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Bending strength and static fatigue of glass fibre in different atmospheres by fibre loop test

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This study deals with the dependence of glass-fibre bending strength and static fatigue on different factors, mainly the ambient atmosphere. The fracture diameter of a loop (as measured by the loop test), which is proportional to the bending strength, was found to be dependent on the diameter of the fibre, as well as on the water concentration of the ambient atmosphere. Heat treatment (105° C) did not increase the bending strength of the fibre. High-temperature treatments (500 to 700° C) decreased the bending strength of the fibre substantially, presumably because of the relaxation of the stress distribution in the fibre. The results showed this to occur in a wide temperature range, whereas in massive glass relaxation has also been found in a wide temperature range. Under long-term stress, the fibres are affected by static fatigue, which is dependent on the diameter of the fibre, the effective force, and the ambient atmosphere. The static fatigue of fibres allows us to explain the long-term properties found in light glass wool-based composites. Difficulties in determining the actual properties of glass wool composites are caused by the considerable inhomogeneity of the composite fibres, rendering usage of them in testing impossible. Accordingly, the fibres are more susceptible to static fatigue than the fibres in the tests.

1. Introduction

Of central importance in the study of glass fibre-based plastic composites is the determination of the properties of the composite itself. For this to be possible, however, it is often essential to analyse the properties of the different components separately.

This study is part of a larger research project concerned with the structure and properties of a porous glass wool phenolformaldehyde resin composite. In the density range 10 to 40 kg m^{-3} and with a resin concentration of 2 to 10 wt %, characteristic of the composite is an almost complete restitution after short-term compression, whereas even with relatively low degrees of compression the duration of the compression causes non-restitution [1].

No answer to this question has to date been found from scrutinizing the structure of the composite, because the fibre–resin bonds have been observed to be extremely strong and atmosphere-resistant in normal conditions [2]. Likewise, the resin used has been found to be completely stable in the examined conditions and time periods [2].

The fibre structure of the composite in question is oriented rather randomly in the direction of the composite plane, and relatively few fibres are oriented perpendicular to this plane [1]. Therefore, most of the fibres are always in a skew position in relation to the effective stress; also, the fibres are, to a great extent, under flexural stress. It has thus been presumed that an increase in non-restitution, as a function of time, is caused by breaking, as a function of time, of those fibres in the structure that were bent.

Composite fibres and their actual bendings cannot be examined directly, as the fibres are in the main rather short and indefinite in shape. For

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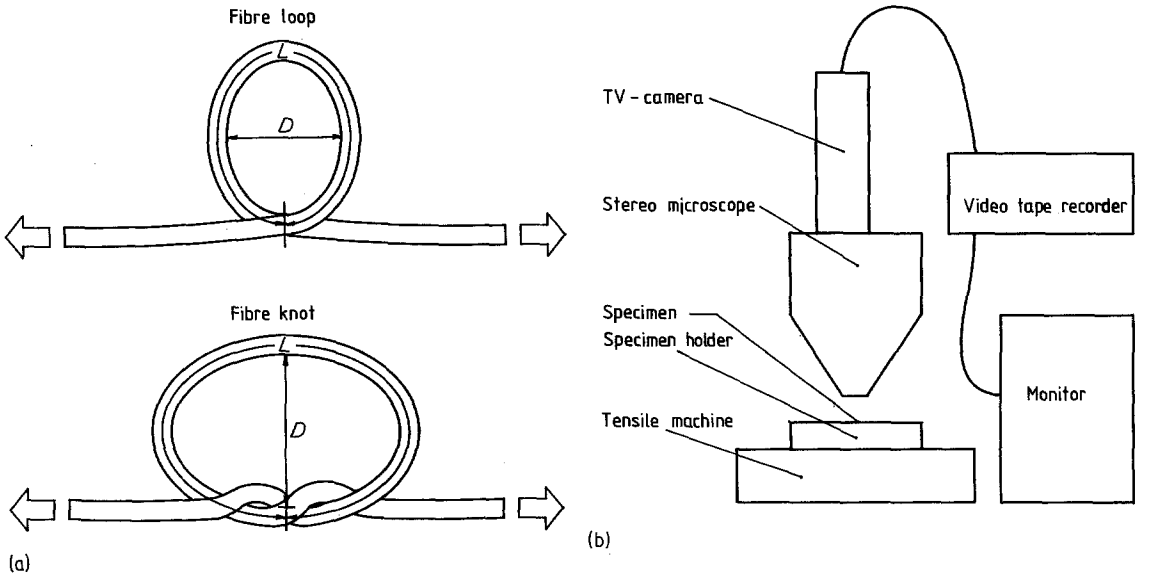


