CREEP, STRESS RUPTURE AND HYDROLYSIS OF POLYESTER GEOGRIDS

GEO REPORT No. 37

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This report was originally produced in September 1993
under Consultancy Agreement CE 19/89

First published, June 1995

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PREFACE

In keeping with our policy of releasing information of general technical interest, we make available some of our internal reports in a series of publications termed the GEO Report series. The reports in this series, of which this is one, are selected from a wide range of reports produced by the staff of the Office and our consultants.

Copies of GEO Reports have previously been made available free of charge in limited numbers. The demand for the reports in this series has increased greatly, necessitating new arrangements for supply. In future a charge will be made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents and presents the results of research work of general interest in GEO Publications. These publications and the GEO Reports are disseminated through the Government's Information Services Department. Information on how to purchase them is given on the last page of this report.

A. W. Malone
Principal Government Geotechnical Engineer
April 1995

FOREWORD

This report presents the results of an in-depth review of published information relating to the subject of creep, stress-rupture and hydrolysis of polyester geogrids.

The study was carried out by Dr J.H. Greenwood of ERA Technology Limited for the Geotechnical Engineering Office (GEO) of the Civil Engineering Department. It was completed in September 1993. It forms part of the GEO research programme on reinforced fill structures.

The draft report was reviewed by Mr J.M. Shen, Mr W.K. Pun and the Endorsement Checking Panel for Proprietary Products for Reinforced Fill Structures of the GEO. Members of the Panel were Messrs K.F. Man, K.K. Pang, K.M. Wong, Y.S. Au-yeung and C.H. Mak.

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April 1995

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SUMMARY

This report reviews the state of knowledge of creep, stress rupture and hydrolysis of polyester geogrids at the time of writing. There is a considerable amount of creep strain data on polyester yarns, extending to 90000 h (10½ years) duration, but data for specific geogrids are limited. There are no published creep-rupture data measured directly on geogrids, apart from some ongoing long-term creep tests. Test results obtained on yarns suggest that in accordance with the kinetic theory of fracture, a design life of 120 year corresponding to a strength of 50-55% of index breaking load.

The temperature dependence of both creep and creep-rupture for polyester is slight. The soil will reduce creep by transferring load to the reinforcing fibres through frictional forces on the sheath and by interlocking with the transverse bars. The hydrolysis of polyester fibres in water and the resulting reduction in molecular weight and strength have been shown to be due to a chemical process whose rate of reaction can, given sufficient data, be extrapolated to a selected service temperature. An alkaline environment above pH 10 causes additional chemical attack. There is still much controversy concerning the hydrolysis of polyester.

1. INTRODUCTION

The design of reinforced soil structures using polyester fibre based geogrids requires information on their creep and rupture behaviour: the first to meet criteria for maximum strain, the second to satisfy design rules for long term strength. This data is variable in its quality and quantity, much of it deriving from tests on yarns and fibres rather than the grids themselves.

One objective of this report is therefore to perform an in-depth survey of available literature information, to assess its relevance to geogrids and to recommend the work required where such data is lacking.

Polyester fibres are generally resistant to chemicals but can degrade in alkaline solutions and, over a longer timescale, in water. This risk of hydrolysis is the subject of much discussion at present. The second objective of the report is therefore to provide an in-depth review of current work and opinions on hydrolysis and to recommend the work required in the same manner as for creep and creep-rupture.

In order to perform this work ERA performed a thorough literature review and contacted a number of organisations, manufacturers, fibre producers, laboratories and approval authorities. Their assistance is gratefully acknowledged.

2. CREEP

2.1 Polyester Geogrids : Creep and Microstructure

With their high strength, high modulus and low creep rate, polyester fibres are prime candidates for geogrid reinforcements. Since, however, the fibres are relatively fine and smooth they are generally covered by a sheath of softer material that provides a mechanical link between the fibres and the soil and at the same time protects the fibres from damage. This material may, for example, be PVC or low density polyethylene. Either the fibre strips may be coated before they are welded together to form grids, or else the polyester fibres are formed into a grid first and subsequently coated.

The creep of polyester reinforced geogrids is governed primarily by the creep of the polyester fibres. There is an initial, relatively large extension on loading followed by a much smaller increase in extension with time, during which the rate of creep decreases. When plotted as strain against the logarithm of time (a semilogarithmic plot) this frequently yields a straight line which persists practically until rupture, there being a minimum of 'secondary' or 'tertiary' creep as found, for example, in polyolefins.

The dependence of strain on load is more complex. The stress-strain diagram of a typical polyester geogrid is shown in Figure 1 (Ref.1). After the first half of one percent strain the gradient decreases until the strain reaches approximately 3%. At this point the gradient increases until, just before rupture, it begins to decrease again. This complex behaviour can be related to the microstructure of the fibres themselves.

The polymer consists of chains of molecules of the basic structure shown in Figure 2 whereby the O-C=O structure is the characteristic ester linkage that gives its name to the product. There are many different structures of polyester fibres used in the textile industry, particularly for clothing, but the type of polyester used in geotextiles, and in automotive tyre reinforcement, is chosen for its high strength or tenacity rather than its comfort, and has a high molecular weight of between 10000 and 60000. This in fact represents a distribution of molecular weights with the mean quoted as around 25000; the mean can be calculated by number (M_n) or weight (M_w). Non-woven geotextiles use polyesters of a lower molecular weight.

The undrawn polymer is semicrystalline, that is it consists of crystalline and amorphous volumes which, when drawn, form chains of crystalline and amorphous regions lined up in the form of 'microfibrils' (Figure 3, Ref.2). The draw ratio is typically about 8:1, less than can be achieved with, for example, polyolefins. Individual molecules can penetrate both crystalline and amorphous areas and pass through more than one crystallite, or travel from one microfibril to another. Such 'tie' molecules play a particularly important part in the mechanical behaviour of the fibre. The proportion of crystalline material is approximately 40-45%.

Most of the activity critical to the tensile and creep properties takes place in the amorphous areas or, more particularly, the 'mesomorphous' areas where crystalline and amorphous regions merge. As the load is first applied, the mechanical properties are governed by the orientation and straightening of the molecules within the amorphous areas and the breaking of bonds between neighbouring polymer chains that are due to Van der Waals and bipolar forces. The gradient decreases. The side chains attached to the polymer can take up two configurations: trans, which favours a linear form, and gauche, which forms a coil. As load is applied, the configuration changes from gauche to trans.

At higher loads the 'tie' molecules begin to stretch and orient further, and the secondary bonds between neighbouring chains re-form. The gradient then increases. Ultimately the strength of individual tie molecules is reached, longer molecules breaking first. At the same time the crystallites themselves begin to deform in shear, both processes leading to a reduction in gradient and ultimately to rupture. The broken chain ends relax and change from trans back to gauche. (Refs 3,4,5). These processes, and thus the stress-strain curve, can be varied by changing the microstructure of the polymer: the crystallinity, crystallite size, degree of orientation, number of 'tie' molecules etc, and it must be emphasised that even high tenacity polyester yarns vary in the 'S' shape of their stress-strain curves as well as in the overall magnitudes of load and strain at failure.

Although it would be expected that the creep properties would depend on microstructure in the same way, no corresponding detailed description is available, except that in contrast to the polyolefins the more complex structure of the polyester, with its carbon rings and bipolar intermolecular bonding, leads to reduced movement between molecules (Ref.6). The difference in the creep parameters of two polyester fibres has been demonstrated by Oudet and Bunsell (Figure 4, Ref. 4). They showed that the creep strain could be reduced by nearly half by changing the microstructure; larger crystallites with a greater number of molecules entering and leaving their surface are beneficial to both creep and tensile properties.

The creep of a geogrid will be influenced not only by the constituent yarn but also by the structure of the grid, but not to the extent to which the structure affects the creep of plain woven or non-woven fabrics. This is because in a geogrid the yarns are predominantly straight. In the standard testing method (Ref.7) the longitudinal members will be securely gripped and the transverse bars have practically no effect. In soil reinforcement, some of the force may be introduced by the soil interacting with, or locking on to, these bars, so that creep and ultimately rupture are possible at the geogrid joints. The remainder is introduced directly into the longitudinal members by friction. Existing creep and rupture tests, and more especially those performed on yarns alone, do not take this into account.

In considering environmental effects it should be noted that high temperatures are used in the manufacture of the fibres, for example in heat setting and annealing. At about 70°C there is a physical transition above which the mechanical properties change. Within the normal range of service temperatures (-20 to + 40°C) the variation in tensile properties is relatively low. While this transition should be reversible, if the sheath of a geogrid has been applied at temperatures above 70°C over an extended period there is an opportunity for further changes to have occurred in the microstructure of the fibres: this must also be remembered when yarn properties are put forward as being representative of geogrids.

Moisture is absorbed into the amorphous regions of polyester fibres, leading to a limited shrinkage and a potential reduction in the transition temperature mentioned above, and can be desorbed without causing any changes to the fibre structure (Ref.8). The effects of hydrolysis, i.e. chemical interaction with water, are described in section 4.

2.2 Presentation of Creep Results

As indicated above, the creep of polyester based yarns, geogrids and geotextiles can generally be described by the formula :

$$\in \ = \ \in_o + \in_t \log t$$

where $\in$ is strain, $\in_o$ the value at a chosen initial time and $\in_t$ the gradient. $\in_o$ has been chosen as the strain after 1 h throughout this work, a time at which no effects of the loading process should remain. $\in_t$ represents the strain increment per decade of time and is dimensionless. These are illustrated in Figure 5 and are quoted in Tables 1 (geogrids) and 2 (yarns). It is important to note that the straight line does not imply a constant creep rate; the rate of creep decreases by a factor of ten each decade of time. Any major deviations from semilogarithmic straight line behaviour are indicated in the tables.

In many design situations the engineer is interested not in the strain on loading but in the additional strain between the moment when the load is first applied in the construction, for example after 1 or 10 h, and the design life, for example 10^6 h. The gradient alone will suffice for him to derive the information he requires.

The loads are expressed as a percentage of breaking load, also known as tensile strength or tenacity. This can lead to some confusion, since a laboratory will tend to use actual breaking load as measured on the product, while a manufacturer may use the nominal or characteristic breaking load, which is normally the lower limit guaranteed to his customers. Where possible, Table 1 quotes the loads applied in kN/m as well as percentage of breaking load. However, breaking load provides the only reference point for the comparison of yarns and geogrids.

The temperature of testing is 20-23°C except where otherwise specified. The effect of temperature is described in section 2.4.

Some of the results quoted have been read off diagrams, which are frequently drawn or printed in small format, so that the process of drawing and reading off results for the tables is subject to some error. It is not always clear where testing ends and extrapolation begins. In some cases the results have been derived from isochronous curves in which load is plotted against strain for fixed durations. Only rarely are sufficient points available to give a measure of scatter. ERA's experience, however, is that variability can only be assessed by performing tests on a number of samples under identical conditions, and that the parameter most sensitive to scatter is $\in_0$, the initial strain.

Results are reported for geogrids and, in view of the scarcity of data, on their constituent yarns. No results from woven geotextiles are reported since these include the effect of the weave structure and are likely to produce results that are unrepresentative of geogrids. Some of the yarns on which results are reported are used in woven materials rather than geogrids, and such data are presented only where they are regarded as providing useful information.

In the absence of an internationally accepted standard the test methods used for measuring creep are varied. BS6906 Part 5 (Ref.7) includes, for example, the necessity of applying a small preload to reduce the variable effects of crimp, and ERA have found major differences between the creep behaviour of yarns and 50 mm and 200 mm wide samples of plain weave fabric. Geogrids are in general less sensitive to such experimental problems provided they can be gripped satisfactorily and that the high experimental loads can be applied rapidly and smoothly.

2.3 Results: Geogrids

2.3.1 Paragrid, Paraweb : Tests on Geogrids

Table 1 presents published creep data for geogrids (Refs.1, 9-14).

Paraproducts consist of polyester fibres encased in a LDPE sheath, the resulting strips welded at the junctions to form Paragrid and woven to form Paraweb.

Creep tests on Paraweb 45 kN strip have been performed by ERA and are shown in Figure 6 (Refs 9-11). The tests continue and the latest results are used to derive the gradients in Table 1. The 1 h strains are the average of several tests and do not correspond exactly to Figure 6.

Of some significance is the higher rate of strain at the low load. The stress-strain curve of the Paraweb strip used exhibits a marked S-shape such that the secant modulus is less at lower loads, indicating that the mechanisms governing creep are different to those at higher loads. While there may be a clear physical explanation for the effect, the test emphasises the need for performing creep tests over the full range of loads. It would also be instructive to perform tests at this load level for longer periods in order to establish whether the rate of creep slows down when the physical mechanism that operates at higher strains begin to dominate.

The Exxon Chemical Geopolymers design manual (Ref.12) provides a generalised set of isochronous curves (Figure 7), data from which have been entered in Table 1.

2.3.2 Fortrac : Tests on Geogrids

Fortrac (manufacturer: Akzo/Huesker) consists of polyester fibres sheathed in PVC, with fibre stitching at the joints. Creep results obtained from two sources for two of the five grades are reported in Table 1 (Refs 1,13). Isochronous curves are shown in Figure 1.

2.3.3 Nicolon Geogrids

Test results are presented in Table 1 and Figure 8 (Ref.14).

2.3.4 Paragrid, Paraweb : Tests on Yarns

Results on yarns are presented in Table 2 (Refs.11, 15-20).

Tests on Parafil yarn have been performed by ERA and ICI (Refs.11,15). Tests on a yarn known to be that used in Paraproducts have been carried out at ERA and the results are entered in Table 2.

The strains on yarns are lower than those measured on the Paraweb strip, when referred to their respective breaking loads.

2.3.5 Fortrac : Tests on Yarns

Akzo have been performing creep tests on their yarns for many years. Fortrac is manufactured from the high modulus low shrinkage yarn Diolen 164S and the results are therefore presented first in Table 3, followed by an unspecified high modulus low shrinkage yarn.

A general diagram for creep of the yarns used in Stabilenka woven materials (notably Diolen 770) is shown in Figure 9, Ref.18 and individual results from Refs.17-19 are presented in Table 3. It was noted that the creep gradients increase sharply above 50% breaking load (Figure 10, Ref.17).

Reference 19 indicates however that the gradient decreases with time; i.e. that the assumption of a semilogarithmic diagram is conservative and that actual strains are lower.

The user is easily confused by the multiplicity of yarns on which results have been reported, and will require assurance that one particular type of yarn will continue to be used consistently in the product he uses.

2.3.6 Rhône-Poulenc Yarns

The Rhône-Poulenc yarn tested in Ref.20 is of a notably different quality with a high initial strain. The creep curves tend to become steeper at higher strains when plotted semilogarithmically. Although the reference quotes the yarn as being used in geotextiles, it is not known to be used in geogrids.

2.4 Environmental Effects

Increase in temperature above 70°C reduces the modulus and breaking load of polyester. Between -20 and 70°C, a range wider than the normal usage range for geotextiles in soil, the tensile properties change little.

Meffert (Ref.3) performed extensive creep tests for use in textile roofs at temperatures of 23 and 70°C for durations up to 1000 h. Having established that the creep behaviour was semilogarithmic, he derived a time-temperature shift relation such that the behaviour at long durations and lower temperatures can be predicted from tests at higher temperature and short durations. The empirical equation he derives relates strain in percent, to time t in hours, absolute temperature T in K, and force F in N as follows.

$$\in \; = \; 3.5 + 0.22 \left[\log t + 9182 \, (1/296 - 1/T) + 4039 \, (1/11.4 - 1/F^{1.6638}) \right]$$

This indicates an Arrhenius type relation between T and log t with the corresponding shift between 20 and 40°C of 2.3 decades. This is equivalent to 200 x, or 14 x for 10°C increase in temperature. ERA's results on Exxon's Terram fabric at 20 and 40°C also yielded a factor of 14 x per 10°C (Ref.10) Since the gradient is slight and scatter is present, any matching of curves by horizontal shifting can lead to large errors in shift factor, but with gradients as low as 0.22%/decade of time (Ref.3) or 0.125%/decade of time (Ref.10) the resulting increase in strain, or conversely the decrease in allowable load, is small. Meffert indicated that short periods at high temperature and high load have a major significance in the subsequent behaviour of the material and recommended that products be designed for maximum load and temperature.

