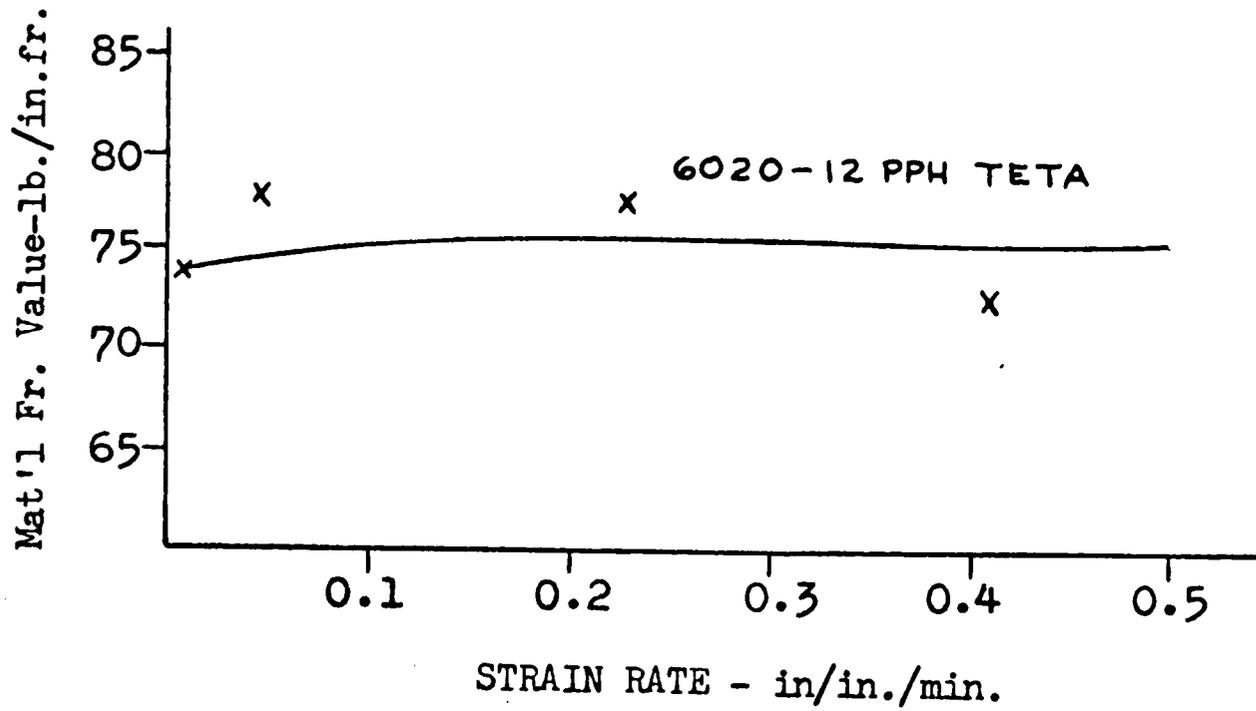


Fig. 6.--Material Fringe Value vs Strain Rate for Araldite 6020

TABLE 4

OPTICAL CREEP CONSTANT FOR MATERIALS TESTED

Material	Optical Creep Constant, min. ^{-1/3} β
502-10pph TETA	.09
502-10pph DETA	.15
502-42pph PA	.22
6010-10pph TETA	.06
6010-10pph DETA	.05
6010-55pph PA	.07
6020-12pph TETA	.06
6020-12pph DETA	.05
6020-50pph PA	.075

TABLE 5

STRESS RELAXATION TIME FOR ARALDITE 502

Material	Stress Relaxation Time, min. θ
502-10pph TETA	635
502-10pph DETA	281
502-42pph PA	123

