Polymer grid reinforcement

A conference sponsored by the SERC and Netlon Ltd

POLYMER GRID REINFORCEMENT

Proceedings of a conference sponsored by the Science and Engineering Research Council and Netlon Ltd and held in London on 22 and 23 March 1984

Thomas Telford
London

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Opening address

Sir Alan Muir-Wood, *Sir William Halcrow & Partners*

I am very pleased to be here on several counts. First of all, I sit on the council of SERC, which is usually backing success, and I am delighted therefore to see that you have an overflow for this meeting as an example of this degree of discrimination. Secondly, on behalf of the Institution of Civil Engineers, I am very pleased to see this conference being held here, and I would remind those who do not know that quite a lot of the innovation in the applications to reinforced earth took place in the bailiwick of Mr Tony Gaffney, the present President of this Institution. Thirdly, this Institution always has seen innovation as being at the centre of its activities, and particularly innovation which cuts across disciplines, which this occasion clearly exemplifies.

I was brought up on the myth of isotropic soils. It was then gradually appreciated that natural soils, by the way in which they are laid down, are almost certain to be anisotropic. We then went in for artificial soils used as fills, and these tended to be rather more isotropic than in nature. Now we reinforce the soils and we put them back to being anisotropic. But just to complete the story I see that paper 8.1 for this occasion is dealing with random reinforcement, so presumably from that we return full circle to isotropic soils of a sort.

Reinforced earth in concept is quite literally as old as the hills, and anybody who has looked at mesas and seen why they stand up will appreciate this. The concepts of reinforced earth were widely used for military engineering through the centuries. I am indebted to Professor Tom Hanna for enlightening me on the building of ziggurats by the Babylonians, reinforced by layers of papyrus in bitumen. So we are not talking about anything particularly new in fundamentals. But on the other hand what we are always talking about as civil engineers is finding how to make use of the forces of nature towards our benefit rather than our destruction.

The military uses I alluded to were for making ravelins and all the other things that Gilbert's modern major-general was so expert upon - in, as I recall, a purely theoretical sense. But nevertheless model tests were undertaken early in the 19th century on the use of reinforced earth. More recently we had the ideas of Vidal which came over in Terre Armée.

The subject area for this symposium is that of net fabrics. It is a pity that there is no account of the extreme ingenuity which went into the origin of the method of forming these nets, but I hope the omission is going to be repaired during the next two days.

In the general process of innovation commonly seen in civil engineering the innovators first step forward out of line, taking a certain amount of risk in so doing. This then results in trials based upon a rudimentary analysis. There is a period of development of the theory, and this leads to acceptance by the few who are in the van. Following this there is great activity in research where it becomes fashionable throughout the academic world. Subsequently this leads to production of codes of practice with their wider acceptance.

There are two particular problems in this area that are worth mentioning. The first is the necessity for those who are familiar with the application of plastics in one form or another to understand the long time-scale of civil engineers. I noticed, for instance, that Professor Ward mentions in his paper that it is not practicable to measure strain rates below 10^{-9} s^{-1}. Now, 10^{9} s is a period of about 30 years, which is well below the normal design life for a civil engineer, so if the strains occur at a rate of 10^{-9} s^{-1}, that may mean that he is going to have rather a pregnant-looking embankment after 30 years.

The second problem is the question of durability. I see that there is no specific paper on durability, which I would have thought needs to be covered fairly fully, because as civil engineers we are well aware of the various forms of attack that we have to contend with, from the aggressive soils of one sort and another. It would be nice to know that what we are talking about in general can also be applied in particular; or, if not, to know what the cautionary tales are so that there is not a history of defect which then tends towards a more suspicious attitude to the use of nets. This is particularly so because of the behaviour of certain polymers in the open air - particularly in sunshine - and the fact that nets have been sold for purposes which should have been accompanied by a government health warning. Those who are gardeners will know that nets, after 2-5 years depending upon which particular material they are made of, tend to look rather like the white suit that Alec Guinness wore in the film of that name. Hence it is necessary to give assurances. Underground you do not have these particular problems, but there may be others which affect longevity.

With those cautionary words, I nevertheless wish to share a feeling of great enthusiasm towards this symposium. I am extremely pleased to see this coming-together of those of totally different disciplines, and I look forward to this as being a thoroughly constructive discussion.

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The research and development programmes for polymer grid reinforcement in civil engineering

Sir Hugh Ford, *Sir Hugh Ford and Associates Ltd*

The development of the properties of polymers to allow them to be used as load bearing structural materials has only slowly invaded the more conventional engineering fields. Much ingenuity has been needed to develop high strength and long term stability. Tensar geogrids are now available to the Civil Engineer for soil stabilisation, reinforcement, road pavements etc. but it is by extensive and careful test work that design guidelines can evolve.

To provide the necessary knowledge of engineering properties, Netlon Ltd is working with four University Civil Engineering Departments through a SERC co-operative award.

The work has progressed sufficiently to mount this Symposium to discuss the results and present examples of applications worldwide.

Although polymeric materials have been around for many years, the development of their properties to allow them to be used as load-bearing structures has been slow to invade the more conventional engineering fields. With their low elastic modulus relative to metals their elasto plastic behaviour and strain-rate dependency, it has been difficult to get acceptance among engineers in general and in heavy engineering situations in particular.

Nor is this surprising. So much of engineering depends upon a sufficient body of practising engineers at all levels gaining sufficient experience and mutual awareness of a new development that behaviour in a range of conditions and environments is appropriately established for reasonable confidence to be generated. Nowhere is this more important than with a new material especially a material like a polymer that has penetrated very dramatically into everyday life as a packaging material or as a substitute for a conventional, well established material.

With Civil and Structural Engineering applications a new material has very considerable obstacles to surmount - perhaps greater than in other branches of engineering. Most long term structures are required to be designed for a life of 120 years. Few polymeric materials have been in large scale production for longer than 50 years and, with their known creep behaviour, predicting acceptable lives of 120 years from short term tests has provided formidable problems to researchers and designers alike.

