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Dr. J. Curiskis and Dr. T.S. Hickie

School of Textile Technology
University of New South Wales

# PHYSICAL PROPERTIES AND TESTING OF STRUCTURAL COATED FABRICS

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# PHYSICAL PROPERTIES AND TESTING OF STRUCTURAL COATED FABRICS

J.I. Curiskis & T.S. Hickie
School of Textile Technology,
The University of New South Wales

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ABSTRACT: Ideal characteristics of structural membranes are described and these are best satisfied by coated fabrics. Membrane properties are optimised by the choice of fibre type, yarn and fabric construction, coating material and coating technology. A review is given of the various physical, mechanical, environmental and endurance properties of coated fabrics, of their importance in practical applications, and of test methods for these properties - particular attention is focussed on mechanical properties and some recent work conducted in our laboratories is reported. Although the performance of structural coated fabrics can be predicted in the laboratory in many ways, such tests do not completely simulate the more complex behaviour that occurs in actual use.

## INTRODUCTION

Growth in the use of structural coated fabrics in lightweight industrial, architectural and engineering applications overseas during the last 25 years is certainly encouraging to note for the future of the Australian market. The range of applications include the tension-membrane and airhouse structures discussed by other authors at this convention and also encompass water-filled and self-sustaining structures (10) and other industrial applications such as bulk container bags, reservoir covers, truck tarpaulins (21), grain bunker covers, etc. Development, however, has not been without setbacks so that the market growth has not met earlier expectations, especially as regards airhouse structures (4). This may be attributed to a variety of reasons but appears, in the main, to be due to the lack of an adequate understanding of the various properties of these materials. This has resulted in some applications/constructions which have not been geared to the material properties or have led to exaggerated expectations on the part of the user. A negative image, therefore, has often resulted. Extensive material testing over recent years and in the future should help to remedy this situation.

This paper seeks to establish an inventory of physical properties and test methods for structural coated fabrics and to indicate their importance for practical applications. Limitations of space and time do not, however, permit a full review of these matters so that the interested reader is directed to other sources (1,8,13,21,27) for further details. Since the mechanical behaviour of structural coated fabrics is of primary importance in the utilisation of these materials in many applications, attention will mainly be focussed on these properties and their endurance.

## AVAILABLE MEMBRANE MATERIALS

In general, structural membranes should be low-cost, lightweight, flexible, durable materials with the ideal characteristics listed in Table I. The list presented contains several incompatabilities so that it is not possible, at present, to simultaneously satisfy all the requirements in a single homogeneous material. As is often the case in materials science, the solution to a series of problems becomes a study on the art of compromise. The best practical solution is often a composite material comprising a fabric substrate, for mechanical performance, coated with an elastomeric or thermoplastic material, to satisfy permeability and environmental considerations. Included in Table I are summaries of the performance requirements of these two components.

## Fabric Substrate

The fabric substrate is the main load-bearing component. Its performance requirements can be achieved in two basic ways: correct fibre/yarn selection as well as fabric construction (21,27). Table II shows some of the characteristics of the most commonly used fibres in structural coated fabrics. In order to utilise efficiently the fibre mechanical properties, suitable yarn and fabric constructions must be employed. The fibres are generally in continuous filament form and are twisted together to form yarns, typically of linear density 1000-2000 dtex, comprising $\sim$200 filaments with a twist $\sim$50 tpm. The yarns are then interlaced to form the fabric and typical constructions include woven fabrics, crossed yarn systems, Malimo fabrics and warp-knitted fabrics with weft insertion (1,21,27). However, in selecting a fabric construction, consideration must also be given to the behaviour of the fabric during subsequent processing (e.g. dimensional stability during handling, penetration of coating material) as well as the fabric performance, pre- and post-coating, for the intended range of applications (e.g. translucency, balanced/isotropic mechanical properties).

## Coating Material

The primary functions of the coating material are related to permeability requirements and the protection of the fabric substrate from all types of environmental deterioration, Table I. The major characteristics of several coating materials are listed in Table III. The application of additional finishing coating films either in manufacturing or in the field provides further protection to the coating by, for example, preventing plasticizer loss, reducing diffusion of colour pigments, and improving dirt repellance; such coating films may be acrylic, methane or polyvinyl fluoride. In contrast to relatively open fabrics made of rough fibres, thick tightly-woven fabrics made of smooth fibres offer the coating a mechanical anchorage/adhesion which is inadequate for most structural applications. Thus an adhesive agent may be employed; e.g. isocyanates for PVC-coated polyester fabrics. However, the degree to which the coating modifies the mechanical properties of the fabric substrate will be determined by the penetration of the coating into the yarn surface fibres and fabric interstices (e.g. formation of small plugs in open and lattice weaves) as well as the chemical coating adhesion and the coating properties.

## Coated Fabric Systems

PVC-coated polyester is the most widely used coated fabric membrane in Western Europe due to the compatability and low-cost of fibre and coating and for the properties previously described. A lifetime of up to 10 years can be expected according to the quality of the PVC. In North America, this material is joined by polyamide plus polychloroprene as well as PTFE-coated glass fabrics. The latter is generally considered for structures of a more permanent nature, implying a lifetime of 25-50 years. The Japanese also use

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PVC-coated polyvinyl alcohol fabrics while Eastern Europe relies heavily on PVC-coated high-tenacity polyamide Malimo fabrics (4,13). In Australia, it would appear that PVC-coated polyester and nylon fabrics hold the larger share of the market.

## ASSESSMENT OF COATED FABRIC PERFORMANCE

Having discussed in a general manner ideal membrane characteristics and the performance requirements of the fabric substrate and coating material, Table IV presents a summary of properties and available standard test methods for the composite membrane material; it must be emphasised that materials testing should be made with proper regard to specimen selection and conditioning. For further details regarding standard test methods, the reader is referred to the various standards handbooks and manuals. It will be observed that the various standards do not cover the full range of properties listed. This reflects our evolving knowledge of these materials as well as the competing demands of manufacturers and users. In essence, manufacturers require cheap and quick tests for quality control; e.g. uniaxial tensile tests for ultimate strength and elongation. Users, however, require more detailed information for design and fabrication; e.g. biaxial mechanical properties, creep rupture.

In the remainder of this paper, some of the properties and test methods in Table IV will be discussed. However, this discussion must necessarily be brief with the main attention focussed on mechanical properties and the limitations of the standards for structural and other applications.

## PHYSICAL PROPERTIES

The list of physical properties, category A in Table IV, are required primarily for quality control, contractual, pre-construction handling and aesthetic purposes. Many of the tests are relatively simple to perform and are given, for example, in BS 3424:1973 (under revision). Tests for the measurement of colour and of colour differences may be made using a spectrophotometer or tristimulus colorimeter as per the textile standards (e.g. BS 1006:J01:1978). The thermal insulation behaviour of coated fabrics is poor so that special material or structural designs are required for heated or air-conditioned enclosures (11,13).

