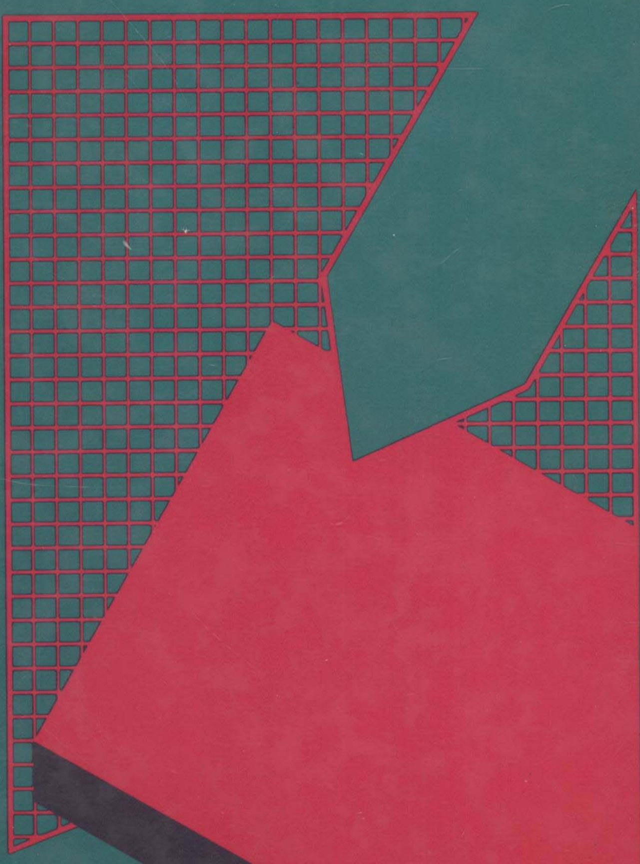
MECHANICAL TESTING OF PLASTICS

Second edition

S. Turner



George Godwin in association with The Plastics and Rubber Institute

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Preface

During the years that have elapsed since the publication of the first edition there have been significant developments and changes of emphasis in the mechanical testing of plastics. For example, fracture toughness is increasingly evaluated by fracture mechanics techniques rather than by the arbitrary 'brittleness' tests of earlier years and much more attention is devoted to the ramifications of anisotropy than hitherto. Coincidentally with such elaborations in the evaluation procedures, the ever-growing complexity of plastics materials and their applications has also contributed to an escalating demand for testing and evaluation, just at a time when commercial pressures have dictated a reduction in them. Much of the original text has been rewritten and new material has been added to reflect the various changes in techniques and attitudes. As before, I am indebted to many of those who were my colleagues in the Plastics and Petrochemicals Division of Imperial Chemical Industries, PLC, for their knowledge and opinions. Finally, I am grateful to the Literary Executor of the late Sir Ronald A. Fisher FRS, to Dr Frank Yates FRS and to Longman Group Ltd, London for permission to reprint part of Tables III, IV and V from their book *Statistical Tables for Biological, Agricultural and Medical Research* (6th Edition, 1974).

Contents

Chapter 1

The mechanical testing of plastics. A preamble

1.1 The growth of materials testing

Mechanical tests on materials are used for several radically different purposes, namely:

As a criterion in quality control
As a basis for comparison and selection of materials
As data for design calculations
As a basis for predictions of service performance
As an indicator in materials development programmes
As a starting point for the formulation of theories in materials science.

These various objectives, which separately demand different qualities of the test methods, have arisen and developed primarily in response to economic pressure, though it is almost certain that the very earliest testing was concerned with the basic issue of survival. One can envisage, for instance, the process of flint selection, the thumb test on the newly cleaved edge and the exacting consumer trials that must have occupied the attention of primitive man. The assessment skills which developed in those early days and assisted the survival of Man as a species, later became incorporated into the crafts that were practised in the earliest days of recorded history. Over a very long period knowledge of materials behaviour was gained merely through actual use, but this was not adequate for dynamic societies with expanding requirements for materials and systematic testing became an economic necessity. Bernal[1] pointed out that the growth of the Roman empire involved an enormous investment in international roads, aqueducts, seaports, etc which engendered a strong sense of caution against the use of faulty materials, and the concept of prior testing to provide some knowledge of materials before they were committed to use. He cited Vitruvius, an architect, who recommended that the Roman engineers should expose their proposed building stone to local conditions for two years to determine its suitability. Thus, whereas the testing of flint tools and weapons during the Stone Age had the simple purpose of quality control in the context of short-term serviceability, the exposure trials on building materials by Roman engineers embraced the concept of long-term durability and recognized the need for assessment of the possibly detrimental effect of exposure to particular environments.