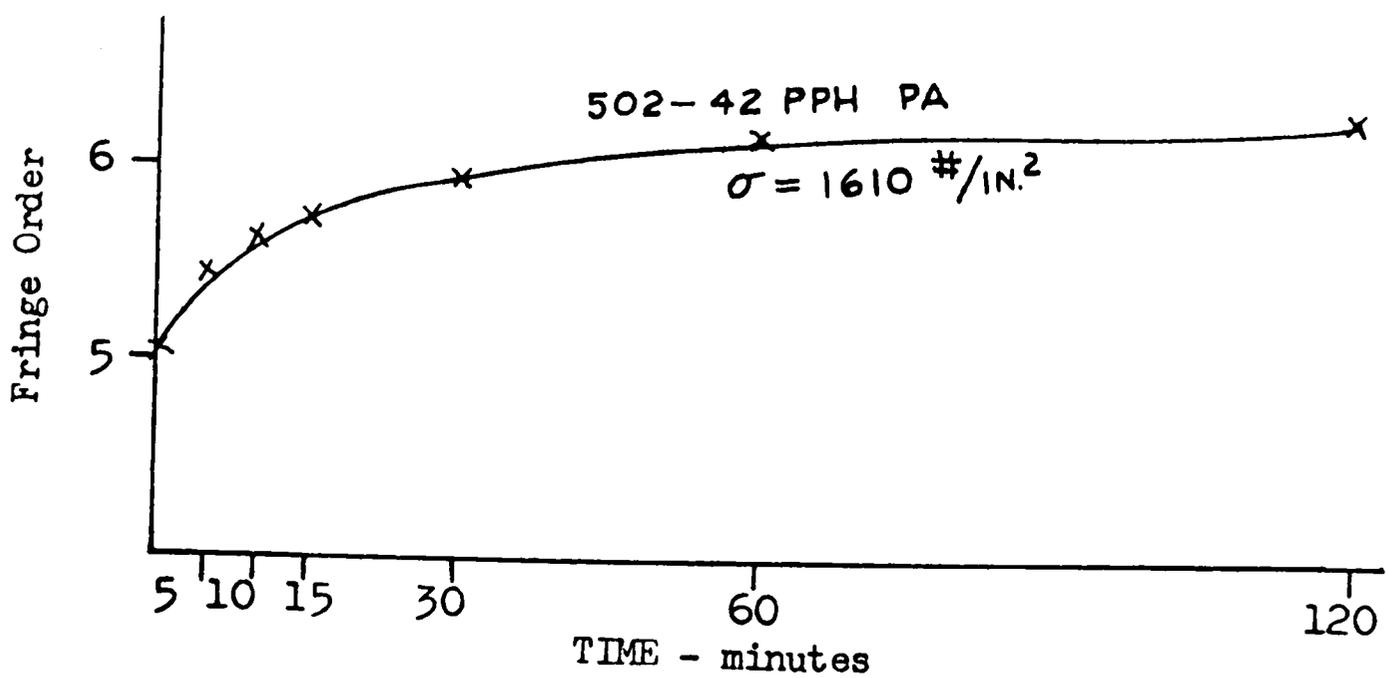
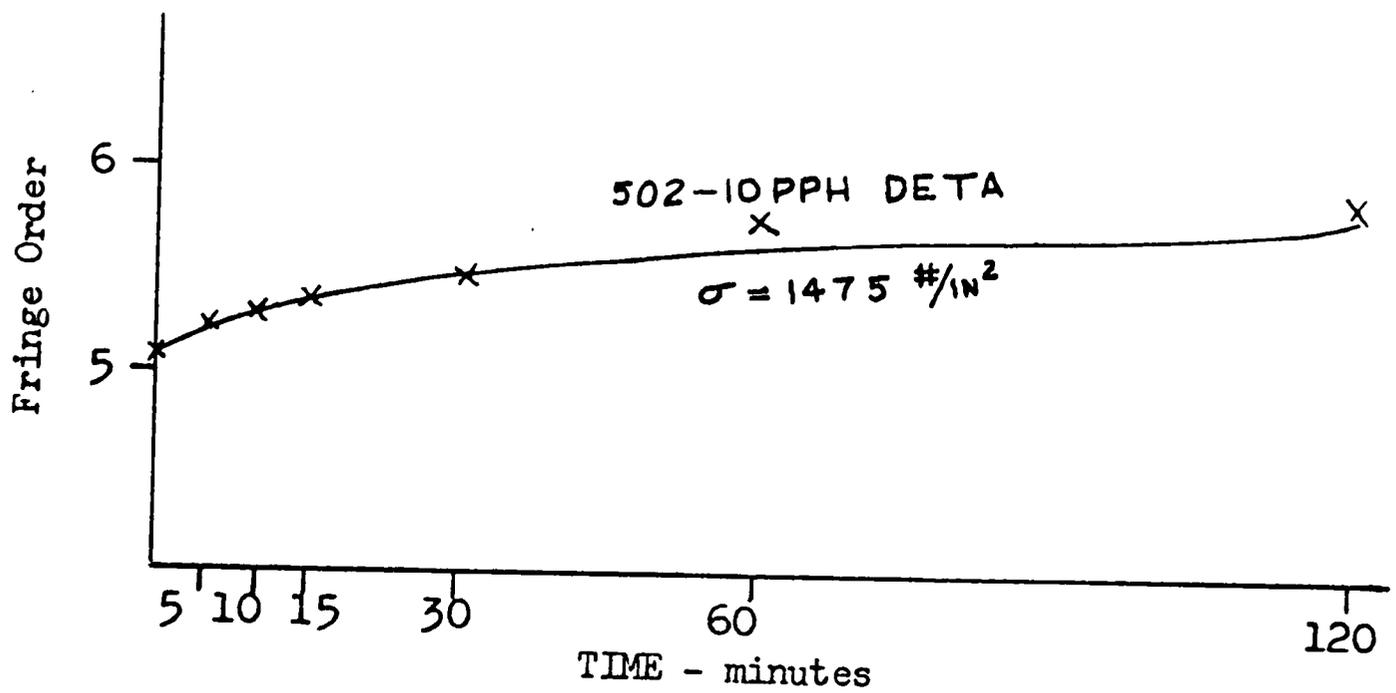
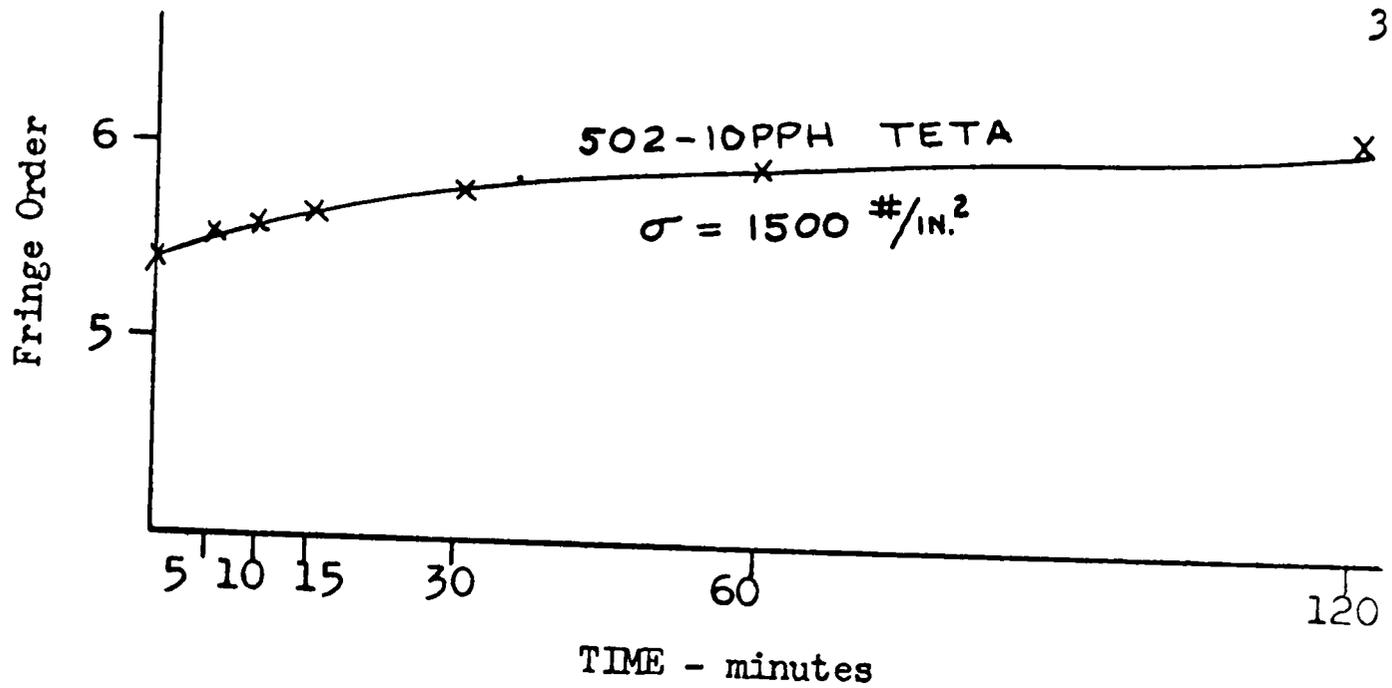