There could be two ways to overcome these barriers to progress. One that is too often used is make a frontal attack with a measure of risk that some applications will fail and need to be remedied - or compensated for - at a later date. Enough experience, it is hoped, will have been gained meanwhile to avoid the difficulties in future applications without the new product's reputation being irreparably tarnished in the process. The other way is to approach the potential market cautiously while undertaking the necessary development and application trials to ensure satisfactory performance to be confidently anticipated: a slower method, perhaps, but one that inevitably has to be followed with a technically sophisticated material such as highly oriented polymer.

It is only by careful and exhaustive experimental studies that it has been possible to evolve grid structures that have the high strength and durability necessary to be used as geogrids in real engineering applications. To take heavy gauge polypropylene or high density polyethylene sheet, to punch clean, regular holes and then to extend the sheet either uniaxially or biaxially under controlled temperatures and strain rates, demanded very great ingenuity in mechanical and control engineering. It will well be appreciated that, while the strain rate, and orientation strengthening characteristics of polymers compensate for the reduction in area effect of the stretching there is inherent in the process the "plastic instability" phenomenon familiar to all in the tensile test.

It is important to draw attention to this aspect of the manufacture of geogrids because upon the knowledge of the behaviour of polymers in such a process and the precision and quality control at each stage depends the reliability and mechanical properties of the final product. The present stage of realisation of a practical engineering material has not been reached without very sophisticated and carefully controlled processes and continuing research into polymeric materials and the optimisation of their orientation.

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One of the most important aspects and certainly the most critical consequence of orientation is the development of stable long term properties. While high strength and an enhancement of the pseudo-elastic properties of the polymers are major objectives that have been achieved by orientation, these properties in themselves are not enough: the creep rates under steady load, of an order to be of practical value, are of paramount importance, particularly in Civil Engineering applications, as has already been said, to be able to predict satisfactory performance over periods of 120 years. Such a requirement is of particular difficulty because, not only are the potential applications extremely varied, but the manufacturers and processors of polymers are not standing still and better materials and controlled processes are constantly coming forward. Moreover, Civil Engineering depends upon a great variety of practitioners, from the highly discerning to the reverse. While the applications of inclusions, whether geotextiles or geogrids, are now established to the extent that there is a growing appreciation of the methods of their applications for soil stabilisation, reinforcement of soils, road and loaded areas, asphalt structures and the like, there is still much debate as to the best design methods and guidelines to be followed to ensure the most economic and long-term performance of such materials. Their use in cement and concrete type composites is less well defined.

With a view to providing both the background knowledge and the necessary design data on the engineering properties of Tensar geogrids, the Netlon Company sought the assistance of the Science and Engineering Research Council in enlisting the services of University Departments to carry out a comprehensive programme of cooperative research. The SERC's scheme of cooperative awards with industry has enabled an extensive programme of objective studies to be undertaken and prosecuted with much greater speed and effectiveness than any other means.

There are four Universities in the scheme and each has support from the SERC and Netlon for at least a three year programme. The Civil Engineering Departments of Nottingham, Oxford, Sheffield and Strathclyde are involved in appropriate parts of the overall programme, while Professor Ward of Leeds University has given considerable help in advice on orientation in relation to the physical performance of the geogrids. More recently the Teaching Company scheme of SERC is being invoked in association with Bradford and Strathclyde in the applicational work.

As Chairman of the SERC Steering Committee the members of which cover the main engineering interests both in the UK and North America, it appeared to me that the work had progressed sufficiently rapidly to enable a Symposium to be mounted, both as a means of reporting on the work done to date and its promise for the future, and also to provide a forum for a wider discussion and dissemination of the actual and potential applications of these important new civil engineering materials. Although there are now many installations around the world - and several of these are being described and assessed in later papers to this Symposium - the objective views and considerations of practising Civil Engineers is most warmly to be welcomed. It is for this reason that we have arranged for as much discussion from the floor as possible.

In the foregoing, the importance of determining the creep behaviour of oriented polymers has been emphasised. The problem from the viewpoint of the application of geogrids as inclusions in soils, unmade roads and pavements or embankments is that while it is necessary to study the creep behaviour of the grids in isolation, creep data in itself is only part of the whole behaviour of the grid and the matrix, since the latter has its own characteristics which interact in varying degrees and in different ways with the geogrid. Much of the work of the Group has been directed towards an understanding of these phenomena and to develop design guides to assist those who wish to employ Tensar grids. At Strathclyde, a major programme of creep testing of significant test pieces of the various grid types has been interlocked with the extensive laboratory facilities built up at Blackburn. Creep tests have been going on continuously now for several years and the whole programme, together with some specific testing at Nottingham is probably the most comprehensive test facility for oriented polymers on a practical basis to be found anywhere.

The interpretation of these data when the grid is included in a matrix, be it for an embankment, a retaining wall, an unpaved road, an asphalt layer or a cement composite, is the crux of our work and the papers presented in the Symposium will, it is confidently hoped, demonstrate that, while much remains to be done, reliable guidelines for the designer can now be proposed.

The application of new materials in situations requiring fitness for purpose for periods up to a hundred years or more presents the researcher and the practising engineer with redoubtable problems. There are no short cuts. Only continuous testing and development, feedback from the field and large scale trials and a professional team of experienced people can ensure the full economic advantages of new technology to be realised. Until there is a sufficient crowd of witness from the field, it is advisable to be cautious in proposing guidelines for load and strain limits when using geogrids. Yet it is my considered view that the thorough and wide-ranging programme of in-house and University research and development is of a quality and extent to justify its presentation at a Symposium on Tensar alone. It is a good example of what can be achieved by vigorous collaboration of industry with Universities, a Research Council and Consulting Engineers on a broad front.

The orientation of polymers to produce high performance materials

Recent research at Leeds University has shown that the physical properties of polymers can be improved dramatically by stretching processes whose principal aim is to produce a high degree of molecular orientation. In polyethylene and a few other polymers, very high degrees of stretch have led to spectacular improvements in stiffness and strength.

In polyethylene, particular attention has been given to the creep behaviour under sustained load. Guidelines have been established for the sensitivity of the creep behaviour to such variables as polymer molecular weight, degree of copolymerisation and draw ratio. With this information, it is possible to optimise the situation with regard to the possibility of ultimate failure.