Creep behaviour of polymers under variable temperature has been studied only to a very limited extent. Since the creep of polyester is not as temperature dependent as, for example, polyethylene, design to the maximum service temperature will not lead to significant overdesign.

Mir-Arabchahi performed tests on polyester fibres at 40, 60, 80 and 100°C and introduced a theory by which the isochronous lines form fans of straight lines radiating from a non-zero origin corresponding to a critical load and strain level (Ref.35). This origin shifts to lower strains and loads at the phase transition of about 70°C. As a result, creep curves can be calculated for all load levels and temperatures. The shift factor is approximately 10 x for a 10°C increase in temperature.

This theory, however, assumes that below the critical load and strain level the creep is effectively zero, which is not observed in practice.

At higher temperatures the rigidity of the sheath will decrease. This may decrease the rigidity of the junctions.

The effect of water on the creep of polyester is generally thought to be beneficial since the water molecules accumulate in the amorphous areas and inhibit the microstructural process of creep. Reference 19 indicates that at 60°C in water the initial creep strain of Diolen 770 yarns at 20% of breaking load is increased from 2.6 to 3.45% but that the creep gradient is unchanged. Continuous immersion of the unsheathed yarn in sodium hydroxide at pH 12 at 20°C did not change the creep behaviour to 3000 h.

The effect of the soil environment by restricting lateral movement will be less significant on polyester geogrids than on woven or non-woven materials, since the fibres in the two directions operate separately mechanically. The effect on creep strain will be complex, since the force will be introduced over a finite length by frictional effects into the longitudinal members or by 'locking' into the transverse members and thence via the joints into the longitudinal members. This area requires further research.

2.5 Technical Conclusions

The information available on the creep of geogrids is sparse but is supported by data on yarns.

The initial strain on loading the creep test depends upon fibre structure and is non-linear with load, as is the normal stress-strain curve. One should therefore not attempt to rationalise the creep behaviour with regard to breaking load for all makes of polyester geogrid, though it may be possible for different grades from the same manufacture.

After loading, the strain generally increases in proportion to the logarithm of time (semilogarithmic behaviour). This assumption has proved satisfactory or even conservative over periods of up to ten years. The exceptions, where the creep strains have been greater, have been fibres of lower modulus or, in some but by no means all cases, close to the breaking load. Extrapolation of creep curves by one decade and even two decades of time therefore can be considered.

The gradient of the creep curve, expressed as percentage strain increase per decade of time, depends upon load level in a complex manner, being generally greater at load levels where the secant modulus is lower (the 'belly' of the S-curve). It is essential that creep is measured over the complete range of loads.

The methods for assessing creep of geogrids (Refs.7,21) are generally satisfactory and comparable, although harmonisation of details will be necessary before they are acceptable as European (EN) or international (ISO) standards. Size of specimen is the item of most current concern.

In many cases results on yarns have been presented instead of those on grids. In some cases where comparative results are available the results on yarns have turned out to be optimistic, although rationalisation with respect to breaking load is inadvisable because the breaking load of a fibre bundle is not necessarily equal to the tensile strength of the fibre multiplied by the number of fibres. It is essential that the load applied is quoted, not just the percentage of breaking load, particularly since this 'breaking load' is sometimes a mean and sometimes a lower bound. No direct effect of the sheath on creep has been found or is to be expected, but in soil reinforcement the manner in which the load is introduced into the geogrid, whether from interlock with the soil, at a junction between geogrids or at a mechanical connection, may make a substantial contribution to the creep strain and could differ from results obtained in the laboratory using carefully engineered grips. Geogrid pull-out tests (Ref.22) are short term and do not address creep strain or rupture.

Temperature accelerates the creep of polyester reinforced geogrids, shifting the creep curves by a factor of 1-1.15 decades per 10°C, or a factor of 10-14 x. However, with gradients of the order of 0.2% strain per decade, the increase in strain for 10°C is only approximately 0.2% strain and the difference in loading capacity 2% of breaking load. Moisture and installation damage would be expected to have negligible effects upon creep strain (Ref.10). Reference 30, while quoting a limited amount of contradictory evidence, confirms this opinion on balance.

3. STRESS RUPTURE

3.1 Introduction

Stress-rupture, known also as creep-rupture or static fatigue, is the phenomenon by which materials under load break after a certain length of time. For materials under continuous load, such as geogrid reinforcements, measurement of stress-rupture data, and its subsequent extrapolation, is essential in order to derive the load at which the material would break exactly at the end of its design life. This load is then modified by suitably chosen partial safety factors, reflecting matters such as installation damage and uneven stresses in the soil, to provide the design load. In spite of several well publicised presentations by the author and his co-workers (Refs.16,23,24) the amount of information available relevant to reinforcing geotextiles and geogrids is remarkably sparse. Most of the information provided is on yarns.

The reason for this is that stress-rupture testing is time-consuming, expensive and difficult to perform. It is customary to measure at high loads, typically greater than 70% of breaking load, which lead to rupture at shorter times, and extrapolate to lower loads and longer times using a single or double logarithmic plot. A typical example is shown in Figure 11 (Ref.12). The slope of these diagrams is generally relatively slight. The scatter in lifetimes at a particular load is, on the other hand, relatively great, often extending over a full decade of time. As a result it is necessary to make at least twelve measurements to define the load-time characteristic and preferably many more, particularly if a confidence limit is to be provided. Tests on grids have to be performed at high loads, requiring large and expensive machinery, and great attention must be paid to the gripping techniques to ensure that the grips do not initiate rupture. Manufacturers have therefore up to now tested yarns or even individual fibres, arguing that since a strength of a grid depends entirely on the reinforcing fibres, the reduction in strength in time will, as a proportion of short-term strength, be similar. Yarns can be slightly damaged during the weaving or grid-making process and it must be assumed that any reduction in strength is reflected equally in a reduction in long-term strength. The sheath will to an unknown extent screen the yarns from external influences such as light, oxygen and humidity and a rupture prediction based on the unprotected yarns is therefore conservative.

If load is transferred from the soil into the load-bearing fibres by means of the transverse bars, such as by 'soil locking', it is important that this should be reflected in the test.

3.2 The Kinetic Theory of Rupture

Extrapolation of the stress-rupture plots described above does not reflect the physical processes that govern rupture. The general kinetic theory of rupture, developed in the 1950's and 1960's by Zhurkov in the then USSR and Bueche and Halpin in the USA, assumes that fracture is the result of an accumulation of microscopic ruptures of chain segments whose rate of occurrence is controlled by chemical rate kinetics. The microscopic event could also be local plastic flow or indeed any event which renders the chain segment incapable of carrying further load. The frequency of bond failure *f* is given by an equation of the form :

$$f = f_o A \exp [-(\Delta G - V\sigma)] / kT$$

where f_o and A are constants independent of temperature, ΔG is the activation energy for bond rupture which is modified by the load σ through an activation volume V, k is Boltzmann's constant and T is temperature. Reverse events, i.e. reformation of bonds, are ignored. If the material is assumed to break when a certain number of bonds have broken, the time to failure t_f is inversely proportional to frequency and

$$t_f = t_o \exp [(\Delta G - V\sigma) / kT]$$

where t_o is a temperature independent constant. Thus a semilogarithmic plot of σ against log t_f should yield arrays of straight lines as shown in Figure 12 (Ref.25), although a correct statistical regression analysis must observe time as the independent and load as the dependent variable, i.e. use different axes to the conventional ones.

The theory, further details of which are given in Ref.25, quoting Ref.26, is widely applicable to those polymers, particularly fibres and linear polymers, which fail as a series of filaments each independently of the other. It provides a satisfactory physical justification for extrapolating the creep rupture of polyester fibres on a semilogarithmic diagram. It does not apply in cases where propagation of a single crack promotes failure at a single stress concentration, such as in brittle solids.

In this section stress rupture diagrams will be expressed as :

$$\sigma / \sigma_B = C_2 + C_1 \log t_f$$

where σ is load, σ_B the breaking load, t_f is time to failure and C_1, C_2 are constants. C_1 is negative and is expressed in % per decade of time.

3.3 Measurements of the Stress-Rupture of Polyester Geogrids

No creep-rupture results have been published, although some manufacturers have performed in-house test. The creep test on Paraweb 45 kN strip at 59% of breaking load shown in Figure 6 had lasted nearly 40000 h at the end of March 1993.

3.4 Measurements of the Stress-Rupture of Polyester Yarns

3.4.1 Yarns Used in Fortrac

Akzo have published widely a diagram illustrating the creep-rupture of their high tenacity Diolen polyester yarns at 20°C, reproduced in Figure 13 (Ref.18). Although the original points are not stated or plotted a 95% confidence lower limit is entered. It is understood as being a composite diagram of tests on different yarns at three loading steps over periods of up to 10 years. The 95% confidence limit should be ignored since it is linear and not a hyperbola and appears to converge at long durations.

Viezee et al (Ref.17) have compiled a further list of creep-rupture data on Akzo's and other yarns, reproduced in Tables 3 and 4. The composite figure is reproduced in Figure 14.

These results contrast strongly with those in Figure 13. In fact the lower limit of these results will, when extrapolated to long times, give a 120 year design load of zero. Akzo's other creep-rupture results, however, suggest that at lower loads (below 60% breaking load) the times to rupture are considerably greater. Viezee et al (Ref.17) therefore put forward the hypothesis that in this load range the elongation at break is indeed constant and that the time to rupture can therefore be predicted by extrapolation of the creep curve on a semilogarithmic scale. The elongation at break is estimated to be 60% of that measured in the tensile test, and the results are reproduced in Table 4 and presented in schematic form in Figure 15.

3.4.2 Yarns Used in Paragrid and Paraweb

Exxon Chemicals' handbook (Ref.12) provides stress-rupture data to 10^5 hours for Paragrid and other products (Figure 11). The extrapolated load required to produce failure at 10^6h (120 years) is 55% of breaking load and application of a materials safety factor f_m of 1.4 leads to a design load of 40% of breaking load.

Results at ERA on yarns provided by Exxon (formerly ICI Fibres Geotextiles Group) are presented in Table 5.

The actual stress-rupture results are lower than Exxon's or Akzo's graphs in Figures 11 and 13 respectively, but the gradient is lower such that the extrapolated 120 year strength remains at 55% of breaking load. This could possibly provide supporting evidence for Viezee's theory of a two-stage rupture curve.

3.4.3 Rhône-Poulenc Yarns

Reference 20 contains limited stress-rupture results on Rhône-Poulenc yarns.

Further work in France by Oudet and Bunsell (Refs.4, 27) on Rhône-Poulenc (Viscosuisse) fibres of 5.3 ± 0.6 decitex gave the data in Figure 16 with median times to failure presented in Table 6. Of particular interest is the scatter: the histograms show a wide variation in lifetime stretching over two orders of magnitude.

It should be noted, however, that they refer to the strengths of the filaments and not the yarn; the variability in the strength of a bundle of filaments, ie a yarn, will be less than that of the filament.

3.4.4 Du Pont Yarns

The only American work we can trace is in Ref.28, from DuPont, on drawn polyester monofilaments of molecular weights 43500 (A) and 53500 (C) respectively with draw ratios of 3 and 4. The four types are therefore referred to as A3, A4, C3 and C4. Between 17 and 19 lifetime tests were made on each type and a regression performed of stress and log (lifetime). The results are presented in Table 7 and Figure 17.

In comparative tests the authors note that square-wave fatigue at 0.0083Hz (1 min load on, 1 min load off) reduces the lifetime more rapidly than in a test under constant load for equivalent loading time.

3.5 Technical Conclusions

In conclusion, therefore :

(a) The only data published on polyester reinforced geogrids are the interim results of creep tests that are still continuing.

(b) Work on yarns generally indicates a semilogarithmic dependence of load on log (time). There may be a separate mechanism operating at higher loads.

(c) Available results extrapolate to approximately 50-55% of breaking load leading to a rupture lifetime of 120 years.

The effect on creep-rupture of the soil interaction with the sheath and in particular the transverse ribs and junctions is completely unknown. LDPE is well known for having a transition in its stress-rupture curve. The US method (Ref.29) imposes a partial factor of safety of 3.0 on stiff geogrids unless creep-rupture and other environmental tests are carried out on specimens including junctions. This matter is attracting some attention in the USA (Ref.30).

4. HYDROLYSIS

4.1 Information on Geogrids and Sheathed Polyester

There is no direct information available on the hydrolysis of polyester fibre reinforced geogrids. Once again, work has concentrated on the effect of the unprotected yarns which present, in effect, a conservative case, since the effect of the sheath, if any, will be beneficial.

4.2 Chemical Nature of Hydrolysis - 'Internal' and 'External' Hydrolysis

Polyester hydrolysis is a chemical process in which the material reacts with water to break the polymer chain at the ester linkage, thus reducing the molecular weight and the tensile strength. It is simply the inverse reaction of the synthesis by which polyesters are formed. It must not be confused with the physical process of moisture absorption in wet conditions which takes place in many textile fibres, leading in polyesters to a 0.6% water uptake and a slight increase in modulus, and which can be reversed by drying out (Ref.8). Hydrolysis is the principal means of degradation of polyester fibres in environments experienced by geotextiles; thermal attack and oxidation proceed much more slowly (Ref.31). Alkaline hydrolysis is used to modify the surface of a textile fibre to improve surface related properties such as absorbency, wicking or 'handle', and until recently degradation by hydrolysis had been studied principally in the context of the effects of laundering, exposure to seawater or the presence of body fluids.

The chemical reactions, as described by Akzo in Ref.32, are illustrated in Figure 18. In neutral water (pH7) the reaction is catalysed by the COOH, carboxyl end group. The rate of hydrolysis depends on the number of ester links and, as fibre breakages develop and the number of carboxyl end-groups increases, it becomes proportional to the square root of the carboxyl end-group concentration. This reaction takes place throughout the thickness of the fibre and is referred to as 'internal hydrolysis'.

In an acid environment ($pH < 7$) the same mechanisms occur but also the free H^+ ions can catalyse the hydrolysis. Since these ions hardly penetrate into the fibres the additional effect should be restricted to the surface. MacMahon et al (Ref.33) noticed no effect of acid down to pH2 concentration.

In an alkaline environment ($pH > 7$) the reaction is with the OH^- ion, yielding a new end group. In geotextiles this effect is observed in particular at pH10 and above where it is characterised by surface pitting but does not appear to penetrate into the depth of the fibre (Ref.34). There is little variation in elongation at break (Ref.35). It is thus referred to as 'external hydrolysis'.

Certain cations, notably calcium (Ca^{++}), which is readily present in the soil, and magnesium, have a major accelerating effect on external hydrolysis (Ref.36). Ammonium salts can also increase the rate of reaction.

4.3 Rate of Hydrolysis: Dependence on Time and Temperature

Of necessity, the hydrolysis of the fibres used in polyester geotextiles has been studied by immersion in water or steam at elevated temperatures, with very small reductions in strength taking place over days or weeks. In order to extrapolate these to longer times, lower temperatures and greater reductions in strength we have to consider the rate of reduction in strength with time, and the variation of this rate with temperature. We then consider how the physical structure of the fibre may affect these parameters.

The simplest approach to this is to observe the times to a set end-point, such as 75% or 50% retained tensile strength, at different temperatures. These can then be extrapolated using the normal Arrhenius relationship which states that the rate of reaction τ :

$$\tau = Ce^{-(E_A/RT)}$$

where E_A is the activation energy, R is the gas constant (8.31 J/K/mole), T is the temperature and C is a constant.

This means that the time to reach that end-point will be related to temperature by the formula :

$$t = Be^{(E_A/RT)}$$

where B is a constant dependent on the chosen end-point.

In comparing the temperatures and times with suffixes 1 and 2,

$$\ln t_1 - \ln t_2 = (E_A/R)\ (1/T_1 - 1/T_2)$$

A more sophisticated approach is used in Ref.33, where it is shown that if x is the number of polyester bonds that have reacted with water and A is their initial number, then the rate of hydrolysis :

$$dx/dt = k_1\ (A - x)$$

where k_1 is the reaction rate coefficient multiplied by the molar concentration of water.

Integrating,

$$\log\ [A/(A - x)] = k_1\ t$$

where $k_1 = De^{(-E_A/RT)}$ with D a constant.