Figure 1 (a) An indirect method to measure the bending strength of glass fibre by a loop test and (b) a schematic illustration of the equipment.

this reason, the phenomenon has been studied on the basis of the properties of the fibre loops made of a continuous fibre.

In the case of macroscopic glass, the fracture of glass under temporal stress is known as static fatigue. In theory, the static fatigue of glass has been explained by the combined effect of stress state, surface structure defects and ambient atmosphere.

2. Experimental details

Due to the small dimensions of glass fibre, there is no direct method for measuring its bending strength. Therefore, it was measured indirectly by means of a loop test, which measures the bending capacity of the fibre. The method has been described and used by Eitel and Oberlies [3] and Anderegg [4].

The method and the equipment used in this study are presented in Figs. 1a and b. The fibre was made into a loop which was forced between a metal plate and a glass disc; at the same time, the fibre was attached to the jaws of the tensile testing machine to subject it to a constant pulling speed. During the tensile test, the fibre loop was observed through the glass disc with an optical stereomicroscope; the picture of the loop was recorded with a television camera onto a video tape. The dimensions of the loop were measured afterwards from a still picture on the television screen. With this method, the dimensions could be measured 25 times a second, and at the latest, 0.04 sec before fracture. The same test can also be performed in a scanning electron microscope; this, however, requires using a knot instead of a loop.

As implied above, the static fatigue of fibres was examined with the loop test: the fibres were formed into a loop close to the fracture point, whereafter the loops were mechanically fastened into that position. The loops were then observed regularly, and the time to fracture was recorded.

3. Results

The test results are presented in various cases as functions of glass type, fibre thickness, loop diameter, ambient atmosphere, time and strength. The fibre thicknesses were measured with an optical microscope, the accuracy of which has been determined to be $\pm 1\,\mu m$ by SEM. Loop diameters were measured directly from the TV screen; the accuracy of measurement here was approximately $\pm 2\,\mu m$.

Fig. 2 shows the loop diameters and distribution of results at fracture in the loop test with different glass types as a function of fibre thicknesses; Fig. 3 presents the loop diameters at fracture in different atmospheres. In the case of E-fibre, the values of static fatigue in different atmospheres are presented as a function of loop diameter, fibre thickness, and fracture time. The results of heat-treated fibres in the loop test are