Of particular importance are the permeability properties. In outdoor use, coated fabrics are expected to withstand or resist penetration by water; e.g. water-filled structures, natural rainfall, pooling, etc. Various tests for water-tightness are given in the standards (e.g. BS 3424:1973, ASTM D 751-79). For pneumatic structures and special applications such as grain-bunker covers (where various poison gases are used to fumigate the stacked grain), the coated fabric membrane should be gas-tight. Two basic approaches are given in the standards to measure gas tightness: a pressure differential is established across a fabric specimen and either (a) the air flow rate (if any) is measured whilst maintaining this pressure (e.g. BS 3424:1973), or (b) the subsequent change in pressure (if any) is monitored (e.g. ISO DP 7618, AS 1066-1973). Apparatus for the latter approach is presently being developed in the School of Textile Technology (UNSW).

## MECHANICAL PROPERTIES

The mechanical behaviour of coated fabrics is of primary importance for structural and other applications. Thus successful utilisation of these

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materials requires an adequate understanding and appreciation of these properties. In general, mechanical properties (both short-term and long-term) are essentially a function of the fabric substrate while durability is mainly governed by the nature of the coating. However, there are a number of other important mechanical properties which follow both components of the composite material.

Short Term Stress-Strain Characteristics

The appropriate constitutive relation for the small-strain elastic behaviour of an initially flat coated fabric is that of a two-dimensional sheet material (23). As indicated in Table V, the most general case contains 21 independent rigidities in the elastic constant matrix. However, symmetry arguments with regard to the fabric construction and material properties in different directions can reduce the number of unknown terms. Of particular interest is the case of an orthotropic sheet, i.e. one possessing two lines of symmetry such as the warp and weft directions in a non-skew woven fabric. Although Table V is restricted to small-strain linear elastic deformation, it does provide a framework when considering more realistic material behaviour. Such behaviour is almost invariably inelastic, non-linear, time and history dependent. Further, any mechanical non-linearity, either of material or geometric (i.e. large strains) origin, may induce further anisotropy and coupling in the stress-strain characteristics. In practice, materials testing has generally concentrated on the membrane parameters $A_{ij}$ in Table V - by definition, a membrane is perfectly flexible so that the $B_{ik}$ and $D_{jk}$ terms are considered negligible (zero). However, the possibility of coupling between the various deformation modes in a full mechanical characterisation should be kept in mind by the user. For example, coated woven fabrics are often skewed or bowed so that the weft yarns are not perpendicular to the warp yarns (27). Under biaxial load, a skewed fabric will distort by shearing and the resultant deformation may be undesirable in a membrane structure.

Uniaxial tensile tests are routinely performed to measure ultimate strength and elongation in the warp, weft and intermediate (bias) directions. Differences between the various standards are chiefly related to the gauge length and test type (i.e. strip versus grab test). Although the stress-strain characteristics can be a by-product of such tests, they are seldom required to be reported in the standards. However, the magnitude of actual membrane loadings in tension-membrane and airhouse structures must often be related to this information — to design cutting patterns appropriate to prestress levels and to predict the effect of higher loading due to wind blasts, etc. (1). Although the strength and elongation of a coated fabric are primarily a function of the stress-strain characteristics of the yarn in the fabric, differences in the mechanical behaviour in the warp and weft directions of woven fabrics are often observed, especially at lower loads. These differences are primarily due to differences in the warp and weft crimp arising from differences in the warp and weft tension levels during the weaving and coating process.

The membrane material, however, is often subjected to biaxial stresses in structural applications. Although considerable research (18,22,25) has been devoted to this load case, no standard test method is presently available. In essence, there are three main groups of biaxial tests (18): bursting (sphere) test, cylinder test, plane biaxial test. Bursting tests are generally considered unsuitable for describing the true biaxial behaviour of coated fabrics (1,18). Krummheuer (13) favours cylinder tests and reports that the breaking strength will be reduced by about 20% from the level found

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in uniaxial tests. Reinhardt (18) argues that only the plane biaxial test adequately simulates a true state of biaxial strain. However, the shape of the test specimen and the method of gripping the specimen are of importance for these tests. His results indicate that the biaxial strength is approximately equal to the uniaxial strength provided the stress in the direction under consideration is equal to or greater than that in the other orthogonal direction. For both cylinder and plane biaxial tests, the elongation at break is less than for the corresponding uniaxial case and the biaxial stress-strain curve has a steeper slope. The latter observation is to be expected due to coupling between the two extensional deformation modes via the $A_{12}$ and $A_{21}$ parameters in Table V and is due to hindrance of crimp interchange under biaxial conditions. For the presentation and use of biaxial stress-strain characteristics, graphical representations called "generalised stress-strain profiles for variable stress ratios" may be employed (8,22).

The remaining membrane parameters in Table V are associated with shear and combined shear-extension load cases. It would appear that the membrane material should ideally have a low shear stiffness to prevent buckling (1). To the authors' knowledge, no such tests are conducted on structural coated fabrics. Various experimental procedures have been adopted to measure the shear properties of textile fabrics and it may be possible to "scale up" these tests for coated fabrics.

Present orthodoxy assumes the remaining parameters in Table V to be unimportant for structural applications. However, the revised edition of BS 3424 is to include a test for bending rigidity. Cantilever bending tests have been used to study the bending behaviour of coated fabrics (30) in terms of the bending length from which a bending rigidity can be calculated. For textile fabrics, such indirect bending tests have been replaced by pure bending testers which permit the full moment-curvature relationship to be determinated. The experimental measurement of the remaining parameters in Table V presents numerous difficulties (23).

## Strength Characteristics

Strength characteristics for coated fabrics broadly fall into 3 categories. First, there is the ultimate load obtained during stress-strain tests as discussed in the previous section. Second, there is the resistance of the coated fabric to the initiation and propagation of a tear or crack and this is the subject of this section. Third, there are the long-term strength characteristics and these form part of the subject matter of the next section. In each case, the strength characteristics are provided mainly by the fabric substrate but modified by the presence of the coating material.

Tear testing of the conventional type and of the fracture mechanics type are essential for an understanding of a membrane's slit-sensitivity, i.e. as an indication of the material's ability to withstand the growth of locally introduced damage. In tear tests, it is generally found that the greater the mobility of the yarns (i.e. bunching/roping), the more flaw/crack insensitive will be the coated fabric. Thus the better the adhesion of the coating to the fabric, the worse is the tear resistance (1,27).

There are several well-established conventional and standard test methods to determine resistance to tear propagation (11,13): leg, tongue, pendulum and trapezoid tests. The first three tests are based on the same principle, viz. the system of yarns under consideration are arranged trans-

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versely to the direction of the applied tearing force. For the trapezoid method, however, the test yarns are arranged parallel to the direction of the applied tearing force. Krummheuer (11,13) suggests use of the trapezoid method together with one of the other three methods, e.g. leg method. For high strength fabrics, Ansell and Harris (1) suggest larger sample sizes than is the norm in the various standards.