As x increases, the molecules divide and the average molecular weight decreases. The molecular weight is normally determined by measuring the intrinsic viscosity and there are established relationships between the two. If, therefore, the intrinsic viscosity is measured at the same time as the tensile strength, then it is possible to relate its change to time and temperature using the formulae given, and this provides a better justified basis for extrapolation. It is still necessary to derive a relation between molecular weight and strength, a relation that will be empirical and probably non-linear. Extrapolation depends critically upon deriving a satisfactory model.

4.4 Observations on Hydrolysis of Geotextiles in Water

The classic work on the hydrolysis of polyester was carried out by McMahon and co-workers (Ref.33). They exposed samples of high tenacity polyester yarn and film (from DuPont) to hot/dry and hot/wet atmospheres and plotted the reduction in properties as a function of time, relating this degradation to the reduction in molecular weight, since when a long chain breaks it increases by two the number of shorter chains.

They deduced a mean activation energy of 108 kJ/mole for 0.5 mil (13 m) polyester film.

Tests in water at 95°C and 80°C have been carried at an individual filaments from several high tenacity polyester yarns by the Texas Research Institute for the Reinforced Earth Company (Refs.31,37). The combined results for water and alkaline media at 95°C are presented in Figures 19 to 22.

The corresponding results at 80°C were presented in Ref.37 and are presented in Figures 23-25. The times to 90% and 80% retained strength read from Figures 19 and 23 (both water) are as follows:

	95°C (368 K)	80°C (353 K)
90% retained strength	30 days	145 days
80% retained strength	47 days	190 days

Using the Arrhenius relation :

$$\ln t = -A + E_A / RT$$

$$\ln t_1 - \ln t_2 = (E_A / R) \ (1/T_1 - 1/T_2)$$

where t = time, E_A = activation energy, R = gas constant (8.31 J/mole/K), T is the absolute temperature and A is a constant, then for 90% retained strength :

$$\ln 145 - \ln 30 = (E_A / R) \ (1/353 - 1/368)$$

$$E_A = 113 \text{ kJ/mole}$$

and for 80% retained strength :

$$\ln 190 - \ln 47 = (E_A / R) \ (1/353 - 1/368)$$

$$E_A = 101 \text{ kJ/mole}$$

Considering the level of approximation, there is remarkable agreement with MacMahon's figure of 108 kJ/mole.

Extrapolation to lower temperatures can be achieved by applying Arrhenius' law with a conservative maximum activation energy of 113 kJ/mole. Taking the 80°C results (190 days) as a base, the lifetimes to 80% retained strength at 40 and 20°C are :

40°C	72 years	80% retained strength
20°C	1388 years	80% retained strength

To extrapolate further to 50% strength it is necessary to estimate the shape of the strength - time diagram. None of the published results using water have progressed this far, and tests in alkaline media are ruled out as the hydrolysis may be 'extrinsic'. Using the curve in Figure 23 for HCl as a guide, the ratio of times to 50 and 80% strength is approximately 2.12. Multiplying by this factor, the lifetimes to 50% retained strength at 40 and 20°C.

40°C	153 years	50% retained strength
20°C	2943 years	50% retained strength

Figure 25 is particularly interesting since it demonstrates that four commercial high tenacity fibres and yarns degrade in a similar manner, although the worst of them has reached 80% retained strength after only 130 days and would therefore reach 50% retained strength at 40°C after 153 x 130/190 = 105 years and at 20°C after 2943 x 130/90 = 2014 years. A normal textile polyester is shown to be clearly inferior.

These results were supported by Differential Scanning Calorimetry (DSC) studies which identified that the temperature of crystallisation, heat of crystallisation and heat evolved all change with ageing, but these quantities have not been used for extrapolation (Ref.38).

Reference 39 describes the hydrolysis of polyester bottles in environments including 0, 45 and 100% relative humidity, wet and dry soil and with ultraviolets irradiation at 60-90°C (Figure 26). It is noted that degradation was negligible under fully dry conditions. Wet soil and relative humidity led to rapid degradation; at 90°C wet soil was more aggressive and this is attributed to the effect of metal ions. The difference between the environments was more accentuated at 80 and 90°C. Under the most extreme conditions the time to 50% reduction in intrinsic viscosity at 80°C is 225 days; this compares well with the figure of 190 days quoted above. The results extrapolated to 50% reduction in intrinsic viscosity are highly non-linear and the extrapolated lifetimes of 27 to 48 years cannot be treated as reliable.

In Ref.40 the results of other authors' immersion test on polyester yarns (not necessarily high tenacity) in various humidities are used to predict lifetime. It should be noted that these predictions are based on small reductions in strength and that this reduction is assumed to proceed linearly with time. By inverting the loss in strength per week he derives the lifetimes shown in Table 8, based on a 25% loss in tensile strength. Rather than using an Arrhenius equation an empirical equation for lifetime is given in with t years as :

$$\log t = 3.61 - 0.034\,T - 0.002\,H$$

where T is temperature in Celsius and H is relative humidity in percent.

For 40°C, 100% RH, t = 1 year and for 20°C, 100% RH, t = 5 years.

An attempt to apply Arrhenius' equation directly to the data used yields an activation energy of about 50 kJ/mole.

Ansell, studying the failure modes of fibres in sheathed polyester yarns following thermal cycling and subsequent immersion in boiling water, noted a change in failure mode from flat brittle to conical 'stake-and-socket' after six weeks (Ref.41). He attributes this to a phase change following which cracks initiated by a brittle 'rim' from a path at a low angle to the orientation line. With further exposure the rim grows larger and the cone smaller.

Schneider and Groh (Ref.36) noted a 50% strength retention after 50 days at 100°C but after only 15 days in steam at 105°C. Risseeuw and Schmidt (Ref.32) ignore tests at temperatures above 100°C.

Using an activation energy derived from Ref.33 and other sources, Risseeuw and Schmidt (Ref.32) derive the residual-strength-lifetime diagram shown in Figure 27.

4.5 Observations on Hydrolysis of Geotextiles in Alkaline Environments

Alkaline hydrolysis in NaOH at 80-100°C is a standard method for processing polyester textile fibres, the effects of which are primarily at the surface and include etching.

The result from Refs.31 and 37 indicate that at and below pH10 the rates of degradation in all media at 95°C are not significantly greater than those in water.

McMahon (Ref.33) had observed no accelerated degradation for acids down to pH2. At pH12, however, there was a significantly higher level of degradation in NaOH and considerably greater in calcium hydroxide. This accelerating effect of calcium ions, which are frequently present in alkaline soils, was also observed by Schneider and Groh at pH 12-13 (Ref.36). Montalvo (Ref.42) observed a 50% loss in tensile strength of an unstated polyester after 22 days (interpolated) at pH12 at room temperature. At pH 10 there was 5% loss after 56 days.

Similar results are quoted from Drexel University (Ref.43). At pH10 the strength retention after 120 days was 91-94% but at pH12 only 70-80%; etching was observed on the fibre surface. In cement and lime leachate solutions the respective times to 50% strength reduction were interpolated to be 69 and 47 days.

Davis (Ref.44) noted severe degradation at 21°C after one year in 15% calcium hydroxide and 2% NaOH. 94% strength retention was found in 0.1% sodium hydroxide. Hoechst give degradation tables for their high tenacity polyester fibre in caustic soda solution corresponding to the pH range 12.5 to 12.7, for durations of 50 hours.

Recent work by Schröder (Ref.34) on polyester nonwovens has demonstrated a linear relation between the square root of percentage retained strength and time. Similar tests on yarns are in progress. Scanning electron micrographs show the formation of circumferential notches, particularly under load. He quotes the rate of degradation to be a linear function of sodium hydroxide concentration with an activation energy of 73.2 kJ/mole.

Horrocks (Ref.48) reports that he has derived an activation energy of 32 kJ/mole for NaOH catalysed hydrolysis from Hoechst data, and that at 25°C a high tenacity polyester yarn will lose 50% strength at pH10 in 214 years. $Ca(OH)_2$ is thirteen times more effective, reducing this figure to 16.5 years.

His results demonstrate that the rate of hydrolysis increases tenfold between pH10 and pH11 and is decreased by a factor of four if calcium ions are removed. He concludes that alkaline hydrolysis takes place down to pH9.

4.6 Synergistic Effect of Load

Viezee et al (Ref.17) demonstrated that alkalis at pH12 had no effect on the creep of yarn and suggested that any effect is restricted to the rupture phase. Schröder (Ref.34) has demonstrated that both creep and time to rupture in calcium hydroxide solution at 65°C are accelerated significantly by loads of 35-60% of breaking load and that this is accompanied by a notching effect on the fibre surface. Since creep-rupture and alkaline or external hydrolysis both take place by a crack growth mechanism, some synergy is to be expected. Synergy between both creep and stress-rupture and internal hydrolysis due to water would be more likely at an advanced state of hydrolysis where the molecular weight has diminished significantly. Synergistic effects have been found in polypropylene geotextiles (Ref.45).

4.6.1 Structural Influences

The rate of internal hydrolysis depends strongly on the molecular structure of the fibre. Textiles can be designed to be very susceptible or, in the case of those used in geotextiles, highly resistant. This resistance is achieved in the first place by selecting a high molecular weight and long chain length. As described in Section 2.1, the molecular weight of the fibres used in geotextiles is approximately 25000.

The molecular weight not only increases the initial fibre strength but also reduces the number of carboxyl groups at the end of the molecules - the carboxyl end-group count. As mentioned above, these groups can assist in promoting hydrolysis, although for geotextile fibres the concentration is stated to be so low that at the point where the material fails the rate of reaction has only doubled (Ref.32). Even in an alkaline environment, the process is still extremely slow at 20°C.

The carboxyl end-group count is used as a quality assurance parameter. While for normal textiles it lies in the range 40-60 meq/kg, for tyre cord a figure of 10-20 is required and Ref.19 suggests that a maximum of 25 is sufficient for geotextiles. Additives have to be used if a figure of less than 15 is required. Non-woven geotextiles use polyesters of a higher carboxyl end-group count.

In the case of internal hydrolysis, the rate of reaction will be influenced by the diffusion of ions into the material (Ref.45). MacMahon et al (Ref.33) demonstrated the difference in degradation rates of 250 m and 13 m thick foils, presumably controlled by diffusion. There is uncertainty about precisely how or whether hydrogen or hydroxyl ions penetrate the material, since the dielectric properties of the material should act as a barrier.

Both diffusion and hydrolysis will take place predominantly in the amorphous areas, where the structure of the polymer is more open and the molecular chains more exposed (Ref.33). Increased crystallinity and molecular orientation reduce the size of these areas and thus retard hydrolysis. Polyester fibres approximately 10 m in diameter hydrolysed more slowly than the foils, due to the effect of orientation. In addition, Ballara and Verdu (Ref.46) have demonstrated that chemical scission of molecular chains can lead to increased crystallinity ('chemicrystallisation'), thus further slowing the process; in addition they comment that ester groups at the centre of the polymer chains are less susceptible to hydrolysis than terminal groups; strengthening the argument in favour of high molecular weights.

It is particularly important to note that there is a phase change in polyester at approximately 60°C. This is a change in structure of the amorphous areas from a glassy state below 60°C to a rubbery state above 60°C, but does not imply any change in crystallinity. Extrapolation across transitions is generally invalid. In this case, however, the process in question is chemical, hydrolysis, while the change is in the form of the physical structure. It is therefore debatable whether or not the results can be extrapolated across the transition or whether the activation energy would be greater or less. Any assumption either way is critical to the prediction of hydrolysis in geotextiles.

4.7 Sensitisation due to Ultraviolet Radiation

Schröder (Ref.34) demonstrated that hydrolysis was accelerated by a short (24 h accelerated) exposure to UV light at 35°C.

Reference 39 demonstrated that hydrolytic degradation proceeded much faster when one side of the material was irradiated with UV light and the other was in contact with the soil than when the material was exposed to UV light alone. In other words, soil and sunlight together cause the polyester to degrade 2.5 times faster than exposure to sunlight only. All this work, however, is on unprotected polyester and the sheath should provide satisfactory protection.

4.8 Effect of the Sheath

Although polymers are not rapidly permeable to water vapour, they present no major barrier when considered in the context of the required lifetimes. In Ref.41 PVC was shown to have lost all adhesion to the fibre after 6 weeks thermal cycling followed by 3 weeks in boiling water. PVC sheaths can degrade through loss of plasticiser, becoming brittle, and could also give rise to degradation products such as hydrochloric acid.

Permeabilities of PVC and LDPE are 1.19×10^{-6} and 0.684×10^{-6} cm^3 vapour at 0°C, standard atmosphere per second, 1 cm thickness and 1 cm^2 surface area per atomsphere respectively (cm^3 vapour $(STP)s^{-1}$ cm^{-1} cm^{-2} atm^{-1}). This means that if saturated vapour conditions exist on the outside of the sheath, similar conditions will be established in the fibres within a few weeks.

4.9 Comparison with Material Extracted on Site

The predictions in lifetime have been compared with actual measurements taken from the soil (Refs.30,32,40). The table from Ref.40 is reproduced as Table 9. It is not stated whether the polyester was unsheathed. This table demonstrates that the results are in line with reality, given the uncertainty in the actual site conditions. The only evidence of severe degradation that can be attributed unequivocally to chemical degradation, and not to mechanical damage, is that in cases where the polyester is close to a concrete wall (Ref.47).

4.10 Use of Microanalytical Techniques to aid Detection of Hydrolysis

Since carboxyl end groups play a significant part in alkaline hydrolysis, carboxyl end group count is an established method for monitoring changes in degradation and quality of the initial fibre. Molecular weight, derived from intrinsic viscosity, is shown to be of critical importance, although Drexel University have observed no changes while ageing polyester. FTIR has also been shown to be unreliable. Thomas (Ref.38) reported that the onset and maximum temperatures in the cooling curve of a DSC trace could be correlated with the ageing time to 70% strength retention. Microanalytical techniques have the great advantage that only small samples are required and are thus particularly attractive for condition monitoring and remanent life assessment. There are, however, as yet insufficient data, nor is it known how accurate the various methods are.

4.11 Quality Assurance Methods

Possible quality assurance requirements include a minimum molecular weight or maximum carboxyl end-group count. An alternative method, used in the chemical and textile industry, is exposure to pressurised steam. CEN TC189 is considering a method for polyester with temperatures of 120 and 90°C with exposure periods of 48 and 168 h followed by measurements of reduction in breaking load and other parameters. No 'passmark' is indicated.

4.12 Technical Conclusions

There is no direct information available on the hydrolysis of polyester reinforced geogrids. All predictions are based on tests on fibres or yarns. Since any effect of the sheath will be retarding, such estimates are conservative.

Accelerated tests in water and steam indicate that the lifetime of high molecular weight, high tenacity polyester due to hydrolysis in water at 20-40°C is measurable in decades at 40°C and centuries at 20°C. This is based on the least resistant of four commercially available polyester fibres. However,

(a) No analysis has been made of statistical variability. Small coefficients of variation can lead to wide variability when logarithmic scales are used.

(b) The sensitivity to temperature is strong; thus between 20°C and 35°C the lifetime is reduced by a factor of ten.

(c) Extrapolation is across a transition in the physical state of the fibre and positive evidence is needed that this transition has no effect: more points are needed to show that the line in the Arrhenius diagram is straight.

(d) Some tests are performed in steam and there is evidence that this is more aggressive than liquid water.

(e) There is clear evidence that exposure to ultraviolet light can 'sensitize' a fibre to hydrolysis.

(f) The argument that the concentrations are too low for autocatalysis to occur needs clearer demonstration.

Tests so far have indicated that acid environments down to pH2 have no effects different to that of liquid water.

Evidence from temperature accelerated tests suggests that alkaline solutions up to pH9-10 have no effect additional to that of liquid water and that above that level there is accelerated attack due to 'external hydrolysis' and surface pitting. This latter effect is accelerated by the presence of calcium ions and previous exposure to ultraviolet light. However, this area remains controversial and any use of polyester geogrids in alkaline soils with pH > 8.5 or near concrete facings should be supported by further testing.

Alkaline hydrolysis is accelerated by mechanical loads greater than 35% of breaking load.

Reference 30 suggests the following safety factors for chemical ageing in general :

(a) For noncritical, temporary structures, soil pH between 3 and 10, soil temperature ≤20°C, design life ≤5 years: 1.06 to 1.25 depending on severity of soil chemistry.

(b) For noncritical, permanent structures, soil pH between 6 and 8, low concentrations of deleterious chemicals, soil temperature ≤20°C, design life ≤50 years: 1.25 to 2.0. Contacts with concrete facings are specifically excluded and require higher safety factors.

