Comparison of strain rate and temperature effects on modulus and ultimate strength of polyethylene-fibre based cross-ply laminates with a glassy and rubbery matrix

Citation for published version (APA):
Vermeulen, R. C. N. (1995). *Comparison of strain rate and temperature effects on modulus and ultimate strength of polyethylene-fibre based cross-ply laminates with a glassy and rubbery matrix*. (DCT rapporten; Vol. 1995.097). Technische Universiteit Eindhoven.

Document status and date:
Published: 01/01/1995

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 07. Oct. 2024

Comparison of strain rate and temperature effects on modulus and ultimate strength of polyethylene-fibre based cross-ply laminates with a glassy and rubbery matrix.

R.C.N. Vermeulen, july 1995
WFW reportnr. 95.097

Stagerapport (artikel Polymer)

Begeleiders: A.A.J.M. Peijs
L.E. Govaert
R.J.T. Frissen

Hoogleraar: Prof. dr. ir. D.H. van Campen

Abstract

In this experimental research the influence of strain rate and temperature on tensile strength and modulus of high performance polyethylene (HP-PE)-fibre-reinforced cross-ply laminates is analyzed for a rubbery (SIS) and glassy (polystyrene) matrix, using tensile tests. The strain rate and temperature dependence of the modulus appears to be dominated in both cases by the behaviour of the PE fibres, whereas at low temperatures or high strain rates the ultimate strength is strongly affected by the type of matrix. A brittle glassy matrix initiates early fibre failure compared with a ductile rubbery matrix.

Introduction

Composites based on HP-PE fibre are well known for their excellent impact performance. They are used in ballistic applications such as protective panels for car doors, military helmets and bulletproof vests.

The stacking sequence and material properties, or in general the total construction, of the composites are optimized by trial and error using ballistic experiments. Although such experiments are inevitable, research on a numerical bases using finite element techniques [1] may provide more fundamental insight necessary to design an optimum composite for each application. To validate a numerical model reliable input parameters have to be measured by experiments during impact conditions. Especially for experiments in this high velocity region measurements are difficult to perform due to reflection, refraction and the existence of wave patterns. On the second hand composites are heterogeneous systems with various complex failure mechanisms like fibre and matrix breakage and delamination.

To decouple the effect of wave patterns and failure on the composite behaviour finite element methods are gratefully used to calculate both features from quasi-static determined input parameters.

The heterogeneity of the material can be encapsulated in the input parameters by performing experiments on basic $[0/90]_2$ laminates. Since the time-temperature equivalency theory holds for polyethylene fibre (PE) and most polymer matrices, the material properties tensile strength and modulus during impact conditions are measured using quasi- static tensile tests at low temperatures (-50°C)

Although the influence of refraction and reflection of elastic wave patterns between fibre and matrix or subsequent layers is neglected, because the material is assumed to be homogeneous, numerical results give insight in the significance of tensile strength on the dynamic behaviour (performance) of the composite. Therefore the material properties of a high performance polyethylene fibre based $[0/90]_2$ laminate with a brittle glassy (polystyrene) or ductile rubbery (SIS) matrix are analyzed for temperatures varying from 23 to -50°C.

In practice a rubbery matrix appears to be better for impact applications than a glassy matrix, indicating differences in the amount of energy dissipation (area under the stress-strain curve).

Tensile tests were conducted at different strain rates and different temperatures to be able to calculate time-temperature shift factors. The combination of quasi-static tensile experiments and low temperatures renders the material properties at an impact situation via time-temperature superposition.

Experimental

Materials

The two cross-ply laminates $[0/90]_2$ used in this study are supplied by DSM High Performance Fibres B.V. The volume fraction of the fibres (Dyneema SK66) in the laminates is approximately 70 %. The cross-ply laminates were available with a polystyrene or SIS rubbery matrix. The material properties of the fibre and matrices are shown in table 1.

Table 1. Material parameters for fibre and matrices, T=23 °C.