I. M. Ward, *University of Leeds*

INTRODUCTION

The discovery of methods for the preparation of ultra high modulus polyethylene by tensile drawing to very high draw ratios[1] raised the possibility that such materials might be used for the reinforcement of brittle matrices such as cement[2], concrete[3] or polymeric resins[4]. This requires that the oriented polymer should be subjected to continuous loading without this leading to failure. During recent years extensive studies of the creep and recovery behaviour of oriented polyethylene[5] and polypropylene[6] have been carried out at Leeds University. The aim of the work was two fold (1) to establish criteria for creep failure (2) to identify structural factors which lead to improvement in creep performance. The results of these studies have been of direct relevance to Tensar and have provided guidelines for the development of Tensar for engineering applications.

THE PRODUCTION AND PROPERTIES OF DRAWN POLYETHYLENE

The discovery of high modulus polyethylene stemmed from the recognition that the Young's modulus of fibres and tapes produced by tensile drawing relates to the draw ratio, and increases steadily with increasing draw ratio[1]. The limitation of a natural draw ratio was replaced by the concept of effective drawing i.e. drawing at a temperature and strain rate which avoids fracture on the one hand, and "flow drawing" where the molecules relax to isotropy, on the other.

It is therefore useful to consider the properties of oriented polymers in terms of the draw ratio as a key variable, alongside other variables such as molecular weight, molecular weight distribution, and degree of branching or cross-linking. Fig. 1 shows the creep compliance (extensional strain/applied stress) for linear polyethylene (Rigidex 50 grade) of draw ratios λ = 10 and 30, each sample being measured at three levels of stress. It can be seen that there is a marked reduction in creep compliance with draw ratio. Although in all cases the creep compliance is not independent of stress level (the behaviour is non-linear) the response is more nearly linear at the highest draw ratio.

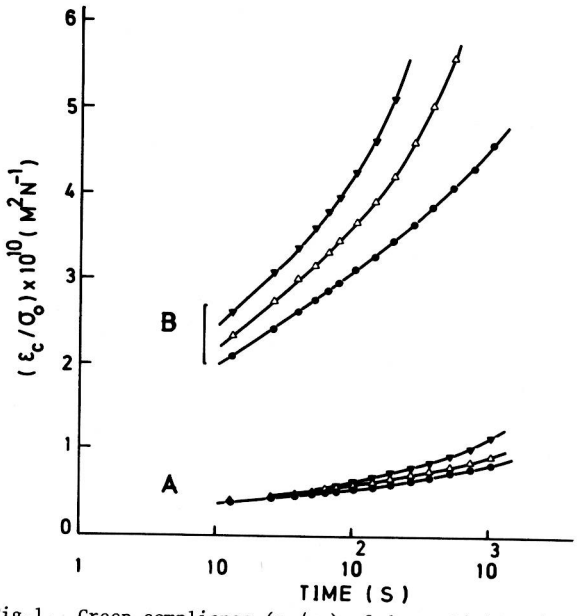

Fig.1. Creep compliance (ε_c/σ_o) of drawn Rigidex 50 samples A, λ=30 and C, λ=10 at 0.1 (●), 0.15 (Δ) and 0.2 GPa (▼) applied stress σ_o as a function of time. (Reproduced from Polymer 19, 969 (1978) by permission of the publishers, Butterworth & Co. (Publishers) Ltd. (C).

Although Fig. 1 shows the effect of draw ratio on the creep behaviour, it is not so revealing as the plots of creep rate versus total creep strain. Sherby and Dorn[6] used such plots to represent their data for the creep of isotropic polymethylmethacrylate (PMMA). This was because they adopted the approach of considering that the total creep behaviour can be represented by a thermally activated process, so that it should be possible to construct a master curve for data over a range of temperatures. Although the case of oriented polyethylene is not quite as tractable as PMMA, we have

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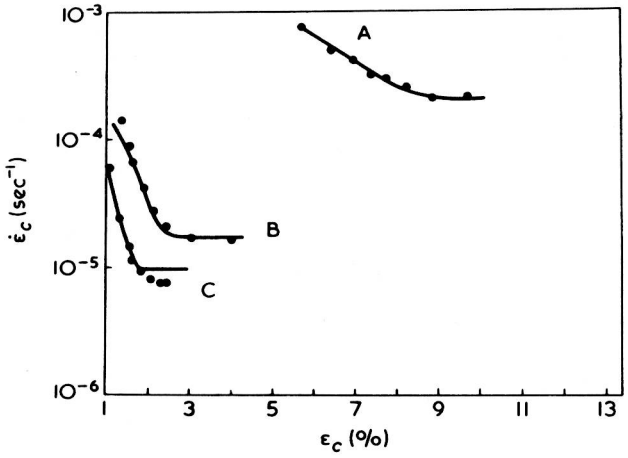

Fig.2. Creep strain rate $\dot{\varepsilon}_c$ as a function of ε_c at 0.2 GPa applied stress for drawn Rigidex 50 samples A, λ=10, B, λ=20, C, λ=30. (Reproduced from Polymer 19, 969 (1978) by permission of the publishers, Butterworth & Co. (Publishers) Ltd. (C).

used "Sherby-Dorn Plots" to describe the results to some advantage.

Fig.2 shows these plots for the same samples as those described by Fig. 1. In contrast to Sherby and Dorn's results, the creep rates fall to a constant rate which is independent of strain and it was established that there was no simplistic stress/temperature superposition rule for the plots as a whole. However, the constant creep rates (which we have termed the plateau creep rates $\dot{\varepsilon}_p$) were shown to depend on stress σ and temperature T in a manner expected for a single thermally activated process, leading to the so-called Eyring equation

$$\dot{\varepsilon}_p = \dot{\varepsilon}_o \exp - \frac{\Delta H}{kT} \sinh \frac{\sigma v}{kT} \qquad (1)$$

where ΔH, v are the activation energy and activation volume respectively, $\dot{\varepsilon}_o$ is a constant pre-exponential factor and k is Boltzmann's constant.