Site tests so far confirm the predictions from the accelerated temperature tests.

Index tests in steam at 135°C are a standard quality control method for the fibre; these could be supported by intrinsic viscosity tests for molecular weight and carboxyl end group counts. Further experiments are needed to demonstrate that index tests of this nature are sufficient as screening and quality control tests for the fibres and to define the specifications required. A well controlled quality assurance system will be needed to ensure that only fibre that satisfies these tests is used in a geogrid, particularly if a manufacturer obtains fibre from more than one source.

Much has been claimed for the value of microanalytical tests. It is our opinion that these tests will play no more than a supporting role (such as the quality control tests mentioned above) in assessing the sensitivity of a fibre to hydrolysis or for condition monitoring in service. It will probably never be possible to predict precisely the rate of hydrolysis of a polyester by knowing the physical structure of the polyester (molecular weight, crystallinity, orientation etc) Even if it were, the manufacturer would be unwilling to release such commercial secrets, and the user would be unwilling to pay for all the analytical work needed to determine them. Nor has any accelerated test been widely enough demonstrated, although screening tests including exposure to steam at 135°C are used in the industry for quality control.

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Geotextiles and Geomembranes, Vol. 7, 1988, pp23-31

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Table 1 - Published Creep Results for Geogrids

Type	Breaking Load (%)	Load (kN)	Strain at 1 h (%)	Strain Increment per Decade (%)	Test Duration (hour)	Reference
Paraweb 45 kN	15%A (19%N)	8.5	2.4	0.62	1800	9 - 11
	31%A (38%N)	17	7.3	0.17	30000	
	45%A (56%N)	25	8.2	0.14	5500	
	59%A (73%N)	33	9.9	0.22	30000	
Paragrid	20%N		2.0	0	no data	12
	40%N		4.7	0.1		
	60%N		7.5	0.5		
Fortrac 80-30/20 (10°C)	25%N	20	4.3	0.13	10000	13
	50%N	40	7.6	0.08	10000	
Fortrac 80-30/20 (30°C)	25%N	20	4.7	0.07	10000	
	50%N	40	7.6	0.05	10000	
Fortrac products	20%N		2.2	0	no data	1
	40%N		5.7	0.1		
	60%N		8.2	0.3		
Nicolon Matrax 240	30	no data	3.8	0.21	10000	14
	35		5.1	0.21	10000	
	45		6.2	0.21	10000	
	55		7.5	0.21	10000	
	60		8.2	0.21	10000	

Legend :

A	Actual breaking load
N	Nominal breaking load

Table 2 - Published Creep Results for Yarns Used in Geogrids

Product	Breaking Load (%)	Strain at 1 h (%)	Strain Increment per Decade	Test Duration (hour)	Reference
Parafil Type A coated yarn	5.9% (0.5 kg)	0.5	0.08	300	15
	23.5% (2 kg)	3.2	0.14	300	
	41.2% (3.5 kg)	5.4	0.17	300	
Parafil Type A uncoated yarn	19%A	2.9	< 0.05 (a)	23000	11, 16
	39%A	5.1	0.08	66000	
	58%A	7.1	0.18 (b)	65000	
			1.1 (c)		
Paraproduct yarn	58%A	6.8	0.2	600	11
	60%A	8.0	0.33	25000	
	60%A	6.6	0.28	2300	
	65%A	9.3	0.37	100	
	70%A	14.3	0.67	600	
Unspecified High Modulus low shrinkage yarn	20	2.5	0.07	2600	17
	40	4.3	0.04	2600	
	60	5.6	0.11	50	
	70	6.8	0.23	1.6	
Stabilenka yarns	20	2.1	0.10	8000	18
	40	4.7	0.11	8000	
	60	7.2	0.12	8000	
	20	2.4	0.06	2200	17
	40	4.3	0.06	1200	
	60	5.6	0.13	190	
	70	6.8	0.28	1.9	
Diolen 770	20	2.6	0.05	2400	17
	40	4.3	0.07	2200	
	60	5.9	0.16	50	
	70	6.9	0.29	1.6	
	10	no data	0.14	3	19
	15		0.11	3	
	20		0.07	3	
	30		0.06	3	
	40		0.06	3	
	50		0.07	3	
Diolen 2500	10	no data	0.09	3	19
	20		0.09	3	
	30		0.05	3	
	40		0.04	3	
	50		0.04	3	
	60		0.07	3	
Rhone-Poulenc Yarn	60	14.9	0.5	200	20
	70	18.9	1.2	200	

Legend :

A	Actual breaking load
N	Nominal breaking load
(a)	After 100 h
(b)	Up to 3000 h
(c)	After 3000 h

Table 3 - Creep Rupture of Akzo Yarns at High Loadings (Ref.17)

Yarn Type	σ/σ_B (%)			Parameters (see Section 3.2)	
	70% (a)	80% (b)	90% (c)	C_1	C_2
	Numbers of Specimens				
Diolen 770	3	2	5	-11.13	80
Stabilenka	3	10	5	-7.69	74
HMLS-yarn (d)	3	5	5	-8.60	80
Diff. brand HM	5	5	5	-14.53	84
Various Diolen	4	4	4	-3.44	84

Legend :

(a) Values in the ranges 65-70%
(b) Values in the ranges 75-82%
(c) Values in the ranges 85-90%
(d) High modulus low shrinkage

Table 4 - Calculated Stress Rupture of Akzo Yarns at Low Loadings (Ref.17)

Yarn Type	σ/σ_B (%)			Assumed Elongation at Break (%)	Parameters (see Section 3.2)	
	20%	40%	60%		C_1	C_2
	Number of Specimens					
Diolen 770	3	3	4	7.2	-0.45	67
Stabilenka	3	3	2	4.6	-1.07	53
Damaged Stabilenka	3	3	1	4.6	-1.07	53
HMLS-type	3	3	2	5.8	-0.95	67
Diff. brand HM-type	3	3	5	6.6	-0.69	60
Various Diolen Cords	-	-	4	9-12	-1.11	75

Table 5 - Creep-rupture Results at ERA for Exxon (formerly ICI Fibres Geotextile Group)

(a) 1100 Denier Polyester Yarn, first batch, 77.6N breaking load	
σ/σ_B (%)	t_f (h) (to March 1992)
90	on loading
80	0.019
80	0.006
70	610
64	> 36000
58	580
58	> 64800
39	> 66100
(b) 1100 Denier Polyester Yarn, second batch, 85 kN breaking load. This Yarn is used in Paragrid.	
65	0.55
65	92
60	2242
60	> 24800

Table 6 - Creep-rupture Data on Rhône-Poulenc Yarns (Ref.27)

σ/σ_B (%)	Median Time to Failure (h)
90	0.007
80	11
70	> 55

Table 7 - Creep-rupture Results on Du Pont Yarns (Ref.28)

	σ_B (N)	σ/σ_B (%)	Lifetime (h)	Gradient (%) per Decade
A3	6.6	90 87.5 85	70 54 256	-3.2
A4	8.0	87.5 75.0 82.5	3.6 15.3 50	-4.3
C3	8.0	85 82.5 80	3.9 13.4 123	-3.3
C4	9.7	82.5 80 77.5	4.2 8.6 23	-6.7

Table 8 - Time to 25% Strength Loss in Years (Ref.40)

%RH	10	20	40	60	80	100
0°C	2404	1202	437	185	75	64
20°C	534	267	87	37	16	13
40°C	107	53	18	8	3	3

Table 9 - Comparison between Measured and Calculated Loss of Strength of Polyester Materials after Soil Burial and Extraction (Ref.40)

Soil Burial Time (Years)	Measured Loss of Strength (%)	Calculated Loss of Strength (%)	Assumed Conditions	
			°C	%RH
12	5	5	15	60
10	4-11	6	20	60
6	25	10	20	100
7	0	2	15	50
6	7-10	19	15	100

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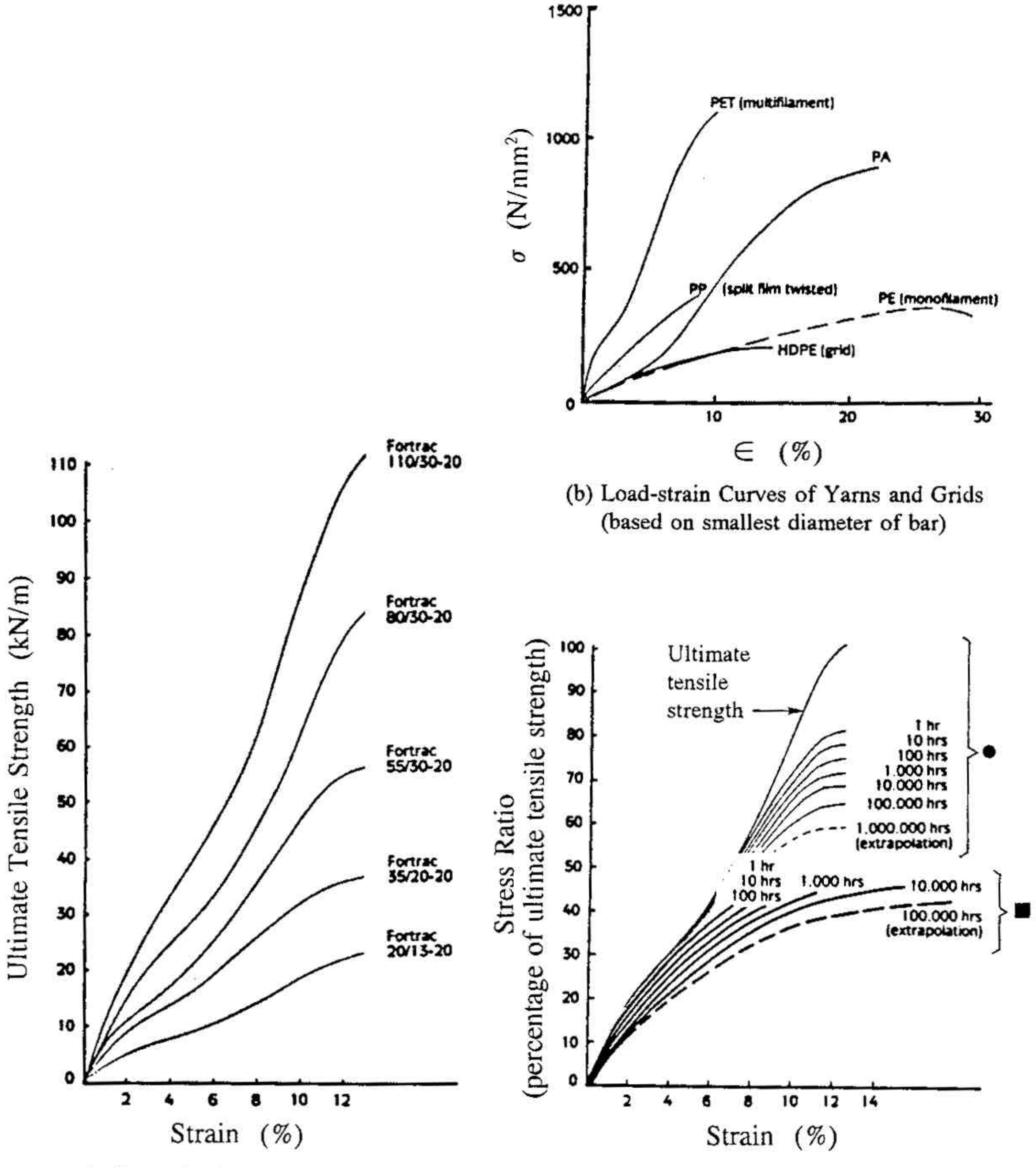


(b) Load-strain Curves of Yarns and Grids
(based on smallest diameter of bar)

(a) Stress Strain Curves (Fortrac)

(c) Isochronous Curves
(Ref. University of Oxford Report Quel 1725/88)

Legend :

● Isochronous curves Fortrac

■ HDPE (grid 20°C)

Figure 1 - Tensile and Creep Data for Akzo Fortrac Products (Ref. 1)

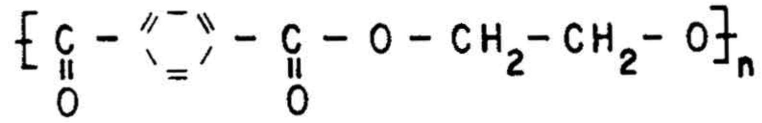


Figure 2 - Chemical Structure of Polyester

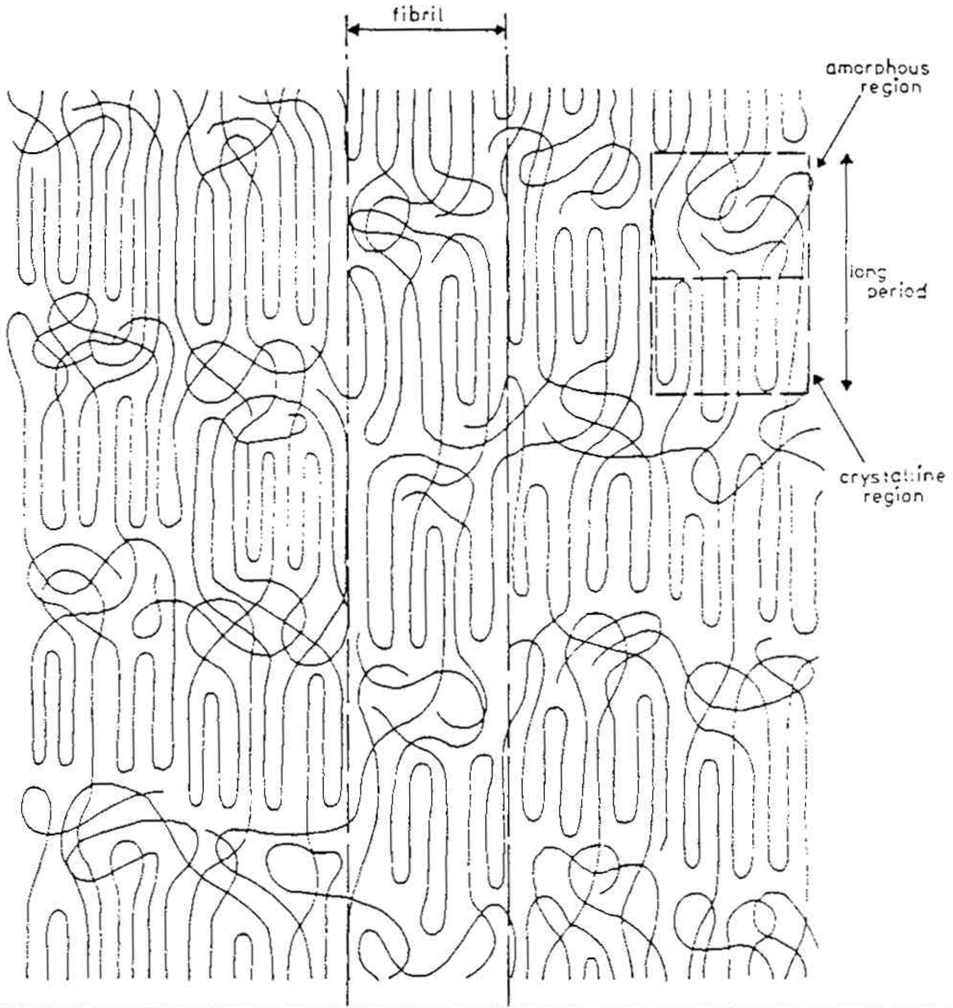
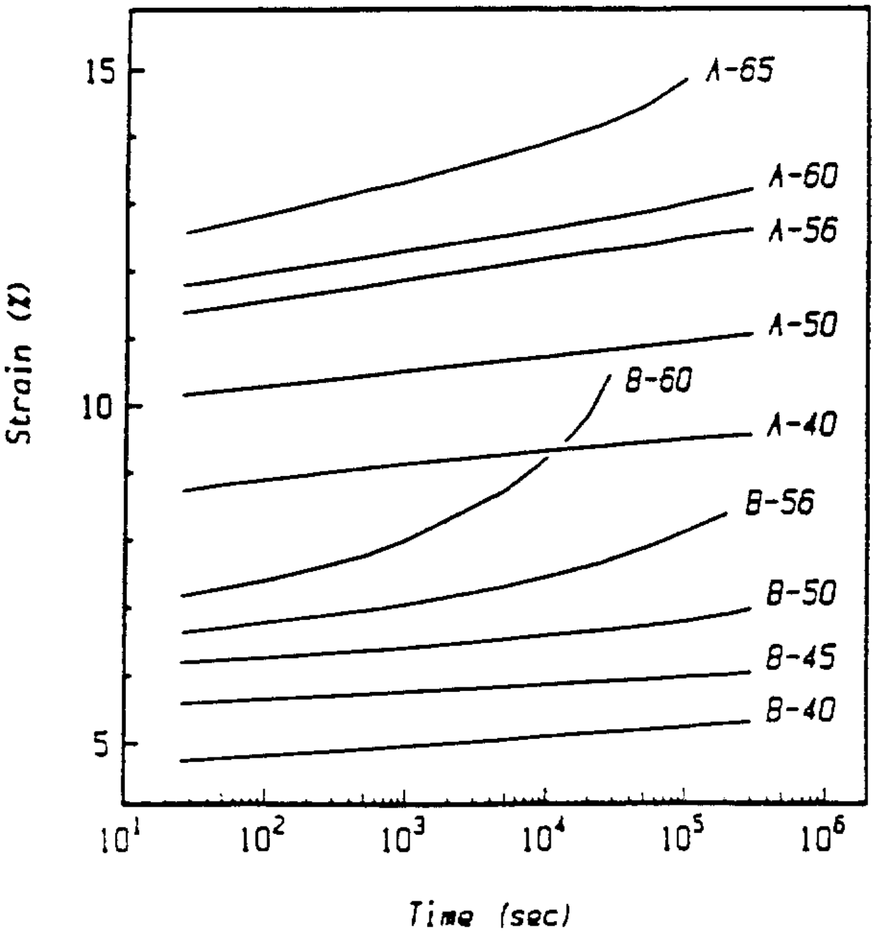


Figure 3 - Crystalline and Amorphous Regions in Polyester (Ref.2)



Note : Type A is of 5.39 dtex, type B is of 5.21 dtex.