Material parameters	HP-PE fibre (orthotropic)	polystyrene (isotropic)	SIS rubber (isotropic)
E_{xx} [GPa]	87	3.4	0.3
E_{yy} [GPa]	3.4	3.4	0.3
σ_{max} [MPa]	3000	≈50	≈30
ε_{max} [%]	3.7	3.5	≈800
T_g [°C]	-120	95	-55

Mechanical testing

Specimens were cut, with a special pair of scissors, to a width of 15 mm and a length of 600 mm. The length-direction of the specimen was always taken in the role-direction. The thickness after hot pressing for 10 minutes at 30 bar and ten minutes at 80 bar at a temperature of 125 °C was 0.135 mm.

Tensile tests on the laminates were performed on a servo-hydraulic Zwick REL tensile tester equipped with a thermostatically controlled oven and pneumatic fibre-clamps.

To avoid clamp slippage special laminate clamps were designed. Due to the circular clamping entrance geometry (radius = 8 mm) a tensile force reduction in the pneumatic clamping unit has been accomplished. The clamps are controlled pneumatically to facilitate the exchange of the specimens at low temperatures. The length of the clamps was chosen 30 mm. The specimen was double folded through the clamping unit and over the circular entrance in order to eliminate slippage. The final length of the specimen between the clamping units (L_0) amounted approximately 275 mm. Tensile experiments were performed on the two types of composites at two strain rates, 0.0036 and 0.72 s^{-1}, and temperatures ranging from -50 to 23 °C. Each experiment is performed 5 times to be able to determine the mean values and standard deviations. Measurements were performed after the specimen had a stable temperature for 5 minutes.

Results and Discussion

Two typical stress-strain curves for a laminate with a rubbery (SIS) and a glassy (polystyrene) matrix at a strain rate of 0.72 s^{-1} and at a temperature of -50 °C are shown in Figure 1 .

Figure 1

From the curves it can be concluded that the failure behaviour of PE fibres in the glassy matrix is significantly different from the failure behaviour of PE fibres in the rubbery matrix. Almost all the PE fibres in the rubbery matrix break simultaneously when the maximum stress is reached, whereas the failure behaviour of PE fibres in the glassy matrix starts earlier at a lower stress level and the fibres break sequentially. As a result of this the area under the stress-strain curve, which is a measure for the energy dissipation, is smaller. Therefore a rubbery matrix will be a better matrix than a glassy one, rendering a higher ballistic performance.

From all stress-strain curves secant moduli were derived between 0.5 and 1.0 % strain. At least five measurements were performed at each evaluated temperature (-50, -30, -10, and 23 °C). For each temperature the average value of the secant modulus as well as the standard deviation were derived from the measurements

Figure 2 shows the average secant modulus as a function of the temperature at a low strain rate (0.0036 s^{-1}) for both composites. Errorbars have been plotted for each temperature, where the total length of the errorbar is two times the standard deviation at that temperature. The solid lines are regression lines according to the method of least squares. For temperatures below 0 °C the average values of the secant modulus are on a straight line, but the average secant modulus at a temperature of 23 °C deviates from that line. The reason for this is, that clamp-slippage occurs at low strain rates in combination with relatively high temperatures (as the friction decreases with increasing temperature). As clamp-slippage occurs the initial gauge length (L_0), necessary to calculate the strain, can be corrected. An increase of L_0 with approximately twice the clamp distance results in the missing positive shift of circa 4 GPa for the average moduli, which agrees with the observed slippage in the clamping units at a temperature of 23 °C.

Figure 2

Slightly higher values for the mean secant moduli are found for PE fibres in a rubbery matrix than for PE fibres in a glassy matrix, however since the errorbars of both materials overlap, there is no significant difference in the secant moduli for the two composites.

Figure 3 shows the average secant modulus as a function of the temperature at a high strain rate (0.72 s^{-1}) for both composites. Again errorbars have been plotted for each temperature, where the total length of the errorbar is two times the standard deviation at that temperature. Once more the solid lines are linear fits.

Figure 3

The values of the average secant moduli are approximately the same for PE fibres in the two matrices at the evaluated temperatures.

From Figure 2 and Figure 3 it can be observed that the incline of all four regression lines are nearly the same. When the regression lines shown in Figure 2 are horizontally shifted over a temperature of about 35 °C a mastercurve is obtained.

The modulus of the matrix and the transversal modulus of the PE fibres can be neglected. The values of the average moduli are, after correction for the facts that 50 % of all fibres are loaded perpendicular to the tensile direction and that the fibre volume fraction is only 70 %, similar to those reported by Govaert et al. [2] for a different type of PE fibre.