It was concluded that there is an initial viscoelastic region, where the creep rate falls with time (and hence creep strain) followed by a second region where the creep rate is constant, and corresponds to a permanent flow plastic deformation process which is irrecoverable and will eventually lead to failure of the sample.

This is the behaviour of the first sample of oriented polyethylene to be examined, a linear polymer of low molecular weight. It could be very well modelled by the arrangement of springs and dashpots shown in Fig.3(b), which is essentially a linear Voigt element in series with a Maxwell element which contains an Eyring dashpot. Materials of this kind would be unsuitable for load-bearing applications as there will always be an element of permanent plastic deformation, even at very low stresses, which could lead to failure, albeit at very long times.

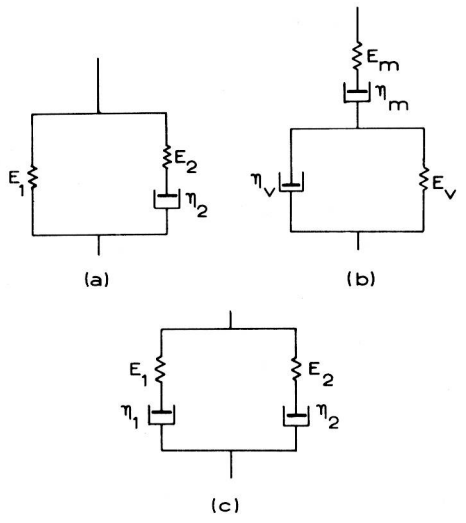

Fig.3. Schematic representation of the four element mechanical model for creep and recovery. (Reproduced from Polymer 22, 870 (1981) by permission of the publishers, Butterworth & Co. (Publishers) Ltd. (C).

It was therefore considered essential to produce oriented polyethylenes of greatly improved creep response esponse, and this has been achieved in three ways

(1) by increasing molecular weight
(2) by cross-linking the polymer
(3) by use of copolymers.

Details of samples studied are given in Table 1.

Table 1.

Polymer Grade†	Sample details $\bar{M}_n$	$\bar{M}_w$	Chemical Composition
Rigidex 50	6,180	101,450	Homopolymer
Rigidex 006-60	6,000	130,000	Homopolymer
Rigidex HO20-54P	33,000	312,000	Homopolymer
Rigidex 002-55	16,900	155,000	Ethylene/Hexene Copolymer ca 1.5 butyl/ 10^3 carbon atoms
Rigidex 50	6,180	101,450	Homopolymer γ-irradiated (2Mr) before drawing

† BP Chemicals International Ltd.

In Fig. 4, Sherby-Dorn plots for a higher molecular weight polyethylene homopolymer are compared with those for the lower molecular weight material shown in Figs. 1 and 2. It can be seen that at the lowest stress level, the Sherby-Dorn plot for the higher molecular weight polymer shows a continuously decreasing strain-rate with increasing strain. This implies that at low stress levels this material reaches an equilibrium

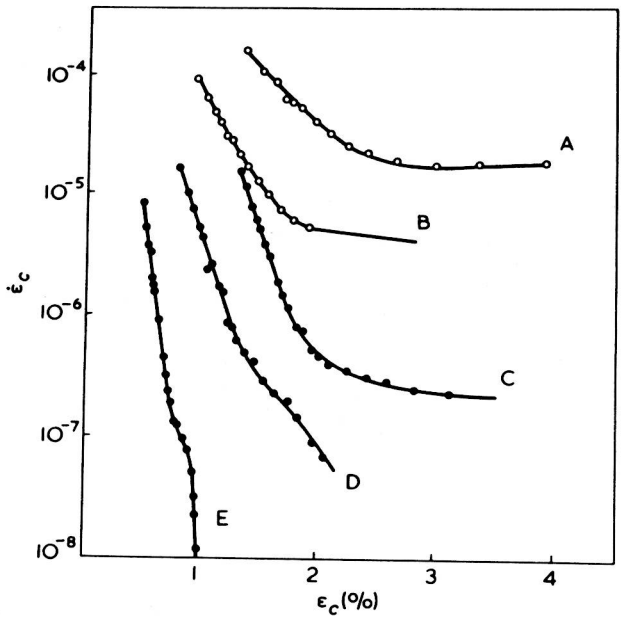

Fig. 4. Creep strain rate $\dot{\varepsilon}_c$ as a function of strain for Rigidex 50, λ=20 (o) ($\bar{M}_w \sim 100,000$) and Rigidex HO20, λ=20 (●) ($\bar{M}_w \sim 300,000$) A, 0.2; B, 0.15; C, 0.2; D, 0.15, E, 0.1 GPa. (Reproduced from Polymer 19, 969 (1978) by permission of the publishers, Butterworth & Co. (Publishers) Ltd. (C)).

strain, as shown in Fig. 5, so that failure does not occur. In practical terms, this means that there is a

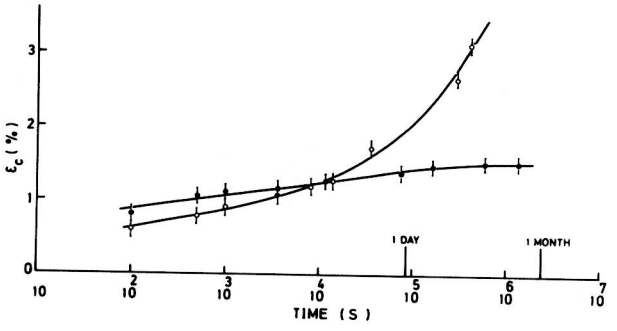

Fig.5. A comparison of the long term creep response of Rigidex 50, λ=20 (o) and Rigidex HO20, λ=20 (●) at 0.1 GPa applied stress (——) are visual fits and the error bars correspond to the accuracy of the measurements. (Reproduced from Polymer 19, 969 (1978) by permission of the publishers, Butterworth & Co.(Publishers) Ltd. (C).