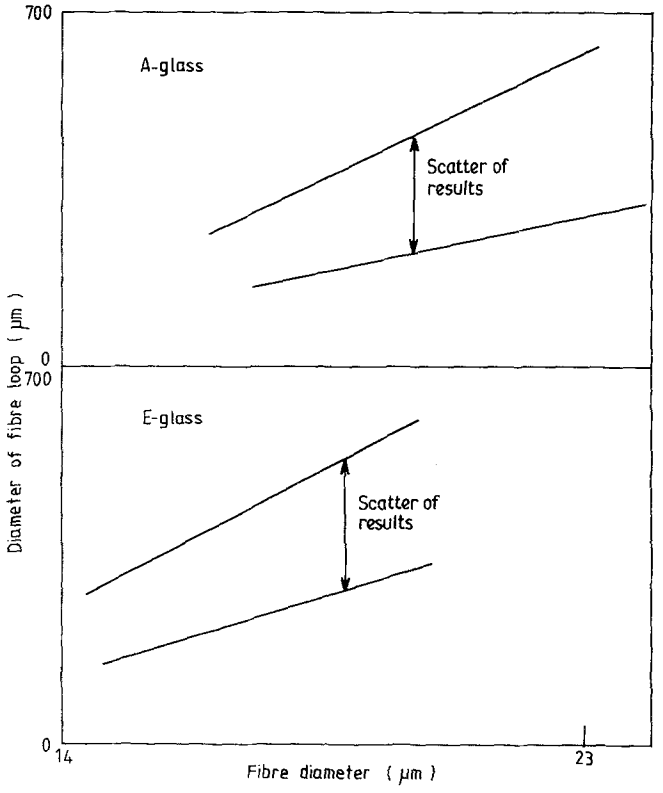


Figure 2 The diameters of fibre loop at fracture in loop test of "A" and "E" glass fibres (in room atmosphere altered fibres and "A" fibre without sizing).

presented in Fig. 4. The corresponding results of heat-treated fibres in a tensile test are presented in Fig. 5.

Fig. 6 shows the fracture surfaces of a fibre after tensile and bending tests as observed by the SEM.

Both short and long term loop tests were performed in different atmospheres, namely, normal room atmosphere, a very low relative humidity (phosphorpentoxide dried exsiccator), a very high relative humidity (water in a closed exsiccator) and water atmosphere (loops submerged in water). The results of the loop tests are presented as functions of glass type, fibre diameter, fracture diameter of loop, and time.

Furthermore, the loop tests were performed with fibres that had been subjected to various heat treatments. With fibres pretreated at 105° C, the aim was to remove water from the surface of the fibre, and to determine the effect of the water absorbed from the ambient atmosphere onto the fibre surface. With higher temperatures (500 to 700° C), the aim was to relax the stress distribution in the fibre and to determine its stress state after the pull. Besides examination in the loop test, heat-treated fibres were subjected to a normal fibre tensile test.

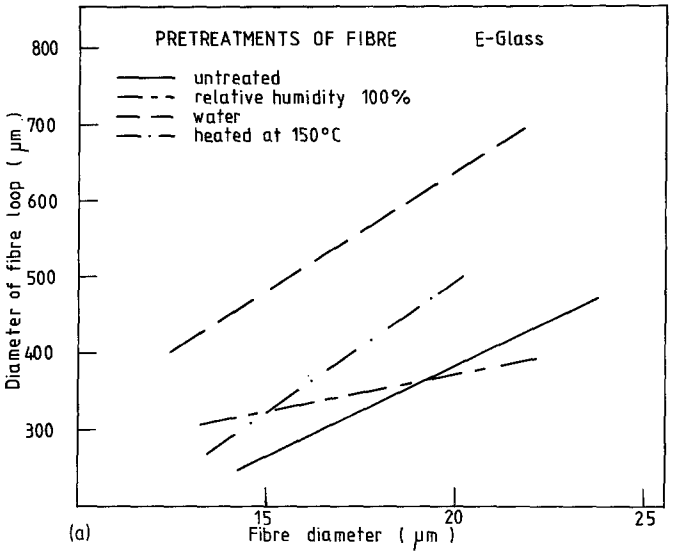
One of the test materials used in this study was a commerical E-fibre, the surface of which had been treated after manufacture. The studies were mainly done with fibres manufactured of A-glass, which was pulled under laboratory conditions and which had not been subjected to any surface treatments.

The test equipment in the loop tests consisted of a stereomicroscope connected to a Sony U-Matic video unit; the microtensile testing machine was self-made. The tensile tests were performed with the JJ T5003 tensile testing machine. Electron microscope analysis was carried out with the ISI 40 SEM (with an anticontamination equipment and an ISI Robinson detector).