The temperature dependence of the average ultimate strength is plotted in figure 4, for both composites at a strain rate of 0.0036 s^{-1}. The solid lines are linear fits.

Figure 4

The ultimate strength of PE fibres in the rubbery matrix is significant higher than the ultimate strength of PE fibres in a glassy matrix for all temperatures.

Figure 5 presents the temperature dependence of the average ultimate strength for both composites at a strain rate of 0.72 s^{-1}. Again errorbars and a least squares regression line for PE fibres in a rubbery matrix are shown. As the ultimate strength for PE fibres in the glassy matrix shows a maximum at a temperature of -30 °C, a second order polynomial according to the method of least squares is drawn through the corresponding data. When the stress regression lines also are horizontally shifted over 35 °C, again a mastercurve can be obtained.

Figure 5

From this graph it can be concluded that at relatively high strain rates the ultimate strength of PE fibres in a rubbery matrix increases with decreasing temperature (for temperatures higher than the glass transition temperature T_g, which is approximately -60°C for SIS rubber), whereas the ultimate strength of PE fibres in a glassy matrix shows a maximum with decreasing temperature. At low temperatures or high strain rates the ultimate stress decreases due to the influence of the very brittle polystyrene matrix. This brittle matrix does not adhere very well to the PE fibres and causes the fibres to fail in a sequentially manner, whereas in the case of a ductile matrix fibre failure is delayed and less scattered. Hence PE fibres in a glassy matrix fail earlier, which makes a glassy matrix less suitable for ballistic applications.

Conclusions

The temperature and strain rate dependence of modulus and ultimate strength of cross-ply laminates based on PE fibres with a rubbery (SIS) and a glassy (polystyrene) matrix were evaluated.

There was no significant difference observed in the values of the average moduli for both materials at different strain rates and temperatures. From the results it can be concluded that the modulus is fully determined by the PE fibres. The ultimate stress increases with decreasing temperature for both materials. However at very low temperatures (-30 to -50 °C) and high strain rates the ultimate stress of PE fibres in a glassy matrix decreases, due to the influence of the very brittle matrix which initiates the failure process. Therefore cross-ply laminates with a brittle matrix are less suitable for applications which demand a high energy absorption.

References

1. Frissen, Govaert and Peijs *"Modelling of the ballistic impact behaviour of polyethylene-fibre-reinforced composites"* in ICCM-10, Conference Proceedings, 1995

2. Govaert and Peijs *"Tensile strength and work of fracture of oriented polyethylene fibre"* in Applied Composite Materials 1: 35-54, 1994

Figure Captions

Fig. 1 Comparison of two typical stress-strain curves of PE fibres in both a SIS rubbery and a polystyrene matrix at a temperature of -50 °C and a strain rate of 0.72 s^{-1}.

Fig. 2 Modulus as a function of temperature at a strain rate of 0.0036 s^{-1}. Closed symbols: PE fibres in a SIS rubbery matrix. Open symbols: PE fibres in a polystyrene matrix. Circled data indicates slippage.

Fig. 3 Modulus as a function of temperature at a strain rate of 0.72 s^{-1}. Closed symbols: PE fibres in a SIS rubbery matrix. Open symbols: PE fibres in a polystyrene matrix.

Fig. 4 Ultimate stress as a function of temperature at a strain rate of 0.0036 s^{-1}. Closed symbols: PE fibres in a SIS rubbery matrix. Open symbols: PE fibres in a polystyrene matrix.

Fig. 5 Ultimate stress as a function of temperature at a strain rate of 0.72 s^{-1}. Closed symbols: PE fibres in a SIS rubbery matrix. Open symbols: PE fibres in a polystyrene matrix.

