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Effects of Moisture and Other Contaminants
in Friction Composites

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ABSTRACT

The role of water and other contaminants like salt water, iso-octane and ethylene glycol on neat resin, composites, and friction materials have been investigated. The maximum solvent uptake and the diffusion coefficient of the solvent in these systems were determined and the experimental data was fitted to a Fickian model. The nature of the diffusion process was determined in each case and deviations from Fickian behavior were accounted for. For the neat resin and the composites, the diffusion coefficients of the liquids were of the order of 10^{-10} cm²/sec. After exposure to these contaminants, mechanical properties of all the systems were determined and a general degradation in properties were found. The flexural strength and fracture toughness showed reduction in values while the flexural modulus was not affected.

INTRODUCTION

This work is part of an ongoing research on non-asbestos composite materials for friction applications. The mechanical properties of several fiber-resin and friction composites have previously been studied.¹ Under actual service conditions, friction materials can be subject to a variety of environmental conditions. The behavior of these materials upon exposure to various conditions is not well characterized. The present study is focused on the role of moisture and other contaminants in friction materials and other model composite systems.

A friction material for a brake lining formulation typically consists of the following ingredients including: a phenolic binder (polymer), fiber(s), filler(s) and friction modifiers. The fiber provides the necessary reinforcement to the lining while the matrix holds the different ingredients together to produce a strong material which will not soften in service. The filler is usually a low cost material which does not adversely affect the properties of the composite and the friction modifier is usually a crosslinked phenolic resin added to increase friction. When a friction material is exposed to the environment, moisture and other contaminants can have adverse effects on its performance. In this work, composite specimens have been subject to different contaminants and the uptake and mechanical properties investigated.

The diffusion of small molecules in composites can often be characterized based on Fick's laws. The first law states that the flux, J_x is proportional to the concentration gradient and represented as:

$$J_x = -D_x(\partial c/\partial x) \quad (1)$$

where D_x is the diffusion coefficient in the x direction. For diffusion occurring in one dimension, Fick's second law states that:

$$\partial c/\partial t = \partial/\partial x(D_x \partial c/\partial x). \quad (2)$$

Fickian diffusional behavior can be represented by a plot of % uptake of solvent versus square root of time in which the % uptake is linear with the square root of time to around 60-70% of the maximum uptake and then the curve plateaus. From the experimental data, one can obtain the maximum solvent uptake, M_{∞} and from the slope of the initial linear portion of the graph one can obtain the diffusion coefficient, D , of the contaminant into the sample. These two values can be used in an analytical model to predict the moisture content in the sample at various times.² Sorption of water and organic liquids in several polymeric materials have been reported in the literature and all types of diffusional behavior ranging from classical Fickian (Case I), Case II, Super Case II to anomalous or Non-Fickian behavior have been observed.³⁻¹³

In order to determine the effect of the contaminants on the physical properties of the composites, the strength, modulus and fracture toughness have been determined after short and long term exposure to contaminants. A deterioration in strength and fracture toughness has been observed while the modulus is not affected upon exposure to contaminants like water, salt water, iso-octane, ethylene glycol and boiling water.

EXPERIMENTAL

The matrix material used in this study is NC 126, (Cardolite Corporation, Newark, NJ), a cashew nut shell liquid modified phenolic resin. NC126 is different from a straight phenolic resin in that there is an alkyl chain substituent in the meta position of the phenol. The resin is derived from cashew nut shell liquid and is a solid prepolymer with approximately 5% hexamethylenetetramine added for curing. Glass fiber (Owens Corning, Columbus, OH) and carbon fiber (Ashland Chemicals, Ashland, KY) were used as the reinforcing agents for making the composites. For the friction materials, in addition to the above, a friction modifier, NC 104-40 (Cardolite Corporation) and a filler, barytes (barium sulfate), were employed. The contaminants used in this study were distilled water, iso-octane, salt water, ethylene glycol and boiling water. Iso-octane (2,2,4-trimethylpentane) was obtained from Aldrich Chemical and ethylene glycol from Fisher Scientific.

The composites were made by hot pressing the resin-fiber mixture at a 25 volume % loading of the fiber.¹ The resin and fiber were mixed until a uniform sample was obtained and then hot pressed by compression molding at 160 °C and 500 psi for 15 minutes. The formulation employed for the friction material was 20/35/20/25 weight % of resin/fiber/friction modifier/filler, respectively.¹⁴ The friction modifier is a highly crosslinked cashew resin and is often referred to as cashew particles. The friction materials were processed by compression molding at 160 °C and 1000 psi for 15 minutes. These were then post-cured in an oven for 2 to 3 hours at 160 °C. Samples of 76 mm x 25 mm x 3 mm were cut from the molded plates, polished on a belt sander and weighed on an analytical balance. The specimens were then immersed in different media kept in enclosed bottles in a constant temperature water bath maintained at 23 and 50 (± 2) °C. The experiments at 100 °C were done by treating the samples under reflux conditions. At

specific intervals these samples were taken out and dried using a paper towel, and the uptake measured by weighing them on an analytical balance. The uptake measurements were carried for several days until saturation was observed. The uptake was reported as:

$$M(t) = \frac{\text{Weight of treated material} - \text{Weight of dry material}}{\text{Weight of dry material}} \quad (3)$$

The specimens thus treated, were then subject to mechanical tests to determine the mechanical properties of flexural strength and flexural modulus. Four-point bend tests (ASTM D 790-86) were done on 1" wide specimens on an Instron test machine with specimen length, support span and load span of 76 mm, 51 mm and 25 mm, respectively, at a loading rate of 1.25 mm/min. In order to determine the effect of moisture on the fracture behavior of the composites, compact tension specimens were prepared and after exposing them to boiling water for 24 hours, they were tested as per ASTM E 399-83 for fracture toughness.¹⁵

To study the effect of moisture uptake by different ingredients in friction materials, the following specimens were molded: neat resin, resin/glass fiber, resin/carbon fiber, resin/filler, resin/friction modifier and friction material. These specimens were exposed to boiling water for 24 hours under reflux conditions, they were dried in the same manner described above and their uptakes were measured. The 24 hour boiling water test is often used as a quick, accelerated test to determine the effects of sorbed moisture on material performance.¹⁶

The glass fiber composites and the friction materials were soaked in different media for 2 weeks. Over an extended period of time, the solvents started leaching out some material from these composites. Consequently, the exposure time was limited to 2 weeks for these samples which were tested for mechanical properties.

ANALYSIS OF SORPTION AND DIFFUSION

The analytical models are based on Fick's laws which indicates that the solvent concentration gradient ($\partial c/\partial x$) is the driving force for absorption. If the initial solvent distribution inside the material is uniform, then the amount of solvent at any time in the material should be given by,¹⁷

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[-\frac{(2n+1)^2 \pi^2 D t}{h^2} \right] \quad (4)$$

where M_t is the amount of the solvent in the material at time t , M_∞ is the maximum amount of solvent which can be attained under the given environmental conditions and is assumed to be independent of temperature, and h is the specimen thickness. Equation 4 may be approximated by the expression:²

$$\frac{M_t}{M_\infty} = 1 - \exp [-7.3(Dt/h^2)^{0.75}] \quad (5)$$

This is valid for moderate to long time periods.¹⁷ In equation 5, D is the diffusion coefficient of the material in the direction normal to the surface. From the initial slope of the sorption curve, the diffusion coefficient of a solvent through the composite can be obtained from the following equation.²

$$D = \pi(h/4M_\infty)^2 \left\{ \frac{M_2 - M_1}{(\sqrt{t_2} - \sqrt{t_1})} \right\}^2 \quad (6)$$

Knowledge of the initial slope of the plot of solvent uptake versus square root of time, plus the maximum uptake, M_∞ , allows the diffusion coefficient D to be calculated. Using

this value of D in equation 5, the amount of contaminant, M_t , at any given time, t , can be predicted. The diffusion coefficient is assumed to be a function of temperature and is not concentration dependent if the polymer does not undergo any swelling and no anomalous behavior is observed. If D is an increasing function of concentration, the uptake may be linear almost up to equilibrium.¹⁸

The nature of the diffusion process can be described by use of the following equation:^{19, 20}

$$M = kt^n \quad (7)$$

where M is the amount of sorbed liquid at any time t , k is a constant characteristic of the system and n is the exponent which defines the diffusion process. This approach has been used by a number of authors to characterize the diffusion process.²¹⁻²⁴ This equation is valid for short times and can be approximated to $\frac{M_t}{M_\infty} = 0.5$. A plot of $\log M$ vs $\log t$ should give the slope which is the exponent n . If the value of n is 0.5, it shows that the nature of the diffusion is Fickian; if it is 1, then the process follows Case II diffusion, and any value between 0.5 and 1 is said to be Non-Fickian or anomalous.