Fig. 7.—Fringe Order vs Time at Constant Stress for Araldite 502

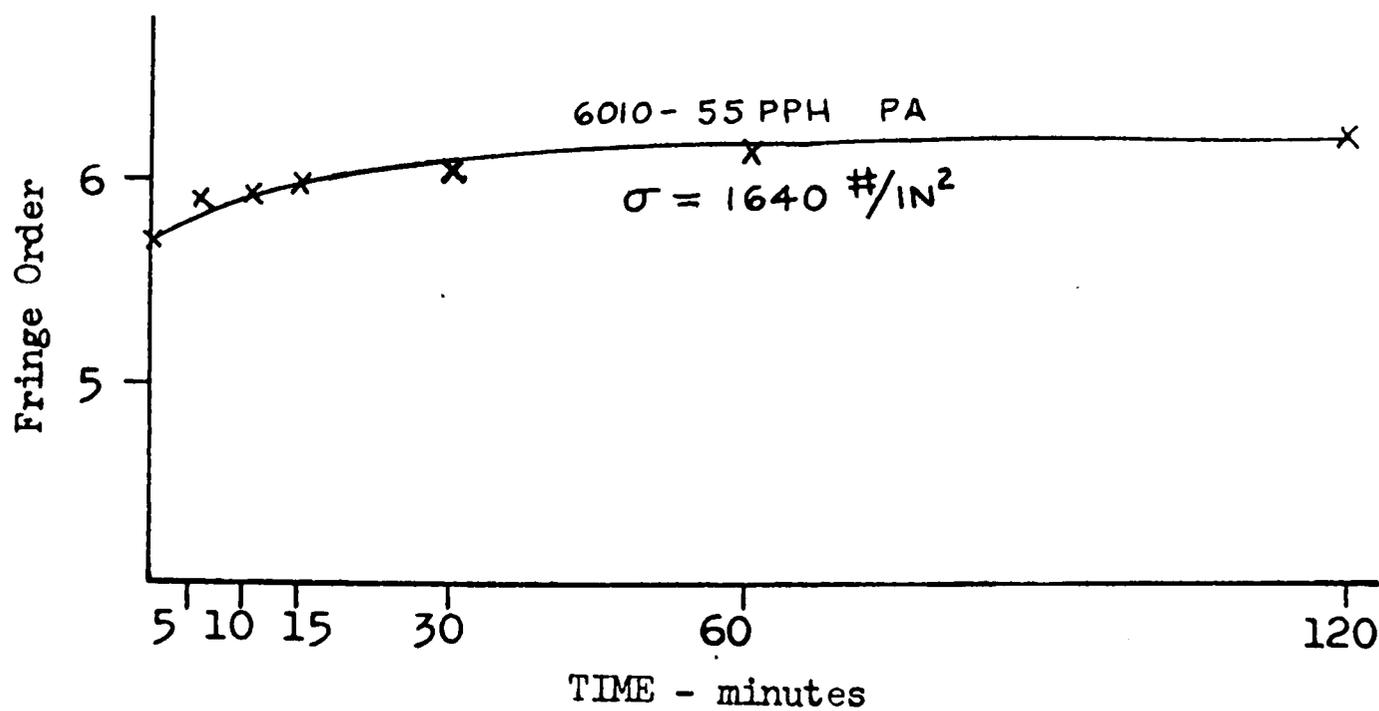
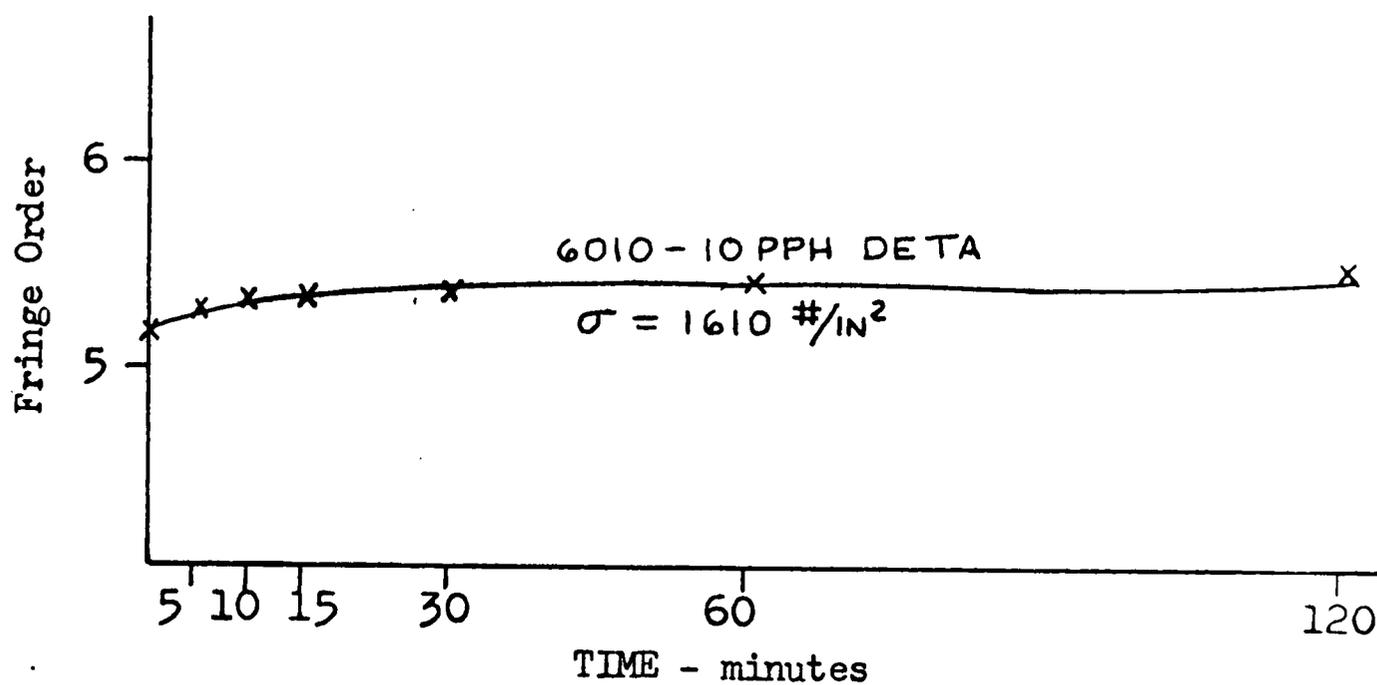
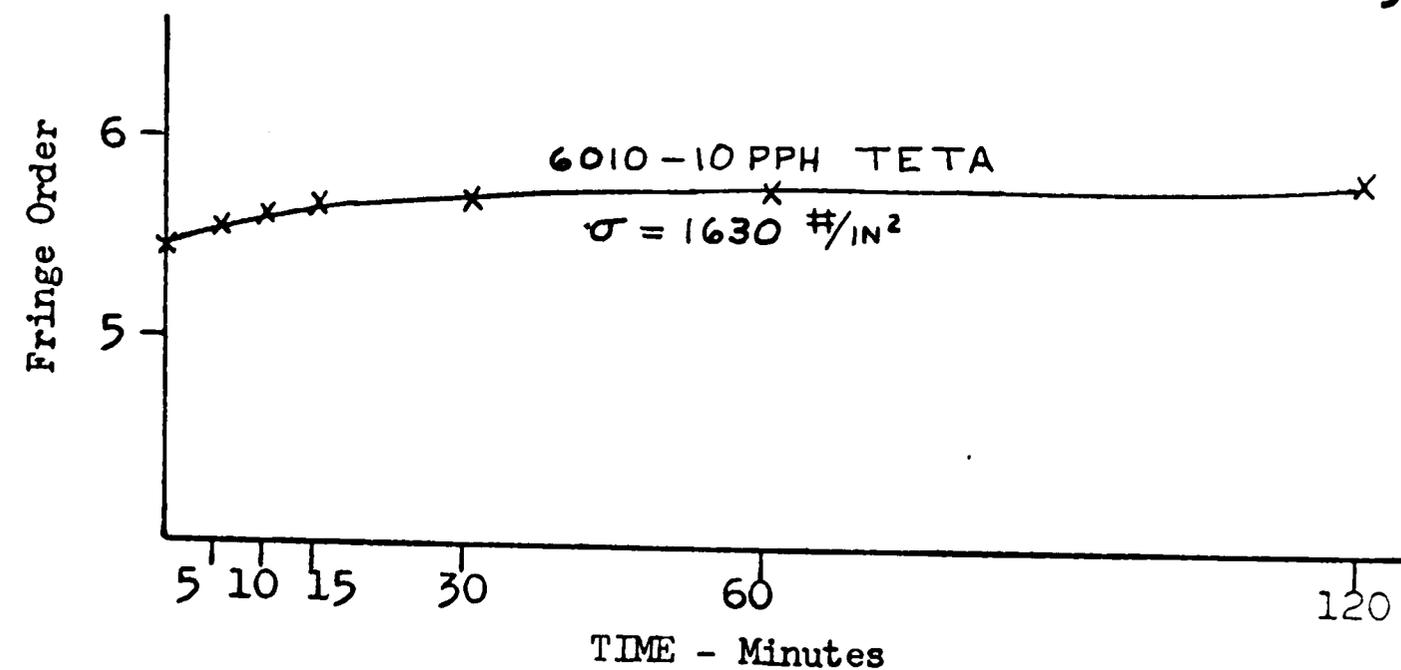