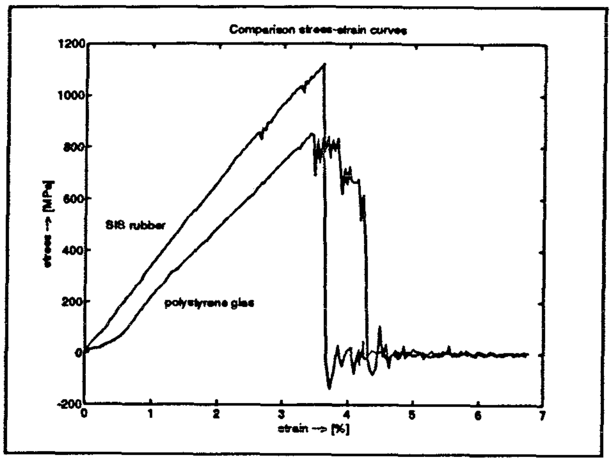

Comparison stress-strain curves
stress --> [MPa]
1200
1000
800
600
400
200
0
-200
SIS rubber
polystyrene glas
0
1
2
3
4
5
6
7
strain --> [%]

Figure 1

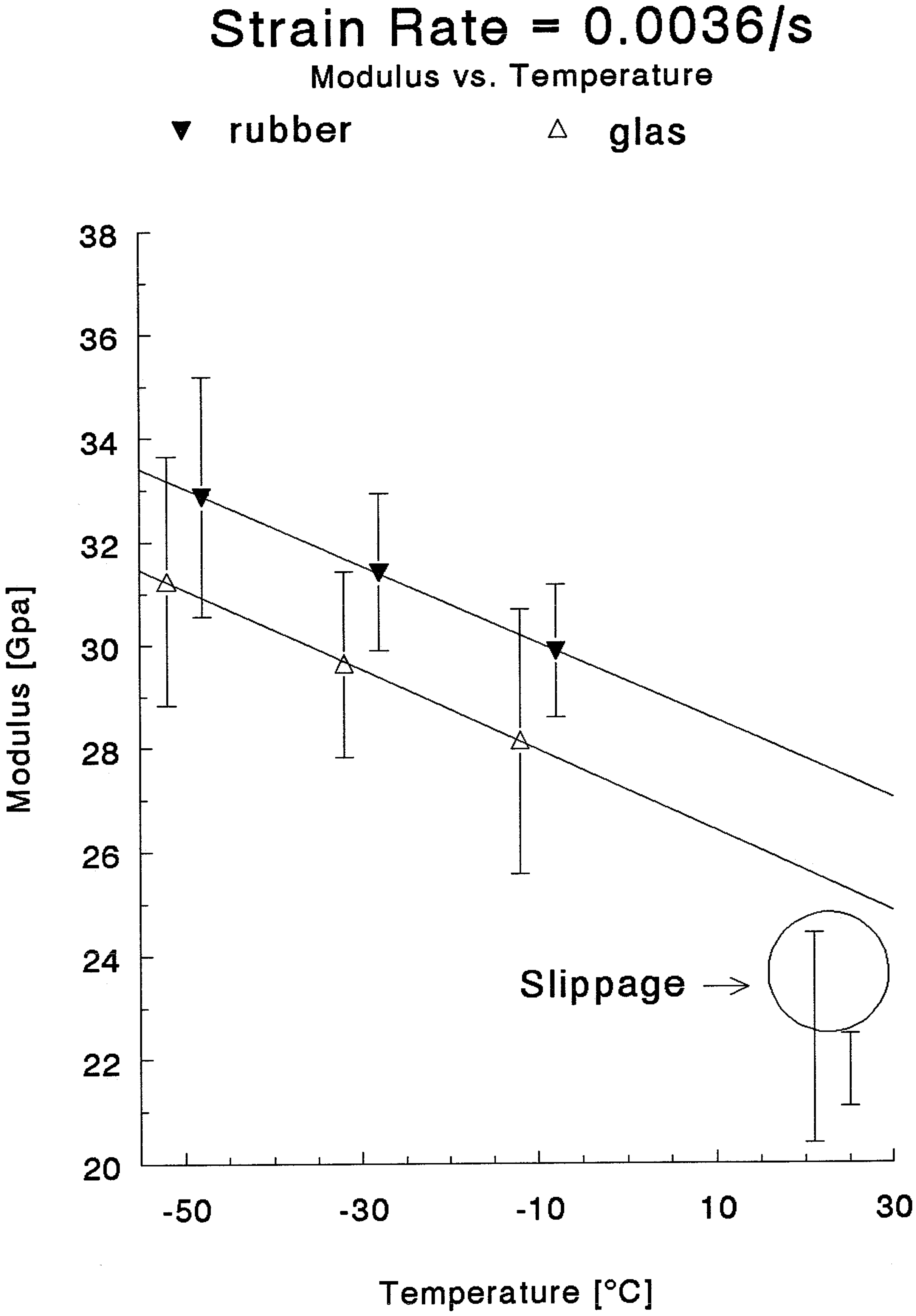
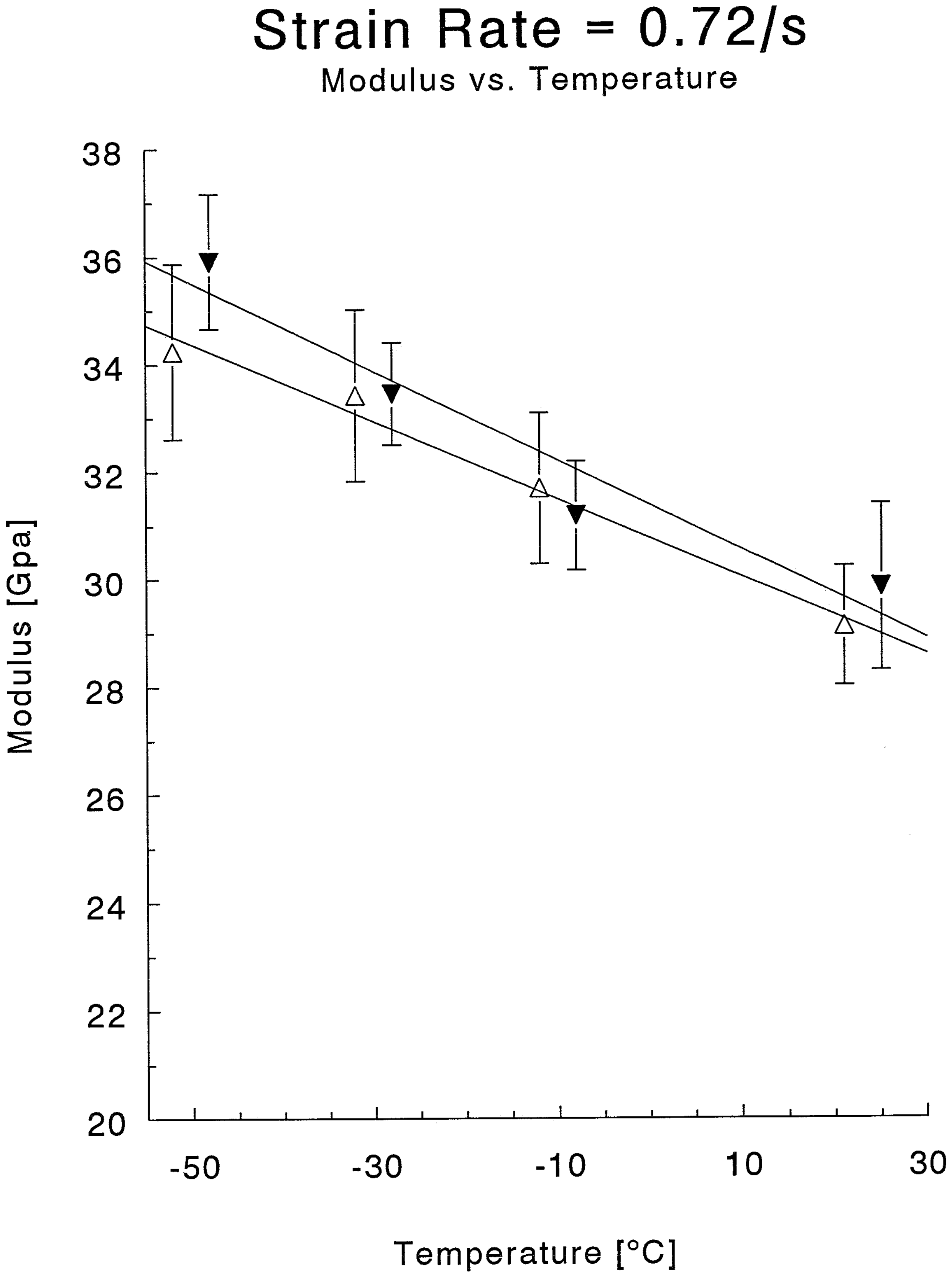

