Mechanical Properties of F.R.P.


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Abstract

Two factors affect the mechanical properties of fiber glass-reinforced plastics (F. R. P.) : (1) Glass volume fraction ; (2) The configuration of glass filled. There are hardly any published analyses of the relation between these factors and the mechanical properties of F.R.P.

This article investigates the relation between glass volume fraction and Young’s modulus of F. R. P. in two different kinds of specimens—one, F. R. P. filled with glass particles; the other, F. R. P. reinforced with glass cloth—selected because they are the simplest of the various configurations of glass fiber with which F. R. P. is filled and because they differ radically from each other in shape.

The article analyzes experimental results according to the isotropic non-homogeneous elastic theory and by means of mechanical models of the two-composite system. The model used in calculating experimental results on the F. R. P. reinforced with glass cloth was a new, modified model.

The relation of Young’s modulus to glass volume fraction, obtained from experimental results, agrees well with results calculated from the models. The relation between the dynamic modulus of F. R. P. and glass volume fraction below 10% is derived from the models at a temperature approximating the glass temperature of resin.

1. Introduction

Glass fiber reinforced plastics (F. R. P.) are in increasing demand as industrial materials and have touched off researches into their mechanical behaviors. However, the relation between the glass content and the mechanical properties of F.R.P. still await theoretical clarification.

Also awaiting full theoretical study is the bearing of the state of assembly shape of glass fiber, such as glass cloth and roving mat, on the mechanical behaviors of F.R.P.

We have investigated the relation between the glass content and Young’s modulus by using two kinds of materials: one, F.R.P. composed of polyester resin and glass particles; the other, F. R. P. consisting of polyester resin and glass cloth.

We have analyzed the experimental results by using various mechanical models, and hit upon a useful model which expresses the mechanical properties of F.R.P.

2. Method of Experiment

The following materials were used in our experiment:

Resin: polylight 8200 (styrene content 37%, density 1.22 g/cc)
Promotor: naphthenic acid-cobalt.
Catalyst: methyl ethyle ketone peroxide.
Filler: glass fiber smashed into minute particles and filtered through 165 mesh wire-network (the smashed particles being 0.02mm in average diameter and 0.14mm in average length).

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Armature: three kinds of plain weaves composed of glass fibers. The plain weaves were numbered G-1, G-2 and G-3 and were of the following densities and gravities:

G-1: density 2.60 g/cc, 44 picks/in.
G-2: density 2.60 g/cc, 35 picks/in.
G-3: density 2.60 g/cc, 19 picks/in.

All the glass fibers being the same in warp and weft.

Out of these materials we produced two kinds of F.R.P.'s; one, polyester resin filled with the glass particles; the other, polyester resin reinforced with the glass clothes.

We measured Young's modulus by both static and dynamic methods using the instruments mentioned below.

Static method:

A static tensile test was made with a tensile tester (made by the Toyo Measuring Instruments Co. Ltd.; Tensilon U.T.M.-2 Type) at constant rates of elongation and under the following conditions:

1) Chuck intervals: 75 mm.
2) Cross head speed: 200 mm/sec for F.R.P. filled with glass particles; 50 mm/sec for F.R.P. reinforced with glass clothes.
3) Elongation rate: 0.45%/sec for F.R.P. filled with glass particles; about 1%/sec for F.R.P. reinforced with glass clothes.
4) Temperature 25 ± 1°C; humidity 65 ± 3% R.H.

Dynamic Method:

Actually, tests were made by three methods—two under normal condition (25 ± 1°C and 65% R.H.) and the other at a temperature exceeding the glass temperature of the resin.


Used for these tests was Direct Reading Propagation Viscoelastometer manufactured by the Toyo Measuring Instruments Co. Ltd.

3) Forced oscillation method [3]: at a constant frequency of 110 c/sec. Direct Reading Viscoelastometer manufactured by the Toyo Measuring Instruments Co. Ltd. was used.

The dimensions of the test pieces used for these testing methods are shown in Fig. 1.

3. Experimental Results Discussed

3-1 Stress Elongation Curves

Stress-elongation curves obtained by the static tensile test are shown in Figs. 2 and 3. All test pieces used for these tests were more than two weeks old. These curves are almost linear in a strain range below 0.5%, the inclination of the line increasing with an increase in glass volume fraction $v_g$.