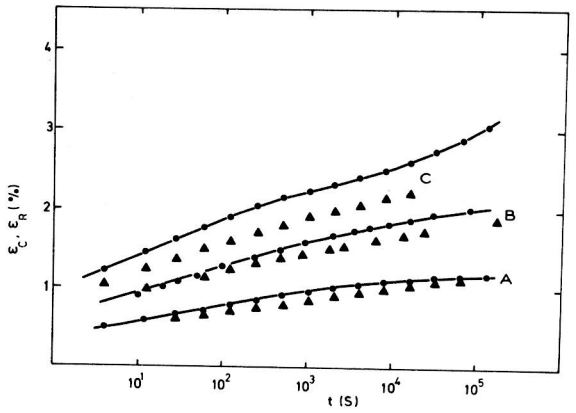

Fig. 6. Creep ε_c and recovery ε_R curves for Rigidex 002-55 copolymer, λ=20 ($\bar{M}_w$ = 155,000, ca 1.5 butyl branches per 10^3 carbon atoms) (●) creep (▲) recovery. A, 0.1 GPa, B, 0.15 GPa, C, 0.2 GPa. (Reproduced from Polymer 22, 870 (1981) by permission of the publisher, Butterworth & Co. (Publishers) Ltd. (C)).

safe critical stress level for long term loading. In Fig. 6, similar results are shown for a copolymer, and it can be seen that the presence of a very small number of side branches ($\sim$ 1 per 1,000 carbon atoms) is extremely effective in altering the creep behaviour.

The concept of a critical stress for permanent flow creep, although valuable for engineering design is somewhat obscure in terms of polymer physics. It is therefore necessary to pursue the analysis of the data further to bring the behaviour within the general scheme of our present understanding of deformation processes in polymers.

It has been proposed that a more appropriate first-order representation for the viscoelastic behaviour of these materials is by two Maxwell elements in parallel, the two dashpots each corresponding to thermally activated processes, (Figure 3(c)). The equilibrium creep behaviour is then described by the situation where the two springs have reached their equilibrium extension and the total creep rate is constant, with the stress divided across the two dashpots. If the two thermally activated dashpots are very different in kind, one having a large activation volume v_1 and the other a small activation volume v_2, we have

$$\frac{\sigma}{T} = \frac{k}{v_1}\frac{\Delta H_1}{kT} + \ell n \frac{2\dot{\varepsilon}_p}{\left[\dot{\varepsilon}_o\right]_1} + \frac{k}{v_2}\sinh^{-1}\frac{\dot{\varepsilon}_p}{\left[\dot{\varepsilon}_o\right]}\exp\frac{\Delta H_2}{kT} \qquad (2)$$

where the two activated processes are denoted by the subscript symbols 1 and 2 respectively. σ is the applied tensile stress at a temperature T^oK, $\dot{\varepsilon}_p$ the creep rate, $[\dot{\varepsilon}_o]$ the pre-exponential factor, ΔH the activation energy and k is Boltzmann's constant.

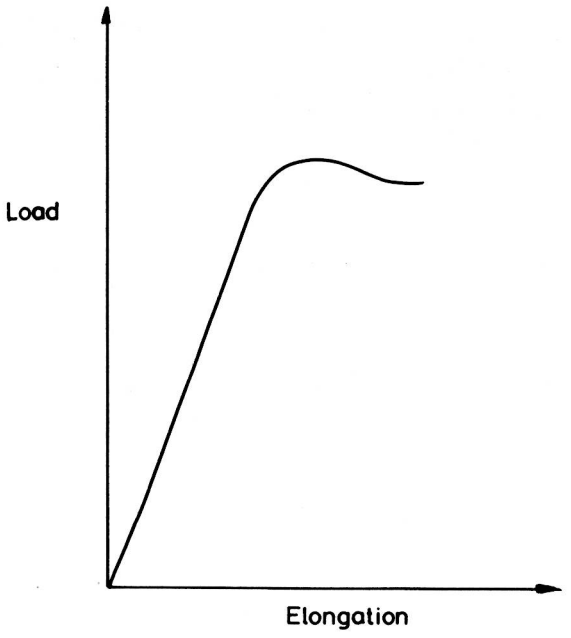

Fig. 7. The yield point in a constant strain rate test.

This representation is familiar to polymer scientists in respect of the yield behaviour of isotropic polymers[7,8]. In general, a yield point is observed in a constant strain rate test (Figure 7). The point of maximum load represents the point at which the plastic flow rate $\dot{\varepsilon}_p$ matches the imposed strain rate of the testing machine. The relationship between the maximum stress (the yield or flow stress) and the imposed strain rate can generally be represented by equation (2), as shown in Fig. 8(a). In Fig. 8(b) an exactly equivalent plot is presented which is the more useful form for considering creep data. Here the creep rate (exactly equivalent to the strain rate) is plotted on the ordinate and stress level is plotted on the abscissa.

At low stress levels, the viscosity of the dashpot η_1 in Fig. 3(c) is much larger than that of the dashpot η_2. Hence η_1 can be regarded as infinite and model 3(c) reduces to model 3(a), the Eyring formulation of a standard linear solid[9]. The apparent critical stress can now also be explained in a more satisfactory fashion. Because of limitations imposed by the creep test itself, it is not practicable to measure strain rates below $\sim 10^{-9} s^{-1}$. There is hence a practical cut-off at very low strain rates, where the plateau creep rates are very small, and plateau creep behaviour would only be observed at very long times ($\sim$ several years). The apparent critical stress corresponding to these very low strain rates has been indicated schematically in Fig. 8(b). At these low stress levels we would also expect to find almost total recovery in terms of the modelling proposed here, and this expectation has been borne out by experiment[5].