Strain Rate = 0.0036/s
Modulus vs. Temperature
▼ rubber
△ glas
Modulus [Gpa]
38
36
34
32
30
28
26
24
22
20
-50
-30
-10
10
30
Temperature [°C]
Slippage →

Figure 2



Strain Rate = 0.72/s

Modulus vs. Temperature

Figure 3

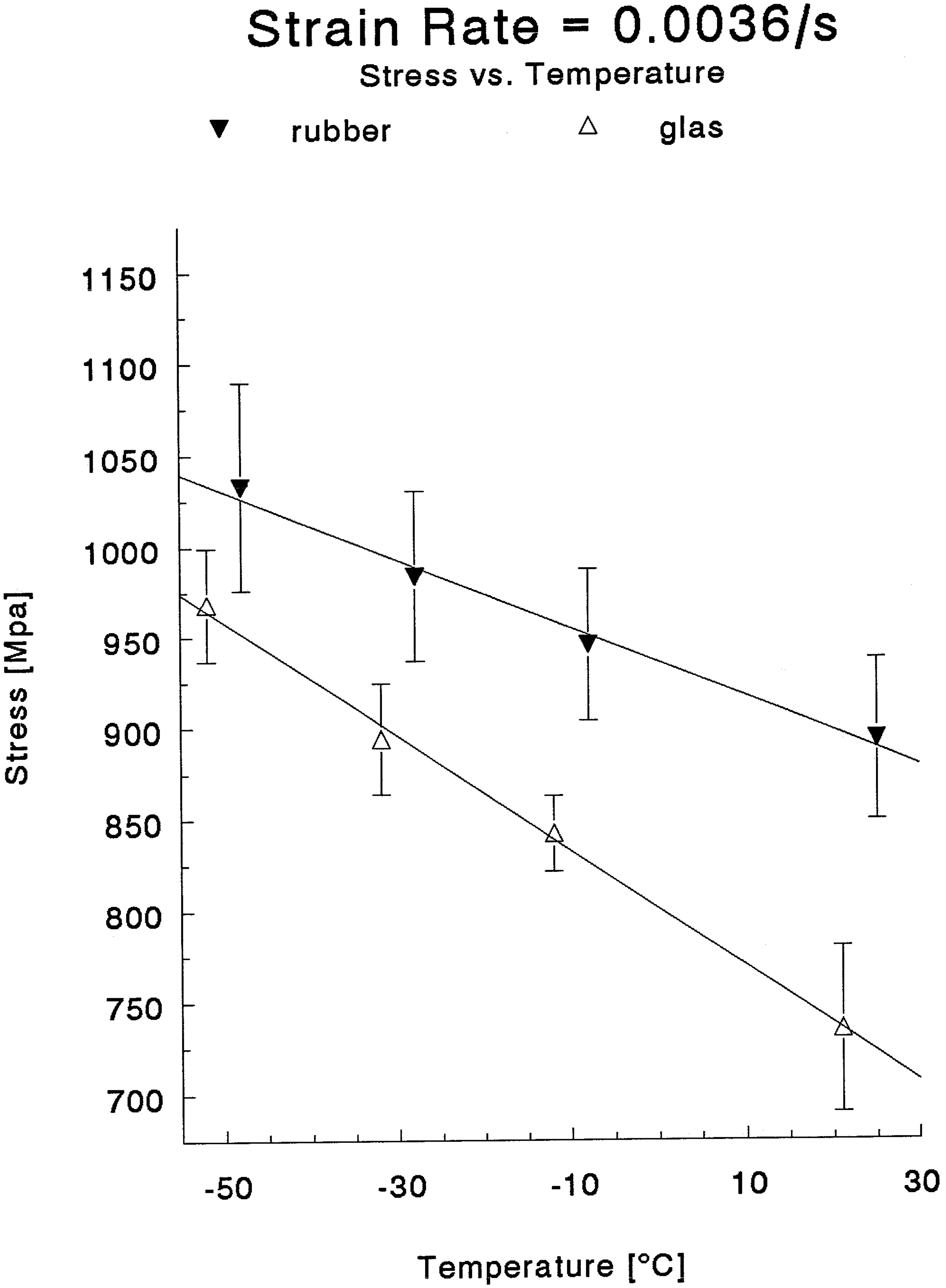
Strain Rate = 0.0036/s
Stress vs. Temperature
▼ rubber
△ glas
1150
1100
1050
1000
950
900
850
800
750
700
Stress [Mpa]
-50
-30
-10
10
30
Temperature [°C]