4. Conclusions

The effect of fibre thickness on the results is clear. This result is congruous with the often found dependence between the tensile strength of a fibre and its thickness. No correlation has been noted in the case of freshly drawn fibres [5]. Small but still clear differences can be found in the absolute values between different glass types. Greater fracture diameters have been measured with E-fibre than with A-type fibres.

The difference noted in the fracture diameters



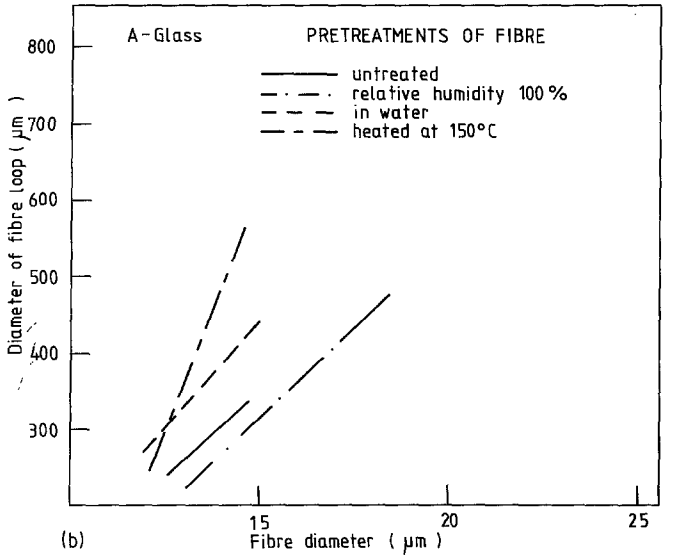


Figure 3 (a) Effect of ambient atmosphere (humidity) on the fibre loop at fracture in the case of "E" fibre and (b) "A" fibre.

of E- and A-type fibres can be accounted for by the tempering or prestressing in the manufacture of fibres. The speed of cooling down to continuous fibre manufacturing by different methods is in the same range. The difference is probably caused by the lower tempering capacity of E-fibre, which has a notably smaller linear thermal expansion coefficient (4.8×10^{-6}) than A-glass (9×10^{-6}).

The most simple way to prove the existence of tempering is to remove it by heat treatment. To achieve this, a heat microscope was used to determine the temperature range where the fibre, supported from its ends, began to bend due to its own weight. Below this temperature, the fibres were subjected to several different heat treatments. In practice, the fibres were heated and cooled down in an oven; the entire process lasted approximately 24 h.

Figs. 4 and 5 show that the fibre values in both bending and tensile tests are clearly lower after the heat treatments. On the basis of these results, it can readily be argued that, coming from the assembly line, the fibre has a prestressed structure, where the surface of the fibre is subjected to compression stress and the core to a tensile stress. The point, then, is that the relaxation of stress takes place in a very wide temperature range.

The structural cause of this relaxation of stress was not examined in this study. The fracture