Fig. 8.--Fringe Order vs Time at Constant Stress for Araldite 6010

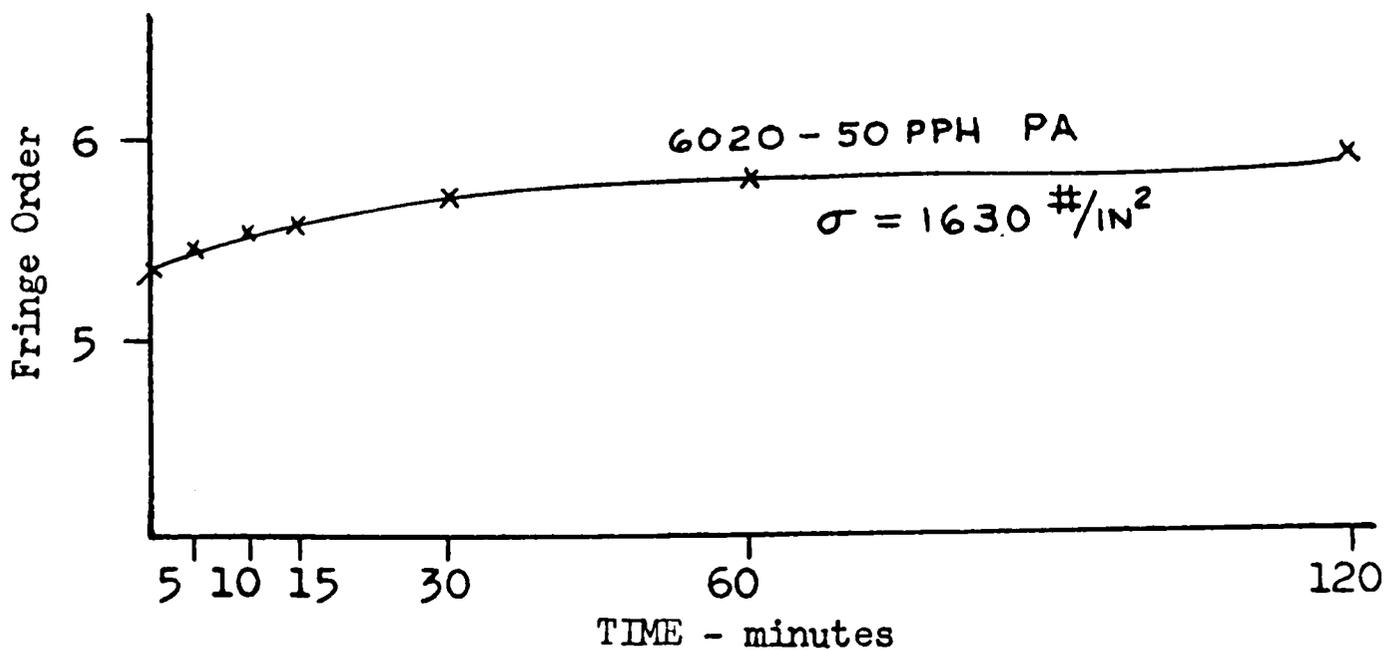
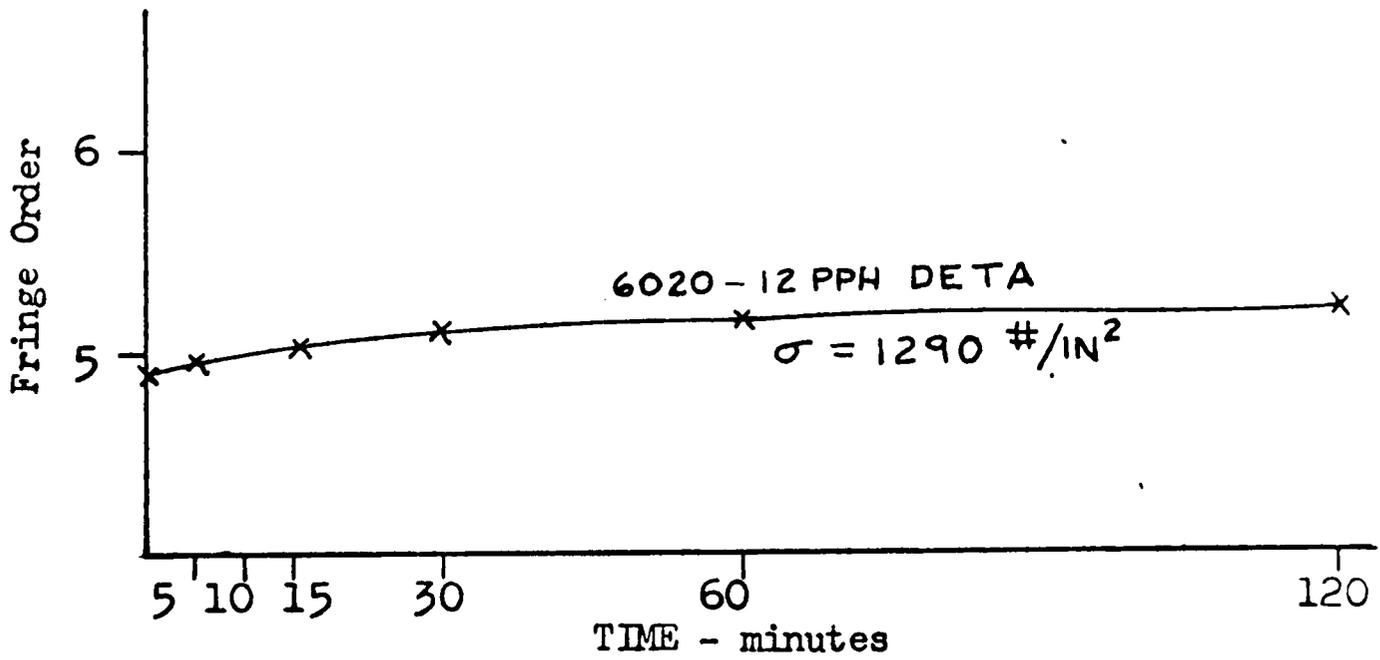
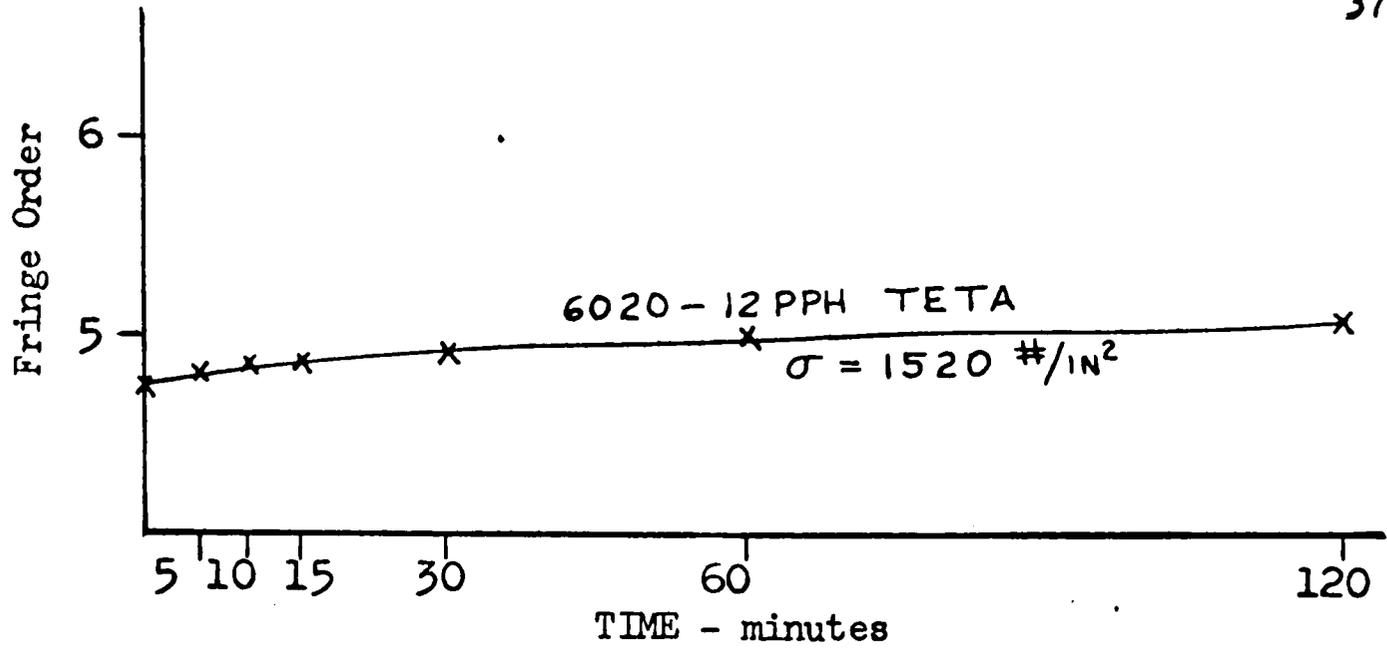


Fig. 9.--Fringe Order vs Time at Constant Stress for Araldite 6010

creep can be neglected. However when the model is loaded it is often fifteen or more minutes before a photograph of the stress pattern is taken. It is then questionable to assume that the stress corresponding to a particular fringe order is the same as it was in the calibration specimen since optical creep will have occurred. With an optical creep constant the fringe order at a point can be projected back to its value just after loading by using Equation 2, thereby giving more accurate results.