Figure 4

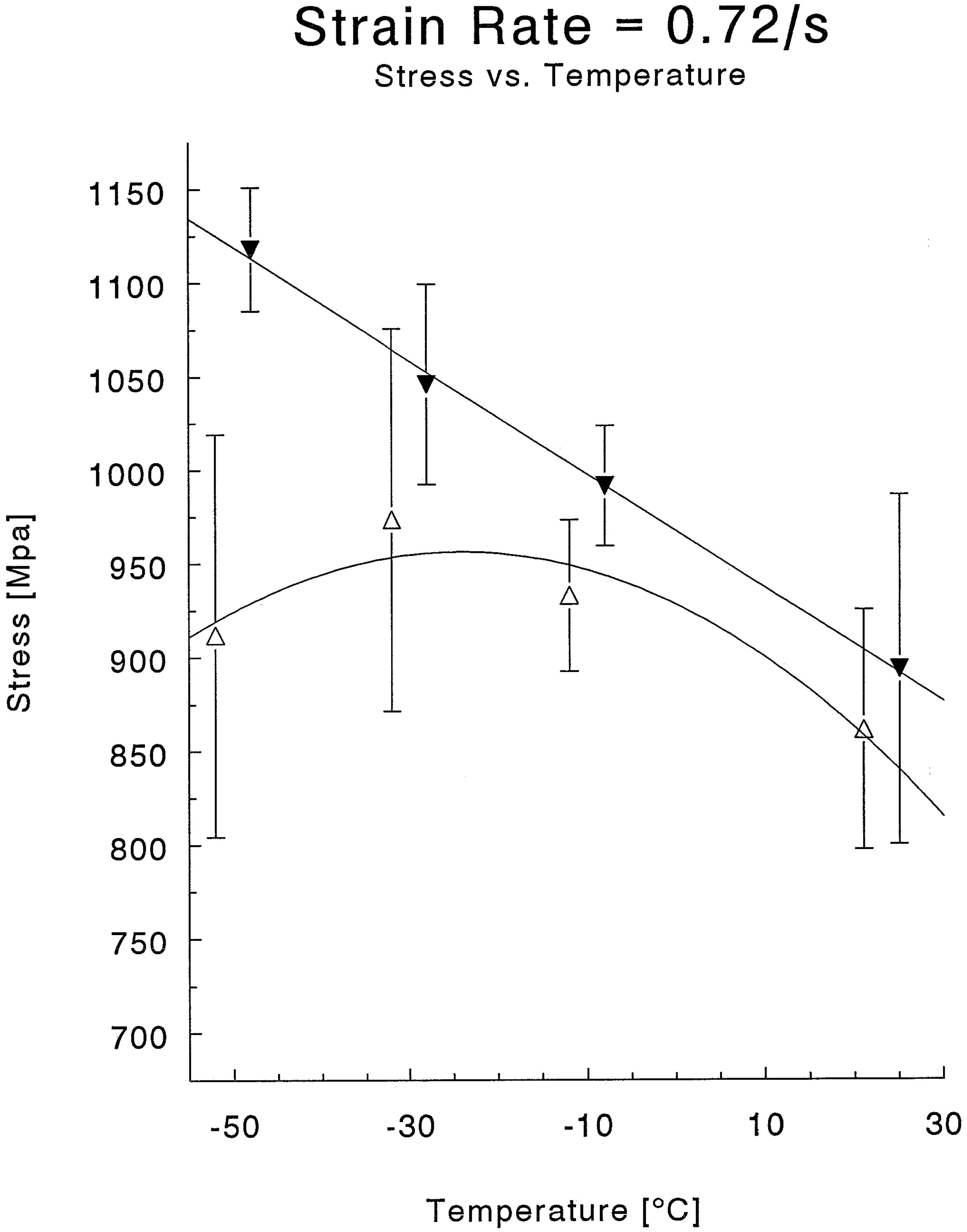

Strain Rate = 0.72/s
Stress vs. Temperature
Stress [Mpa]
1150
1100
1050
1000
950
900
850
800
750
700
-50
-30
-10
10
30
Temperature [°C]

Figure 5