![Fig. 1 Dimensions of test piece](image)

![Fig. 2 Stress-strain curves of polyester resin filled with glass particles](image)
Fig. 3 shows stress-elongation curves produced by the stretching in the warp direction of the glass cloth. Plastics reinforced with glass cloth have, in general, anisotropic mechanical properties. In the present discussion, however, we shall confine our attention to Young's modulus only of the warp or weft direction.

3-2 Relations between Glass Content and Young's Modulus of F. R. P.

These relations, obtained by the dynamic and static methods are shown in Fig. 4 for F. R. P. filled with glass particles, and in Fig. 5 for F. R. P. reinforced with glass clothes.

Measured values obtained under various conditions are plotted almost on a straight line in these figures. The values of Young's modulus in the static method were lower than in the dynamic one and the difference increased with an increase in the glass content.

Generally, resin becomes stiffer with time during a period after the second cure. Therefore, Fig. 5 additionally shows results obtained by measuring specimens differing in oldness. Fig. 4, however, relates only to test pieces used more than two weeks the second cure. Each line in Figs. 4 and 5 was obtained by the method of least mean square.

Comparing the line denoted by the symbol ● in Fig. 5 with the line denoted by the symbol ○, or comparing the line denoted by the symbol ○ with the line denoted by the symbol △, we find that a test material which passed two weeks after production has a larger value and a higher ratio of increase in Young's modulus to volume fraction than a piece used immediately after production.

Comparing the lines designated by the symbols ×, △ and □ with one another, we find that they are the same in the value of Young's modulus in a range where glass volume fraction is small; but that the materials reinforced with the glass cloth increase in the value of Young's modulus with an increase in their glass content, if they contain more threads per inch.

Test pieces stiffen gradually after production and
reach a saturating point in about two weeks. Assume that the increase in the stiffness of the materials is induced by the growing stiffness of the resin constituting F.R.P. Then plot the relation between $E/E_R$ and $v_e$ as curves in a figure, where $E$ is Young's modulus of F.R.P. and $E_R$ is that of polyester resin, assuming that the specimens measured were produced at the same time. It should then be possible to bring various $E/E_R-v_e$ into agreement with one another.

Therefore, the measured value shown in Figs. 4 and 5, and the values obtained by the pulse propagation method, when plotted with $E/E_R$ taken as an ordinate and $v_e$ as an abscissa, are expressible as in Figs. 6-9. Test pieces made of F.R.P. filled with glass particles were used for Figs. 6-8.

Comparing the various samples which used glass cloth G-1, and which are shown in Fig. 9, we find that the values of Young's moduli of the samples more than a week old are plotted on nearly the same line. The values of Young's moduli of the samples, tested three days after production, as well as samples reinforced with glass cloth and containing only a few threads per inch, are plotted on a line having a milder inclination than the other line.

![Figure 6 Applying Bruggeman's formula](image1)

![Figure 7 Applying Kerner's formula](image2)

![Figure 8 Applying mechanical model of a two-composite system](image3)

![Figure 9 Comparison of calculated and measured values for polyester resin reinforced with glass cloth](image4)
It follows, then, that the samples tested soon after production were easily deformed and displaced at the joints of the glass cloth in the samples; but that the samples tested more than a week after production were almost completely restrained by the surrounding resin from deformation or displacement at the joints of the glass cloth.

If glass cloth composed of very few threads per inch is layered, it is easily deformed and decreases in Young’s modulus because the number of joints is very small.

3-3 Analysis by Mechanical Models

a) Applying the theoretical formulas of isotropic non-homogeneous elastic body.

The minor deformation of two-composite systems containing glass particles embedded in the matrix of polyester resin may be thought of as the deformation of an isotropic non-homogeneous elastic body composed of isotropic elastic rigid particles and an isotropic elastic matrix which differ from each other in the modulus of elasticity.

There are many published theoretical discussions on the relations between the elastic constant of an isotropic non-homogeneous elastic body, that of a matrix or embedded particles and the volume fraction of embedded particles. Those discussions, however, concern only spherical particles, which differ more or less from our experimental materials.

The glass particles contained in our experimental materials were small enough and the ratio of their average length and diameter equalled 1 : 7, thus making the isotropic non-homogeneous elastic theory applicable to our experimental results, if the volume fraction of glass was not very large.