It can be seen that the plots of material fringe value versus strain rate and fringe order versus time for a given material are very similar. This similarity suggests the possibility of testing a photoelastic material at constant stress using a static load, and predicting the increase in material fringe value with strain rate. At least, this static load data should give an indication of whether or not the material shows promise of being a good photoelastic material for dynamic loading.

Data taken to determine the stress relaxation time were for Araldite 502 resin cured with each of the three hardeners. The stress relaxation time was difficult to determine for the materials because a very small change in load made a large difference in the stress relaxation time. Figure 10 shows a plot of stress versus time at constant strain for the 502 resin, and the corresponding values of stress relaxation time are given in Table 5. It can be seen from Table 4 and Table 5 that materials with lower optical creep constants have longer stress relaxation times, which leads to the conclusion that materials with low optical creep constants are the best for both

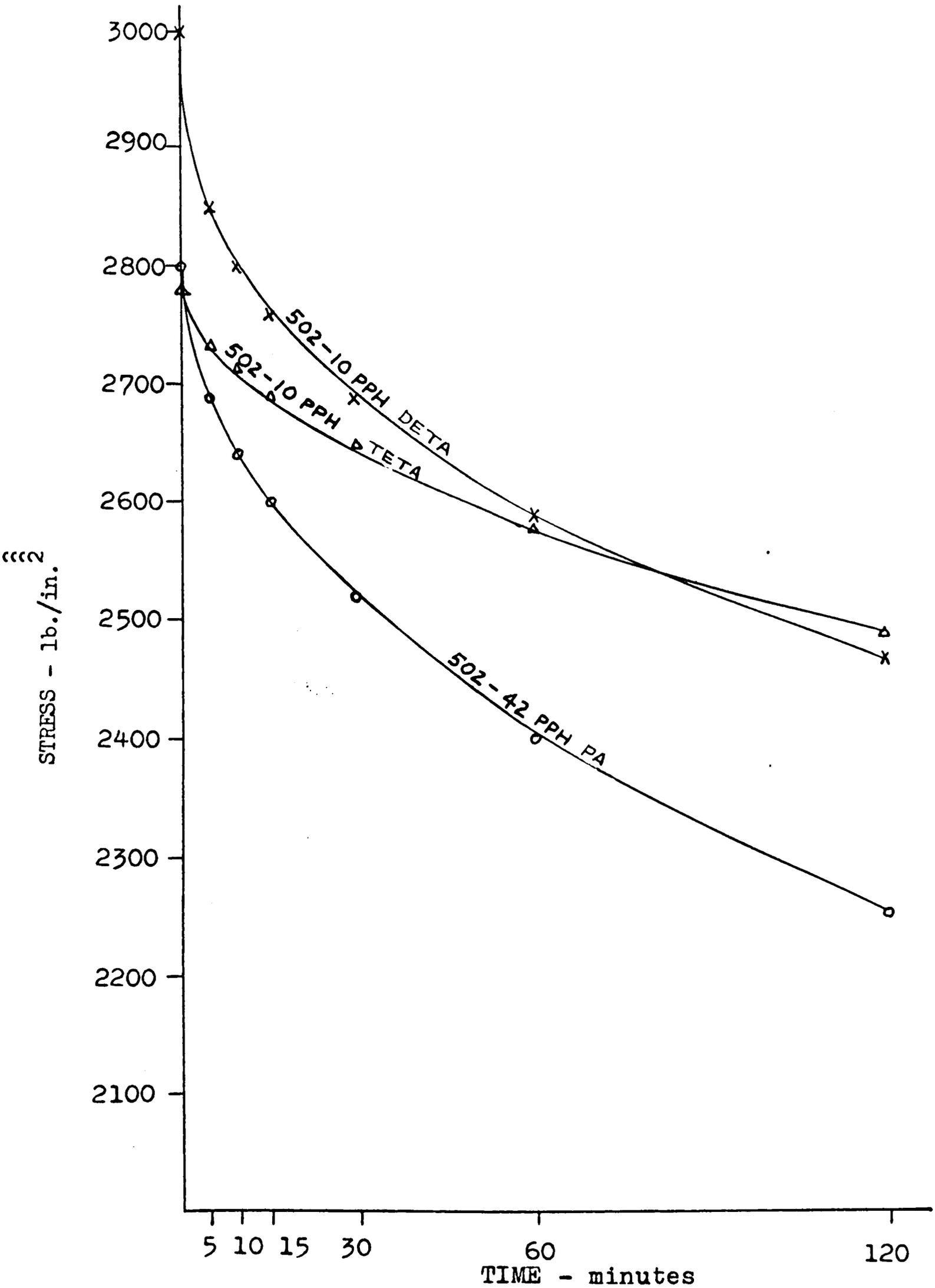


Fig. 10.--Stress vs Time at Constant Strain for Araldite 502

constant stress and constant strain loading as far as introducing errors in photoelastic test results.

The difference in the linear stress-retardation region for the various epoxies is shown in Figures 11, 12, and 13. These curves are the result of statically loading the specimens in the Dillon testing machine, observing the fringe in a standard polariscope, and recording the corresponding load. The strain rate was not constant, and the loading time to twenty-five fringes varied from five to ten minutes. These curves show that for each resin there is little difference between the DETA and TETA cured systems, and that they both have a shorter linear stress-retardation region than the corresponding PA cured material.

All values presented can be taken only as typical values. There are so many variables controlling the properties of epoxy plastics that definite values can not be given. There is a large variation between different batches of the same epoxy resins and hardeners. Also, the properties are very dependent on the exact amount of hardener used to cure the resin, and the curing time and temperature the material is given.