In succeeding periods, the motivations for testing became progressively more complicated as science, technology and commerce developed under the competing and changing influences of economic, religious and social conditions. The changes due to such factors were inevitably slow in the days of poor communications but there were nevertheless many relatively sudden changes due to major developments in abstruse subjects such as mathematics. For example, the introduction of decimal notation, of logarithms, of the differential calculus and of other mathematical techniques provided both direct assistance through the easing of calculations, and indirect stimulus by opening up new possibilities for development during the sixteenth and seventeenth centuries, the period during which the technical use of materials first became a major preoccupation. The Industrial Revolution which followed demanded a yet more rapid utilization of raw materials and a corresponding new level of knowledge of their nature and their behaviour, so that by the middle of the nineteenth century the testing of materials had acquired an aura of prestige and a reputation that implied decisive trial, critical examination and thorough characterization. This reputation rested on the scientific and technological skills on which the testing method relied and supported the commercial interests in 'product quality' and 'fitness for purpose' which ultimately entailed the standardization of the tests on a national and an international basis.

The British Standards Institution was founded at the turn of the nineteenth century in order to bring some organization into engineering production, and its first achievement was the rationalization of structural steel sections. Since then 'standard' test methods have proliferated at all levels (international, national, company, laboratory) to a degree that may sometimes be regarded as wasteful but in general to good purpose since adequate testing is one of the foundations to the correct use of materials in a socially acceptable context. They now exert an important influence on both the layman, who tends to view them with favour as guardians of his standards of living, and the scientist, who sees them as a basic framework against which his own special experimental techniques may be devised.

1.2 The growth of plastics testing

In its relatively brief history of roughly half a century, the mechanical testing of plastics has developed from a system based on the simplest of concepts to one of high sophistication, interwoven with hundreds of standard tests, seemingly reproducing within that short period an evolutionary path not very different from that which had taken several millenia to pass from the flint test to the technological respectability of the twentieth century.

The analogy is fanciful of course, and, even more than most, it would be misleading if pursued too far, but the early testing of plastics seems, in retrospect, to have been relatively crude and out of keeping with the general level of the skills in contemporary science and technology. This was almost certainly because the new plastics materials exhibited properties that were radically different from those commonly encountered hitherto so that there was neither practical experience nor convenient theory to provide guidance. The pressing need for data on properties was superficially satisfied by the adoption of some of the test methods then used for metals or rubbers. The data so produced were often misleading, however, because of interactions between the test and the relaxation processes inherent in the long-chain polymeric nature of plastics. Such relaxation processes are virtually absent in metals and so rapid in rubbers that interactions are seldom troublesome, and therefore test methods that are satisfactory for these classes of material are not necessarily so for plastics. The use of inappropriate tests had a restrictive effect extending far beyond misleading data, however. It initiated and sustained a looseness of nomenclature and a confusion of principles that persisted until the emergence of new, soundly-based methods for measuring phenomena such as stress-relaxation, creep, crack growth and toughness.

These sounder tests were developed in response to the technical demands placed on the burgeoning plastics industry and were in harmony with the simultaneously improving theories of polymer physics and applied mechanics, but their evolution from crude origins did not necessarily follow the most direct or the most logical paths, nor was there always close correspondence between the course of events in different countries. Creep testing provides a pertinent example. In the USA, Findley (see Ch. 5) developed a highly accurate machine with which he studied the creep behaviour of a wide range of materials long before such data were in demand. In England, comparable work, with which the author was directly associated, arose almost by chance. The starting point was an investigation into certain discrepancies and irregularities that confounded measurement of the modulus of polyethylenes for quality control purposes. A satisfactory solution emerged through the construction and use of an elementary device for measuring creep stain, but the early results bore intimations of such a wealth of pertinent information on viscoelasticity and practical mechanical performance that the original design was extended and refined in order that the creep behaviour of any plastic could be measured accurately. The data which emerged revealed a degree of complexity in the behaviour that had been unsuspected hitherto, and the results proved to be very relevant to the characterization of plastics materials and the prediction of service performance. However, considerable subsidiary effort was required before these virtues could be exploited: efficient methods of data presentation had to be evolved, abbreviated evaluation procedures had to be developed to limit the cost, and the validity of various design procedures had to be assessed. What started as a straightforward problem in quality control evolved, within a very few years, into a full-scale creep laboratory undertaking comprehensive evaluation programmes and serious studies of non-viscoelasticity. The subsequent course of events in the USA was unaffected by the developments in England; the total numbers of creep test sites remained small and the main activity was directly towards the establishment of superposition theories for the prediction of the strain response to combined stresses and complex stress histories. In Europe, on the other hand, particularly in Germany, hundreds of creep test sites were installed to produce data for design calculations, comparable in function and effectiveness to the facilities established for metals several years earlier.