Now to compare the experimental results with values calculated from the formulas of Bruggeman and Kerner.

Bruggeman deduced a formula, shown below, to calculate shear modulus \( G + \delta G \) of a concentric sphere having mixed spherical rigid particles of shear modulus \( G' \) in the inner sphere and a matrix of shear modulus \( G \) in the outer shell, under a condition where displacement and stress are continuous on the boundary surface. (See Fig. 10. a)

\[
G + \delta G = G \left[ 1 + \frac{3(G'-G)}{G'+2G} \cdot v_f \right]
\]

where \( v_f \) is the total volume fraction of the mixed particles.

Even when the small particles are scattered in the matrix, as shown in Figure 10. b, eq. (1) is perhaps approximately applicable to this system, if the particles are small enough in total volume fraction and are roughly distributed in the matrix.

To apply eq. (1) to our experimental materials, we use the following symbols:

- \( G_R \): shear modulus of resin
- \( E_R \): Young’s modulus of resin
- \( G \): shear modulus of F.R.P.
- \( \nu_R \): Poisson’s ratio of resin
- \( \nu \): Poisson’s ratio of F.R.P.
- \( G_G \): shear modulus of the glass
- \( E_G \): Young’s modulus of glass
- \( \nu_G \): Poisson’s ratio of glass
- \( v_k \): total volume fraction of glass

Then we obtain:

\[
G = G_R \cdot \left[ 1 + \frac{3(G_G - G_R)}{3G_G + 2G_R} \cdot v_k \right] \quad \ldots \ldots (1)'
\]

From the relation \( E = 2G(1+\nu) \) we obtain the following approximation:

\[
\frac{G}{G_R} = \frac{E}{E_R}(1+\nu) = \frac{E_R}{E} \quad \ldots \ldots (2)
\]

Substituting \( 2 \) into \( 1' \) gives us:

\[
E/E_R = 1 + 3v_k \cdot \frac{x - 1}{x + 2} \quad \ldots \ldots (3)
\]

Averaging the dynamic experimental results in Fig.4 which correspond to glass volume fraction 0%, we obtain \( E_R = 3.46 \times 10^{10} \) dyne/cm² and, assuming \( E_G = 6.7 \times 10^{11} \) dyne/cm², we derive \( x = 20 \).

The values calculated from eq. (3) for the samples differing in volume fraction \( v_k \) and the measured values of \( E/E_R \), in Fig.4 are compared in Fig.6. In this figure, experimental results obtained by the dynamic test are plotted on the line indicated by \( x = 20 \), in a range below \( v_k = 10\% \).

Kerner derived a formula to express the relation between shear modulus \( G \) and the volume fraction of a two-composite system (as shown in Fig. 10. b) in which spherical particles of shear modulus \( G_1 \) are scattered in a medium of shear modulus \( G_2 \) and both
materials stick to each other on the boundary surface.

Modifying Kerner's formula by the same procedure by which eq. (3) was derived, we obtain:

\[
\frac{E}{E_R} = \left( \frac{(7-5v_g)/x + \frac{8-10v_g}{15(1-v_g)}}{1-\frac{1}{v_g}} \right) = (7-5v_g)/x + \frac{8-10v_g}{15(1-v_g)} \quad \ldots \ldots (4)
\]

The values calculated from eq. (5), assuming \( v_g = 0.5 \), and the measured values of \( E/E_R \), are compared in Fig. 7.

In this figure, all experimental results are on the curve indicated by 20. Therefore, eq. (4) can be extended in its application to a range larger than that in eq. (3).

b) Applying mechanical model of a two-composite system, Kawai, et al. gave a two-composite system model (shown in Fig. 10 c) consisting of poor and insoluble polymers. The phase indicated by the sign R in the figure is composed of resin. The phase indicated by G is composed of glass, where parameters \( \lambda \) and \( \varphi \) showing the scattered condition of the glass are decided by the condition \( \lambda \cdot \varphi = v_g \) and by the aspect of the dispersion of the mixed phase.