Figure 4 - Comparison of the Creep Behaviour of Two Polyester Fibre Types Subjected to Loads of 40 to 65 Cn/tex (Ref.4)

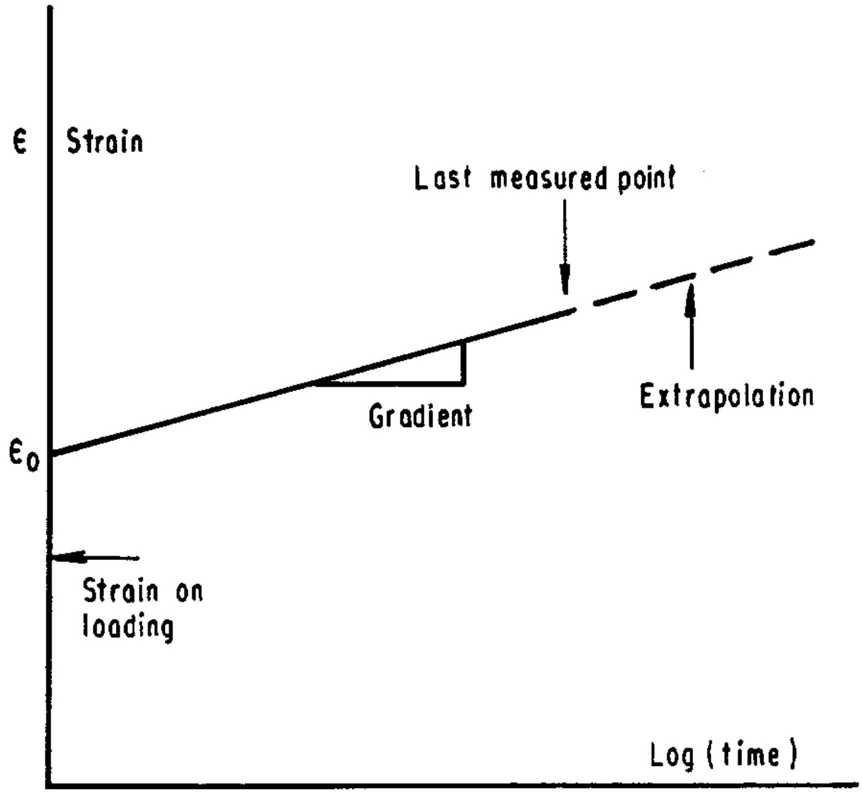
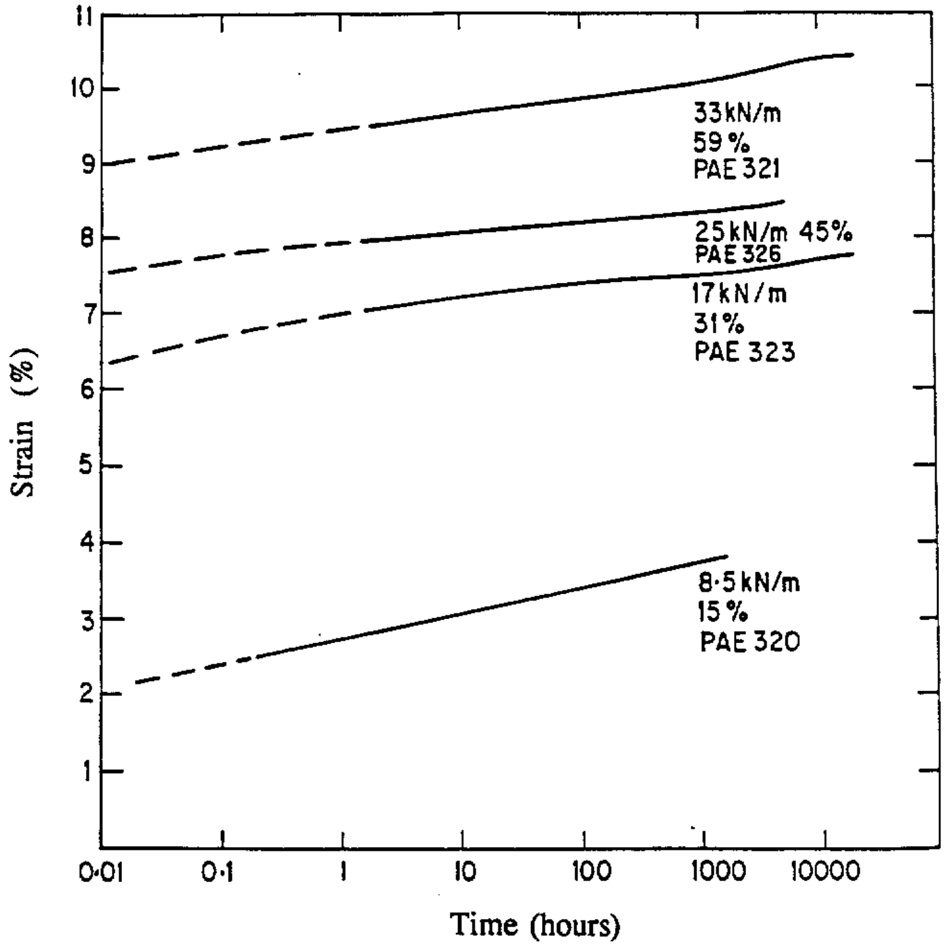


Figure 5 - Generalised Creep Curve for Polyester



Note : Percentages are of breaking load.

Figure 6 - Creep Curves for Paraweb 45 kN (Refs.9-11)

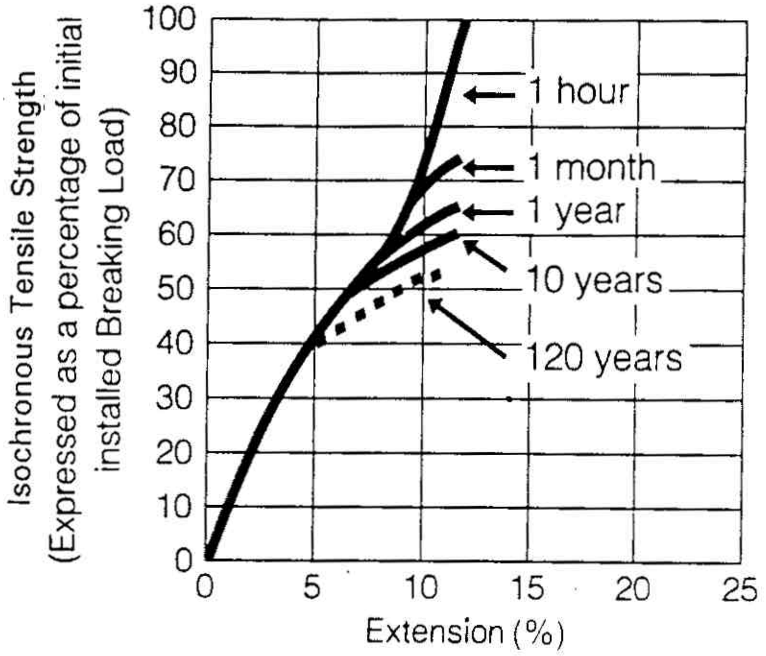


Figure 7 - Isochronous Creep Curves for Paragrid (Ref.11)

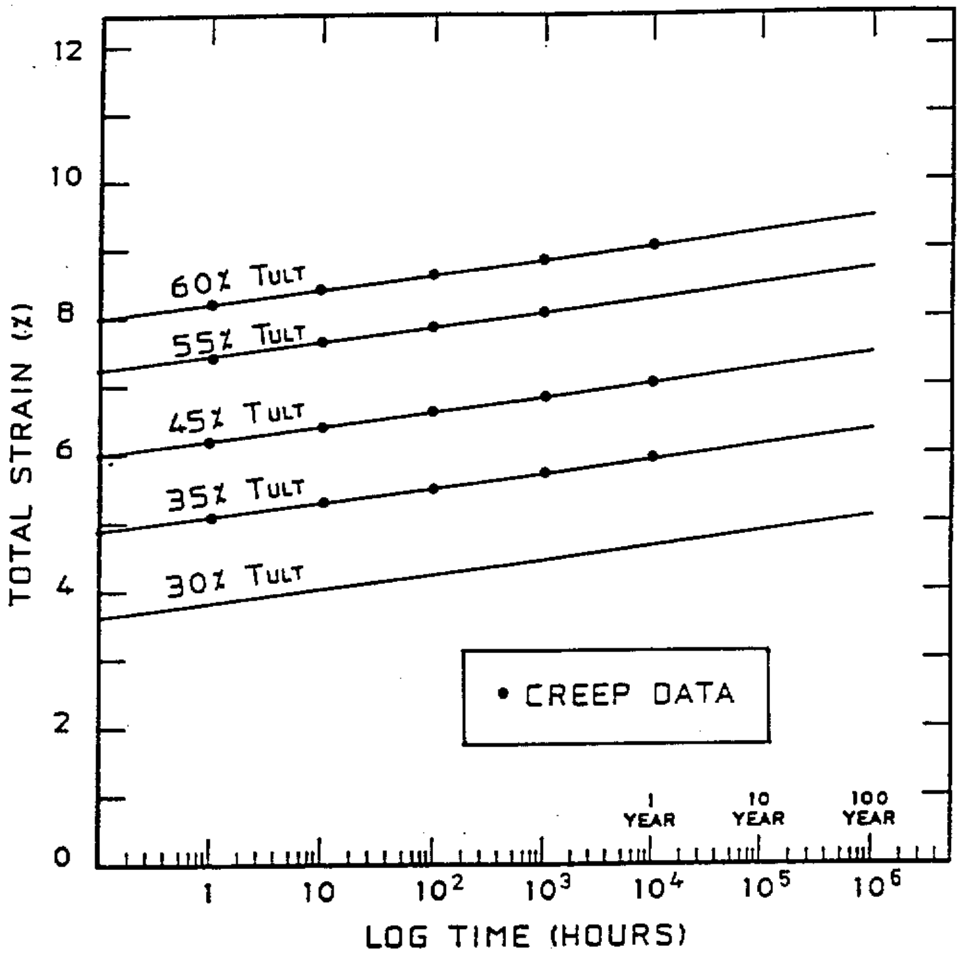


Figure 8 - Creep Curves for Nicolon Matrax 240 (Ref. 14)

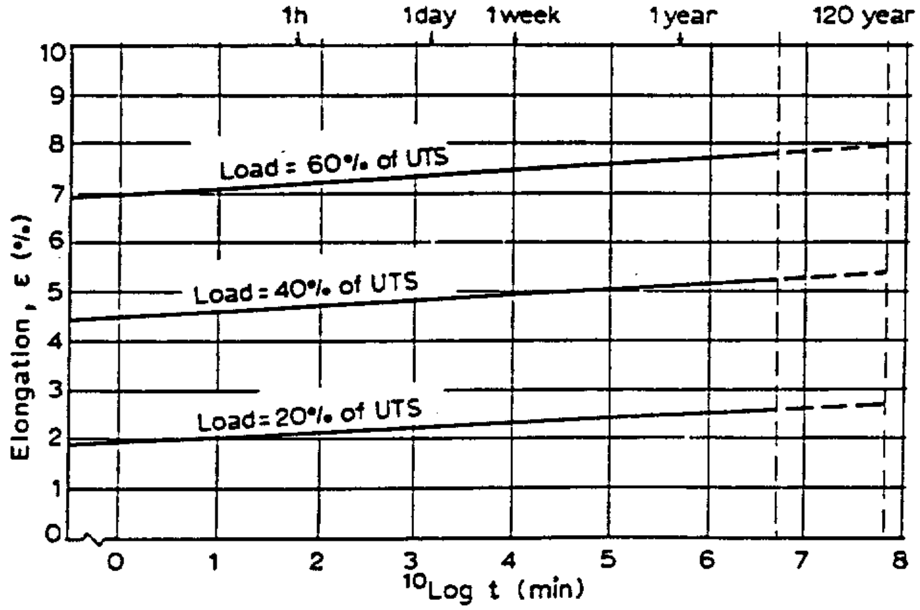


Figure 9 - Creep of Stabilenka Yarns at Different Percentages of Breaking Load (UTS) (Ref.18)