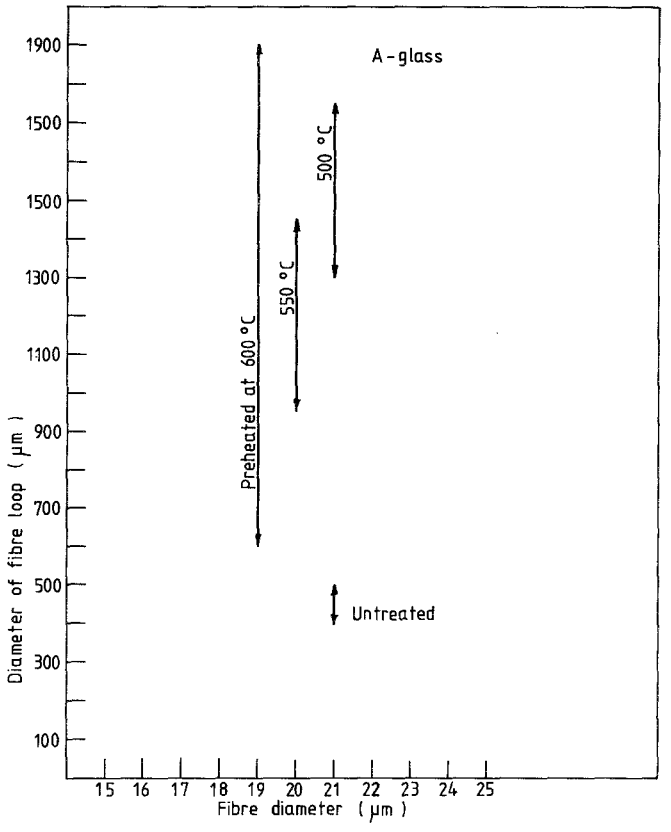


Figure 4 Effect of heat treatment (500 to 650° C) on the fracture loop of "A" fibre.

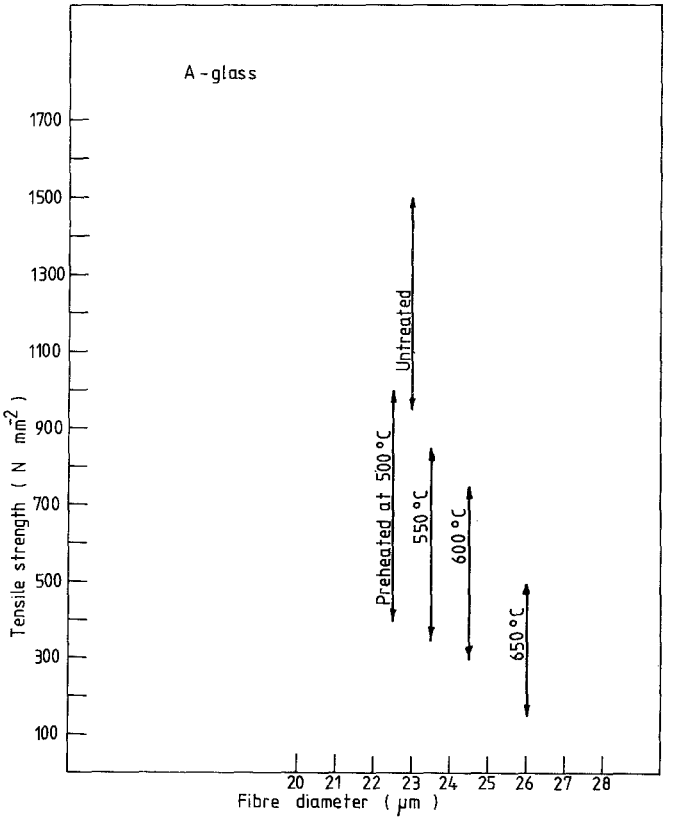


Figure 5 Effect of heat treatment (500 to 650° C) on the tensile strength of "A" fibre.