Assuming that strain is uniformly distributed in both phases and is additive, the model shown on the right-hand side of Fig. 10 c gives:

\[
\frac{E}{E_R} = \left( \frac{(7-5v_g)/x + \frac{8-10v_g}{15(1-v_g)}}{1-\frac{1}{v_g}} \right) = (7-5v_g)/x + \frac{8-10v_g}{15(1-v_g)} \quad \ldots \ldots (5)
\]

where the above-mentioned symbols are used directly.

Takayanagi, et al. [10] point out that the conditions for equivalence between the model depicted in Fig. 10 c and the model shown Fig. 10 b (a non-homogeneous isotropic elastic body in which spherical rigid particles are embedded) are

\[ \lambda = \frac{1}{5} (2+3v_g) \quad \varphi = 5v_g/(2+3v_g) \quad \ldots \ldots (6) \]

Calculating the values of \( E/E_R \) from eqs. (5) and (6), we obtain the curves shown in Fig. 8 for \( x = 10 \), \( x = 20 \).

For simplification, we assume that glass particles are uniformly distributed in resin and the force line passes through both R-phase and G-phase. Then we get:

\[ \lambda = \varphi = v_g \quad \ldots \ldots (7) \]

Substituting eq. (7) into equation (5) gives us:

\[
\frac{E}{E_R} = \left( \frac{1}{1-\frac{v_g}{x-1}} \cdot \frac{1}{v_g} \right) = \frac{x}{2} + \frac{1}{2} \quad \ldots \ldots (8)
\]

Eq. (8) gives each curve drawn in dotted lines in Fig. 8, and the dynamic experimental results are nearly plotted on the curve \( x = 20 \).

The results described in paragraphs a and b lead to the conclusion that both the non-homogeneous isotropic elastic theory and the mechanical model of a two-composite system are applicable in calculating Young's modulus of F.R.P. filled with glass particles by means of the values of the composition. However, the model depicted in Fig. 10 c is considered more useful because we can depict the make-up of glass cloth and the complex shape of glass intuitively.

c) Young's modulus of polyester resin reinforced with glass cloth.

Paragraphs a and b considered Young's modulus of polyester resin filled with glass particles by means of a model. Now to describe some models which represent the relation between the glass content of polyester resin reinforced with glass cloth and its Young's modulus parallel to the warp direction.

i) Usual models[11]

When the direction of external force coincides with the direction of warp or weft of the glass cloth (assuming that only the resin and the threads oriented in the direction of external force resist the force), Young's modulus is calculable from the model shown in Fig. 11, as follows:

![Fig. 11 Usual model of F.R.P.](image)

The following symbols are used:

- \( \varepsilon \) : longitudinal strain of F.R.P.
- \( E \) : Young's modulus of F.R.P. of polyester resin
- \( E_G \) : Young's modulus of glass thread
- \( v_g \) : volume fraction of glass
- \( A \) : effective cross sectional area
- \( A_G \) : total effective cross sectional area of glass fiber
- \( E_R \) : Young's modulus of resin
- \( R \) : polyester resin
- \( G \) : glass
- \( A \) : cross sectional area of F.R.P.

We obtain:

\[ \varepsilon A E = \varepsilon (A_G E_G + A_R E_R) \quad \ldots \ldots (9) \]

\[ A_G = A \cdot v_g/2, \quad A_R = A \left( 1 - \frac{v_g}{2} \right) \]

holds good for the materials used in our experiments.

Therefore, by substituting it into (9), we obtain:

\[
\frac{E}{E_R} = x \left[ \frac{v_g}{2} + \left( 1 - \frac{v_g}{2} \right) \right] \quad \ldots \ldots (10)
\]

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Adding the volume fraction of weft directly to warp transforms eq. (10) into:

\[
\frac{E}{E_s} = x \cdot v_w + (1 - v_w) \quad \text{......(11)}
\]

The effects of the weft located perpendicular to the force line and the effects of the joints are underestimated or overestimated. Therefore, the measured values come between them, as a matter of course.

The measured Young's modulus of the glass threads constituting glass cloth is about \(3.4 \times 10^{10}\) dyne/cm² for both G-1 G-3. Young's modulus of the resin is about \(3 \times 10^9\) dyne/cm². Accordingly, \(E_0/E_s = 10\).

Substitute this value of \(x\) into eqs. (10) and (11) and calculating the value of \(E/E_s\), gives curves a and b shown in Fig.9. The measured values come between the above-mentioned two curves.

ii Unit cubic two-phase model

First, we investigate the applicability of the model of a two-composite system depicted in Fig. 10 c.