RESULTS AND DISCUSSION

Diffusion of solvents.

The uptake of water in neat resin as a function of the square root of time is shown in Figure 1 at different temperatures. It can be seen that the uptake is linear with respect to the square root of time and then the curve plateaus for the 100 and 50 °C experiments, exhibiting Fickian diffusional behavior. The maximum amount of water sorbed by the neat resin is about 4.5% at 100 and 50 °C. This confirms the independence of M_{∞} on temperature for water in the neat resin. The time to reach saturation level is faster at higher temperatures as expected. The assumption that the maximum contaminant content is independent of temperature (4.5% water for M_{∞}) has been used in equations 4 and 5 to generate the fits for all three temperatures. For water in the neat resin the uptake curves are well described by a Fickian process. Values of n and k from equation 5 are listed in Table I along with the data for the other systems studied. The values of D and M_{∞} from the Fickian analysis are listed in Table II. Consideration of edge effects in the calculation of D had negligible effects and therefore were not included in the reported data.

The uptake of water in carbon composites at 23 and 50 °C is shown in Figure 2. The maximum water content attained by the composite is 6.0% and is higher than the neat resin. This is expected because of voids in the composite at the fiber-matrix interface. It can be seen that at 23 °C, the system has not attained equilibrium under the experimental conditions. The measured diffusion coefficients are slightly larger than in pure water and the uptakes are significantly larger.

The effect of uptake from saturated salt (sodium chloride) solutions is shown in Figures 3 and 4 for the neat resin and carbon composite, respectively, at 23 and 50 °C. Again there are larger uptakes and diffusion coefficients from salt water for carbon composite than for the neat resin. There is a negative deviation from Fickian behavior in the initial region for

salt water diffusion in the neat resin. This is also observed in the carbon composite, although the effect is not nearly as large. No indication of anomalous behavior is apparent from the exponent n , although the k value is retarded.

The neat resin degraded in ethylene glycol and hence was not studied further. The carbon composite showed a relatively high uptake of ethylene glycol, 10.7% at 50 °C, as seen in Figure 5. At 50 °C the diffusion coefficient is relatively fast, while at 23 °C it is much slower. The difference in the experimental data and the fit in Figure 5 for ethylene glycol could be due to a deviation from normal Fickian diffusion. There seems to be some sort of a time lag or induction time before sorption begins. It is possible that the small induction period may be the result of sorption balanced by extraction of material. This kind of an induction time has been observed with other systems.^{26,27} The reason for this behavior is attributed to the molecular relaxation of the polymer before it attains equilibrium surface concentration. If one plots the uptake against time, in which the initial portion of the curve has an intercept on the x-axis, the diffusion coefficient can be calculated by what is known as the time-lag method.¹⁷ This gives a value of 1.8×10^{-7} cm²/sec for the diffusion coefficient of ethylene glycol in carbon composite, whereas that obtained from fitting the sorption curves is 4.4×10^{-9} cm²/sec. The fact that the two diffusion coefficients are so different suggests a deviation from Fickian diffusion. In Table I it can be seen that the value of the exponent n for ethylene glycol at 23 °C suggests Fickian behavior, but at 50 °C there is a marked deviation from Fickian behavior, tending towards anomalous or non-Fickian behavior. It is possible that the 'induction' period observed here is due to extraction of some of the resin by the solvent, however, the resin is highly colored and no observation of the solvent coloration was observed. This was the case for the pure resin, however. It is possible that this occurs to a lesser extent in the other systems as well.

The neat resin and carbon composite in iso-octane show a Fickian behavior initially, in

Figure 6, in that the uptake varies linearly with $\sqrt{t}$. After a certain period there is a jump in the uptake, following which there seems to be an overshoot in the curve followed by saturation. It is possible that the resin and the composite undergo some swelling in iso-octane causing a sudden increase in the uptake, resulting in an earlier saturation than predicted. The kind of overshoot seen in these curves has been noticed with a number of amorphous polymers exposed to organic liquids.^{21,23,25} An explanation for this kind of behavior has been proposed by Vrentas, Duda and Hua based on the slow relaxation process of the polymer.²⁶ Solvent gets absorbed into the polymer before the polymer chains have a chance to completely relax. As the chains eventually reorient, some of the solvent from the sample is occluded. Such solvent exclusion is seen in systems where the diffusion rate is faster than the rate of chain relaxation. The value of the exponent n shown in Table I also indicates a deviation from Fickian behavior and therefore the diffusion of iso-octane in the resin and composite may be described as non-Fickian.

For glass fiber/phenolic composites a linear behavior in the uptake was observed initially. But then the composites were prone to attack by the contaminant resulting in loss of the material. The initial results from the plots of % uptake for these glass composites seem to suggest that the behavior is Fickian although values of maximum moisture content (M_{∞}) and diffusion coefficient (D) could not be obtained. Further uptake measurements with this composite were therefore suspended.

The diffusion coefficients shown in Table II characterize the speed at which the contaminant is transported through the material. It can be seen that diffusion is faster in the composite systems than the neat resin for a given system. For example, the water diffusion coefficient has a value of $1.4 \times 10^{-10} \text{ cm}^2/\text{s}$ in the neat resin and $2 \times 10^{-10} \text{ cm}^2/\text{s}$ in the carbon composite at 23 °C. A comparison with other systems is in order. The diffusivity of water in epoxies is of the order of $10^{-9} \text{ cm}^2/\text{s}$ at room temperature.^{5,7,28-30}

For polyesters,³¹ D at 20°C is 2.50×10^{-8} cm²/s. In addition, the uptake of water in epoxies have been reported ranging from 3-6% depending on the nature of the epoxy-hardener system.^{5,28,32,33} For systems in which deviations from Fickian behavior was observed, the values of D were calculated in the same manner as for Fickian behavior and can be treated as apparent diffusion coefficients.²

The diffusion coefficients of water in the neat resin was plotted as $\log D$ vs $1/T$ (not shown). The plot was linear and the slope was used to estimate the energy of activation, E_a as per the Arrhenius equation:

$$D = D_0 \exp(-E_a/RT) \quad (8)$$

For the neat resin, E_a for water was found to be 66.8 ± 3.3 kJ/mol. This value seems reasonable compared to the value of 55 kJ/mol for the diffusion of water in epoxy resins³⁰ and 45 kJ/mol for the diffusion of water in polyesters³¹ This is again in accordance with the fact that polyesters and epoxies are more hydrophilic than phenolics and hence water is expected to diffuse more easily into epoxies and polyesters. This is also consistent with diffusion of water being faster in polyesters and epoxies than phenolics.

In order to measure the effect of different ingredients in friction materials on the water uptake, different systems were exposed to boiling water for 24 hours. Table III shows the water uptake for different systems which were processed in the same manner described earlier. The maximum water uptake is highest for the friction material, which is expected because of the presence of many ingredients. The presence of the friction particles or the filler do not seem to affect the uptake of the neat resin. However the glass fibers play a major role in absorbing water.

Mechanical properties.