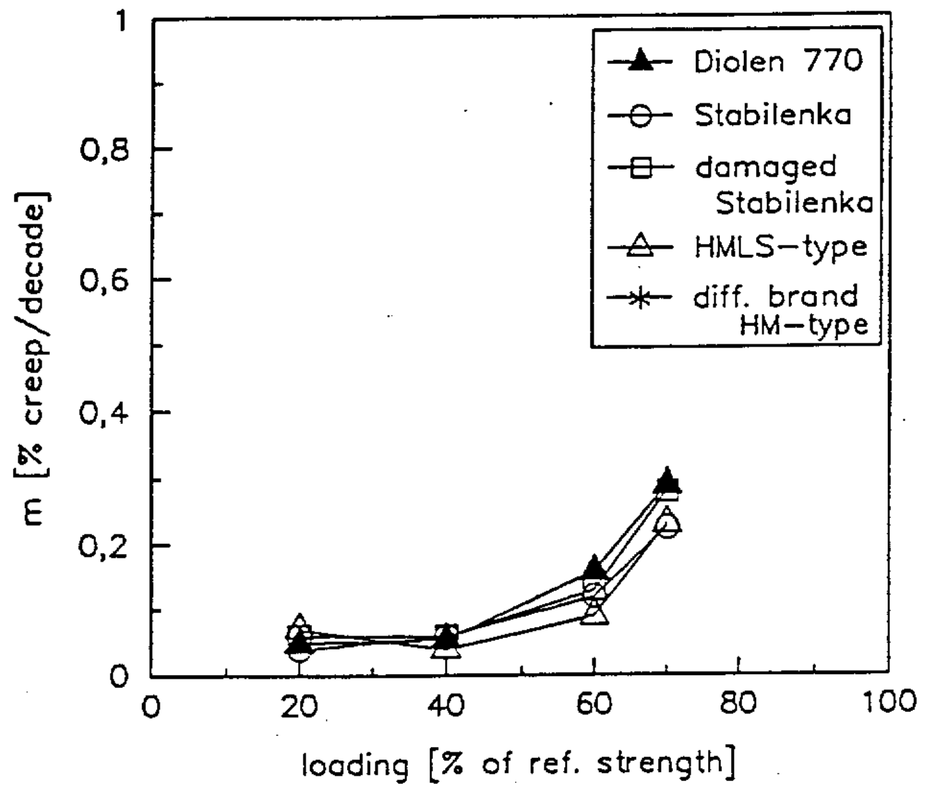
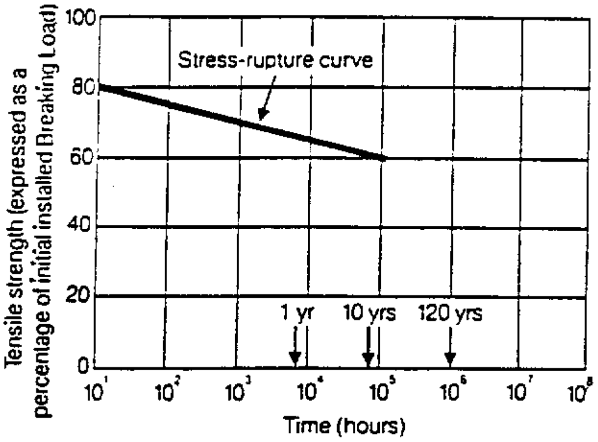
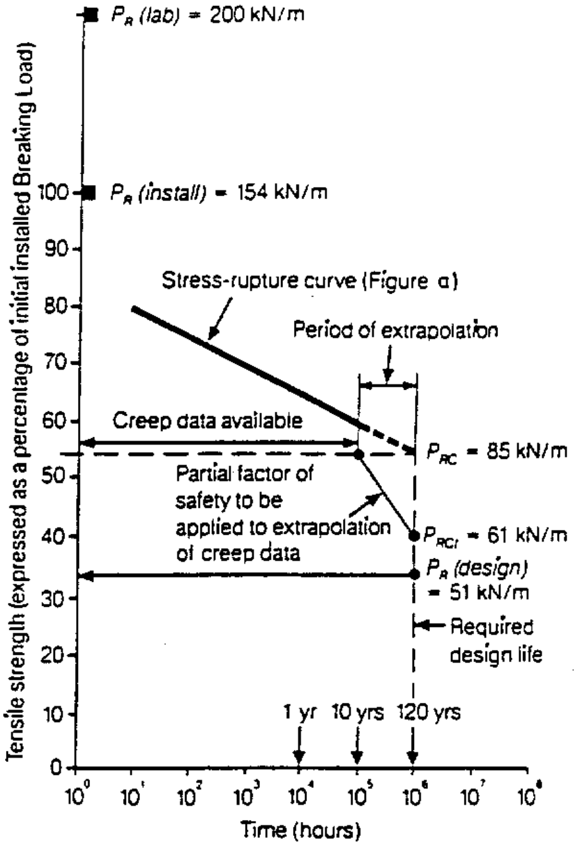


Figure 10 - Creep Gradient of Akzo Yarns as a Function of Loading (Ref.17)



(a) Stress-rupture Curve for Proposed Geotextile Reinforcement



(b) Method of Determining the Design Working Load in the Geotextile Reinforcement

Figure 11 - Schematic Stress-rupture Curves (Ref.12)

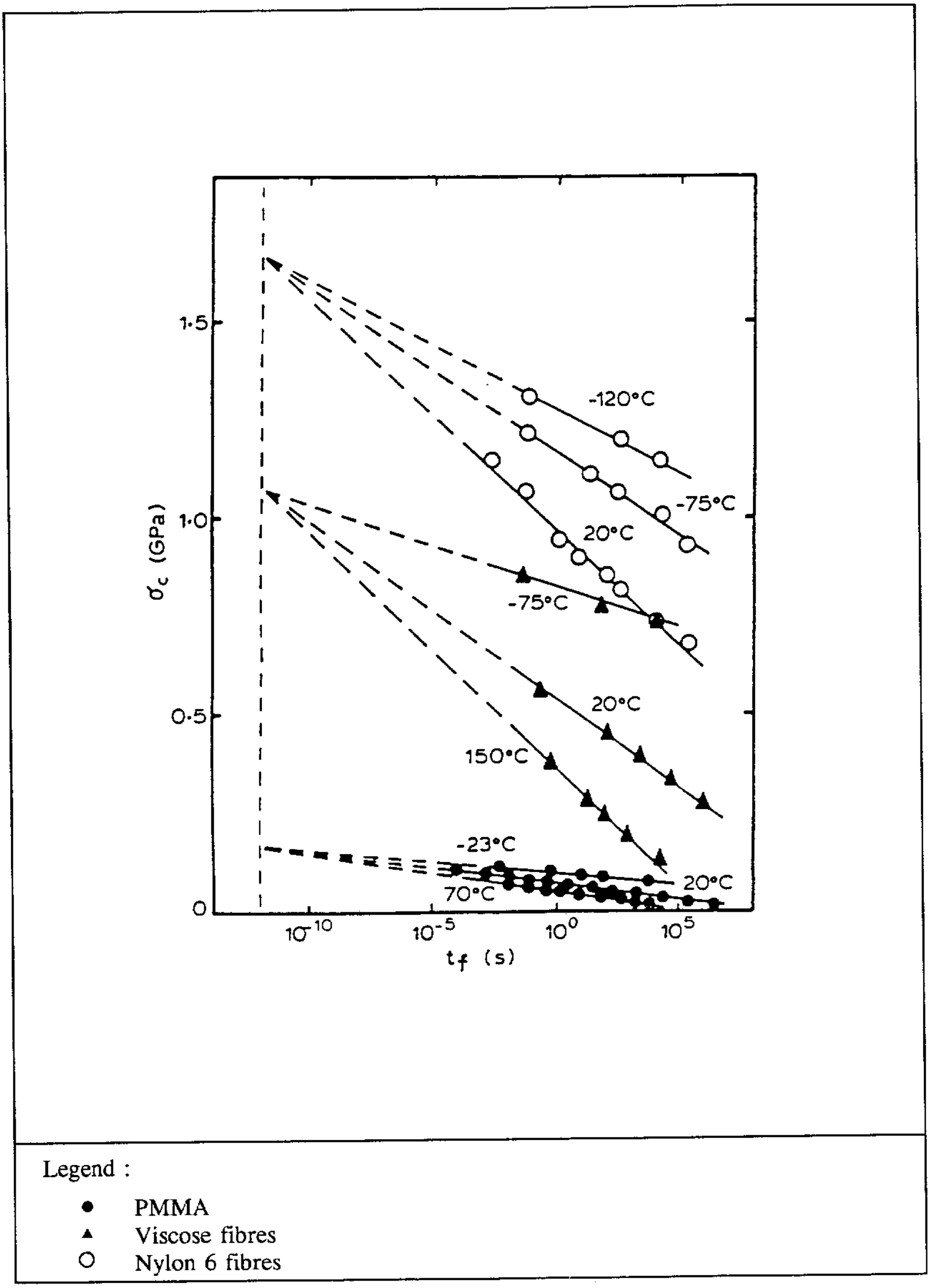


Figure 12 - Stress-rupture Curves for PMMA, Viscose Fibres and Nylon 6 Fibres Illustrating the Kinetic Theory of Fracture (Ref.25)

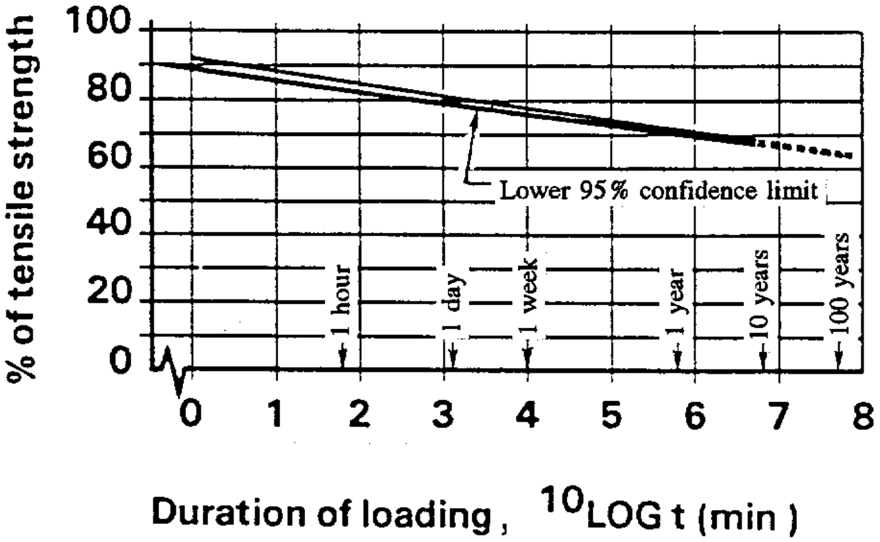
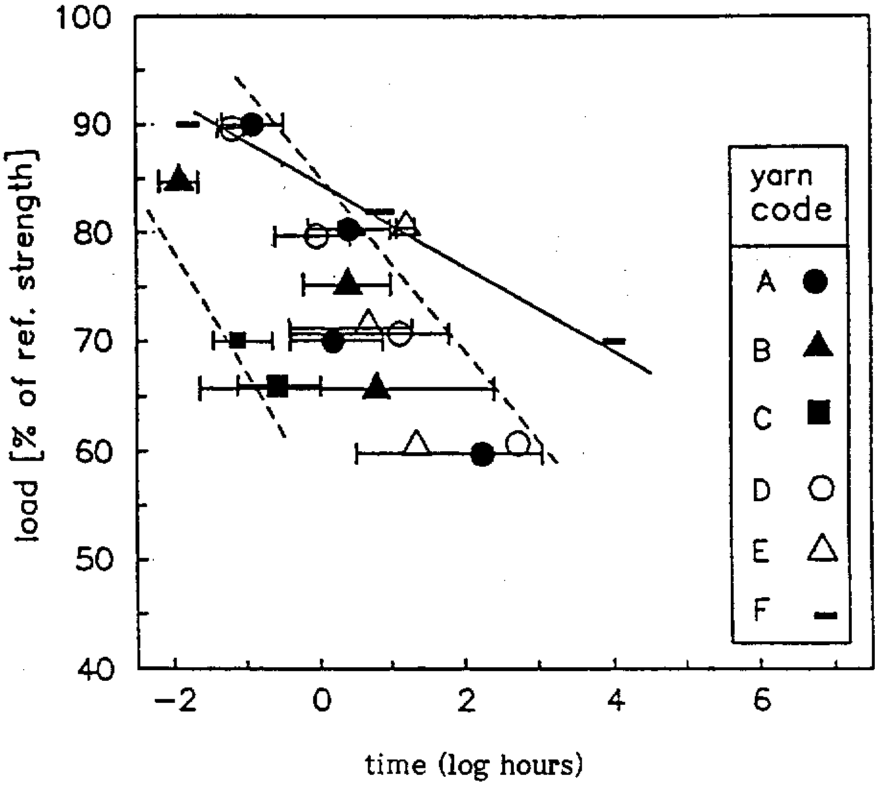


Figure 13 - Summary Stress-rupture Data for Akzo Stabilenka Polyester Fibres (Ref.18)



Legend :

- A Diolen 770
- B Stabilenka
- C Damaged Stabilenka
- D HMLS
- E Different brand of High Modulus
- F Diolen Cords (published earlier)

Figure 14 - Stress-rupture of Akzo Polyester Yarns (Ref.17)

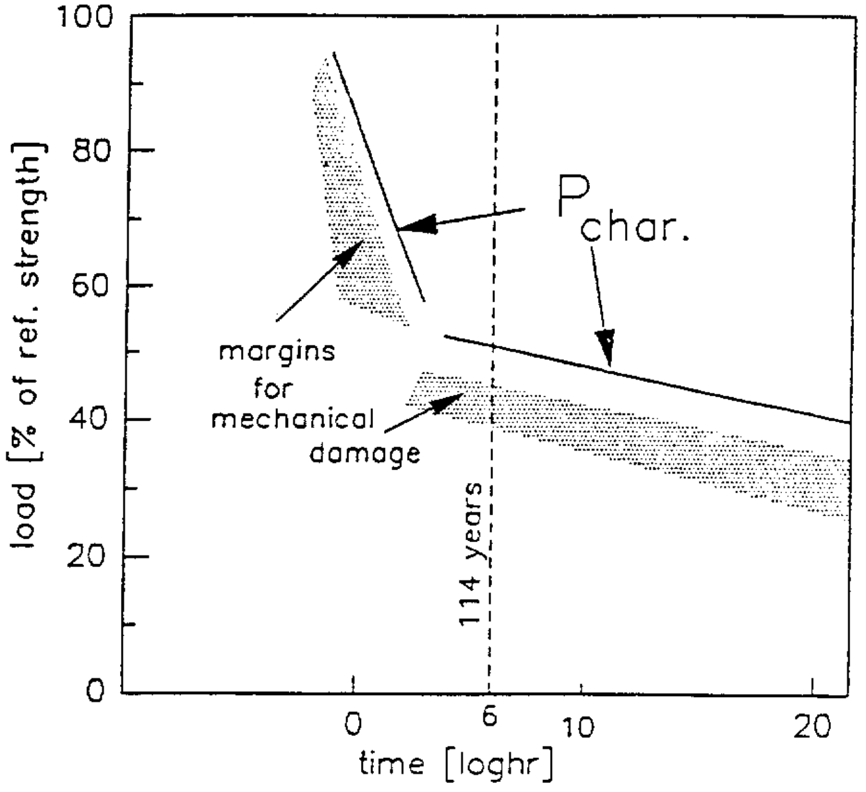
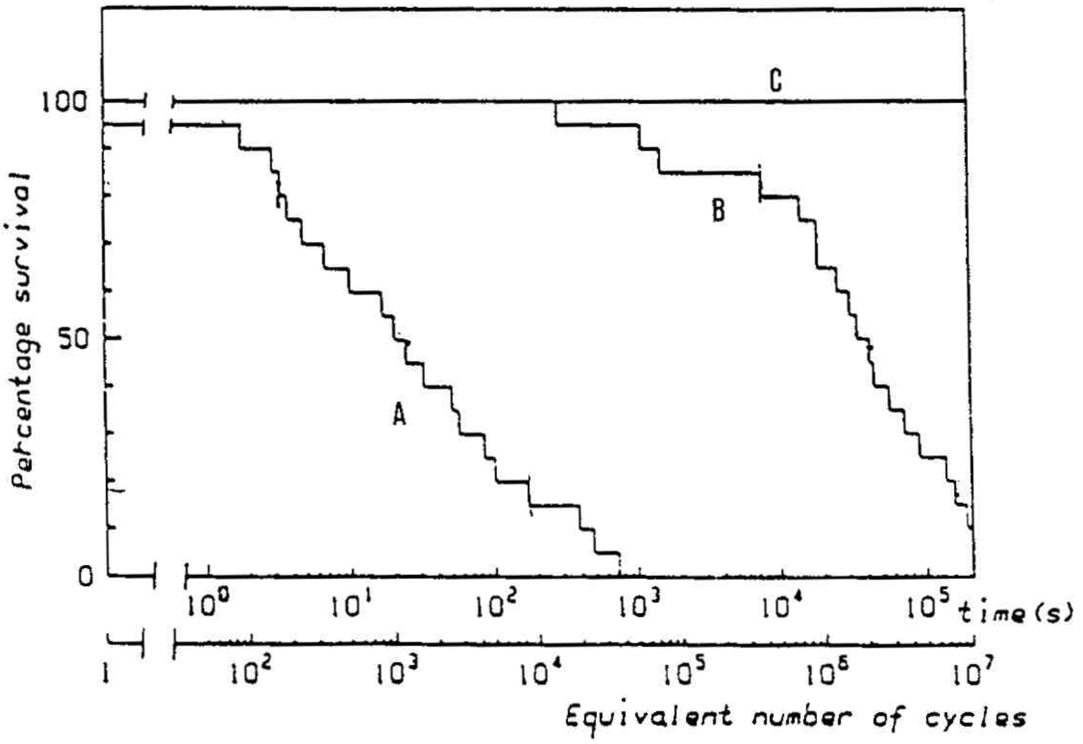


Figure 15 - Stress-rupture of Akzo Polyester Yarns (Ref.17)



Legend :

A	90% of breaking load
B	80% of breaking load
C	70% of breaking load

Figure 16 - Cumulative Histograms of Creep Lifetimes (Ref.27)