Fracture mechanics approaches evaluate the progress of slits leading to tears in the coated fabric. Small regions of damage may be introduced to fabric sheets held under tension, or a flawed specimen may be progressively or shock loaded from zero load. Abbott and Skelton (28) used the former procedure to determine critical tensions for crack propagation and crack propagation velocities. Minami (15) used the latter procedure (with slow progressive loading ) to determine the maximum tension as a function of crack length and derived a formula for the fracture toughness of coated fabrics. Topping (31) also used the latter procedure to study the critical slit length of pressurised coated fabric cylinders. Ansell and Harris (1) suggest such tests to be of greater relevance to the prediction of membrane failure, especially for airhouses, than the preceding tear tests. However, Racah (17) suggests that in an airhouse membrane where large cracks ( $\geq$ 100 mm) may stably exist, the propagation of these cracks under increased load will be further complicated by buckling around the flaw. It would appear, therefore, that large scale tests are required to quantify this effect and some work is in progress to this end (17). Further, Racah argues strongly for a more thorough fracture mechanics investigation and the development of suitable standard test methods based on this approach.

Another strength test often listed in the standards is the bursting strength. Such tests have been mentioned with regard to biaxial testing for which they are considered unsuitable. However, they are indicative of a puncture type of failure. For this purpose, a plunger test (quasi-static) or a drop-cone test (shock loading/impact) may be considered. Finally, mention should be made of a tack-tear test listed in ASTM D 751-79. Although this test is intended primarily for coated upholstery fabrics, it may be indicative of tearing via snagging of a structural coated fabric. Indeed, such a test is to be included in the revised BS 3424 standards.

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## Long-Term Mechanical Behaviour

Resistance of the coated fabric to prolonged loading/deformation is of particular importance as conditions in practical use are more of the continuous rather than temporary type. Uniaxial stress relaxation tests, in which the fabric is held at a constant elongation, are relatively easy to perform and reflect the viscoelastic nature of the composite material. For practical purposes, such tests indicate the need for retightening the membrane structure shortly after installation (13). Similarly, uniaxial creep tests, in which the fabric is held at a constant load, are also relatively easy to perform. Of particular importance for these tests is the creep rupture strength (the applied load) as a function of time from loading to fabric failure. Krummheuer (11,13) notes that there exists a linear relationship between the logarithm of applied load and the logarithm of time until failure for PVC-coated polyester fabrics. Thus it is possible to extrapolate the results to obtain a load which will not lead to failure of the material within the expected lifetime of the membrane structure (e.g. 10 years). Further, Krummheuer (13) states that the creep rupture elongation corresponds to the elongation in short-time tests and seems to be independent of the time of loading. Little attention appears to have been paid in the literature to the in uniaxial tests. Reinhardt (18) argues that only the plane biaxial test adequately simulates a true state of biaxial strain. However, the shape of the test specimen and the method of gripping the specimen are of importance for these tests. His results indicate that the biaxial strength is approximately equal to the uniaxial strength provided the stress in the direction under consideration is equal to or greater than that in the other orthogonal direction. For both cylinder and plane biaxial tests, the elongation at break is less than for the corresponding uniaxial case and the biaxial stress-strain curve has a steeper slope. The latter observation is to be expected due to coupling between the two extensional deformation modes via the $A_{12}$ and $A_{21}$ parameters in Table V and is due to hindrance of crimp interchange under biaxial conditions. For the presentation and use of biaxial stress-strain characteristics, graphical representations called "generalised stress-strain profiles for variable stress ratios" may be employed (8,22).

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Actual conditions of use, however, never show a constant load level as assumed above. Thus it is of considerable importance to assess the material's response to intermittent fatigue loads. Such loads may be of high frequency (e.g. impact of high winds, hail stones) or of low frequency (e.g. moderate winds, snow loads). The former are of a dynamic type and will be considered in the next section while the latter correspond to a (quasi-static) cyclic loading situation.

The effect of cyclic loading in uniaxial tensile tests have been reported by several authors (13,24,29). As the number of load cycles increases, the slope of the stress-strain curve increases while the hysteresis decreases. Further, at the end of each unloading cycle, the coated fabric shows residual elongation. However, these effects are of decreasing severity, i.e. approach constant values, as the number of cycles increases. It is interesting to note the hysteresis energy losses per cycle (29). This energy must be dissipated in the coated fabric system in the form of heat which could lead to thermal degradation of the material if it cannot be dissipated into the surrounding environment. Shimamura and Takeuchi (24) also studied the cyclic fatigue rupture of PVC-coated polyvinyl alcohol fabrics. They report a linear relation between the maximum cycle stress and the logarithm of the number of cycles to failure; note that the number of cycles to failure is roughly proportional to the time to failure. Krummheuer (12,13) states that the material resistance and elongation to prolonged but cyclic loading (both low and high frequency) is essentially dependent on the maximum load applied. Thus he suggests that such effects can be reliably estimated by creep rupture tests at that maximum load.

Of greater interest, however, are the effects of cyclic stresses superimposed on a biaxially stressed membrane. Preliminary results by Ansell and Harris (1) show that significant residual extensions can remain after all load is removed. Obviously, further studies analogous to the above uniaxial tests are required for long-term constant and cyclic biaxial loads.

From the above results one may argue that overloading of membrane structures due to service loads can be expected to increase the irreversible creep of the coated fabric as a function of the degree of overload above the prestress level. As each previous maximum stress is exceeded, new stress-strain characteristics are evolved as a result of irreversible viscous flow within the membrane material.

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## Dynamic Properties

There are various methods of measuring the dynamic mechanical behaviour of solid materials, viz. free vibrations, resonance methods (forced vibrations), wave propagation methods, and direct observation of stress-strain curves at very high strain rates. Although small-scale vibration testing has been used in coatings research (19) to detect structural modifications, little information on coated fabrics has been reported in the literature. Baffico et al (2) examined the uniaxial dynamic creep of rubberised nylon fabrics for use in flexible dams - the dynamic deformation mode was superimposed on a static load. For loads in excess of 30-50% of the uniaxial (static) tensile strength, dynamic creep increased at an accelerating rate and led to rapid failure of the membrane unlike the case with the quasi-static cyclic testing described in the preceding section. Recently, acoustic pulse propagation techniques have been applied in our laboratories (29) to determine the sonic velocities, and thus the dynamic elastic moduli, of several coated fabrics. Figure 1 illustrates some representative results. The primary advantages of acoustic pulse propagation techniques include relative simplicity, non-destructive testing and independence of the modulus measurement to sample cross-sectional shape and dimensions.