After exposing the neat resin, composites and friction materials to several contaminants

they were then tested for their mechanical properties. Figure 7 shows the flexural strength of different systems before and after subjecting them to boiling water for 24 hours. There is a definite reduction in the strength of all the systems after exposure. Figures 8 and 9 illustrate the flexural strength of neat resin and carbon composites, respectively, before and after exposure in various media. In this case, the samples had sorbed the maximum amount of the contaminant to which they were exposed. The flexural strength of the exposed samples were also lower than that of the control. Figure 10 shows a similar study for glass fiber composites and friction materials for a period of 2 weeks. The strength of the composites and friction materials containing glass fibers after exposure seems to be significantly affected in a short period of time.

In general, the deterioration in mechanical properties could be due to several possible reasons. Extensive work has been done on epoxy matrices and one significant finding is that matrix plasticization occurs due to the presence of water or other solvents. Water or any other solvent that enters the polymer matrix acts as a plasticizer,³⁸ thereby reducing the glass transition temperature, T_g , of the polymer. Since the T_g is directly related to the performance of a polymer, a lowering of the T_g obviously reduces the mechanical properties.^{3, 7, 32-37} The T_g of epoxy was lowered by as much as 60 °C by approximately 4 wt% sorbed moisture.^{3, 32} In the present case, the glass transition temperature of the dry neat resin (NC 126) went down by as much as 50 °C for a 4.5% uptake of water, as determined by dynamic mechanical analysis (DMA).

The depression in glass transition temperature of a polymer may be estimated using the Fox equation,³⁹

$$1/T_g = W_p/T_{g,p} + W_w/T_{g,w} \quad (9)$$

where the subscripts p and w refer to the polymer and water respectively. Here W_p and W_w are the weight fractions of the polymer and water in the wet resin and $T_{g,p}$ and $T_{g,w}$ are the glass transition temperatures of the pure polymer and water. Using a value of 138

K for the T_g of water³⁹ and 433 K for the T_g of the dry resin, the T_g of the wet resin containing 4.5% water turns out to be 395 K, which reasonably agrees with the experimentally determined value of 383 K.

The large reduction in strength of glass fiber composites and friction materials seen in Figure 10 can be explained by the high uptake of water in both cases. This happens since glass is hydrophilic and will have a tendency to absorb water on its surface.⁴⁰ Secondly, voids are present in the composite at the fiber-matrix interface and these provide additional sites for absorption of water. Due to imperfect adhesion between the matrix and fiber at the interface, water molecules could migrate to the fiber-resin interface by diffusion through the resin or by penetration through voids, cracks or other defects and by migration along the fiber surface and possibly cluster there.

Studies done on glass-epoxy and graphite-epoxy composites show that changes in property of resin, interface and fiber degradation and resin stress relaxation could be the reasons why properties deteriorate.¹⁶ Glass fibers themselves are quite sensitive and may undergo fracture as was observed in glass epoxy composites after a 72 hour boil.⁴¹ Since diffusion occurs more rapidly in the composite than in the resin and since equilibrium sorption is also much higher, it is possible that diffusion and sorption is occurring along the interface.^{5,39} Another factor that contributes to the degradation of mechanical properties is solvent crazing which leads to collection of solvent in cracks and voids. This could lead to a stress cracking mechanism resulting in failure of the material.⁴²

The mechanical properties of the neat resin and the composites before and after exposure in different media is summarized in Table IV. The flexural strength goes down in all cases after exposure while there is hardly any noticeable change in the flexural modulus. Table V shows the fracture toughness of different systems before and after immersion in boiling water for 24 hours. The control specimens have higher fracture toughness than the exposed

ones. The fracture toughness, after exposure to contaminants does not seem to be affected as much as the flexural strength. This has been observed with other thermosets.⁴³ Since fracture toughness is a measure of the materials ability to resist crack propagation, it means that water absorption affects this to a lesser extent.

CONCLUSIONS

The diffusion of water and salt water in neat cashew modified phenolic resin and its composites shows Fickian behavior. Solvents like iso-octane at 23 °C and ethylene glycol at 50 °C show a departure from classical Fickian diffusion. The maximum moisture content in these systems and their diffusivities have been determined and an analytical model used to predict the contaminant content. The mechanical properties of these systems like flexural strength and fracture toughness show a reduction in values after exposure to different environments while the flexural modulus is not significantly affected. This deterioration in properties may be due to matrix plasticization which causes a reduction in T_g and hence material performance. The contaminant may be migrating to the fiber-matrix interface and causing interface degradation.

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Table I: Values of n and k in equation 7

solvent	temperature (± 2) °C	<u>RESIN</u>		<u>COMPOSITE</u>	
		n ^a	k ^b	n ^a	k ^b
water	23	0.57 $\pm$.03	0.10	0.58 $\pm$.06	0.11
	50	0.57 $\pm$.04	0.36	0.53 $\pm$.04	0.54
	100	0.44 $\pm$.03	0.60	-	-
salt water	23	0.49 $\pm$.03	0.15	0.50 $\pm$.06	0.15
	50	0.55 $\pm$.04	0.26	0.52 $\pm$.04	0.54
ethylene glycol	23	degraded		0.57 $\pm$.06	0.07
	50	degraded		0.97 $\pm$.04	0.15
iso-octane	23	0.81 $\pm$.06	0.21	0.75 $\pm$.05	0.02

a. $\pm$ is the 95 % confidence limit.

b. g/(g daysⁿ)

Table II: Diffusion coefficient and maximum solvent uptake

MEDIUM	TEMPERATURE, °C	RESIN		CARBON COMPOSITE	
		D ^a	M _∞ , %	D ^a	M _∞ , %
water	23	1.4	4.5 ^b	2.0	6.0 ^b
	50	12	4.7	13	6.0
	100	400	4.5	-	-
salt water	23	1.2	4.1 ^b	1.9	7.1 ^b
	50	14	4.1	18	7.1
ethylene glycol	23	degraded		0.2	11 ^b
	50	degraded		44	11
iso-octane	23	0.9	2.1	1.9	2.6

a. D, 10⁻¹⁰ cm²/sec

b. assumed

Table III. Uptake of different systems in boiling water
for 24 hours

SYSTEM	UPTAKE, %
Neat resin	2.4 ± 0.1
Carbon composite	2.7 ± 0.1
Glass fiber composite	5.8 ± 0.5
Barytes/Resin	2.4 ± 0.2
Friction particles/resin	2.1 ± 0.1
Friction material	6.5 ± 0.6

Table IV. Mechanical properties of neat resin and composites after exposure. FS: Flexural strength, MPa, FM: Flexural modulus, GPa; a) 6 months, 50° C; b) 2 weeks, 50° C; c) 24 hours; d) 23° C. The errors are ± 1 standard deviation.

Environment	Neat resin		Carbon composite		Glass fiber composite		Friction material	
	FS	FM	FS	FM	FS	FM	FS	FM
Control	68.72 ± 10.18	7.74 ± 0.60	87.86 ± 10.08	10.82 ± 0.95	90.69 ± 8.06	13.84 ± 1.30	46.01 ± 4.23	4.65 ± 0.23
Water	47.58 ^a ± 5.30	7.25 ^a ± 0.46	61.50 ^a ± 7.20	10.51 ^a ± 0.91	75.60 ^b ± 5.40	13.30 ^b ± 0.85	29.5 ^b ± 2.56	4.16 ^b ± 0.30
Boiling water ^c	59.46 ± 4.68	6.91 ± 0.61	71.51 ± 1.84	9.99 ± 0.41	57.17 ± 4.44	13.10 ± 0.97	31.14 ± 3.27	3.99 ± 0.28
Salt water	37.69 ^a ± 6.10	7.14 ^a ± 0.52	55.13 ^a ± 6.50	10.02 ^a ± 1.10	73.10 ^b ± 8.90	13.68 ^b ± 0.29	23.40 ^b ± 3.10	3.90 ^b ± 0.33
Ethylene glycol	degraded		54.97 ^a ± 7.68	10.16 ^a ± 1.09	68.99 ^b ± 5.23	12.78 ^b ± 1.10	28.60 ^b ± 2.60	3.76 ^b ± 0.50
Iso-octane ^d	30.20 ± 3.00	7.60 ± 0.50	78.00 ± 1.20	10.30 ± 0.15	75.12 ± 8.13	12.95 ± 1.20	26.23 ± 4.50	4.59 ± 0.53