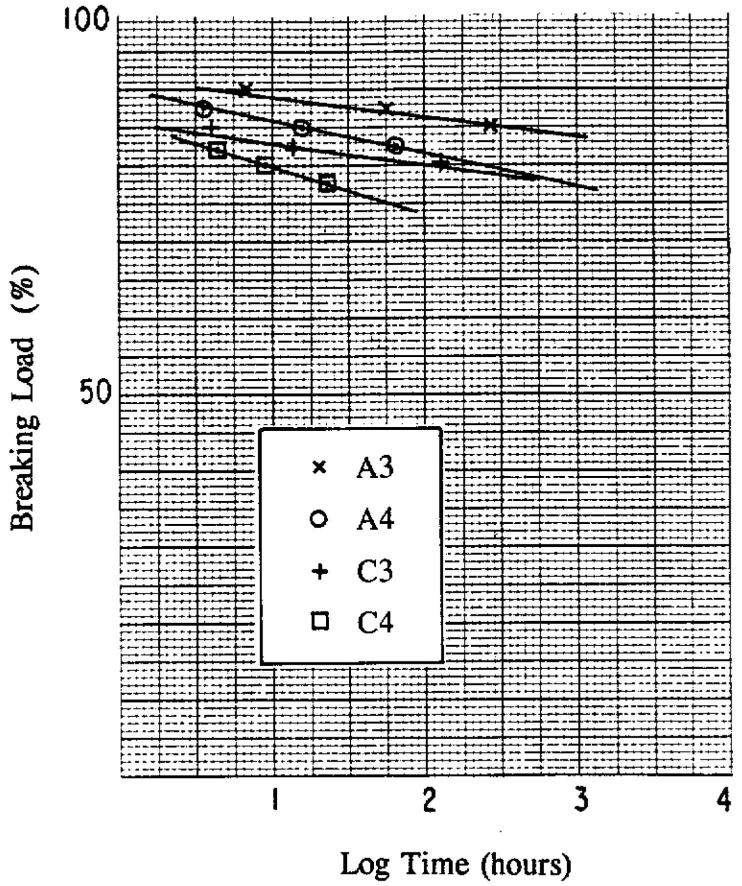


Figure 17 - Stress-rupture of Du Pont Fibres (Ref.28)

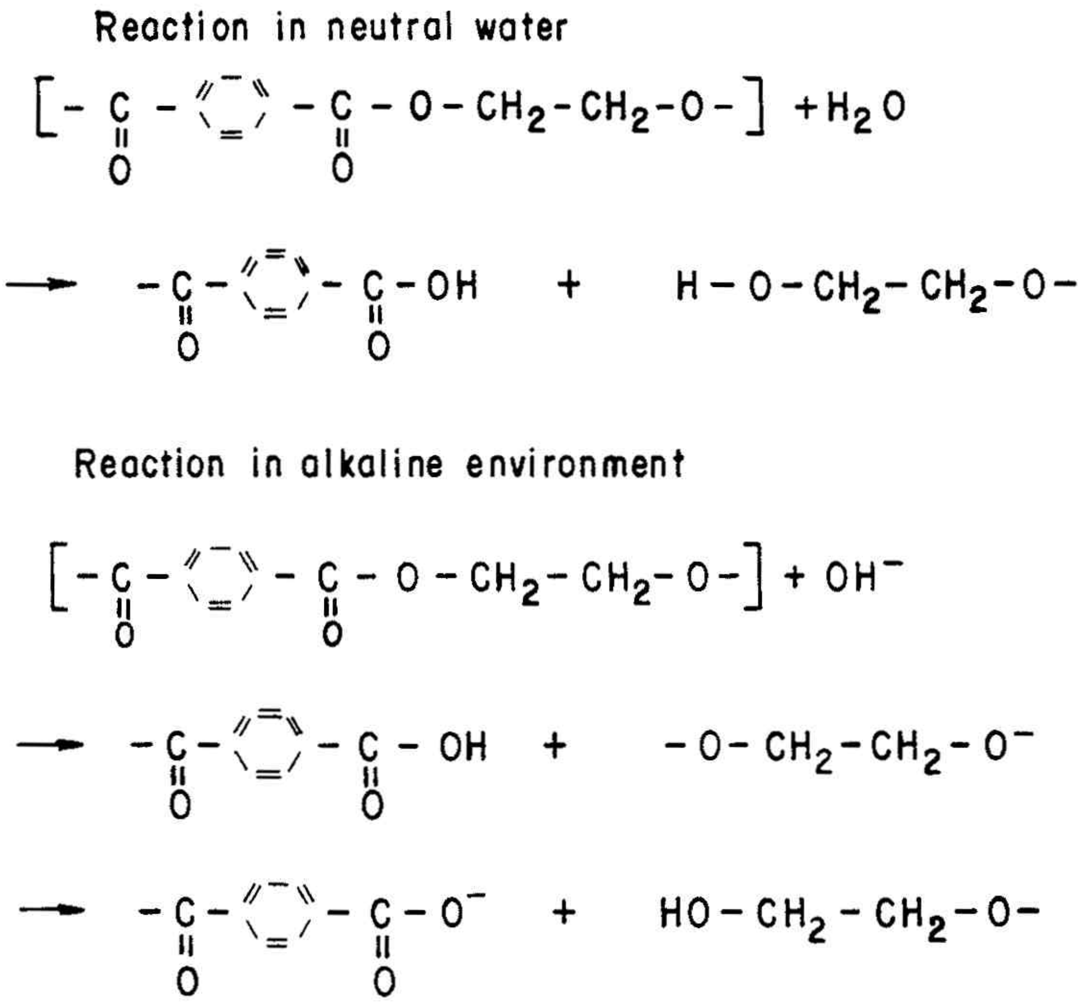


Figure 18 - Chemistry of Hydrolysis Process (after Ref.31)

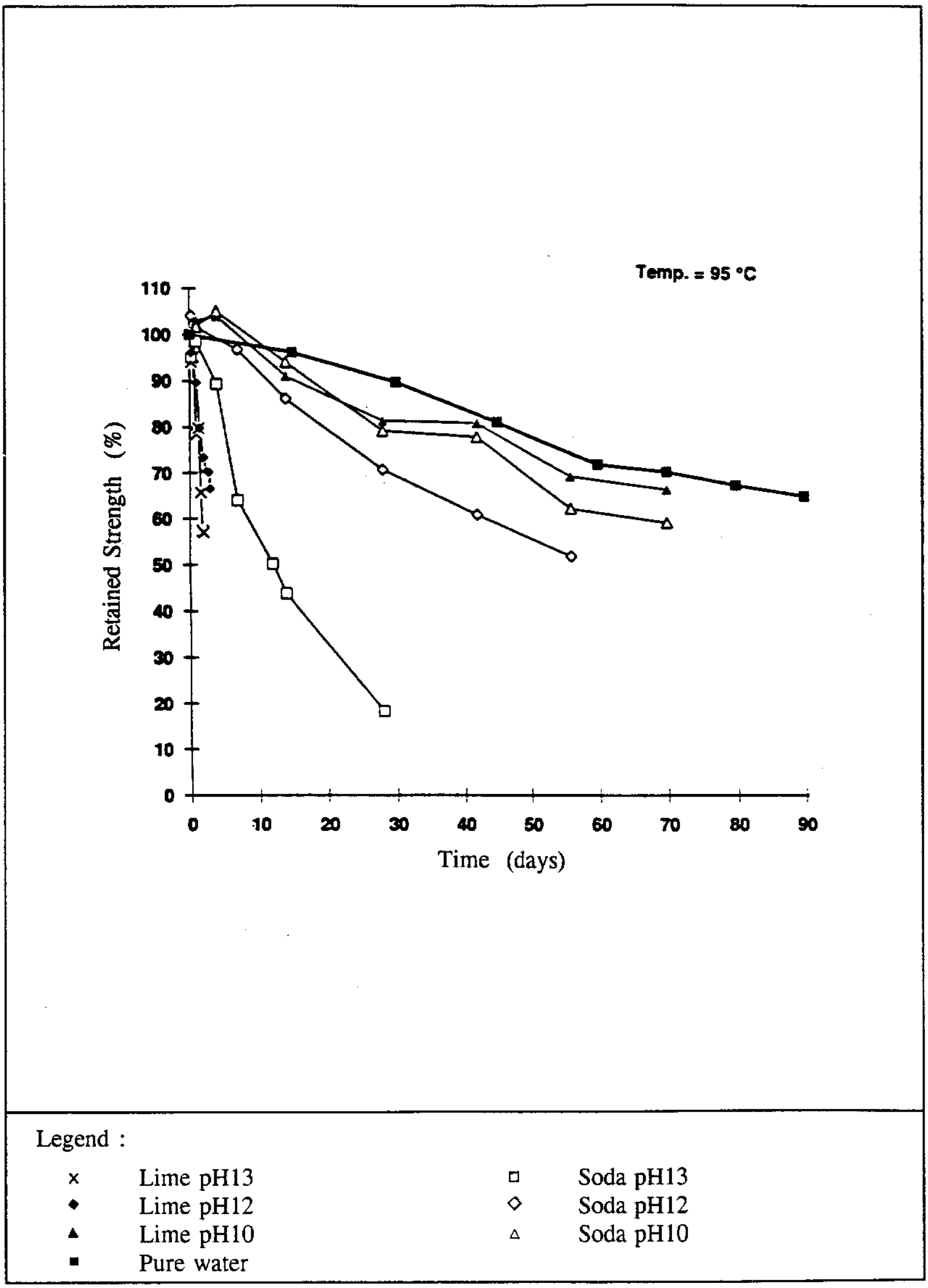


Figure 19 - Strength Degradation of Polyester in Water and Alkaline Media at 95°C (Ref.31)

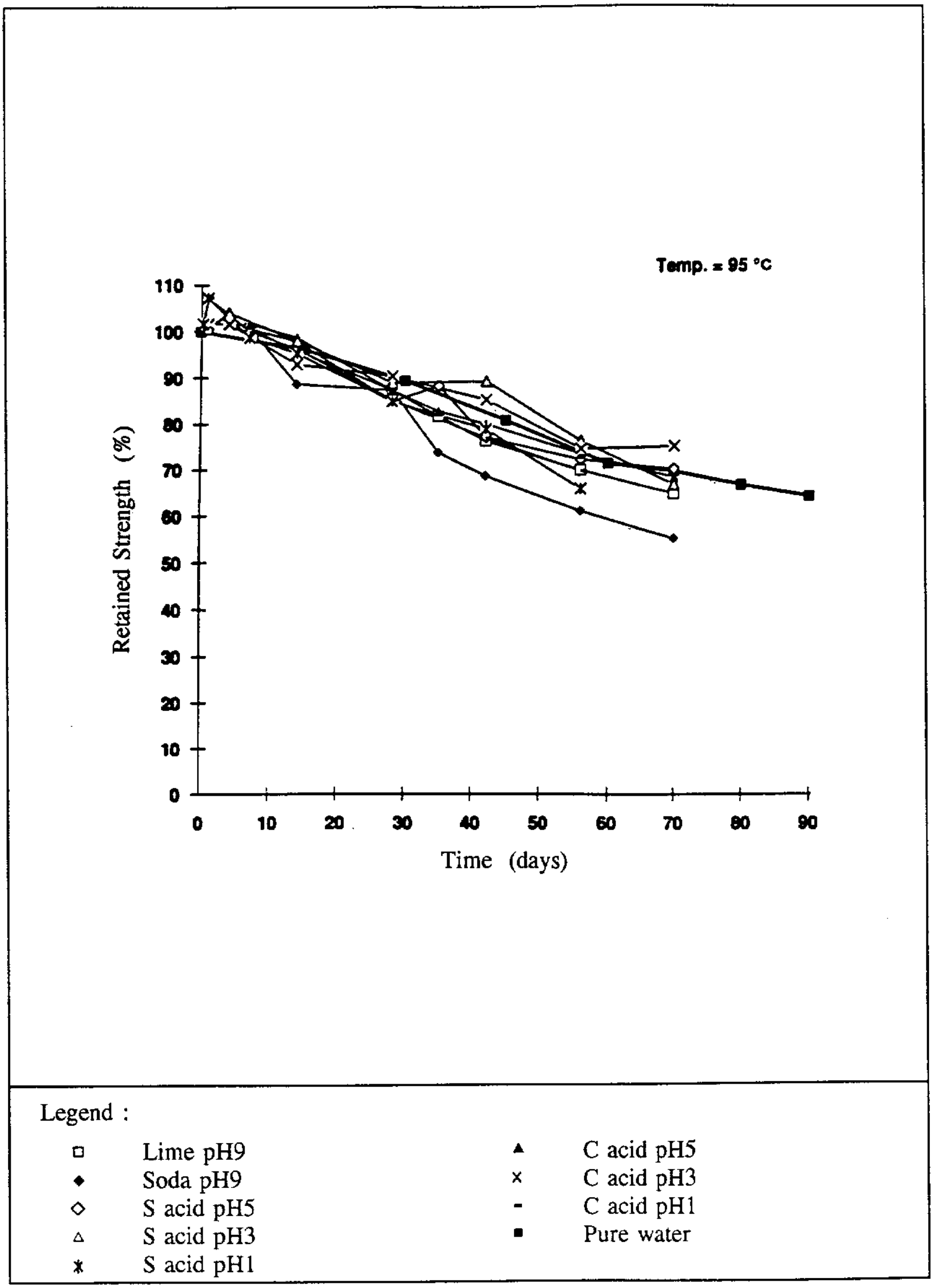


Figure 20 - Strength Degradation of Polyester in Neutral and Acid Media at 95°C (Ref.31)

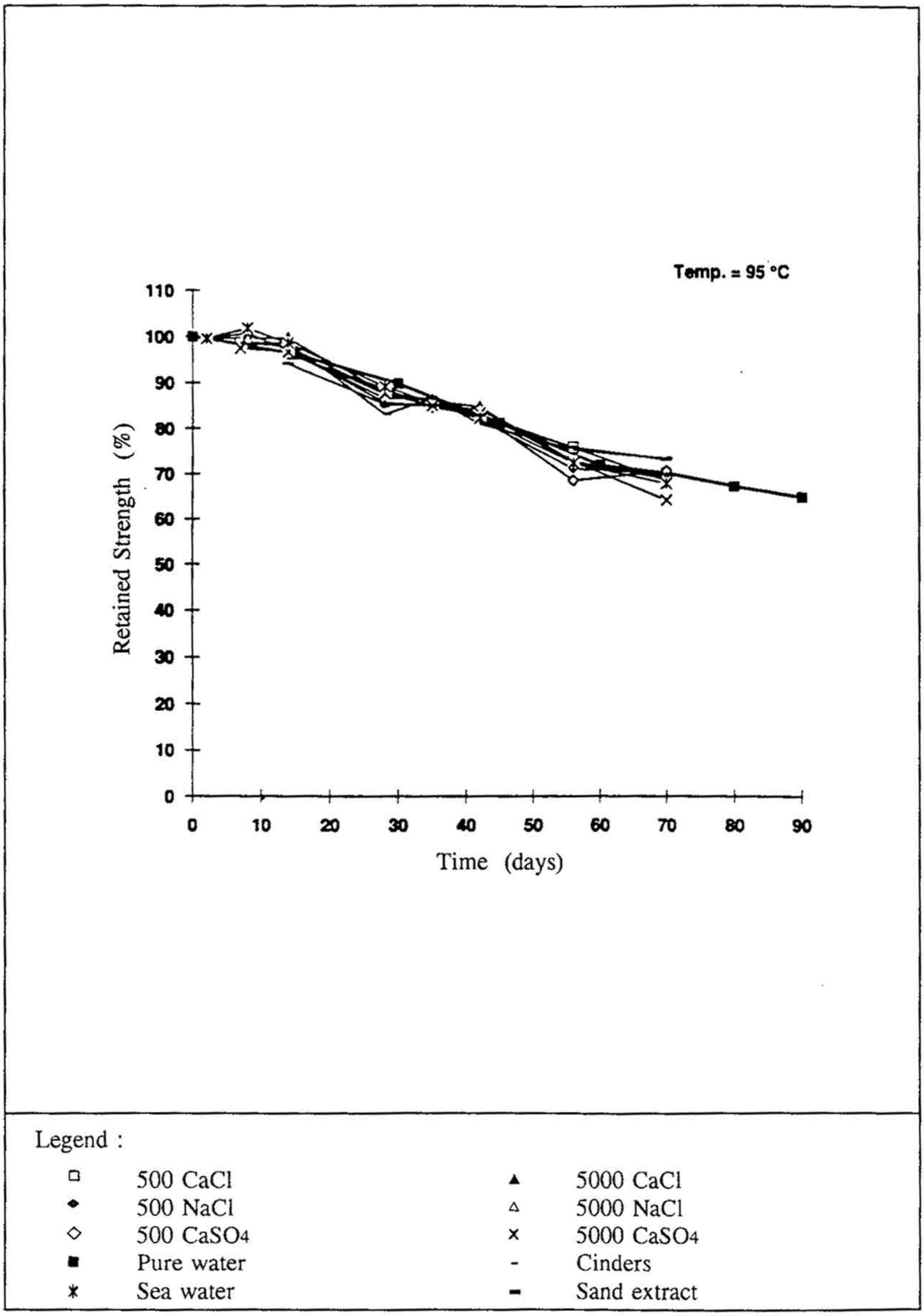


Figure 21 - Strength Degradation of Polyester in Other Media at 95°C (Ref.31)