RELATIONSHIP OF CREEP BEHAVIOUR TO STRUCTURE

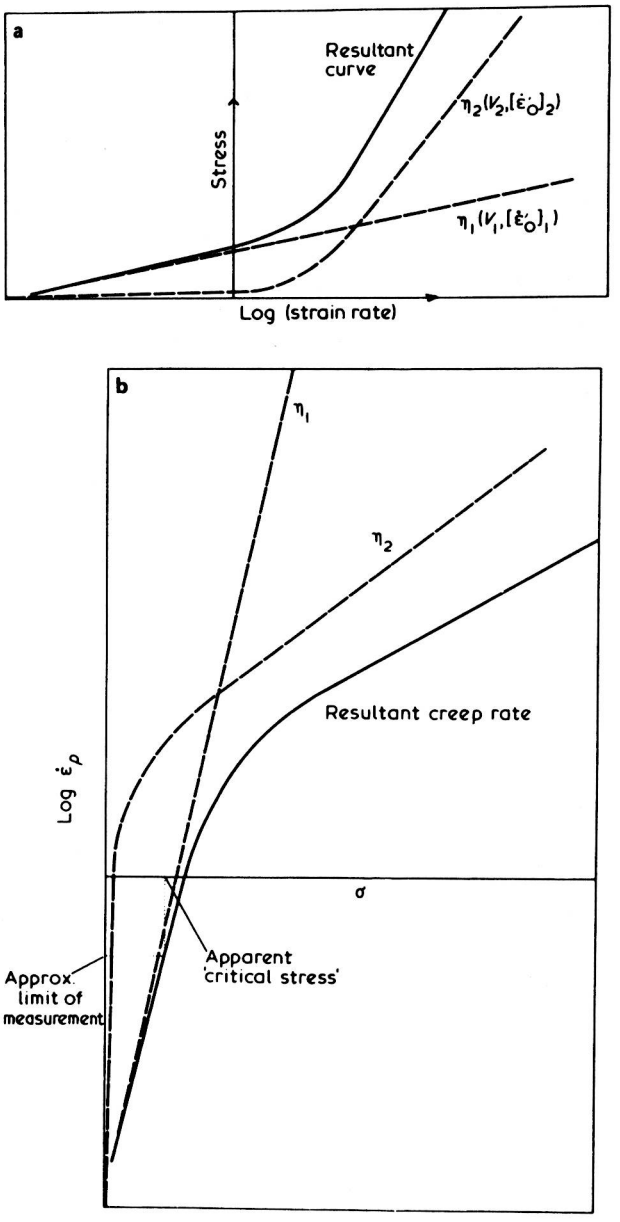

Fig. 8. Schematic representation of plastic flow for the 2-process model; (a) yield stress vs applied strain rate; (b) creep strain rate $\dot{\varepsilon}_p$ vs applied stress. (Reproduced from Polymer 22, 870 (1981) by permission of the publishers, Butterworth & Co. (Publishers) Ltd. (C)).

RELATIONSHIP OF CREEP BEHAVIOUR TO STRUCTURE

At high stress levels, equation (2) gives the relationship between the plateau creep rate and stress in terms of an apparent single activated process as

$$\frac{\sigma}{T} = \frac{k}{v_{eff}} \left[\frac{\Delta H_{eff}}{kT} + \ln \frac{2\dot{\varepsilon}_p}{\left[\dot{\varepsilon}_o\right]_{eff}} \right] \qquad (3)$$

where v_{eff} and ΔH_{eff} are the effective activation volume and activation energy respectively.

Because the term σv_{eff} is small, small variations in v_{eff} with temperature can be neglected and plateau creep rates determined at a constant stress level can be described by the equation

$$(\log \dot{\varepsilon}_p)_\sigma = \log \left[\dot{\varepsilon}_o\right]_{eff/2} - \frac{\Delta G_{eff}}{2.3kT} \qquad (4)$$

where ΔG_{eff} is an activation free energy.

Results for two samples (Rigidex 50, λ=20 and Rigidex HO20, λ=20) are shown in Fig. 9. There is a good linear relationship between log $\dot{\varepsilon}_p$ and 1/T, giving a value for ΔG_{eff} of 28 kcals/mole. Assuming a constant activation volume v_{eff} of 100Å^3 gives a value of 30 kcals/mole for ΔH_{eff}. This is in the range quoted for the α-relaxation in polyethylene by previous workers on the basis of dynamic mechanical experiments[10-12]. Now

$$\Delta H_{eff} = \frac{v_2 \Delta H_1}{v_1 + v_2} + \frac{v_1 \Delta H_2}{v_1 + v_2} \qquad (5)$$

so that ΔH_{eff} is primarily determined by ΔH_2 (unless ΔH_1 is very much larger than ΔH_2). It is therefore reasonable to conclude that the smaller activation volume process relates to the α-relaxation process.

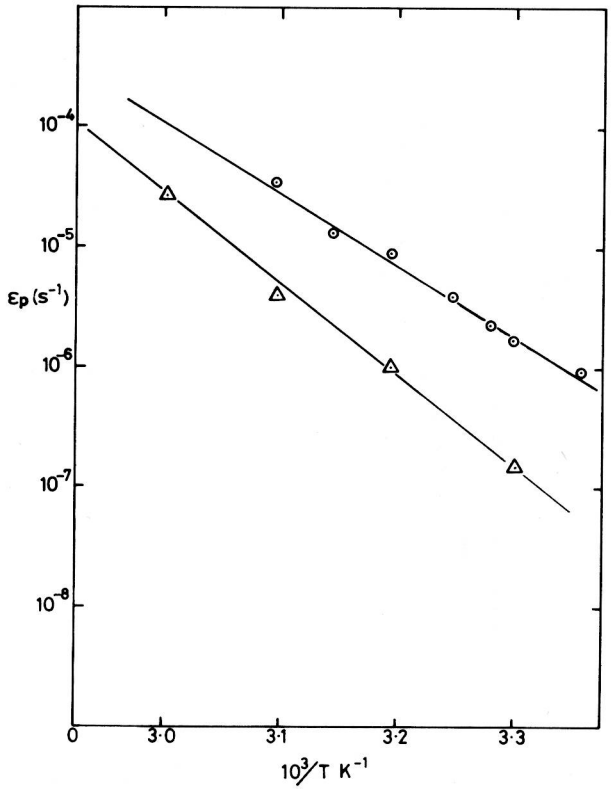

Fig.9. Temperature dependence of plateau creep rates $\dot{\varepsilon}_p$ for two samples Δ Rigidex 50, λ=20, stress level 0.1 GPa; Θ Rigidex HO20, λ=20, stress level 0.25 GPa. (Reproduced from J.Polym.Sci., Polym. Phys. Edn., (in press).