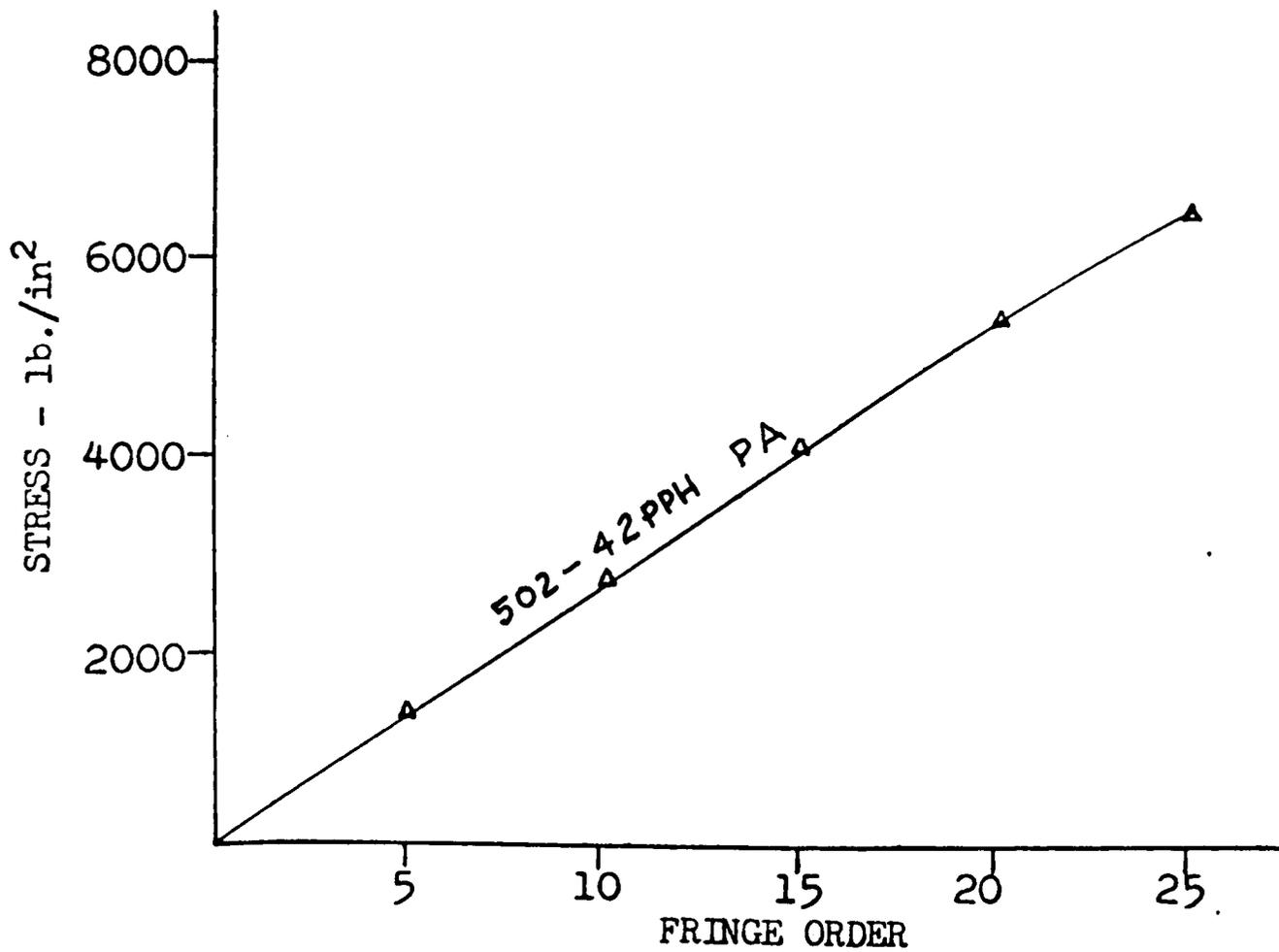
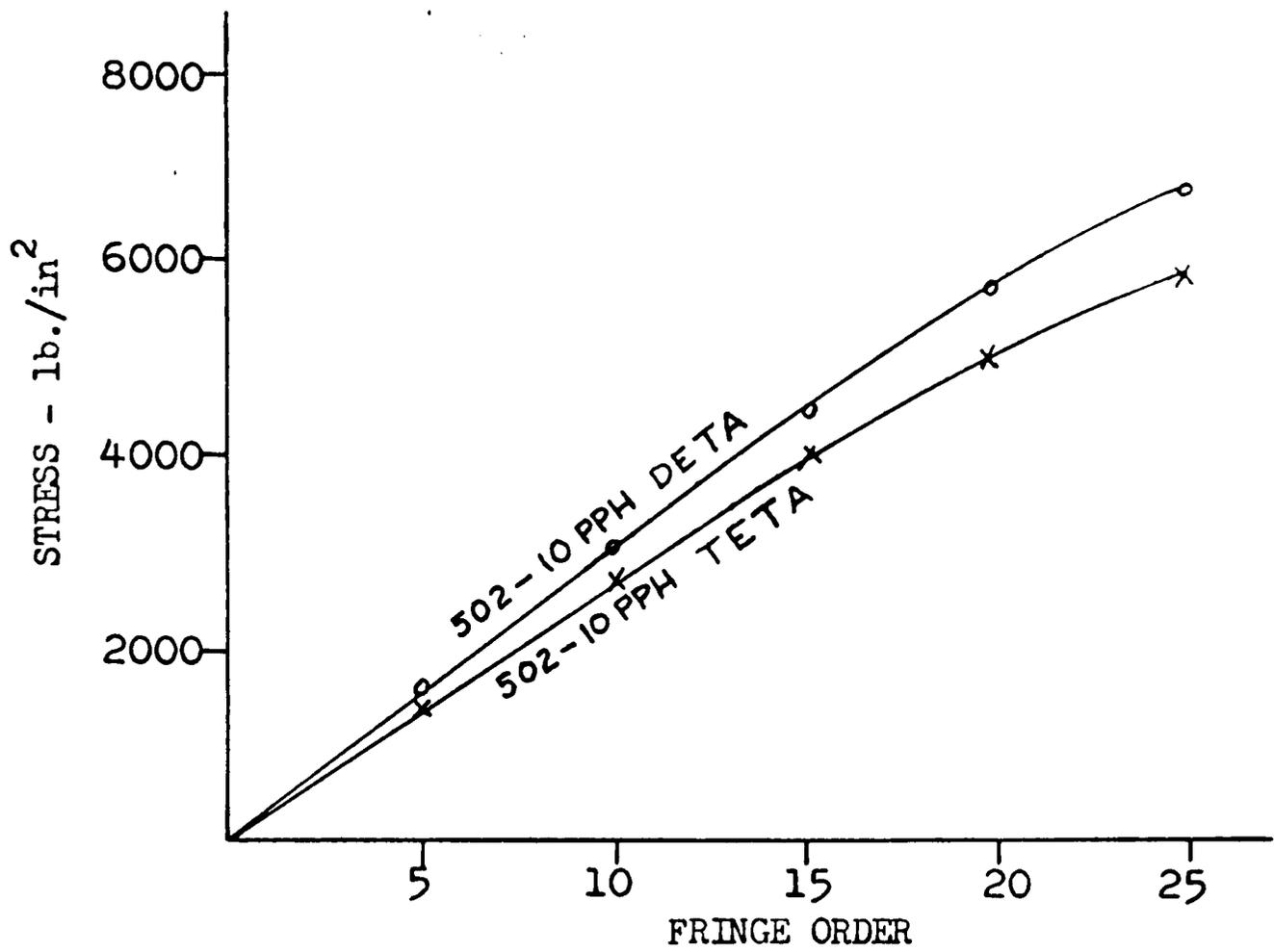