Judging by the make-up of glass cloth layered in the test materials, assume that \(\varphi = \lambda\) and substitute \(x = 10\) into eq. (8). We then get the three curves shown by dots and bars in Fig. 9.

The measured values come above the curve \(x = 10\) as well as on \(x = \infty\). This means that the models described in paragraphs a and b are inapplicable to F. R. P. reinforced with glass cloth.

Let us try to apply some models which concretely express the make-up of glass cloth layered in resin. Assume that there are no knots to join warp and weft. Collect all warp and weft threads independently of each other by shifting them parallel to each other. Then the layers consisting of warp and the layers made up of weft can be approximately represented by a thin plate of length 1 and width \(\varphi\) or length \(\lambda\) and width 1.

Pile the layers on top of one another to make a unit cubic model and define the thickness of the layer composed of weft as \(\mu\). If there is a knot at any joint, its effect will be that resin gets harder and the value of \(\mu\) decreases with an increase in resin hardness. Thus, the thickness of the layer composed of warp increases consequently, i.e., \(\mu \leq 0.5\).

If resin is not hardened enough or the joints in glass cloth are roughly distributed, the value of \(\mu\) gets close to 0.5.

The same is true if samples are heated at high enough temperature. In that case, the value of \(\mu\) exceeds 0.5 because the influence of weft increases at a temperature far above the glass temperature of resin.

In F. R. P. with more than two sheets of glass cloth embedded in it, a rise in the surrounding temperature reduces the strength of the knots at the joints, slackens the contact pressure of the layers, increases the actual value of \(\mu\) over that expected from eq. (10) and, indeed, brings it close to 1 if the surrounding temperature exceeds the glass temperature of resin.

Having defined the thickness of the layer composed of weft, we can calculate Young's modulus of F. R. P., as follows, by using a unit cubic model composed of plane-like layers (for warp: \(1 \times \varphi \times (1 - \mu)\), for weft: \(\lambda \times 1 \times \mu\), the rest being polyester resin).

\[
\begin{align*}
\mu \cdot 1 + \varphi (1 - \mu) \cdot 1 & = v_w \quad \text{......(12)} \\
\text{Substituting the relation } \lambda = \varphi \text{ into equation (12), we get:} & \\
\lambda & = \varphi = v_w \quad \text{......(13)} \\
\text{Then,} & \\
E & = \frac{\mu E_0 E_s}{E_0 - v_w (E_0 - E_s)} + (1 - \mu) \left\{ (1 - \varphi) E_s + \varphi E_0 \right\} \\
& \text{is derived from Fig. 12 b.} \\
\text{Substituting eq. (13) into the foregoing, we get:} & \\
\frac{E}{E_s} & = \frac{\mu E_0}{E_0 - v_w (E_0 - E_s)} + (1 - \mu) \left\{ 1 + v_w \left( \frac{E_0}{E_0 - 1} \right) \right\} \\
& \text{......(14)} \\
\text{Eq. (14) modified by using the relation } x = E_0/E_s & \text{transforms into:} \\
\frac{E}{E_s} & = 1 + v_w (x - 1) - \frac{\mu v_w (1 - v_w)(x - 1)^2}{x - v_w(x - 1)} \\
& \text{......(15)} \\
\text{If we put } \mu = 0 \text{ as the extreme limit to eq. (15), it equals eq. (11). In eq. (14), if we put } \mu = 1, \text{ then} & \\
\left( \frac{E}{E_s} \right)^{-1} & = \frac{v_w}{x} + (1 - v_w) \\
& \text{......(16)}
\end{align*}
\]
Comparing the various curves and measured results (see Fig. 9), we find that the experimental results on the samples tested more than a week after production are all plotted on the curve indicated by $\mu=0.125$. As for the samples in which glass cloth G-3 is embedded or the samples in which glass cloth G-1 is embedded (tested three days after production), measured values are plotted on the curve $\mu=0.4$ or $\mu=0.5$, respectively. Therefore, the measured results on the last two samples show that the effect of a knot decrease for the reason already stated.

d) Dynamic modulus and loss tan $\delta$ of F.R.P. at high temperature

i) Dynamic modulus $E'$

The temperature dependence of $E'$ is shown in Figs. 13 and 14. Fig. 13 is for F.R.P. filled with glass particles; Fig. 14, for F.R.P. reinforced with glass cloth.