To examine the changes in behaviour which occur on changing the structure of the oriented polymer, plateau creep data at 20°C for a number of different samples were fitted to the constant temperature form of equation (2)

$$\frac{\sigma}{T} = \frac{k}{v_1} \ln \dot{\varepsilon}_p - \ln \left[\frac{\dot{\varepsilon}_o'}{2}\right]_1 + \frac{k}{v_2} \sinh^{-1} \frac{\dot{\varepsilon}_p}{\left[\dot{\varepsilon}_o'\right]_2} \qquad (6)$$

where $\left[\dot{\varepsilon}_o'\right]_1$ and $\left[\dot{\varepsilon}_o'\right]_2$ include the temperature dependence exp ΔH/kT term.

It was shown that the data could be equally well fitted to either a variable value for v_1 or a constant average value for v_1 and that the latter constant affected the values obtained v_2 to a very small extent only[13]. The results of these fitting procedures for a fixed value of v_1 are shown in Table 2, and some of data

TABLE 2

Activation parameters for the 2-process model

Sample	v_1 fixed (Temperature 20°C)			
	v_1 (Å^3)	$\left[\dot{\varepsilon}_o'\right]_1$ (sec^{-1})	v_2 (Å^3)	$\left[\dot{\varepsilon}_o'\right]_2$ (sec^{-1})
Rigidex 50, λ=20	456	2.2×10^{-8}	78	1.0×10^{-6}
006-60, λ=10	456	2.1×10^{-9}	720	2.6×10^{-11}
006-60, λ=20	456	1.7×10^{-14}	126	7.8×10^{-7}
006-60, λ=30	456	2.1×10^{-16}	78	6.6×10^{-7}
HO20-54P, λ=10	456	5×10^{-14}	98	1.3×10^{-6}
HO20-54P, λ=20	456	8.4×10^{-18}	95	1.6×10^{-7}
γ-irradiated Rigidex 50, λ=20	456	1.1×10^{-16}	103	1.2×10^{-6}
002-55, λ=20	456	1.6×10^{-18}	88	4.7×10^{-7}

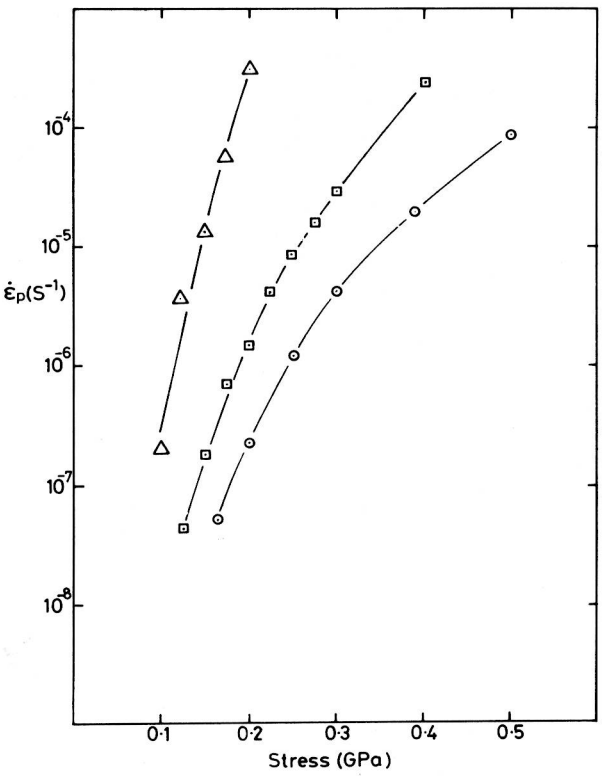

Fig. 10. Effect of draw ratio on plateau creep behaviour at 20°C for 006-60 samples
Δ λ=10, □ λ=20, ○ λ=30
(Reproduced from J.Polym. Sci., Polym. Phys. Edn., (in press).

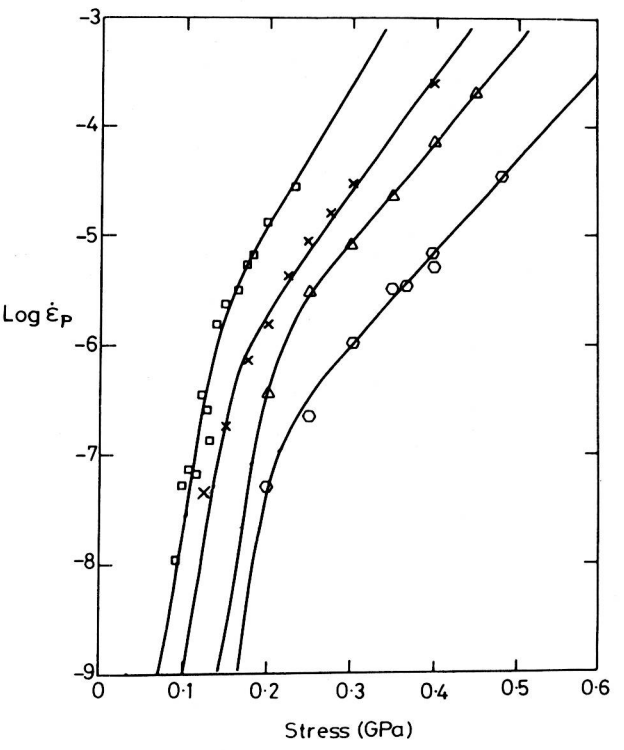

Fig. 11. Fitted curves to plateau creep data on the basis of the two process model, assuming that process 1 has an activation volume of 456Å^3
□ Rigidex 50, λ=20, x 006-60, λ=20,
Δ γ-irradiated Rigidex 50, λ=20,
H020, λ=20
(Reproduced from J. Polym. Sci., Polym. Phys. Edn., (in press).

(there is considerable overlap between results for several samples) in Figs. 10 and 11.