Fig. 11.--Stress vs Fringe Value for Araldite 502

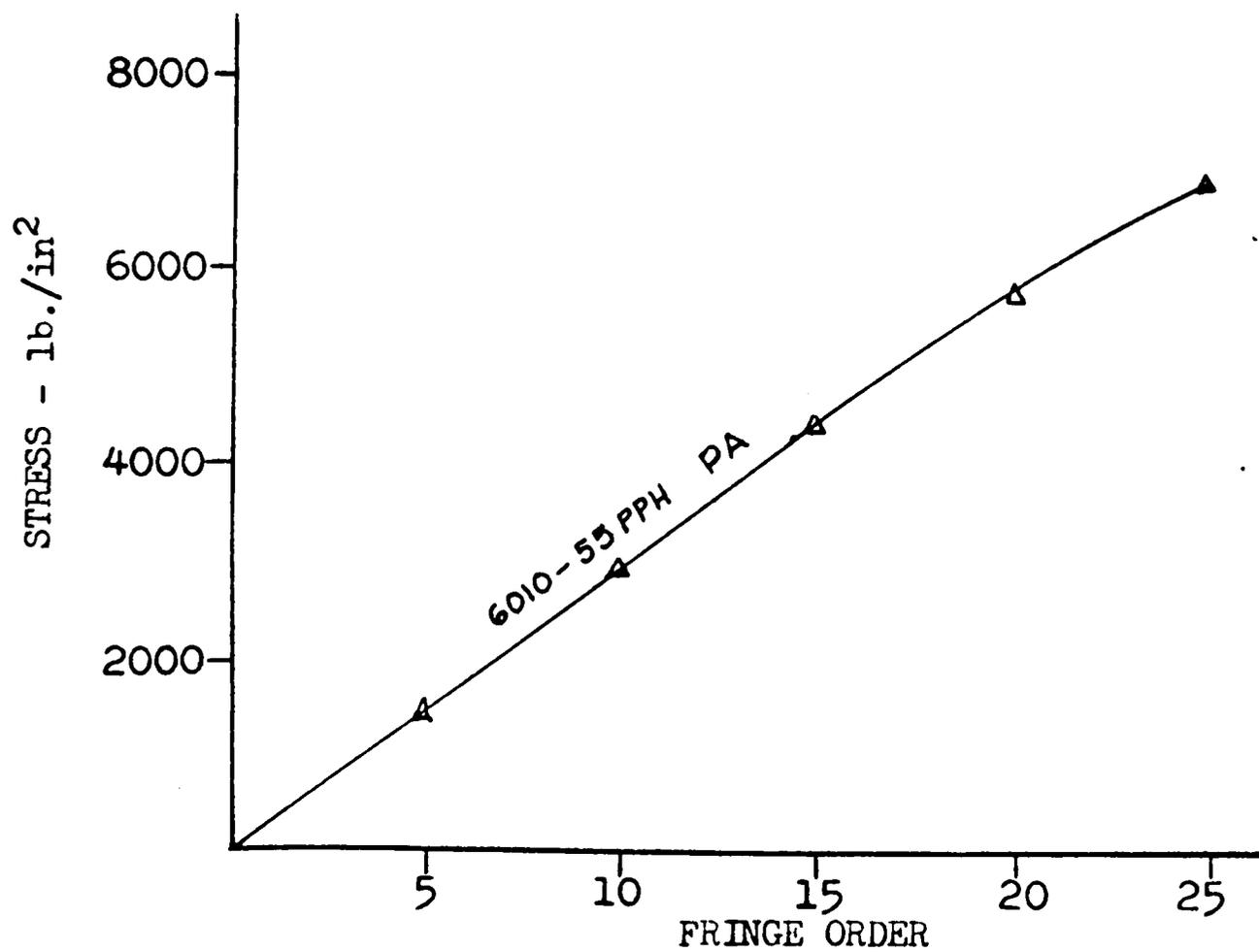
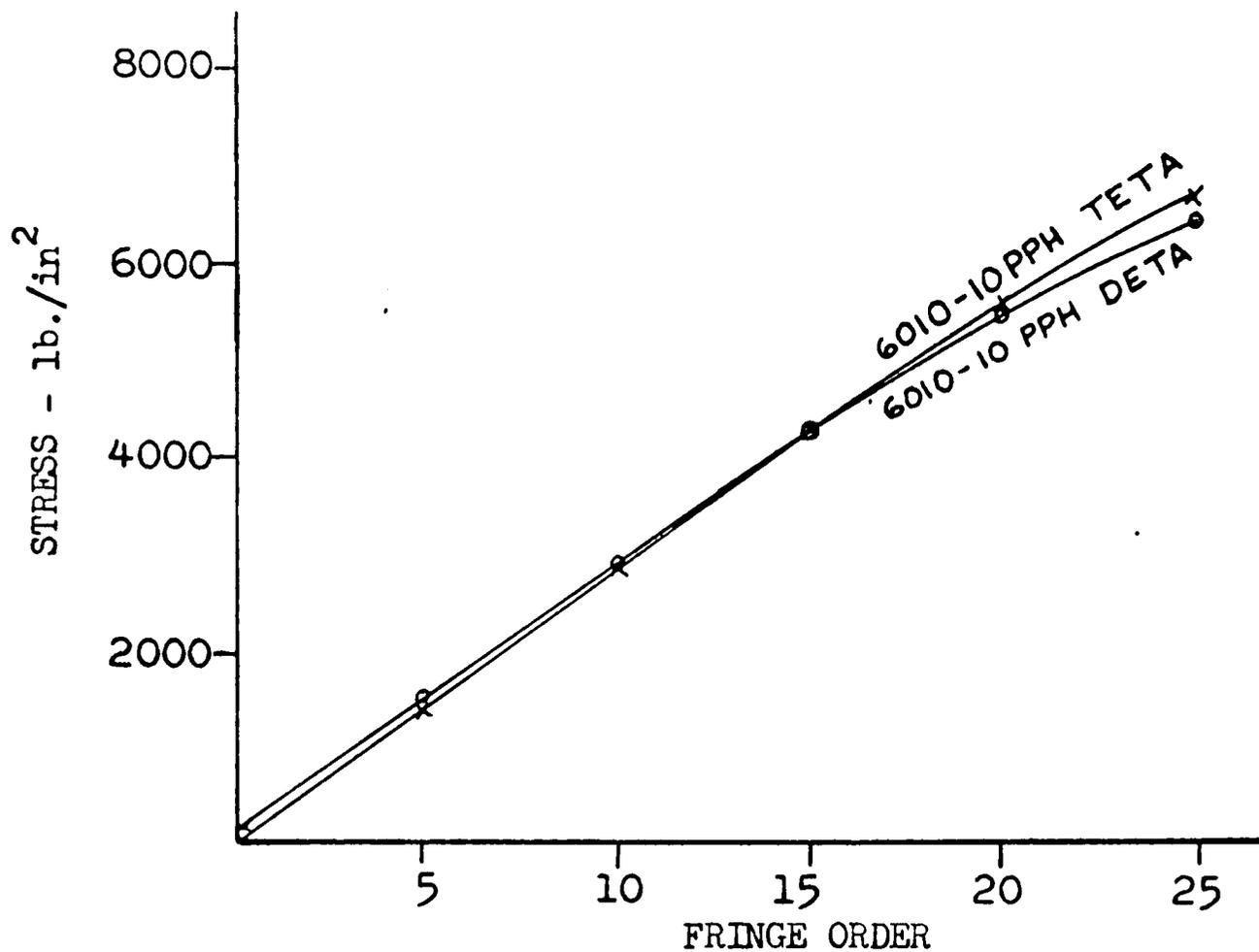