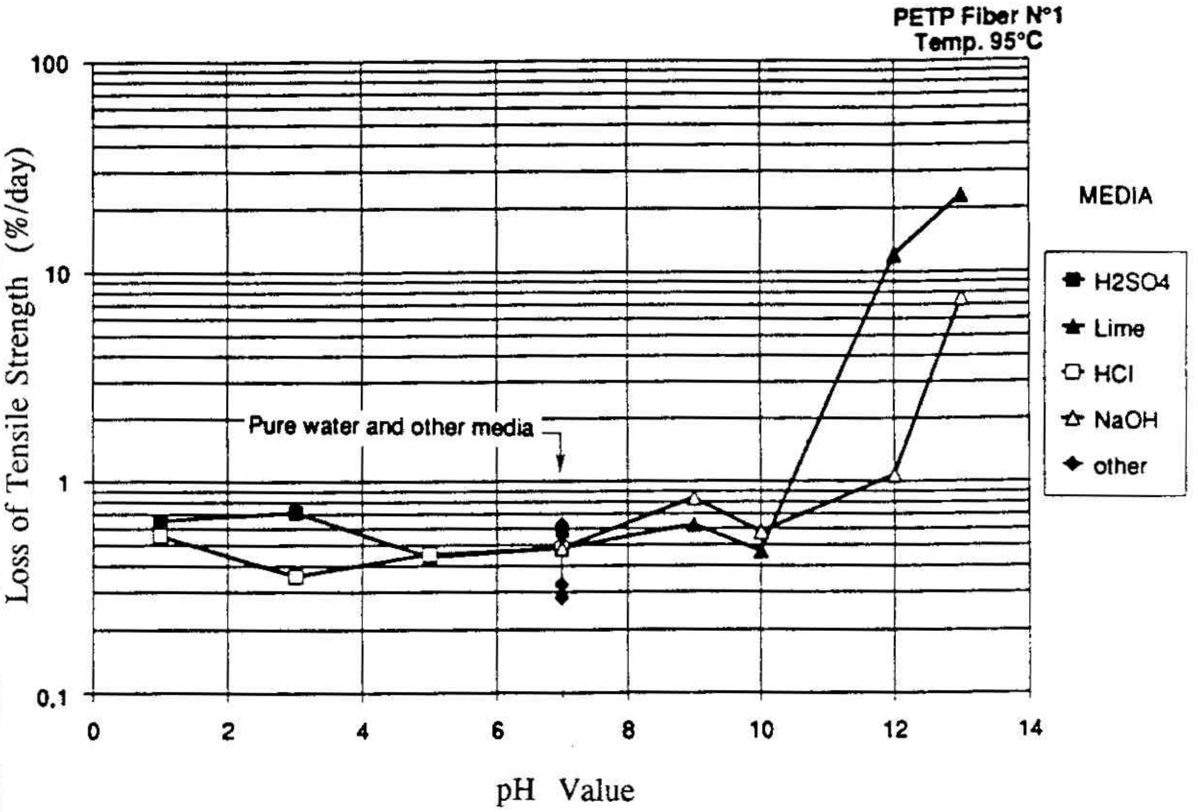


Figure 22 - Dependence of Rate of Degradation at 95°C on pH (Ref.31)

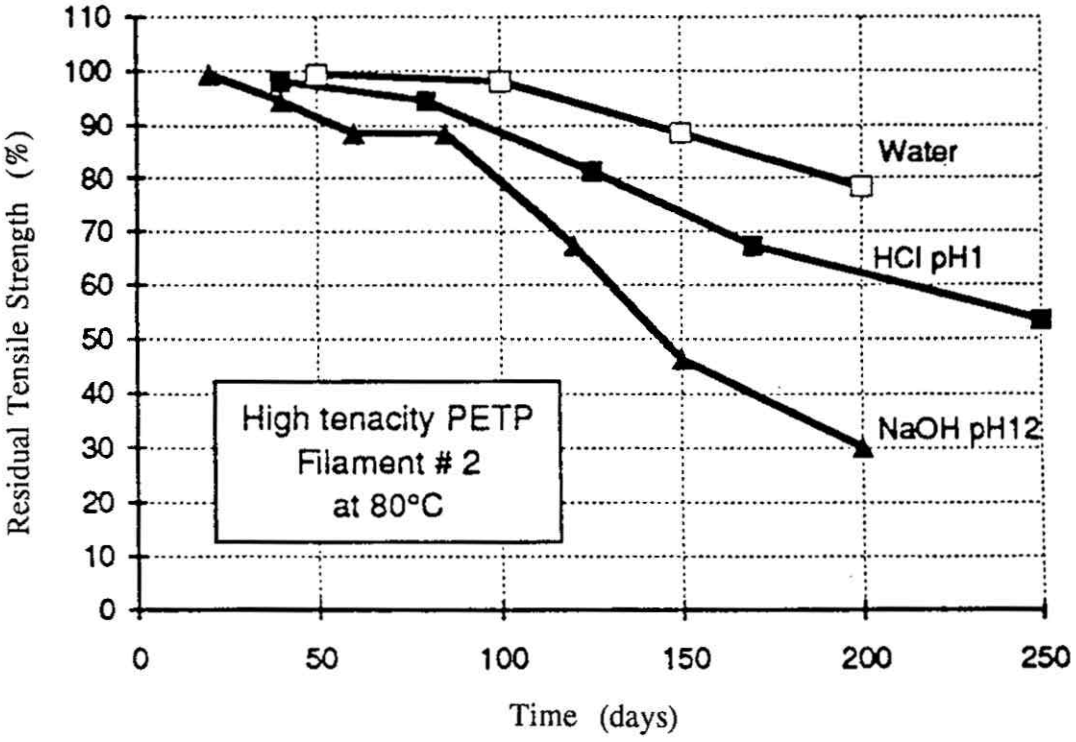


Figure 23 - Strength Reduction of Polyester Fibres at 80°C (Ref.37)

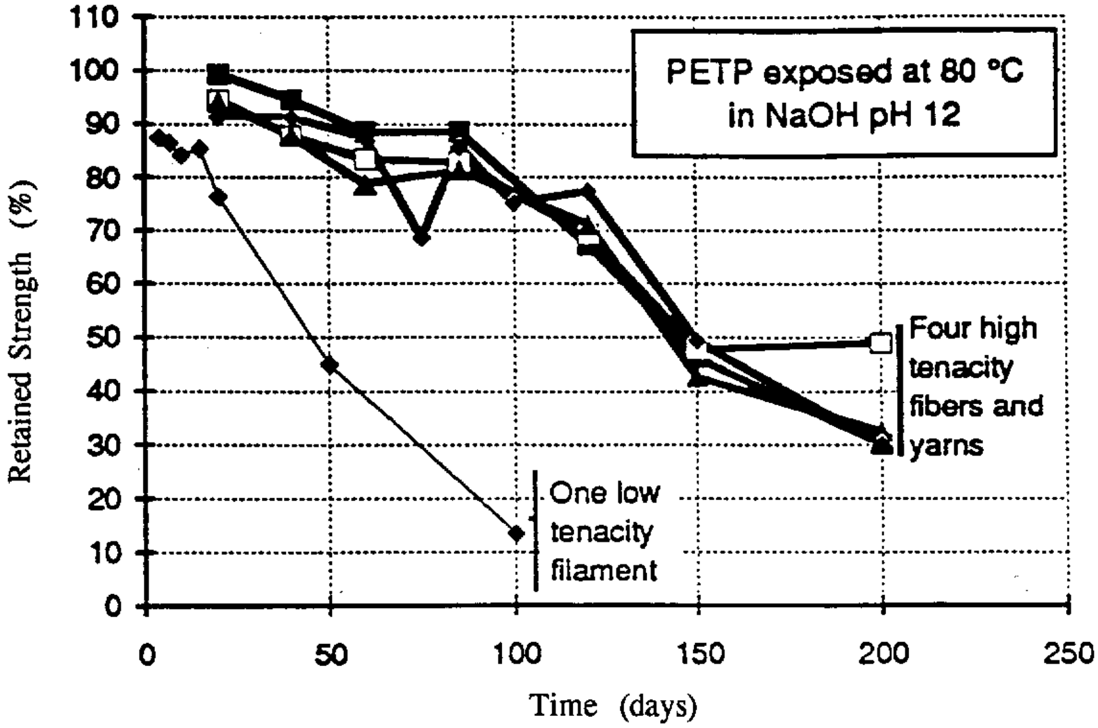


Figure 24 - Comparison of Strength Decay for Five PETP Materials
Exposed at 80°C in Soda (Ref.37)

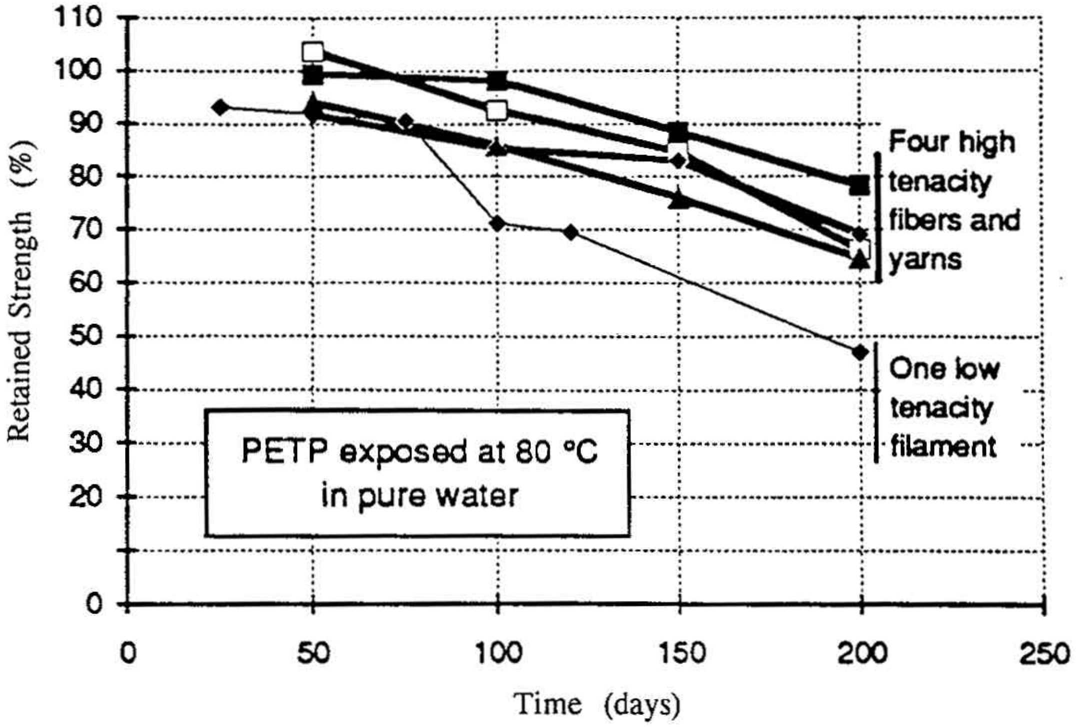


Figure 25 - Strength Degradation of Various Polyesters in Water and Other Media at 80°C (Ref.37)

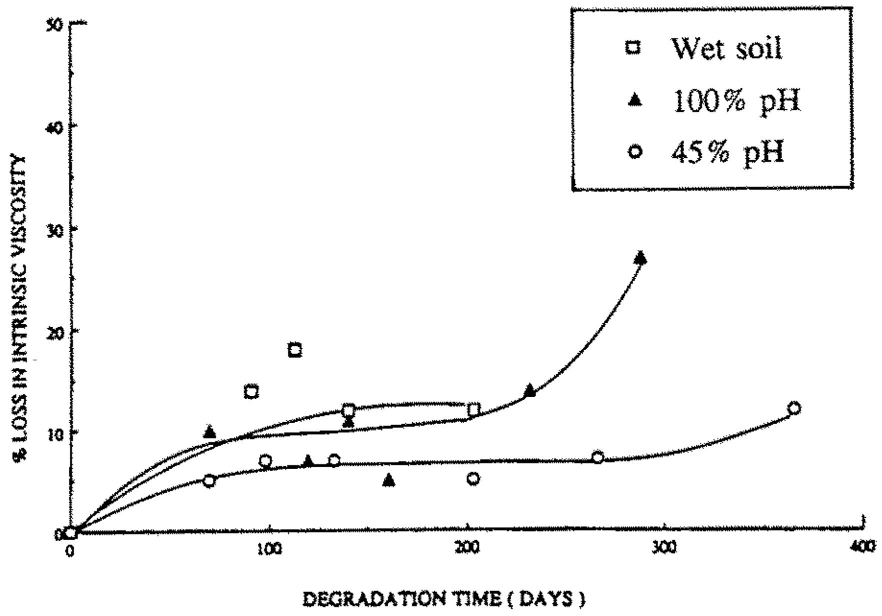


Figure 26 - Degradation of Polyester Film in Wet Soil at 100% Relative Humidity and at 45% Relative Humudity at 60°C (Ref.39)

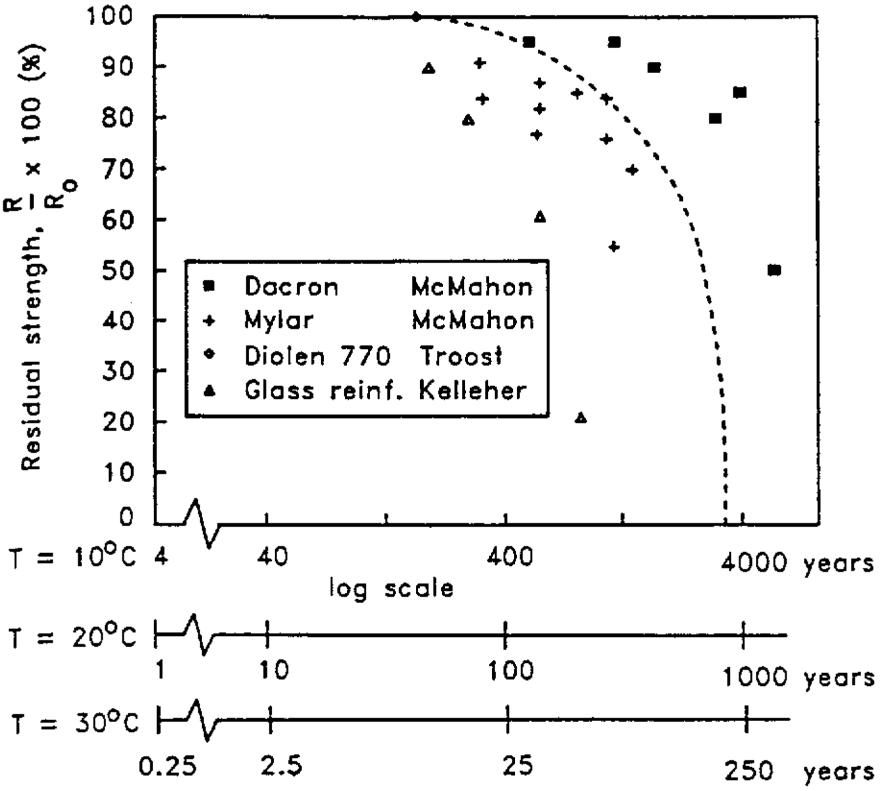


Figure 27 - Time-dependent Loss of Strength of Akzo and Other Yarns due to Hydrolysis, Temperature = 10°C, 20°C and 30°C, at 100% Relative Humidity (Ref.32)