The differences between different materials are primarily reflected in the relative contribution of process 1, the large activation volume process. We note from Table 2 that the pre-exponential factor $[\varepsilon_o']_1$ falls substantially with increasing draw ratio and there are large differences between samples of different chemical composition. In particular both γ-irradiated low molecular weight Rigidex 50 and the 002-55 copolymer behave like the high molecular weight H020-55P. The activation volume of ∿ 500 Å^3 for process 1 is consistent with that for an oriented non-crystalline polymer, and it has been suggested that this process is associated with the non-crystalline regions[5]. It is then attractive to speculate that γ-irradiation of low molecular weight polymer produces a comparable molecular network by incorporating chemical cross-links to that obtained in high molecular weight polymer due to physical entanglements. It is surprising that introducing a small proportion of branch points as in the 002-55 copolymer has the same effect. However, these results are consistent with observations of the tensile drawing of these materials. Increasing molecular weight, γ-irradiation prior to drawing and the introduction of side branches have all been shown to give rise to increased strain hardening[14-16].

With regard to the practical consequences of this work, it can be seen from Figs. 10 and 11 and Table 2 that although there is also merit in increasing the draw ratio, either increasing the molecular weight or γ-irradiation prior to drawing or introducing side branches, are equally effective in increasing the critical stress below which plateau creep cannot be observed within a sensible experimental time-scale. In the case of Tensar, a copolymer with a somewhat larger branch content than the Rigidex 002-55 grade was selected, to ensure a maximum critical stress compatible with achieving a good degree of molecular orientation by drawing.

CONCLUSIONS

The steady state creep behaviour of oriented polyethylene can be satisfactorily represented by two thermally activated processes acting in parallel. One process has a comparatively small activation volume and is primarily affected by the draw ratio, decreasing with increasing draw ratio. Its activation energy is close to that for the α-relaxation process, consistent with its identification with a deformation process in the crystalline regions of the polymer.

The second process has a comparatively high activation volume which is not significantly affected by changes in structure or chemical composition. The contribution of this process is markedly affected by the molecular weight of the polymer, by γ-irradiation prior to drawing and by branch content. It has been tentatively associated with the molecular network.

A result of practical importance is that for each drawn polymer, a critical stress can be defined, below which permanent flow is negligible and on unloading, recovery is virtually complete. This concept has been used to select a suitable polymer for Tensar and can also be applied to practical performance of Tensar grids, as described in a subsequent contribution to this symposium.

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The load-strain-time behaviour of Tensar geogrids

A. McGown, K. Z. Andrawes and K. C. Yeo, *University of Strathclyde,* and D. DuBois, *Netlon Ltd*

TENSAR geogrids are a new generation of soil reinforcing materials manufactured by heat stretching a perforated sheet of co-polymer to form a grid-like structure. In order to use them to their maximum efficiency it is necessary to establish the loads which they may carry for any period up to 120 years, the design lifetime of many civil engineering structures. In this paper the basic definitions that should be used to describe the geometry of the grids are given and then employed to identify the representative sizes and shapes of test specimens. Test methods which have been developed for quality control purposes and for performance data acquisition are detailed. Following this the method of analysing and presenting test data are given together with typical data for both uniaxial and biaxial grids.

INTRODUCTION

Soils have little or no tensile resistance; therefore inclusion of tension-resistant materials within the soils is an effective means of reinforcing them. To optimise the efficiency of these inclusions, they should be placed in the zones of largest tensile strains and in the directions of principal tensile strains. The mechanism of stress transfer from the soil to the inclusion depends primarily on the geometrical properties of the inclusions. For rods, strips and sheets, the stress transfer mechanism is one of surface friction; but for grids, nets and meshes, it depends upon the more efficient interlock principle. When stressed, the inclusions must of course be capable of sustaining the load without rupture and without generating unacceptably large deformations during the design lifetime of the structure. Thus the two properties of tension resistant soil inclusions which must be established in order to allow the design of reinforced soil structures are their surface friction or interlock properties and their load-strain-time behaviour over the lifetime of the structure.

Tensar geogrids are molecularly oriented polymeric grid structures specifically developed for use as tension-resistant inclusions in soils. Jewell et al (1984) deal with the measurement of the interlock that develops between Tensar geogrids and various soil types. In this paper the methods of measuring and presenting the load-strain-time behaviour of the geogrids are detailed and their applicability to civil engineering specifications and designs is fully identified.

MATERIALS TESTED

In order to develop and prove the methods of testing and the analysis of test data for geogrids, control batches of two geogrids, Tensar SR2 and SS2, were used throughout. Tensar SR2 is a uniaxial geogrid manufactured from co-polymer grade high density polyethylene (H.D.P.E.). Tensar SS2 is a biaxial geogrid manufactured from homo-polymer polypropylene. Prior to the production of both these grids, 2.5% of carbon black was added to provide ultra-violet protection.

The terminology used to describe the sizes and shapes of Tensar SR2 and SS2 is as shown in Fig. 1 and the mean dimensions of the materials in the control batches are given in Table 1, together with the mass per unit area of each product.

CLAMPING ARRANGEMENTS AND TEST SPECIMEN SIZES

In order to determine the load-strain-time relationship properties of the geogrids, specialised end clamps were developed, as shown in Fig. 2. The top and bottom bars of uniaxial grid test specimens are held directly by these clamps but the cross ribs of biaxial grid test specimens are cast into the clamps using a low melt point alloy "Ostalloy 158", manufactured by Fry's Metal Limited, Glasgow. The composition and properties of the alloy are given in Table 2.

By a programme of constant rate of strain testing at 2% strain per minute, 20°±2°C, and 65%±2% relative humidity, the minimum sizes of test specimens at which the measured load-strain properties of the grids are independent of sample size were established to be as shown in Table 3. These test specimen sizes are used in all subsequent testing.

CONSTANT RATE OF STRAIN TESTING

A constant rate of strain of 2% per minute and standard test conditions of 20°±2°C and 65%±2% relative humidity were used to establish reference load-strain properties for the geogrids. These properties are termed the "Index Properties". The effect of humidity on the properties of Tensar geogrids is negligible, but as with all polymeric materials, their load-strain properties vary with strain rates and temperature.

Polymer grid reinforcement. Thomas Telford Limited, London, 1985