Fig. 12.--Stress vs Fringe Value for Araldite 6010

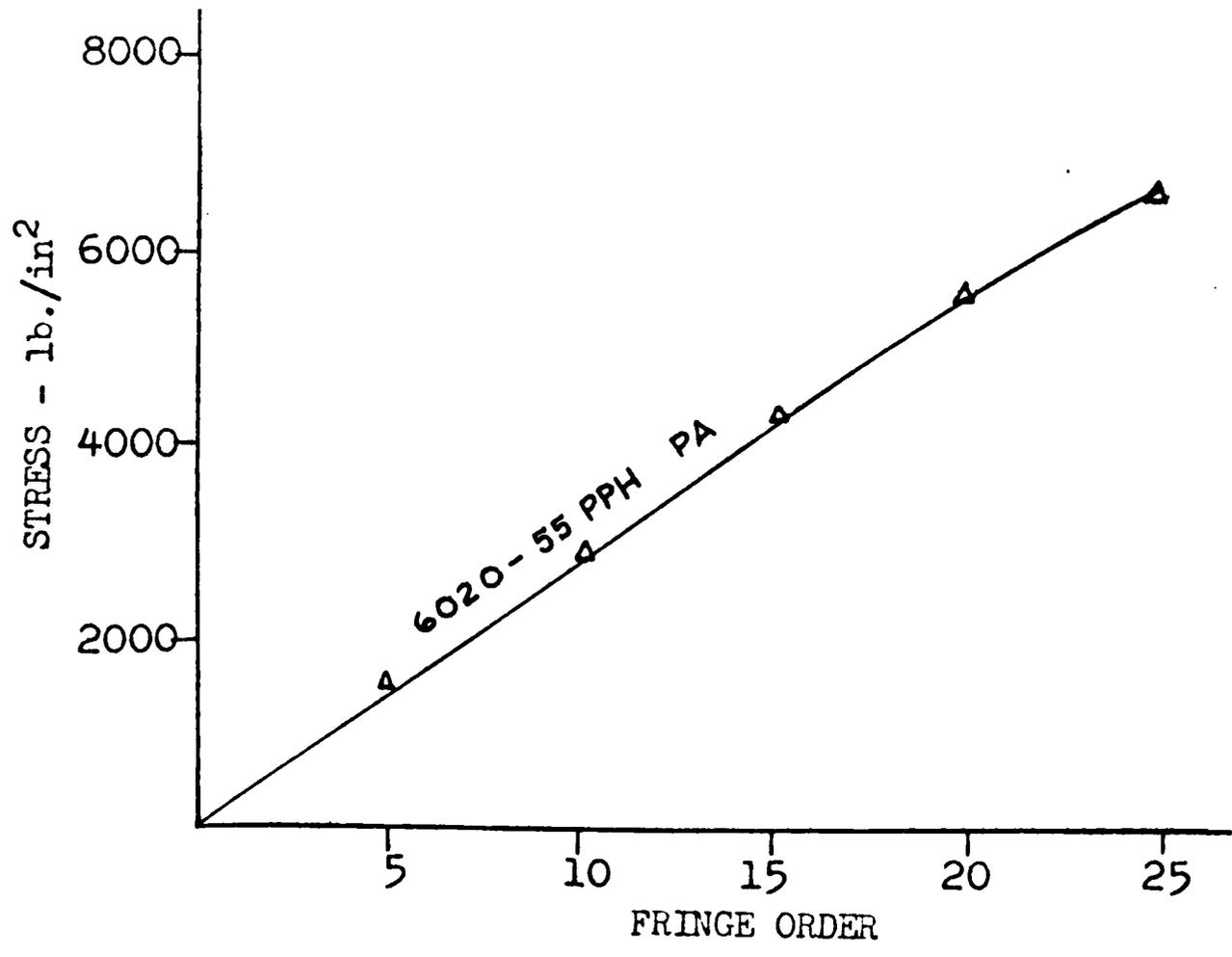
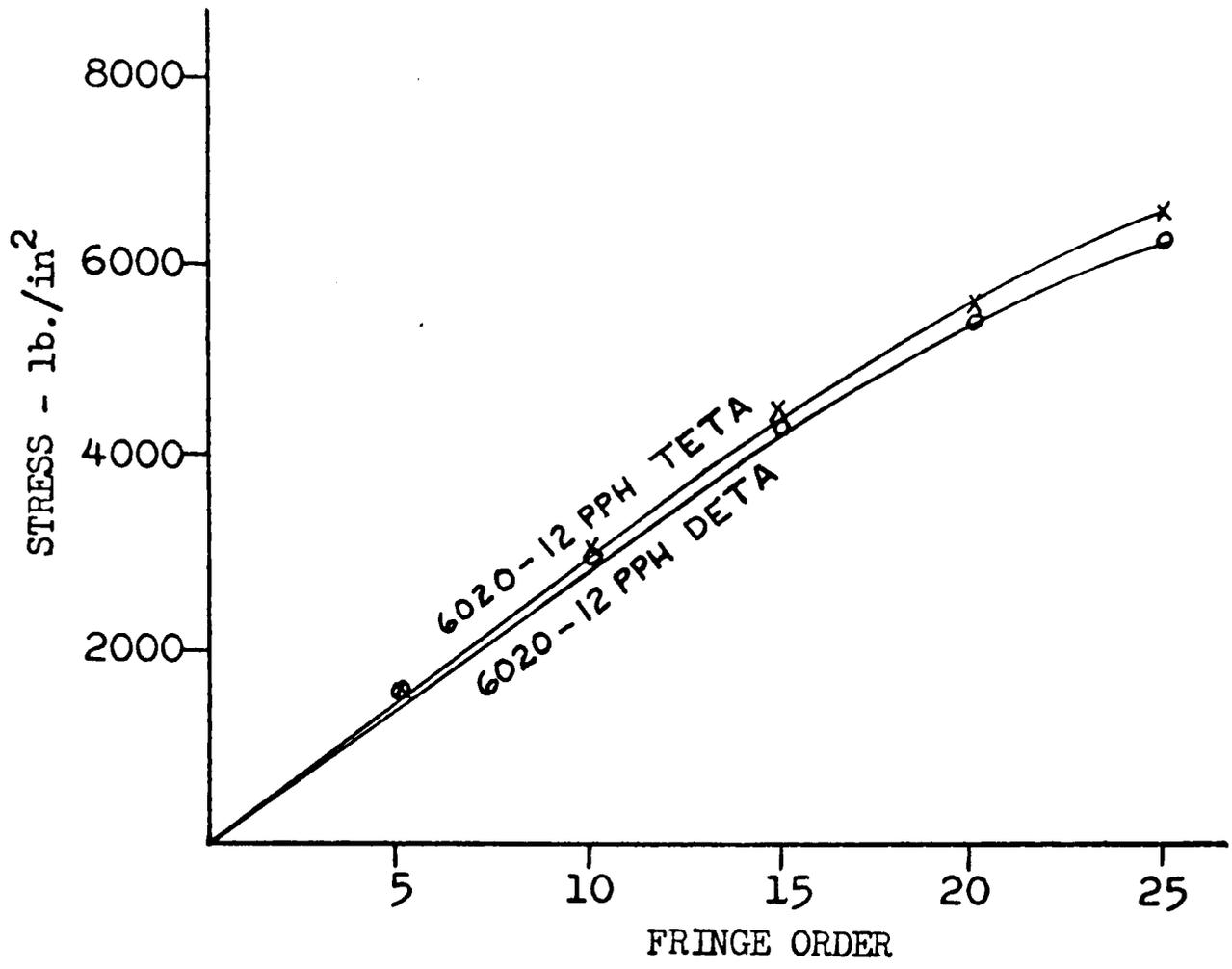


Fig. 13.--Stress vs Fringe Value for Araldite 6020

CHAPTER IV

CONCLUSIONS

As far as photoelastic properties are concerned, the only epoxy which would not make a suitable material for photoelastic tests is Araldite 502 cured with phthalic anhydride, which has a high optical creep rate. Two of the epoxies, Araldite 6010 and 6020 cured with TETA, have poor casting properties. The 6010 and 6020 resins have high viscosities, and are difficult to mix and cast without trapping air bubbles.

There is no particular advantage among the remaining epoxies. Araldite 6010 and 6020 resins have very similar properties when cured with the same hardener, but 6010 resin has the advantages of having a lower viscosity and forms an epoxy with a slightly lower material fringe value. Araldite 502 cured with TETA and DETA has a greater increase in material fringe value with increasing strain rate than the other materials, and they also have slightly higher optical creep constants than the remaining epoxies.

The remaining choices are Araldite 6010 cured with DETA hardener and with PA hardener. The 6010 cured with PA has a greater tensile strength, and a larger linear stress-retardation and stress-strain region than the 6010 cured with DETA. It can be cast in large sheets since it has a low exotherm, and it does not have to be centrifuged to remove the air bubbles. It also has slightly better machining characteristics than the DETA cured epoxy, and according to Leven [2] the PA cured epoxies have less time-edge effect than the epoxies

cured with other hardeners. On the other hand, the 6010 cured with DETA has a smooth surface finish, is very transparent, and takes less time to cast. Everything considered, the 6010 resin cured with PA is probably the best epoxy for photoelastic use if the casting is being done in the laboratory. It is slightly more difficult to cast than the DETA cured resin, but the casting is generally better and the PA cured resin also has better photoelastic properties.

The casting procedure is difficult for all the epoxies investigated. It is probably worth the difference in price to use the epoxy sheets which can be bought in pre-cast sheets. Hysol resin R9-2053 cured with hardener H5-3401 has properties similar to Araldite 6020 cured with PA [9], and can be obtained in the pre-cast sheets. This epoxy has all the advantages of the Araldite 6020 cured with PA, and also has a smooth surface finish.

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