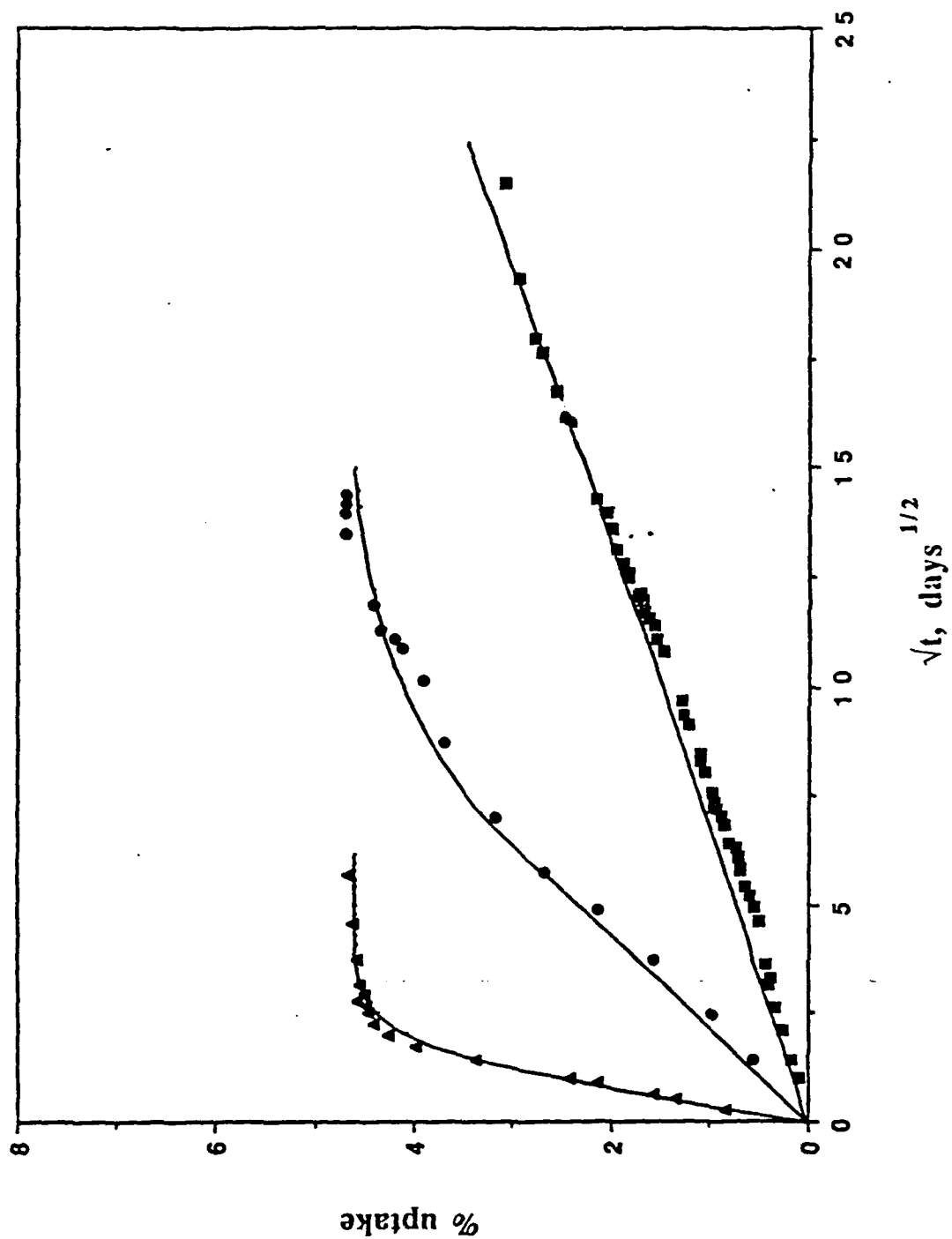
Table V. Fracture Toughness of systems before and after 24 hours in boiling water.

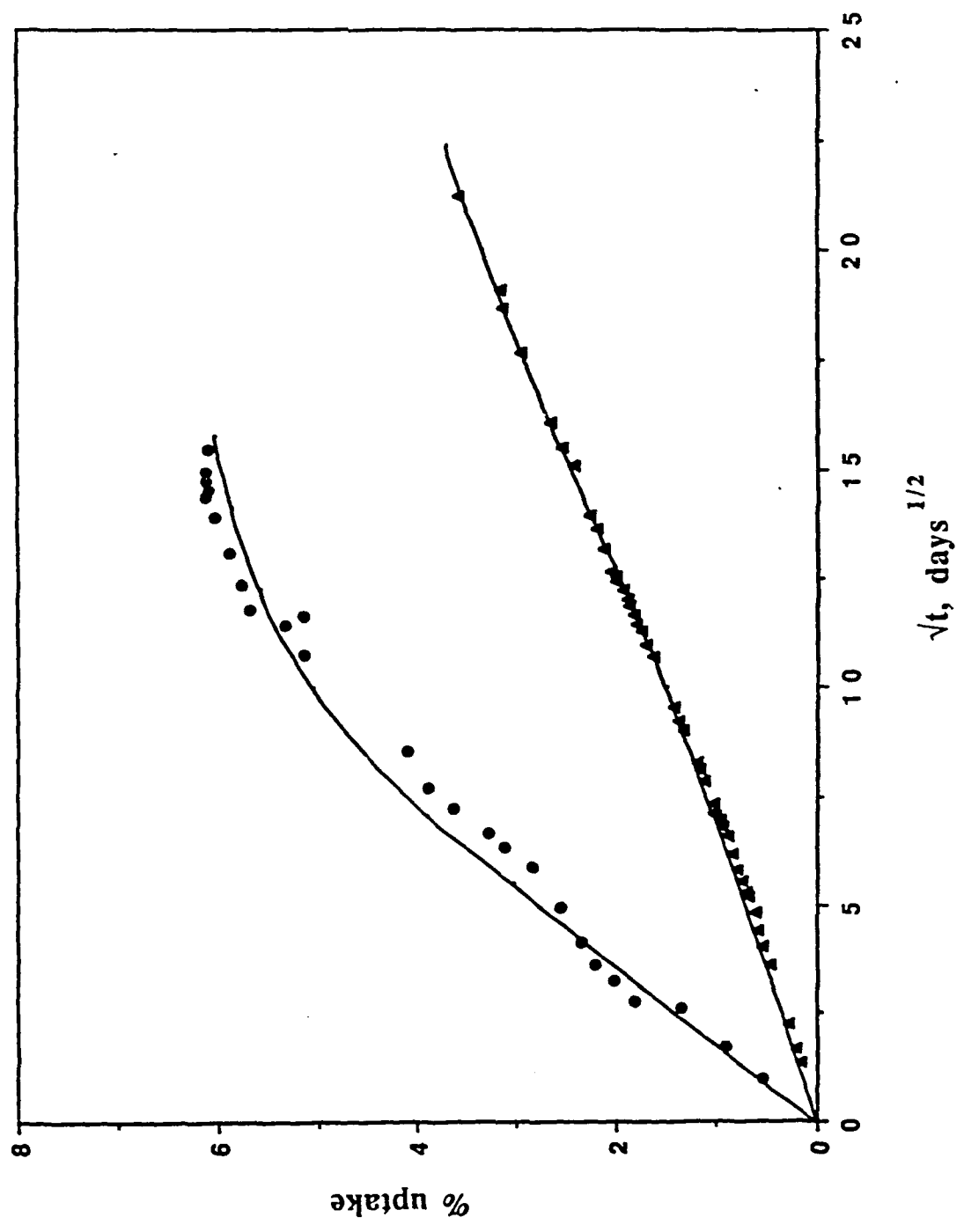
System	Fracture Toughness K_{IC} , MPa, m ^{1/2}	
	Control	Boiling water
Neat Resin	1.28	1.13
Glass Fiber Composite	6.16	5.72
Carbon Composite	2.60	2.06