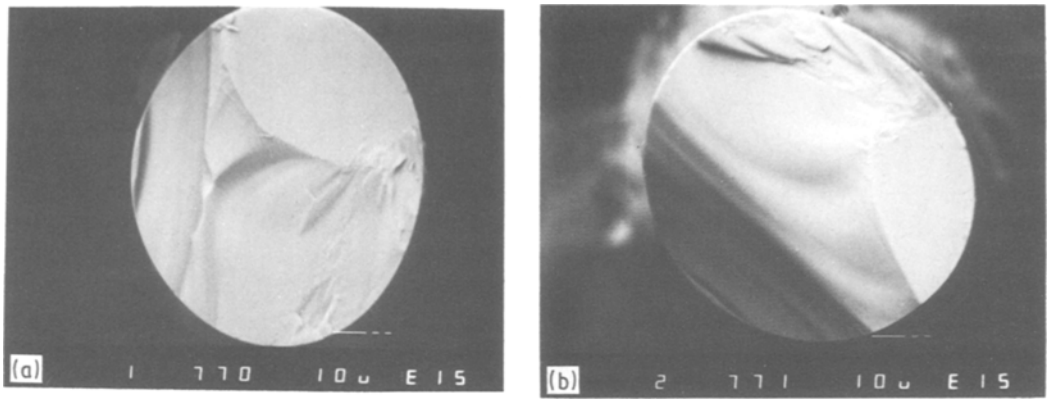


Figure 6 Scanning electron micrographs of the fracture surfaces of "A" glass fibres (loop test).

strain of glass fibre in tension was 2 to 6%, depending on the degree of stress required for fracture [6]. Notes on microplastic deformation of glass can be found in earlier literature; we can thus presume that it is possible for stress relaxation of glass fibre to happen through relaxations in a wide temperature range.

Heat treatment at a lower temperature (105° C) did not, neither in the loop nor in the tensile test, have any effect on glass fibre as compared with the nontreated material. At this temperature, there is no free water; but the small layer of water on the surface of the glass might stick to it so tightly that it cannot be removed. A good example of this is the strong bond between ice and water.

Where humidity is above normal, fracture occurs in the loop test with a loop larger than normal. The difference in the size of the loop is considerable. The tensile tests were also carried out with fibres subjected to various water treatments, and the results were similar. As a matter of fact, the tensile tests were not carried out in precisely these conditions, but immediately after removing the fibres from these conditions.

Similar results of static fatigue in different atmospheres were received in all different conditions. As regards time, loop fracture happens almost immediately if the diameter is close to the short-term test fracture diameter. The greater the ratio between the loop diameter and the fracture diameter of the short-term test, the longer the time before the loop breaks. This phenomenon is presented graphically in Fig. 7; only average numerical values can be given. This is mainly due to the fact that it is not possible to predict the fracture diameter of the loop in

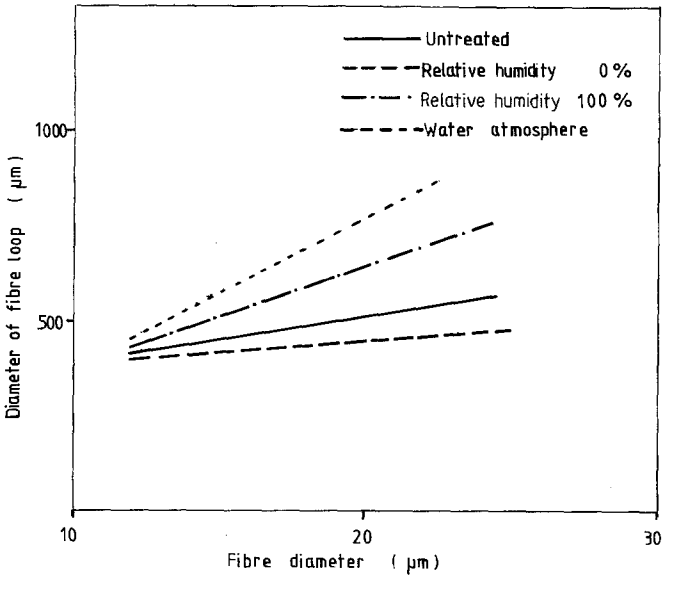


Figure 7 The static fatigue of "E" glass fibre by loop test in different humidity conditions.

the short-term test as it may fluctuate over a very large area. In the case of bulk glasses the long time behaviour of static fatigue can be determined from the short time tests. The strength distribution of glass fibre is very different and the surface of glass fibres is complicated and those two factors have a great influence on the properties of glass fibre in the stressed state over a long time. Therefore, it is not possible to adjust the results of the short and long-term tests together. In this study, the mean value of the test results in the short-term test was thus used as a comparison value.

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