The polar plots in Fig. 1 essentially show two maxima, corresponding to the warp and weft directions, with a minimum along the bias. The fabrics were in some cases skewed and this may explain the "fan-tail" shapes illustrated for three of the fabrics in Fig. 1. Comparing fabrics A and B suggests little differences in their warp and weft sonic velocities, especially in view of experimental error. This further suggests that the coating has little effect on these sonic velocities - at least for these fabrics. This is not unreasonable in view of the less anisotropic and less stiff nature of the coating. For all the fabrics in Fig. 1, the weft sonic velocities are consistently lower than the warp sonic velocities. This may be attributable to two possible factors: different warp and weft yarns; the pulses travel through a greater distance in the weft direction, as compared to the warp direction, for a given nominal distance due to the weft having a greater crimp than the warp yarns. Neither of these factors were tested in the present work. However, it is to be noted that for uncoated conventional textile fabrics (20), the dynamic elastic modulus is not only dependent on the fibre species but is also dependent on fabric construction parameters such as yarn crimp, fibre diameter, degree of set, interlacing density and the configuration of individual fibres within the fabric. Further, these authors also showed that the pulses propagated through the uncoated fabrics as flexural pulses as distinct from torsional or longitudinal pulses. Finally, Fig. 1 compares the directionality of the sonic velocity profiles with the theoretical relation given by Blyth and Postle (32). The agreement is quite remarkable with the major differences being due to the "fan-tail" effects. Incidentally, this technique may provide a useful quality control tool for the determination of such fabric skewness - it is, in fact, often used by the synthetic fibre producers to check molecular orientation resulting from drawing processes.

As indicated by the above discussion, there is certainly scope for more work in this area. In particular, determining the influence of the coating on the sonic velocity profile of the fabric substrate. Should this influence be sufficiently small, then one could determine the dynamic modulus by the thickness and density of the coating. However, this raises the question as to which density should be used in the calculation of dynamic modulus (20,32): the fibre density or the coated fabric density.

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## Coating Adhesion and Seam Strength

Two associated mechanical tests are measurements of seam strength and of coating adhesion.

As noted earlier, adhesion between the coating and the fabric substrate may be achieved through mechanical and chemical means. Adequate adhesion is required to prevent separation of the coating from the fabric and to secure welded and cemented seams. Further, low adhesion strength can be a contributory cause of low abrasion resistance. However, high adhesion strength can reduce tear propagation resistance. Various peel tests are available in the standards to determine coating adhestion strength (e.g. BS 3424:1973). The main difficulty with these tests is associated with the sample preparation, i.e. initial separation of the fabric from the coating.

There are several methods of joining or seaming coated fabrics (12,13, 27): high-frequency welding, heat-sealing, cement-sealing, sewing and combinations of these. The first three methods rely on the shear strength of the interface between the two fabrics (including any intermediate layer of elastomer or cement) and on the coating adhesion strength. The strength of a sewn seam depends on the strength of the sewing thread, the seam and fabric construction (26,27) and on the coating adhesion strength (13). Although the sewn seam is light, can take up little fabric, and is usually quite flexible, it is not air or water-proof and so may need sealing. Mechanical tests for seamed fabric samples are generally limited to short-term and long-term uni-axial tensile tests (12,13) as discussed above for coated fabrics. Of particular importance is the seam efficiency derived from short-term strength and creep rupture tests. This is derived from the ratio of the seam strength obtained to the original fabric strength. Seam efficiencies are generally less than ∿95%. In the case of PVC-coated polyester fabrics (12,13), the highest efficiency is shown by high-frequency welded seams. It is to be noted that in structural applications, the fabric envelope is composed of seamed fabric panels and is generally in biaxial tension. To the authors' knowledge, seam mechanical properties under biaxial tension has received little attention.

ENVIRONMENTAL AND ENDURANCE PROPERTIES

Ideally, coated fabric membranes should be durable materials and so retain their original properties when subjected to all aspects of environmental degradation over long periods of time. Whilst in recent years there have been many developments in fibres, coatings and coating technology, such an ideal material has so far not been developed. This, of course, is not surprising when the many agencies and varied sets of conditions to which these materials must be resistant are considered: sunlight, temperature and humidity changes, oxidation, pollutants, chemical attack, microbiological attack, penetration by water and other fluids in contact with the material, fire, mechanical degradation (pre-stress and service loads, abrasion) and time itself. In order to be able to predict the in-use behaviour of membrane materials, and thus material life-time, average levels of all properties of interest in the original materials should be determined and changes in these properties monitored during extended trials during which exposure conditions should be at least as severe as those likely to be met in use. In practice, only those properties indicated in Table V appear to be mentioned in the standards on structural coated fabrics. Further, most of these properties are tested in the virgin state rather than during or after exposure to weathering, either simulated or in field trials.

It should be emphasised that where durability data in relation to time is required, the only method is by "outdoor" weathering or exposure (16) and standard test methods do exist, e.g. 'Outdoor Weathering of Plastics in the Australian Environment' (AS CK 24-1972) and as a "Guide for Design Purposes' (AS 1745-1975). Thus materials under load are exposed in the field for long periods of time. Quite often, because of time constraints, such exposures are not feasible and accelerated weathering techniques are therefore required. As well, it must be realised that materials behaving satisfactorily in weathering tests carried out in one geographical area may have an unsatisfactory performance in a different location with harsher conditions.

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There have been many studies on the photo-oxidation of polymeric materials occurring during weathering and during exposure to many agencies simulative of weather. These have indicated that quite complex processes are involved. It would seem that there are three prime factors (viz. ultra-violet radiation, temperature and water-vapour pressure) controlling degradation rates and that generally the influence of these is non-linear with time. It is unlikely, therefore, that increases in intensity of any or all of these factors will each superimpose with time to enable valid quantitative acceleration of degradation under any artificial chamber conditions. It therefore follows that any general simulation and acceleration of photo-oxidation weathering will not provide reliable data relating time of exposure in the chamber to time of exposure outdoors. Thus it seems useful in weathering chamber exposures to relate the performance of a test specimen to that of a control specimen of similar type to that being examined and of known outdoors performance.

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## Instrumentation for Accelerated Weathering

A whole range of apparatus simulating natural weathering is presently available commercially. Sources of radiation are mainly xenon burners, carbon-arcs and special fluorescent tubes.

Xenon burners are known to simulate the sunlight spectrum more closely than other sources (5) and mainly for this reason have a great number of advocates. However, it has now been well-established that it is the ultra-violet component of sunlight at the earth's surface in the range 290-315 nm that is responsible for most photochemical degradation (7). Thus, weathering apparatus utilising xenon burners these days incorporate filter packages to restrict radiation to specific spectral ranges. Again, whilst carbon-arcs emit the majority of their energy in the ultra-violet region, modern carbon-arc weatherometers also include special filters to screen out the visible portion of the spectrum. Apparatus using special fluorescent tubes as a source of radiation (e.g. as described in ASTM G53-77), uses tubes in which the spectral distribution covers the approximate range 280-400 nm with the peak intensity at 315 nm.

All of the above units include temperature and humidity control as well as facilities for programmed wetting, either simulating rain or by condensation or even flooding.

Most commercially available apparatus based on xenon burners or carbon-arcs is relatively expensive. Users of devices based on fluorescent tubes claim that their main advantages are, 1. simplicity (they plug directly into a simple power outlet: 240V, 50Hz), 2. comparatively low cost (in terms of initial outlay, running costs, maintenance costs), 3. results are usually produced faster than by either carbon-arc or xenon burners, and 4. physically they take up less space.