The solid line in Fig. 13 indicates the measured results, while the dotted line, chain line (two dots) and chain line (one dot) indicate values calculated by substituting the corresponding values of $E'$ of various temperatures into eqs. (3), (5), and (8), respectively.

We assumed, however, that the dynamic modulus of glass was kept constant in a temperature range of 100~200°C and used value, $E_g'=6.7 \times 10^{11}$ dyne/cm².

If follows from these results that $E'$ of polyester resin decrease to about 1/15th of the order of magnitude; but that the rate of decrease in Young's modulus of F.R.P. decreases with an increase in glass volume fraction; and that, at the point of $V_g=30\%$, Young's modulus declines to one-third of the magnitude of the value measured at normal temperature.

The calculated values agree with the measured values if volume fraction is below 10\%, but the measured values exceed calculated values if volume fraction is above 10\%.

Fig. 14 shows the temperature dependence of the dynamic modulus of F.R.P. reinforced with glass cloth. The solid lines indicate the experimental results.

The decrease in dynamic modulus $E'$ of F.R.P. is extremely slight compared with the modulus $E'$ of resin due to a temperature rise. Clearly, then, the heat resistance strength of polyester resin can be increased markedly by reinforcing it with glass cloth.

Substitute the ratio of $E_g'$ to $E_r$ shown in Fig. 14 for $x$ into eq. (15). Calculate the values of $E'/E_r'$ corresponding to various temperatures. Then fix parameter $\mu$ to fit to experimental results. By these procedures we obtain $\mu=0.82$ for F.R.P. with $V_g=15.5\%$, and $\mu=0.63$ for that with $V_g=6.24\%$.

All these values of $\mu$ far exceed the 0.125 given in Fig. 9. It is clear, then, that the effect of the joints...
in glass cloth decreases and so does the resistance force generated by the friction of two adjacent sheets of layered glass at high temperature.

ii Loss tan $\delta$

The variations in loss tan $\delta$ in a range of 100~200 °C are shown in Fig. 15. The upper curves in Fig. 15 are for samples made of unfilled polyester resin or of F. R. P. filled with glass particles. The two lower curves are for F. R. P. in which one or two sheets of G-1 glass cloth were used.

Polyester resin has a maximum at a point about 135 °C in a damping curve corresponding to glass transition. Therefore, the peak in the damping curve of F. R. P. shifts slowly to the right with an increase in glass volume fraction.

The value of tan $\delta$ at the peak in the damping curve decreases slowly as $v_g$ decreases. Each damping curve becomes broad in shape.

Take tan $\delta$ and a temperature corresponding to the maximum of the damping curve as ordinates, volume fraction $v_g$ % as an abscissa. The relations between the values thus obtained are shown in lines in Fig. 16 for F. R. P. filled with glass particles. It is particularly interesting that glass particles are very similar in its effect to that of crystallite in crystalline polymers.[12]

As shown in dotted lines in Fig. 15, a very broad damping curve is one of the special features of F. R. P. reinforced with glass cloth.

4. Conclusions

1) The relation between Young’s modulus and the glass volume fraction of F. R. P. filled with glass particles can be theoretically predicted from numerical calculation of formulas derived from the isotropic non-homogeneous elastic theory and from dynamic models of a two-composite system.

2) The relation between Young’s modulus of F. R. P. reinforced with glass cloth and glass volume fraction at normal temperature can be clarified qualitatively by using a unit cubic two-phase model.

To analyze this model qualitatively, however, value $\mu$ of the parameter of the model must be given theoretically in future.

3) Each model referred to in this article well illustrates the temperature dependence of dynamic modulus $E'$ of F. R. P. which contain a small volume fraction, i.e., $v_g$ 10%, in a temperature range from the glass temperature of resin to 200°C.

Compared with the decrease in dynamic modulus $E'$ of the resin caused by a rise in temperature, the
decrease in $E'$ of F.R.P. reinforced with glass cloth is very slight. Therefore, we may expect that piling glass cloth in resin promotes its heat resistance strength markedly.

References


[8] D. A. Brugeman; ibid, 24, 635 (1935)