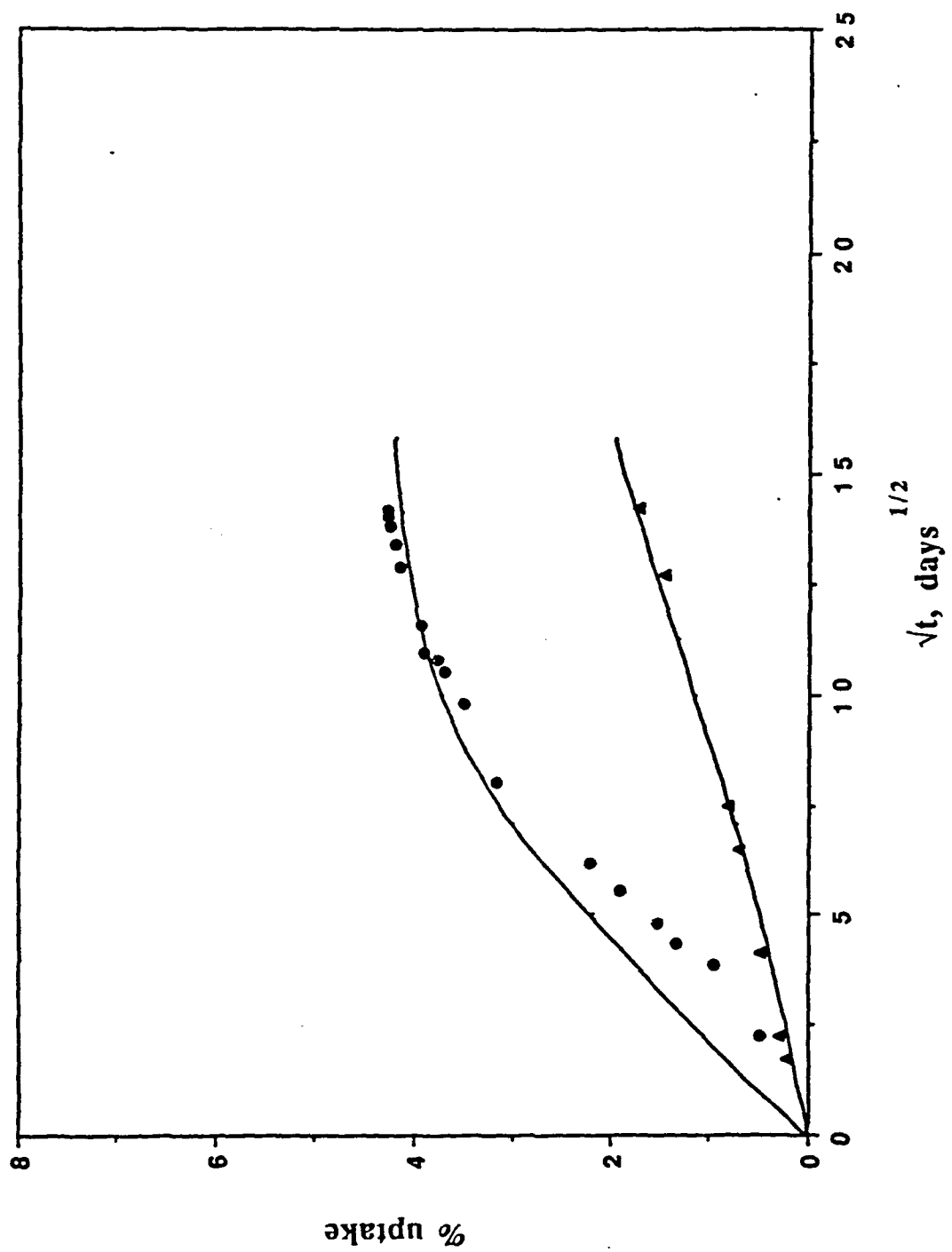
FIGURE CAPTIONS

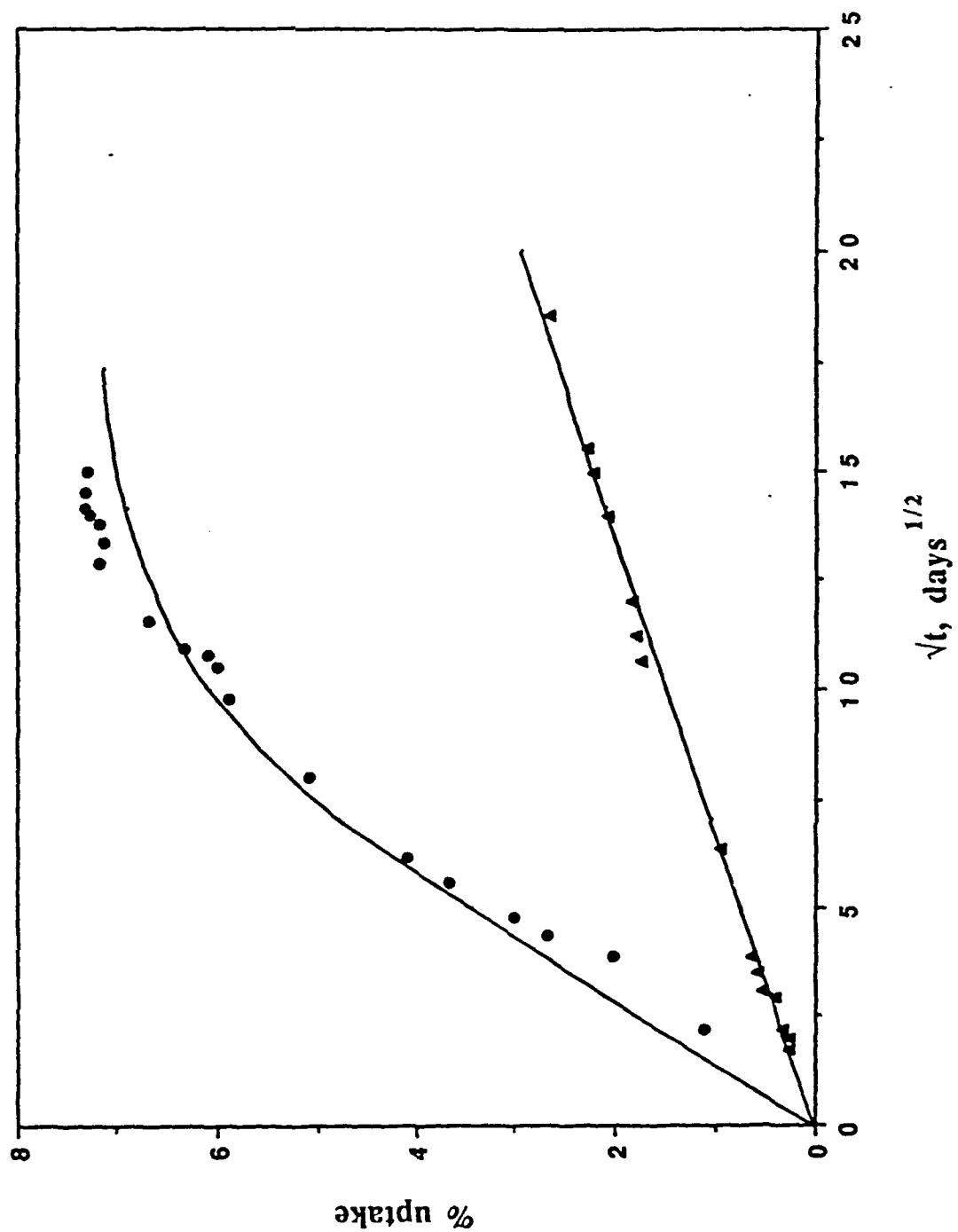
1. Water uptake for neat resin in water, as a function of square root of time at 100°C (▲), 50 °C (●) and 23 °C (■). The fits from the Fickian model are also shown.
2. Water uptake for carbon composites at 23 (▲) and 50°C (●).
3. Water uptake from saturated salt solution for neat resin, at 23 (▲) and 50°C (●).
4. Water uptake from saturated salt solution for carbon composites at 23 (▲) and 50°C (●).
5. Ethylene glycol uptake in carbon composites at 23 (▲) and 50°C (●).
6. Iso-octane uptake in neat resin (▲) and carbon composite (●) at 23°C.
7. Flexural strength of different systems before and after exposure to boiling water for 24 hours.
8. Flexural strength of neat resin after exposure to different contaminants. Resin in iso-octane is at 23°C for 18 months, all the rest are at 50°C for 6 months
9. Flexural strength of carbon composites after exposure to different contaminants. Composite in iso-octane is at 23°C, all the rest are at 50°C.
10. Flexural strength of glass fiber composites and friction materials after exposure to different contaminants for 2 weeks. Systems in iso-octane are at 23°C, the others are at 50°C.