In Australia, in recent years, there has also been a move to use the MBTF lamp (a mercury vapour, tungsten filament, internally phosphor coated lamp) of power output either 500W or 1000W in weathering studies. Originally developed as an ordinary street lamp, the 500W lamp is now utilised as an artificial source in the determination of colour fastness to light of textile and other materials (AS 2001.4.21-1979). Its use is also specified in Australian Wool Corporation test methods for the determination of the degradation of such materials as polypropylene wool packs (AWC/TM33) and wool and wool-blend upholstery fabrics for vehicle use (AWC/TM2). Whilst such exposure lamps are extremely cheap to manufacture and run, they are limited in their applicability since they operate at a constant temperature (500W ∿ 65°C; 1000W ∿ 110°C) and have no facility for humidity control or for wetting of specimens in any way.

Radiation meters able to be used with any of the above instruments are available. The sensors of these cover various spectral ranges and are capable of indicating momentary and/or total incident radiation on the specimen during a given test period. Finally, chamber temperatures are usually measured using black-body thermometers.

Physical Properties

The Australian standards as well as other national and international standards list a whole series of test methods for the determination of colour fastness, discolouration or staining of materials to a wide variety of agencies - including light and weathering, sulphur or its compounds, wet and dry rubbing and soiling (e.g. BS 3424:1973). Whatever the method used, the assessment of colour change, etc. is based on three internationally accepted scales. These, and the ways in which they are to be used, are described in detail in AS 2001.4.21-1979 and AS 2001.4.1-1980. Briefly, the conditioned sample or a specified material in contact with the sample is subjectively assessed against the relevant scale and given a rating value; all scales are of the geometric type. Because of this subjective assessment, which can lead to differences in ratings even between skilled observers, there has been a move to use the same scales but to measure such colour differences, etc. instrumentally. Work is going on at the present time, in fact, related to the development of an international standard concerned with the instrumental assessment of colour fastness to these various agencies.

Frequently associated with colour changes are the concomitant changes of loss of gloss/lustre, and chalkiness of the material, either or both of which may occur after relatively short periods of exposure. Even though serviceability may not be immediately impaired, such changes may detract greatly from the appearance of an architectural structure. Methods for the assessment of gloss and of infra-red reflectance are given, for example, in BS 3424:1973 (appendix). Further, it is of interest to note that instruments for the measurement of gloss and/or chalkiness have been utilised by the paint industry for many years and methods covering their measurement and assessment may be found in the appropriate paint standards.

Plasticizer migration and/or eventual loss of plastizer can lead, in some instances, to increased soiling rates resulting in stickiness of the membrane surface or to coating embrittlement leading in turn to lower flex resistance and coating cracking and break-down. Methods of test for plasticizer migration and loss are listed in BS 3424:1973 and AS 1441:1973 and satisfactory levels can be determined for use in commercial specifications.

As noted earlier, coated fabrics in outdoor use are expected to resist or withstand penetration by water. The tests for water penetration should be repeated on weathered specimens - similarly gas tightness tests should also be repeated. Another form of water penetration is that due to wicking whereby water is absorbed into the coated fabric through capillary action by the yarn fibres. Tests for wicking behaviour are again listed in the standards, e.g. BS 3424:1973. For resistance to penetration by other liquids, such as fuel and lubricating oils, cement and water mixes, which are used extensively in

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industrial environments and may come in contact with the coated fabric due to accidental spillage, a simple test method is given in BS 3424:1973. However, the particular method quoted is to be withdrawn and replaced in the revised British standards. Other tests are described in reference 21 together with some results for various coated fabrics.

In most instances synthetic polymers are insensitive to microbiological attack. Thus little attention has been paid to the development of tests specifically aimed at determining the resistance of coated fabrics to such agencies as mould fungi - although there appears to be a German standard for this purpose (6). However, there have been rare instances reported (13), particularly in humid climates, of some fungal growth even if fungicides have been added to the PVC paste. This is probably due to the addition of plasticizer to the PVC coating formulation (3). In these instances, it is unlikely that serviceability of the fabric membrane will be affected and only changes in appearance are likely. However, the consumption of plasticizer in PVC coatings by micro-organisms, coupled with poor wicking performance of the coated fabric, may accelerate embrittlement of the coating, thus resulting in degradation of the coating and of the yarn fibres (21). Tests to determine resistance to mould fungi and other micro-organisms are standard in the biological area and these could, it would seem, be easily adapted to coated fabrics and membranes (3,21).

For the resistance of coated fabrics to chemical attack. several standard test methods exist (e.g.BS 3242:1973, ASTM D-814-55). Results of the chemical resistance of polyester fabrics coated with different materials are given by Seaman and Venkataraman (21). Krummheuer (11) also tested various mechanical and physical properties of PVC-coated nylon and polyester fabrics after prolonged exposures to different chemicals. It would appear that almost all degrees of chemical resistance required for particular end-uses may be achieved by selecting the correct yarn and coating material/formulation. However, there may still be cases where tests closer to in-use conditions may be required, especially where the effect of interactions between several chemicals is unknown or where the material may also be subjected to micro-biological attack.

Structural coated fabric membranes must be shown to be incapable of supporting fire. In New South Wales, the Theatres and Public Halls (General) Regulation 1977 (N.S.W. Government Gazette, No. 111, 30 Sept. 1977) lays down certain requirements for materials for use in those buildings and these requirements could conceivably apply to airhouse and other membrane structures. Such regulations are based on given values of a flammability index (AS 1530-Part II) and of the early fire hazard properties (AS 1530-Part III) of the material. The flammability index is based on the measurement of a speed factor, a heat factor, and a spread factor and ranges from 0 to 100, with relatively "safe" materials having indices less than 10. The early fire hazard properties tests apply to building materials and their surface coatings and classifies them according to their tendency to: 1. ignitability (0-20), 2. heat evolved (0-10), 3. spread of flame (0-10), and 4. smoke developed (0-10). Again, these indices for "safe" materials are quoted in the Schedule and vary between 0 and 7 depending on location.

There still appears to be some confusion or disagreement, internationally, over the preferred type of flammability tests for coated fabrics. Some suggest, rather idealistically, that complete structures should be tested in the field in order to assess their safety - some such tests for airhouse structures are reported by Herzog (8). Others suggest strip tests of some

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type, e.g. AS 1530 or BS 3119 (in a modified form, this test is part of the specification requirements for coated tarpaulins for the Victorian Railways). Others, as a means of assessing ease of extinction, prefer to measure the limiting oxygen index (BS 2782, Part I, Methods 141A-D, 1978) but, in practice, the proportion of oxygen to nitrogen surrounding the fabric membrane varies very little. It would seem certain, however, that some consensus in this area is long overdue.

Many PVC coatings, these days, contain fire retardants and satisfy Australian as well as British and American standards - the fabric substrate material appears to play a secondary role (11). PTFE coatings have excellent fire-resistance properties although some problems have been reported with regard to obtaining a fire-resistive rating (1). For further information on the various flammability tests available and the results of such tests, the interested reader is directed to references 9,11 and 21.

<u>Mechanical Properties</u>

All of the mechanical tests discussed previously should be repeated after field trials or after exposure to standardised simulated use conditions. Thus, the effects of ultra-violet radiation, temperature, relative humidity, wetting, etc. can be assessed by determining changes in mechanical properties.