There was a marked contrast between the methodical, disciplined test procedures that prevailed in the creep laboratories and those that apparently sufficed for the evaluation of many of the other properties. Creep testing is of relevance to five of the six objectives listed in the first paragraph of this monograph and hence one might expect it to be more elaborate, more comprehensive and better conducted than testing of a more limited relevance. However, by that argument one would expect the assessment of impact resistance, for instance, to be correspondingly reputable and systematic, which is not the case. The explanation of the difference may simply be that creep and the various other manifestations of 'stiffness' are relatively simple phenomena, well supported by viscoelasticity theory, whereas impact resistance and other aspects of strength and toughness are not simple concepts because failure phenomena generally involve a combination of pseudo-plasticity and crack growth. With no single theory to provide a formal framework for ideas and experiments impact testing developed by *ad hoc* steps rather as the subjective skills of the craftsmen did many centuries ago. In a book dedicated to 'Bill', Scott–Blair[2] has described the process by which the skills of some of the traditional crafts based on naturally occurring organic substances were adopted, in more quantitative form, within the early technology of plastics. Bill's art was interpreted in terms of simple classical elements, which was in harmony with the mathematical modelling that was then in vogue for the so-called 'non-ideal' materials such as thermoplastics. The simple modelling was a better approximation to reality in relation to stiffness phenomena than it was in relation to strength and toughness. Thus the former group of tests flourished whereas the latter remained mainly as arbitrarily prescribed procedures of no general validity.

Arbitrariness in test methods is not peculiar to the plastics industry, however, and it is not necessarily a straightforward consequence of any complexity of the physical behaviour. The transition from an era of craftsmanship to one of technology was coincidental with, and possibly even due to, a growing commercial awareness. In such a climate, realistic appraisals of costs and profits sometimes led to constraints on testing and resort to simple arbitrary tests in place of more comprehensive and physically meaningful ones on the grounds of economy. This is only seriously detrimental when the arbitrariness imposes constraints on further progress but the latter can be avoided if the tests are viewed as a single entity in which each plays a defined part.

1.3 The rationalization of test methods for plastics

Although the various categories into which mechanical tests on plastics can be placed are clearly separable, they are nevertheless mutually interdependent, and common features in the associated experimental methods can be identified. The fundamental studies may be criticized on the grounds that they rarely bear more than a tenuous relationship to the requirements of the user of plastics, whilst the evaluation methods may be criticized generally for being oversimplified and for merely providing *ad hoc* answers. The difference between these two extreme cases is one of underlying philosophy as well as one of technique, but it is obvious that each group of tests could benefit from the other and that advantages might accrue from some coordination and unification.

The dichotomy cannot be resolved easily, however; at one extreme, the scientifically sound methods developed for the fundamental studies are too elaborate and expensive to be adaptable to quality control purposes, and at the other extreme the arbitrary, standard tests are often too specialized to provide sound data of wide generality. In addition, some of the standard tests are poor. It was almost inevitable that such deficiencies would arise because the first tests were developed in haste, before the properties of the new materials had been measured or studied, and the later ones were formulated under the influence of a commercial philosophy that demanded a technical compromise and imposed the role of quality control rather than scientific assessment. There is nothing disreputable in such restrictions, of course; adequate quality control is an essential part of production processes, and if there is any fault it lies with any experimenters who misappropriate the available test methods, rather than with those who established the tests originally. However, the number of standard test methods is so large, and their application within national and international commerce is so long established, that their status should be questioned, and revised as necessary, from time to time in the interest of both efficiency and conciseness.

It is not the purpose of this monograph to review and assess these established tests, or to condemn them. Any overall condemnation would be unfair because even a test that gives biased or inappropriate results may nevertheless be informative and several such tests used in conjunction may provide an assessment that is adequate for most purposes. It can be assumed that each standard test fulfils some useful function, that improvements will be introduced gradually where gross deficiencies are manifest and that, on balance, even a bad standard is better than no standard at all. However, whatever the merit of the test, the results generated by it may be misused, and the best safeguard against this is a proper understanding of its significance within the overall framework of polymer physics and an appreciation of what purpose the test was intended to serve. With such proper understanding, there should be no chance of gross misuse of test results such as that deplored by Horsley[3] and others where standard single-point test data, intended originally for quality control and of no wider applicability, were used for design calculations and other predictions of performance.