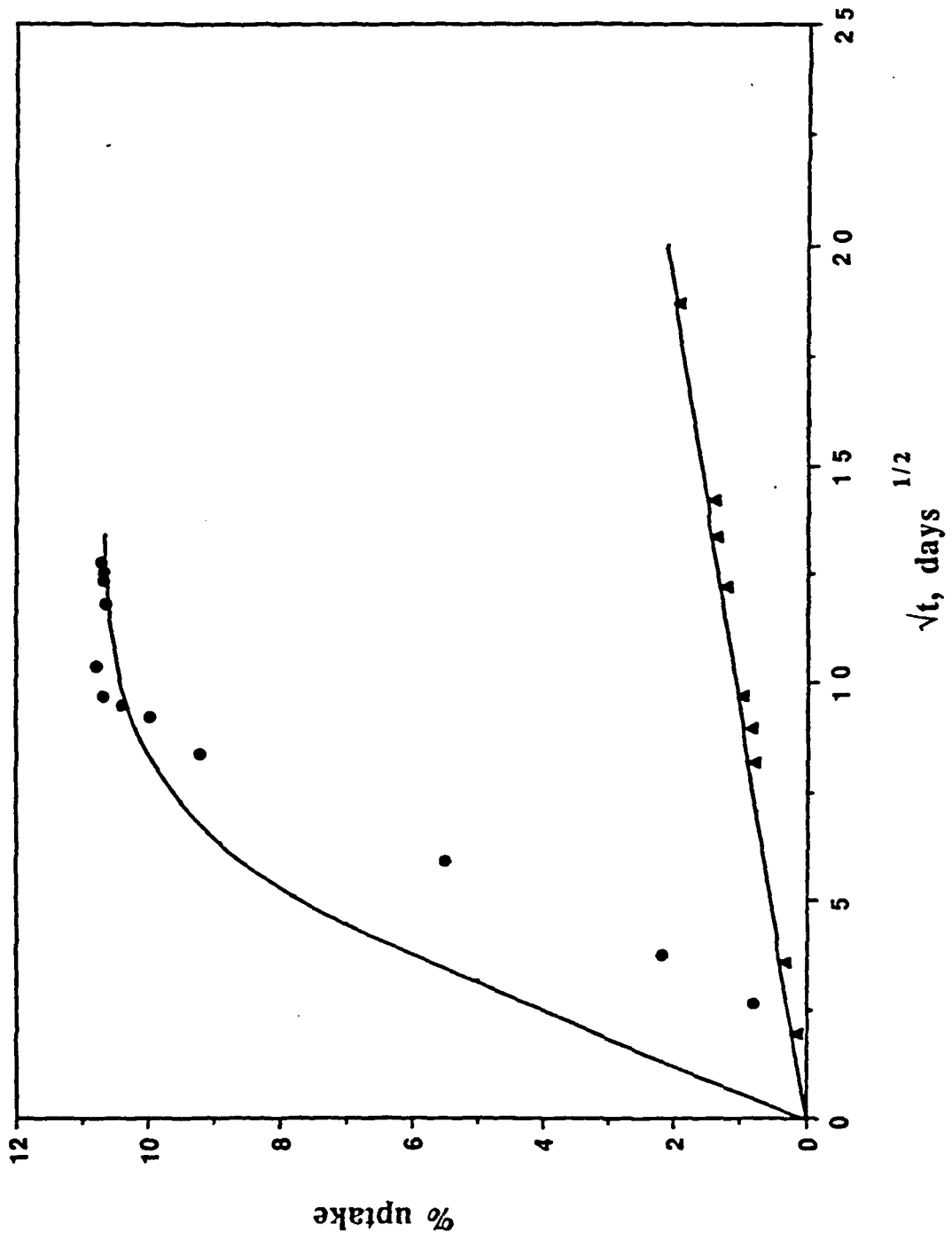
Fig. 1

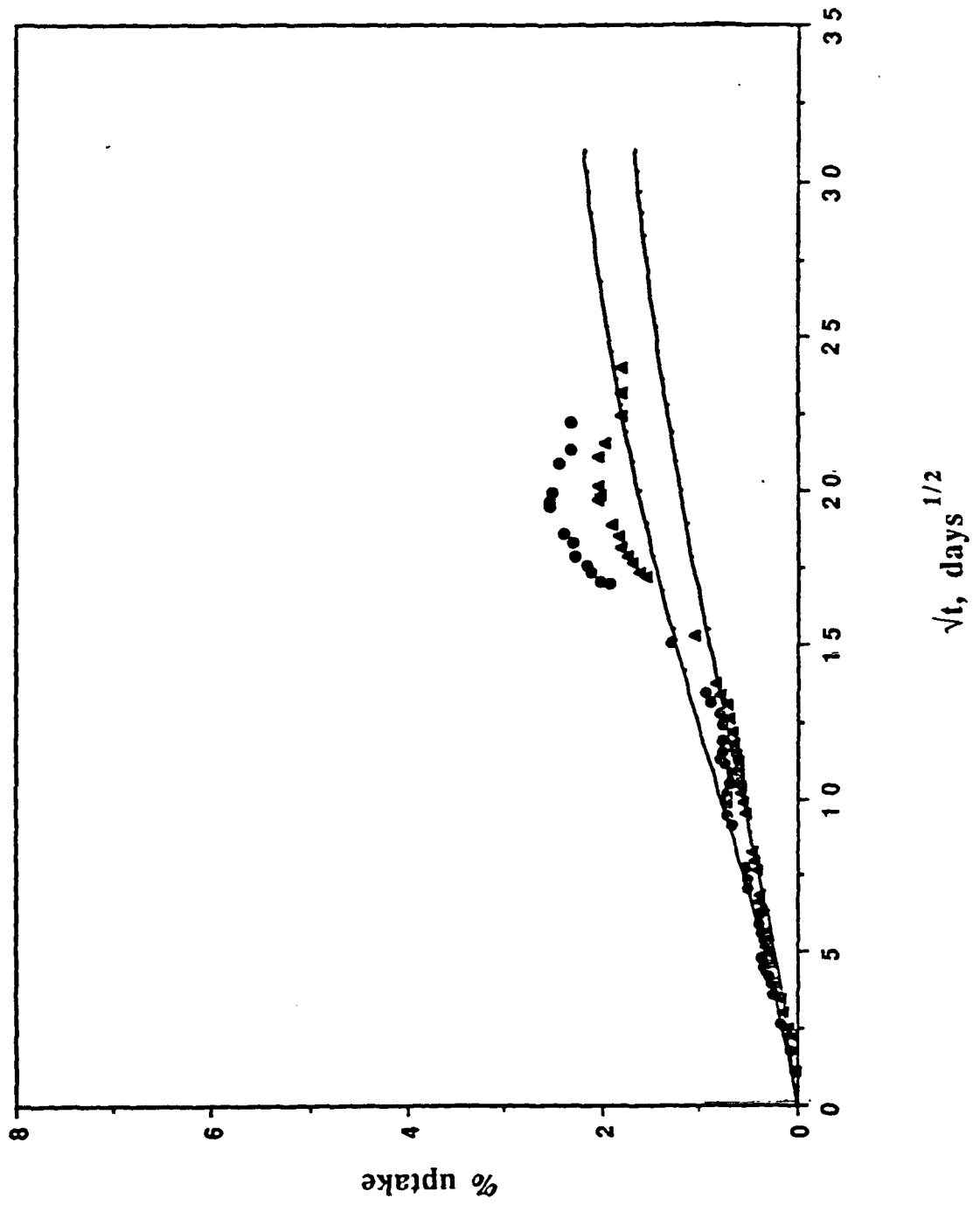