Krummheuer (12,13) reports the effect of temperature on various mechanical properties of PVC-coated polyester fabrics; the temperature chosen was 70°C as this is considered to be the maximum temperature that the material experiences under temperate Central European conditions. Reductions in the levels of fabric and seam strength and creep rupture, as compared to the values obtained at room temperature, were observed. Krummheuer also reports residual strength results of some weathering tests conducted over a two year period at various locations in Europe and in North America. These results indicate the importance of the coating thickness on the exposed side of the coated fabric and suggest that this thickness should not be less than $\sim 150$ $\mu$m in order to restrict strength losses to $\leq 10\%$. Strip tensile tests for breaking load and extension conducted on various coated fabrics subjected to ultra-violet radiation have indicated, in our laboratories, that loss of extensibility appears to be the most sensitive and useful parameter to measure to indicate instability in the material; Fig. 2 presents some representative results. Such a result has also been obtained for plastics sheet materials by Martin and Sasnaitis (14).

Mechanical tests not considered earlier but mentioned in the standards include cold cracking, low temperature flexibility, abrasion resistance, flex cracking and crumpling (e.g. BS 3424:1973); ASTM D 751-79 also includes a test method for low temperature impact. The results of these tests are often assessed visually although BS 3424:1973 allows assessment in terms of the hydrostatic head test for abrasion resistance, flex cracking and crumpling. Ansell and Harris (1) note that the latter two tests are particularly relevant to airhouse membrane materials, especially at airlocks and fan ducts. Further, they prefer the crumpling method to flex cracking in order to avoid repetitive deformation at folds.

## CONCLUDING REMARKS

The ideal characteristics of a structural membrane for light-weight architectural and engineering structures and other industrial applications are presented and it has been indicated how a coated fabric can fulfil many

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of these requirements. Further, this paper has sought to establish an inventory of the physical, mechanical, environmental and endurance properties, and tests methods for these properties, for structural coated fabrics, and to indicate their importance for practical applications. In this, the authors feel, it has been reasonably successful. However, the reader, if interested in a fuller discussion of the various matters raised, is directed to the bibliography and to the various standards hand-books and manuals.

Obviously, there are various areas where further research could be profitable and some of these have been mentioned in the text. One area not discussed is the development of techniques for the detection of early signs of weathering. This may reduce the time required for weathering trials in the field. Since the primary function of the coating is to protect the fabric substrate from environmental degradation, examination of the first 100Å of the surface of the coating would seem to be indicated. This may be achieved, for example, by scanning electron microscopy studies of by employing electron spectroscopy for chemical analysis to detect the early onset of chemical change. Another matter not discussed is the development of actual performance specifications. Work is proceeding to this end in various countries and internationally for these materials.

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TABLE I: Ideal Membrane Characteristics and the Performance Requirements of the Fabric Substrate and of the Coating Material §

| IDEAL MEMBRANE CHARACTERISTICS | FABRIC SUBSTRATE | COATING MATERIAL |
|---|---|---|
| Low Cost | * | * |
| Lightweight | * | * |
| High tensile strength | * | |
| High tear strength | * | |
| Resistance to tear propagation | * | |
| Puncture resistance | * | |
| Flexibility (low shear and bending stiffness) | * | * |
| Dimensional stability: | | |
| (a) high tensile modulus to minimise stretch under load | * | |
| (b) unaffected by changes in temperature and humidity | * | * (1) |
| Resistance to all aspects of environmental degradation: | | |
| (a) sunlight (especially UV-radiation) | * | * |
| (b) chemical attack (including oxidation, oils, pollutants) | * | * |
| (c) microbiological attack | | * |
| (d) soiling | | * |
| (e) flame resistance | . | * |
| (f) abrasion resistance | | * |
| (g) temperature and humidity changes | * | * |
| Impermeable to air and moisture/water | | * (2) |
| Control of optical properties | | * (3) |
| Control of thermal radiation transmission | | . (4) |
| Ease of fabrication, relocation and repair: | | |
| (a) capable of being joined/seamed | | * |
| (b) reparable in the field | | * |
| Maintain these properties after years of outdoor exposure | * | * |
| | | Protect yarn fibres |
| | | Quality adhesion to yarn fibres |

(1) high temperature dead-load performance
(2) and non-wicking
(3) colour capability (non-fading); translucency sometimes required.
(4) special constructions, e.g. double-skinned membrane structure, one side foam coated.

§ Adapted from references 1,21 and 27.

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TABLE II: Properties of Fabric Substrate Fibres §

| | |
|---|---|
| NYLON: | Adequate breaking load and stiffness. Good recovery properties. Excellent abrasion and crease resistance. Affected by moisture, sunlight and oxidation. Flammable. |
| POLYESTER: | Not quite as strong as nylon and a little more expensive. Higher stiffness than nylon and better dimensional stability (i.e. low extensibility). Abrasion resistance is not quite as high as nylon. Insensitive to water and environmental degradation (e.g. UV and acid attack). Flammable. |
| GLASS: | Strong material with high dimensional stability (stiffness $\sim$10 x greater than established textile organic fibres; very fine filament diameters allow flexibility). Moisture can weaken glass fibres in the long-term but otherwise inert to environmental attack. Poor abrasion resistance (can impose handling problems). Translucent. Flame resistant. Sewn seams are unsatisfactory. |
| POLYPROPYLENE: | Strong. Outstanding resistance to chemical degradation. Experimental materials have very high strength. Adhesion problems reported. Coating materials must have a low temperature cure. Subject to UV-degradation. |
| ARAMID: | Recent development in fibrous polymers combining many of the good properties of conventional textile and glass fibres; specific strength is twice that of polyester and glass and the stiffness is high. Considerably degraded by UV-radiation. Cost is considerably higher than nylon and polyester. |

§ Adapted from references 1,21 and 27.

## TABLE III: Properties of Coating Materials §

| | |
|---|---|
| HYPALON: | Excellent resistance to acid, oxidation, ozone, heat and sunlight ageing. Good mechanical properties. Excellent abrasion resistance. Low water absorption. Good colour retention - can be made translucent. Poor low temperature resistance. Low cost. Requires cemented or seamed joints. |
| NEOPRENE: | Very similar to hypalon in resistance and weatherability. Better tear resistance and adhesion to fabric substrate. Suitable for dark coating only. Low cost. Non-weldable - requires cemented or seamed joints. |
| VINYL (PVC): | Low cost material which can be given good mechanical and weathering properties by suitable choice of formulation (plasticizers, heat and light stabilizers, fillers, flame-retardants, fungicides, etc). Deterioration is caused mainly by loss of plasticizer. Range of colours can be achieved. Can be made translucent or even transparent but at the cost of reduced service life. Stiffens in cold environments. Can be heat-sealed. |
| FLUOROELASTOMER: | Good to excellent mechanical properties. Outstanding resistance to all types of deterioration (e.g. weathering), particularly at high temperatures (including fire resistance). Non-adhesive and thus self-cleaning. Can be made transparent or translucent. High cost. PTFE can be welded by sandwiching a layer of hexafluorpropylene film between two layers and applying heat and pressure. |
| POLYURETHANE: | Excellent mechanical properties and superior abrasion resistance. Excellent adhesion to fabric substrate. Reasonable weather resistance, only fair acid and flame resistance. Can be made transparent or translucent. Medium cost. Can be heat sealed. |

§ Adapted from references 1,21 and 27.