In the field of mechanical testing, the dichotomy is at least partly resolvable, simply because there are certain principles underlying experimental technique whose validity remains unquestionable whatever the practical situation, and there are certain attitudes that might be said to represent the art of testing, as distinct from the science. It is possible, for instance, to design the fundamental experiments in such a way that selected small parts of the procedure can be used in isolation, to give data that are comparable to the present standard data in general simplicity but without the disadvantage of arbitrariness. There is more to be gained from this unifying procedure than the mere rationalization of standard tests in terms of fundamental physical quantities; it provides also the means for the definition and evaluation of the physical properties that are important for design calculations, and for the rational use of materials. In this way formal interrelationships can be established between the six motivations listed at the beginning of this monograph.

The starting point for any rationalization and unification of the mechanical tests for plastics is the viscoelastic nature of that class of material, which is defined in Chapter 2 and which in practice usually involves observation of either the strain response to an applied stress or its inverse, the stress response to an applied strain. Virtually all the mechanical properties are known to depend on these response functions, which are interrelated and hence interchangeable in principle even though not readily so in practice. Since the various mechanical phenomena are related to these linked functions and hence to one another, the tests can be represented schematically as an annular cluster about a mathematical core with a major grouping into those with connotations of 'stiffness'†, e.g. creep, stress relaxation, heat distortion temperature, and those with connotations of 'strength', e.g. impact resistance, yield stress, fracture toughness, where both terms are used in a rather general sense. Figure 1.1 is one such diagram which, for simplicity, only includes the most important phenomena. Within each major class, subdivisions according to general nature, e.g. 'long-term' and 'short-term', and

† There are possibilities here for confusion. 'Stiffness' is a property of a structure, i.e. the modulus of a *material* is transformed into the stiffness of a *beam*, a *plate*, etc. 'Stiffness' is often used colloquially where 'modulus' would be the correct word and more precisely in 'stiffness coefficients', the constants in the theory of anisotropic elasticity. It is used loosely here because no one word embraces the various phenomena.

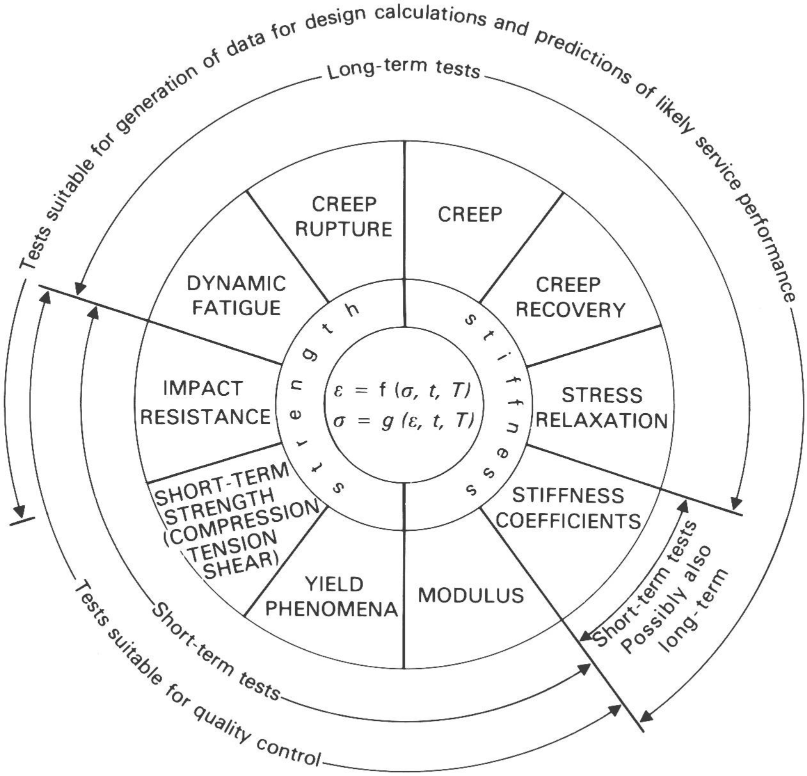

Fig. 1.1 Mechanical properties of plastics – a linked system of tests.

according to function, e.g. quality control, design data and prediction, can be effected. In some respects the description 'short-term' can be associated with quality control and 'long-term' with service performance, but the distinctions are not entirely clear-cut, if only because there are inevitable overlaps between the constituents, for instance between modulus and stress relaxation. There are also less obvious links between the listed items that allow useful inferences about the likely behaviour in one test to be drawn from behaviour observed in another. This facility of mutual support is the second stage of the integrating process, mentioned above, through which the effectiveness of plastics testing might be increased.

The very simplest evaluation schedule for a plastic must involve two tests, one associated with stiffness and one associated with strength, because the molecular and structural features of the material that confer high modulus and creep resistance are simultaneously detrimental to toughness. If the two datum points are taken as coordinates, the mechanical properties can be represented in a very rudimentary fashion as a point on a grid and the position of this point is a rough measure of the mechanical attributes of the material