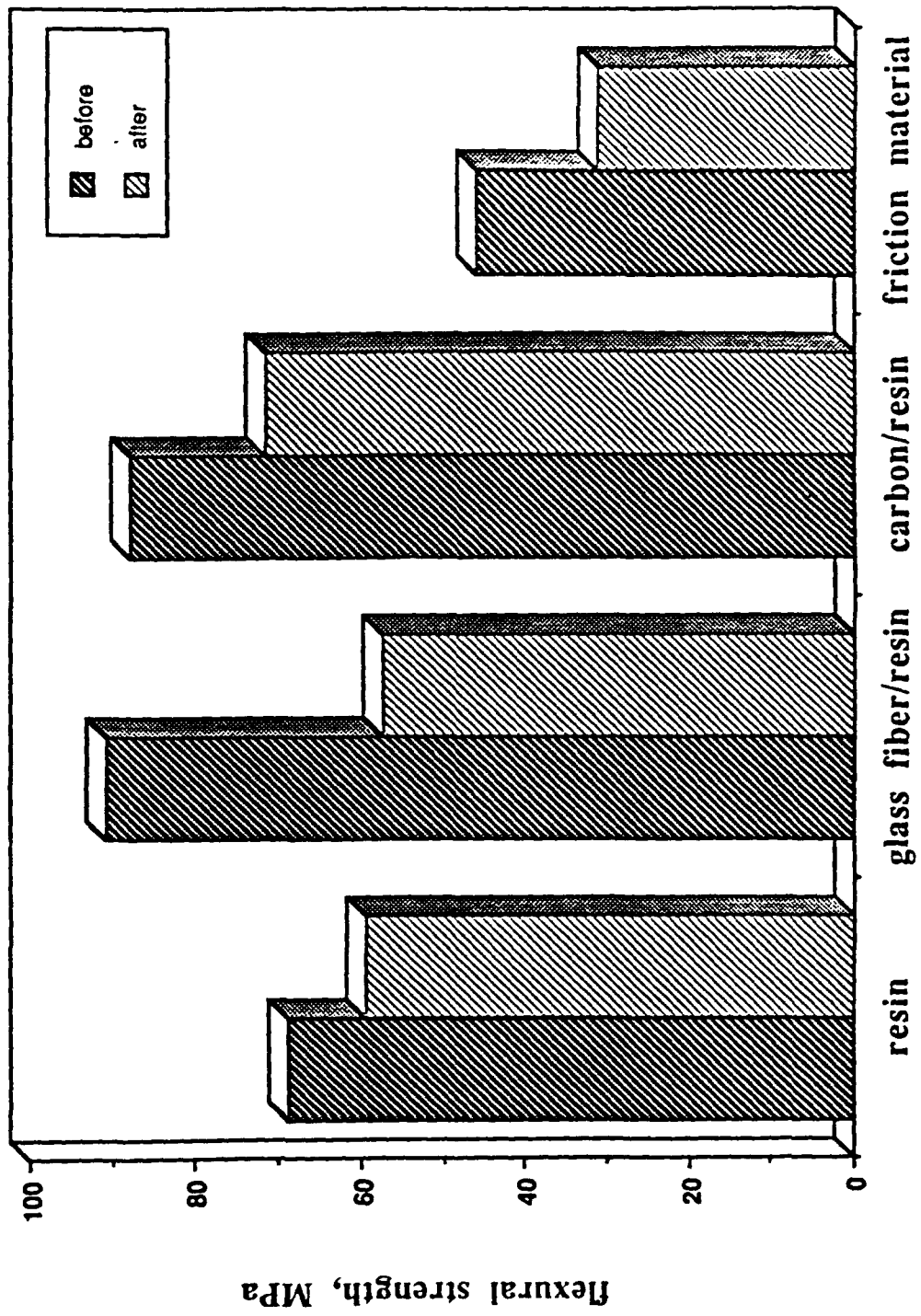


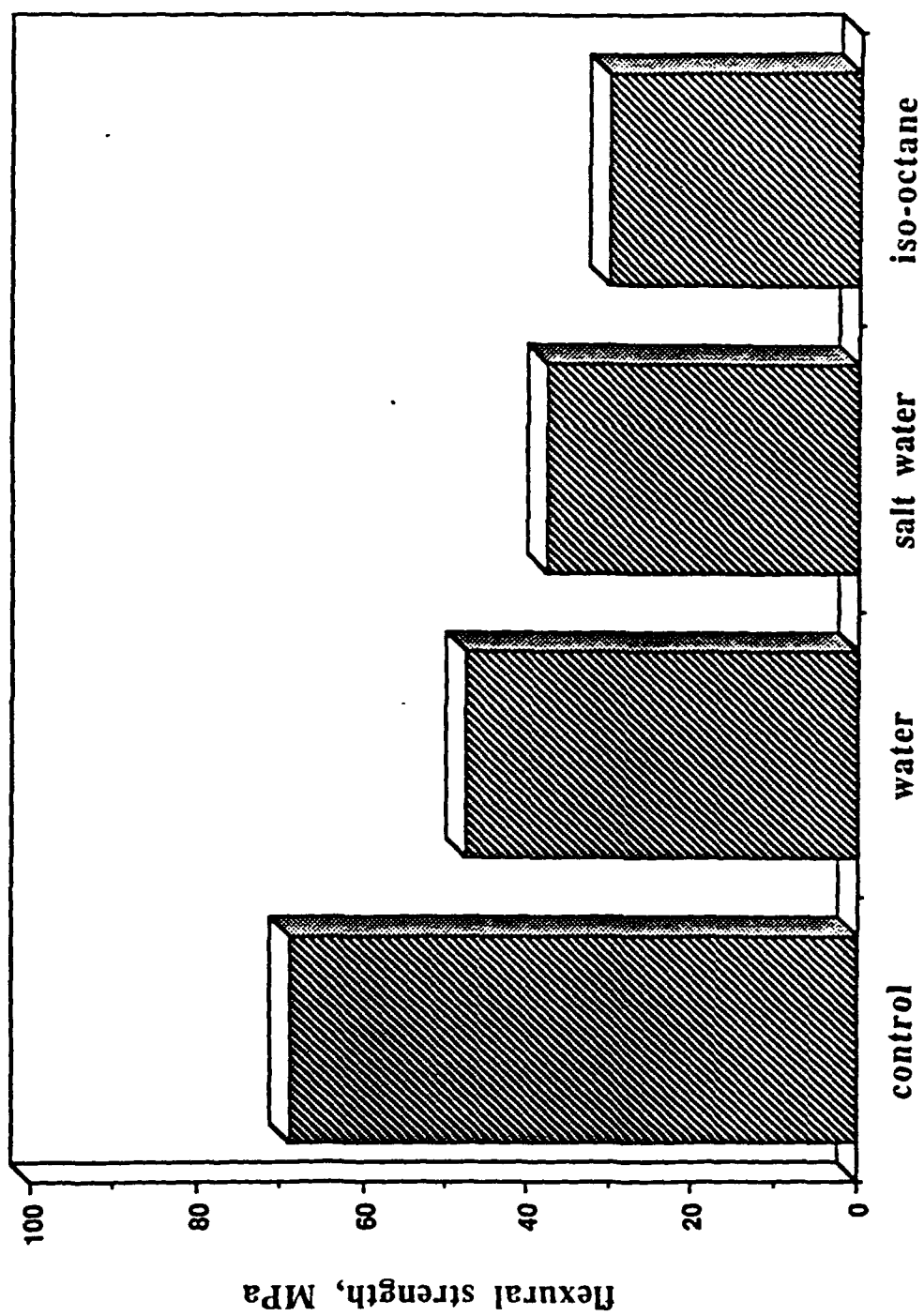