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TABLE IV: Properties and Test Methods for Structural Coated Fabrics §

| A. PHYSICAL PROPERTIES | Aust. | I.S.O. | U.S. | German | British |
|---|---|---|---|---|---|
| (i) Basic Characteristics | | | | | |
| 1. roll characteristics (width, length, mass) | | | * | | * |
| 2. thickness (fabric substrate, coating, composite membrane) | * | | * | * | * |
| 3. mass per unit area (fabric substrate, coating, composite membrane) | * | | * | * | * |
| 4. details of fabric substrate, coating material and application (including special additives) | | | | | |
| (ii) Other Physical Properties | | | | | |
| 1. dimensional stability | | | | | |
| (a) from roll (flat test) | | | | | * |
| (b) to immersion in water | | | | | * |
| (c) elongation and tension set | | | | | * |
| 2. permeability to air and other gases (gas-tightness) | | * | * | * | * |
| 3. permeability to water and water vapour (water-tightness) | | * | * | * | * |
| 4. degree of fusion of PVC coatings, state of cure of vulcanates | | | | | * |
| 5. blocking resistance (material adhesion | * | * | | | * |
| 6. spectral and optical properties (including infra-red reflectance, gloss) | | | | * | * |
| 7. thermal properties (insulation, conductivity) | | | | * | |
| 8. electrostatic behaviour | | | | * | |

§ No claim is made to completeness of the list of test methods.

TABLE IV: Cont'd

| B. MECHANICAL PROPERTIES | Aust. | I.S.O. | U.S. | German | British |
|---|---|---|---|---|---|
| (i) Short-Term Properties | | | | | |
| 1. stress-strain characteristics: | | | | | |
| (a) uniaxial tensile | | | | | |
| (b) biaxial tensile | | | | | |
| (c) shear properties | | | | | |
| (d) flexural properties | | | | * | * |
| 2. strength properties | | | | | |
| (a) ultimate strength/elongation (from a. above) | * | * | * | * | * |
| (b) tear/crack initiation (impact, snagging, tack-tear) | | | * | * | * |
| (c) tear/crack propagation | * | * | * | * | * |
| (d) bursting/puncture strength | | * | * | * | * |
| 3. coating adhesion strength | * | * | * | * | * |
| 4. seam strength | | * | * | | * |
| (ii) Long-Term Properties | | | | | |
| 1. stress relaxation | | | | | |
| 2. creep and creep rupture | | * | * | | * |
| 3. low frequency (quasi-static) cyclic loading and fatigue failure | | | | | |

in principle, for all of the stress-strain characteristics of the composite membrane and seams;
in practice, restricted to uniaxial tensile creep and/or creep rupture.

(iii) Dynamic Properties

* a research area

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TABLE IV: Cont'd

| C. ENVIRONMENTAL AND ENDURANCE PROPERTIES | Aust. | I.S.O. | U.S. | German | British |
|---|---|---|---|---|---|
| (i) Physical Properties | | | | | |
| 1. colour fastness to light and weathering, wet and dry rubbing | * | * | * | * | * |
| 2. discolouration by sulphur or its compounds | * | * | | * | * |
| 3. resistance to soiling | | | | | * |
| 4. resistance to penetration by water and other liquids | | | | * | * |
| 5. resistance to wicking | | | | * | * |
| 6. resistance to mould fungi | | | | * | |
| 7. resistance to chemical attack | | | | | * |
| 8. plasticizer migration | * | * | | * | * |
| 9. resistance to fire | * | * | * | * | * |
| (ii) Mechanical Properties | | | | | |
| 1. temperature effect on strength | * | * | * | | |
| 2. ultra-violet radiation effect on strength | | | * | | |
| 3. low temperature performance (cold cracking, low temperature flexibility) | * | * | * | * | * |
| 4. abrasion resistance | * | * | * | * | * |
| 5. flexural cracking | * | * | | * | * |

* in principle all properties of interest in A and B should be re-examined after weathering and degradation by various agencies (see text) and including those above.

TABLE V: General Constitutive Relationship for a Thin (Two-Dimensional) Sheet

$$\begin{Bmatrix} T_1 \\ T_2 \\ T_{12} \\ M_1 \\ M_2 \\ M_{12} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & B_{14} & B_{15} & B_{16} \\ & A_{22} & A_{23} & B_{24} & B_{25} & B_{26} \\ & & A_{33} & B_{34} & B_{35} & B_{36} \\ & & & D_{44} & D_{45} & D_{46} \\ & & & & D_{55} & D_{56} \\ \text{symmetric} & & & & & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \\ \kappa_1 \\ \kappa_2 \\ \kappa_{12} \end{Bmatrix}$$

1-2 plane corresponds to the central plane of the sheet.

$T_{ij}$, $\varepsilon_{ij}$ and $A_{ij}$ are membrane stress-resultants, strains and rigidities respectively.

$M_{jk}$, $\kappa_{jk}$ and $D_{jk}$ are bending/twisting stress-couples, curvatures and rigidities, respectively.

$B_{ik}$ are coupling rigidities connecting the membrane and bending/twisting deformation modes.

Example: non-skew woven fabric corresponds to an orthotropic sheet with

$$A_{13}=A_{23}=D_{46}=D_{56}=B_{16}=B_{26}=B_{34}=B_{35}=0;$$

remaining $B_{ik}=0$ if fabric is also symmetrical about its central plane.