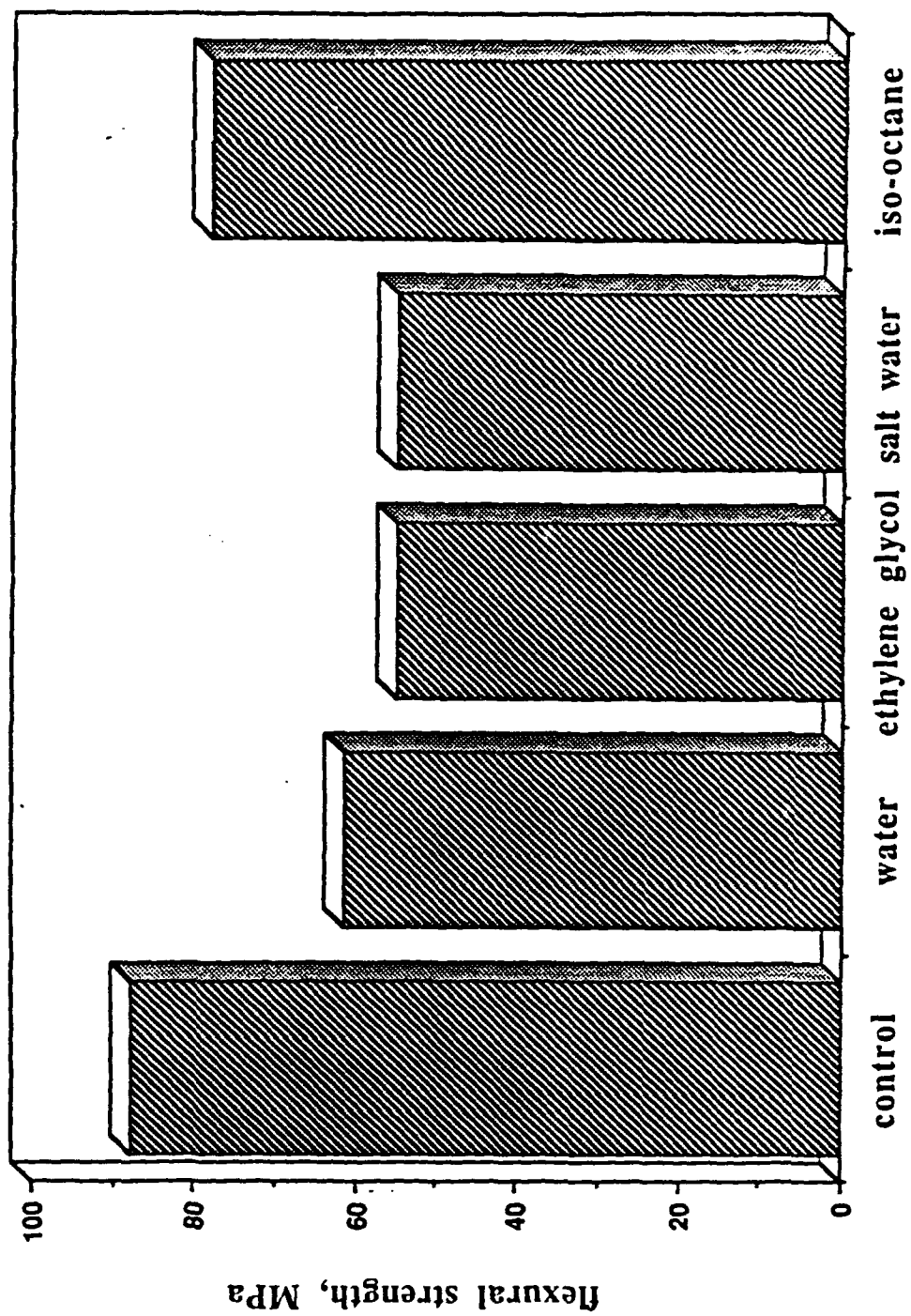












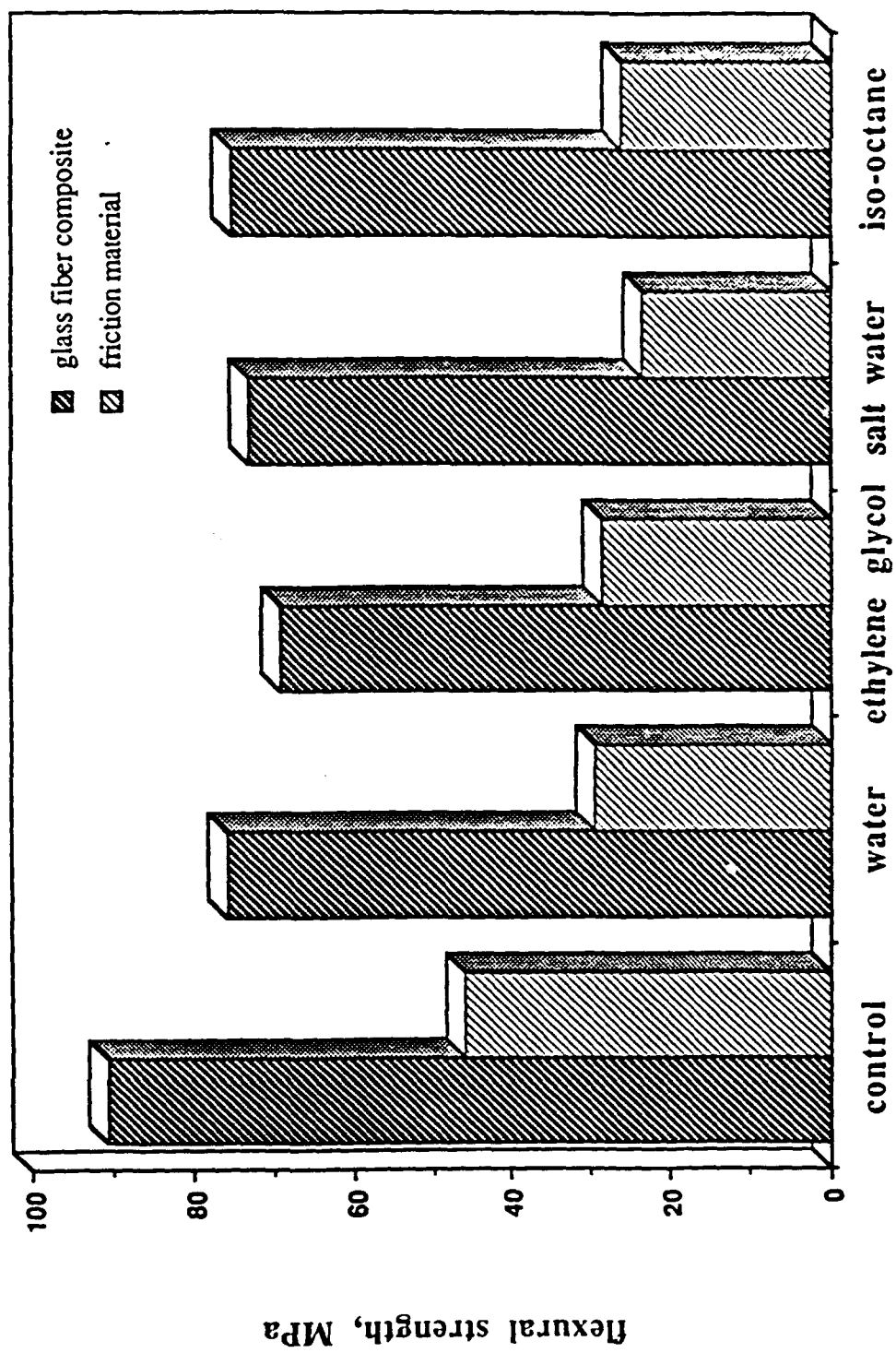


Fig 10