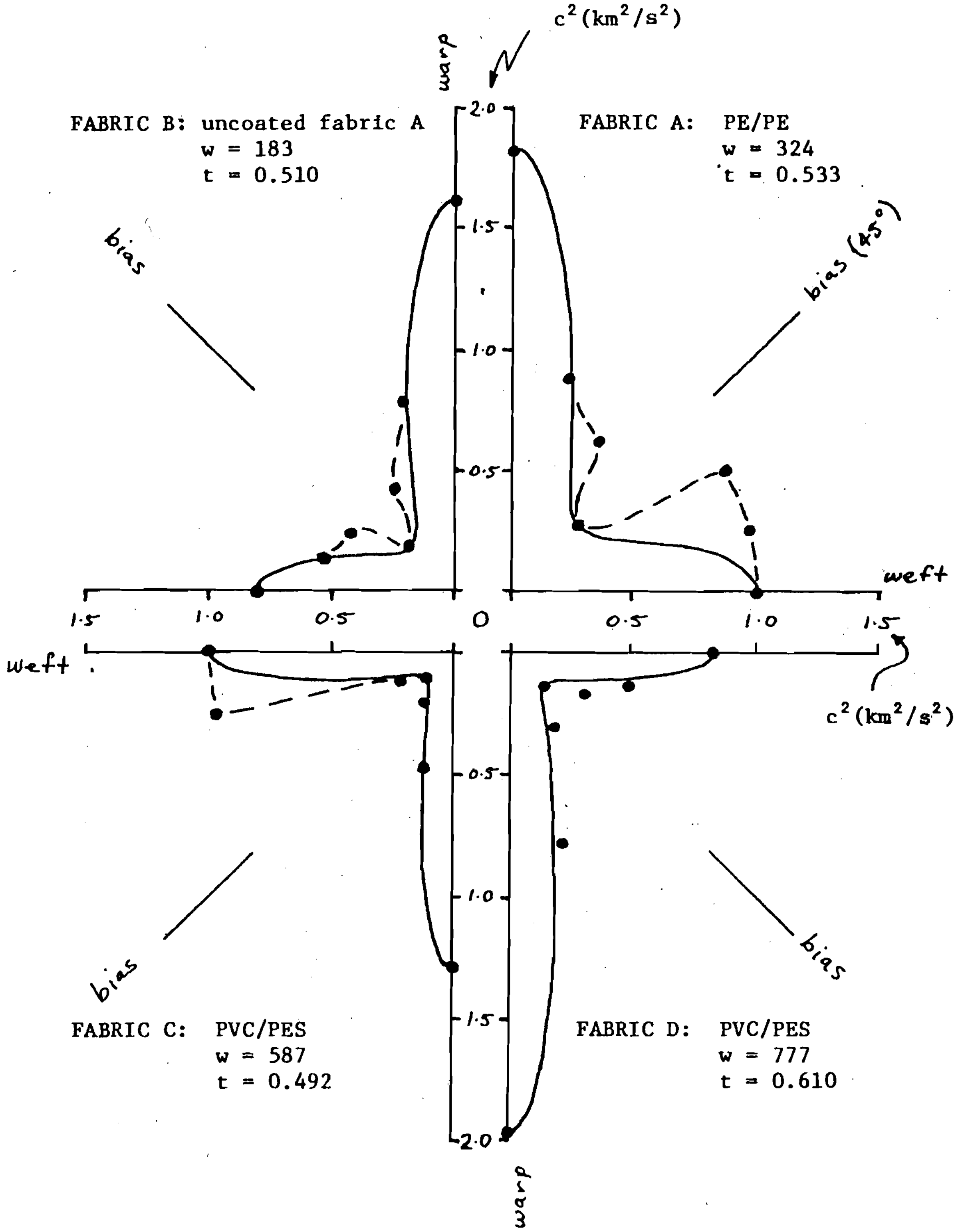


Fig. 1: Polar profiles of sonic velocity (c) squared for some fabrics; — — ● — — experimental, ——— theory (32); error in c ranges from 14-21% (29); dynamic elastic modulus is given by $E = \rho c^2$ where ρ is the density; t = thickness (mm), w = weight (g/m²).

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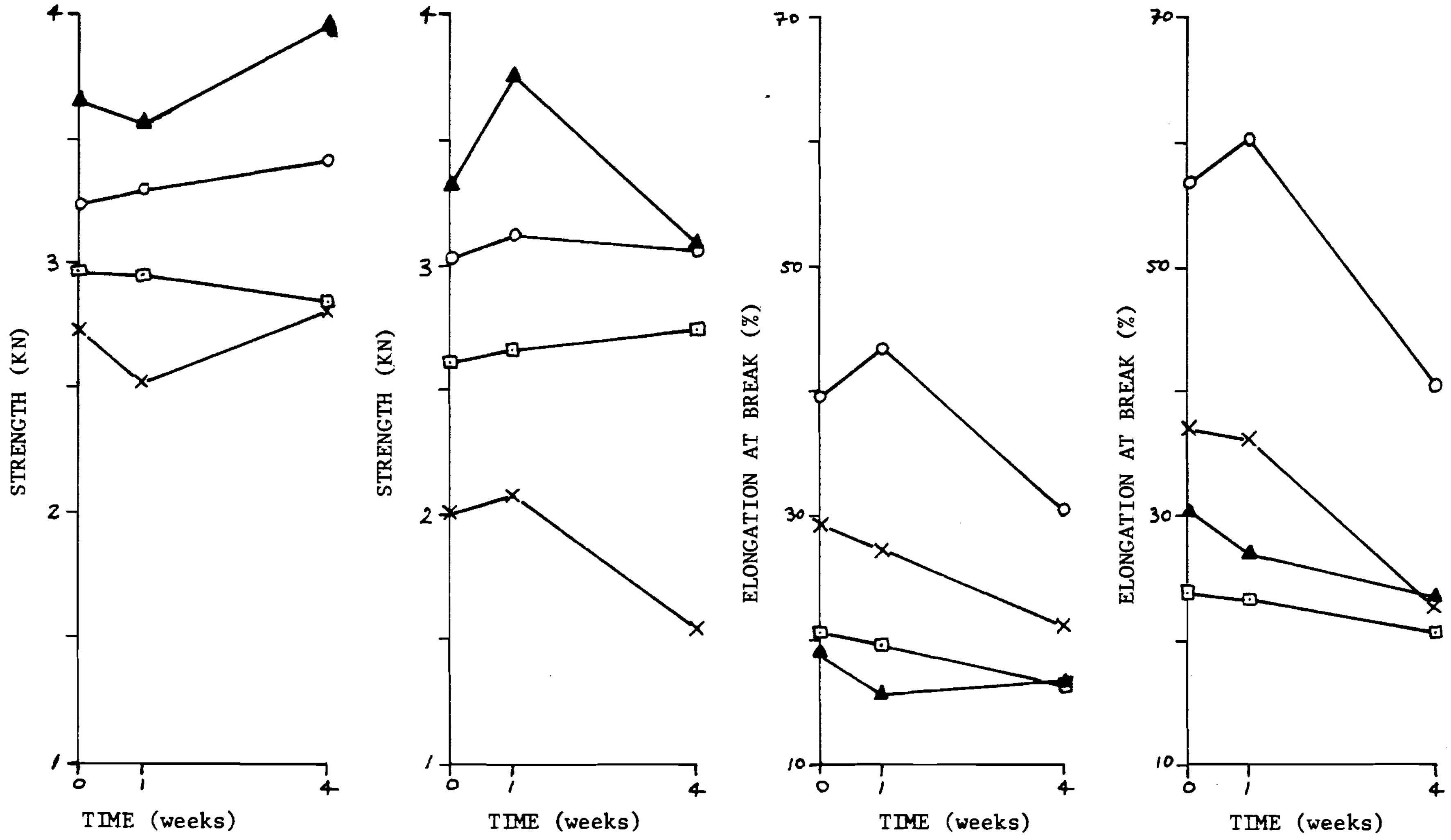


Fig. 2: Effect of UV-irradiation on strength and extensibility of some coated fabrics

▲ PVC/PVA (w - 645 $g/m^2$)

□ PVC/PES (w - 594 $g/m^2$)

o PVC/PA 6.6 (w - 587 $g/m^2$)

× PVC/PES (w - 621 $g/m^2$)

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