

NPL REPORT

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**Physical Characterisation
of Soft-Touch Polymers**

**P E Tomlins, M Rides, A
Dawson, M Gee, G Dean, C
Hobbs, C Allen, S Gnaniah, A
Calver and R Darling**

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July 2005



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Physical Characterisation of Soft-Touch Materials

P E Tomlins, M Rides, A Dawson, M Gee, G Dean, C Hobbs, C Allen, S
Gnaniah, A Calver and R Darling

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National Physical Laboratory

ABSTRACT

The perceived and physical tactility of soft-touch surfaces can play a key role in our assessment of product quality and performance expectation. This report describes methods that can be used to measure a number of key physical attributes of soft-touch materials including surface texture, surface friction, thermal diffusivity and mechanical ‘compressibility’.

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1 INTRODUCTION

Our perception of an object or material is based on a range of inputs. These inputs range from visual cues e.g. it looks expensive and to some assessment of feel e.g. it feels ‘soft’, ‘luxurious’, ‘warm’, ‘right’. Visual appearance and previous experience play a key role in determining our perception of an object. Based on previous experience and to some extent cultural conditioning we even make a judgement on how the material will feel without making contact with it, e.g. we expect suede shoes to feel comfortable based on our experience. In most cases this judgement is reliable, but there are occasions when our perceptions based on handling the material are significantly different to those we had anticipated.

The purpose of this investigation is to measure the physical properties of typical ‘soft-touch’ materials that are likely to be significant factors affecting our tactile perception of them. The physical properties that primarily influence our perception of a material based on touch alone include:

- Surface texture
- Surface friction
- Thermal diffusivity, a combination of thermal conductivity and heat capacity
- Mechanical properties – a measure of the materials response to prodding, squeezing and shearing/stroking

The methods that have been investigated and used to characterise the materials are laser profilometry, scanning electron microscopy, and gloss for surface texture. These methods cover different length scales as well as instrument and measurement costs. A novel device to assess the interaction between skin and a surface has been developed and assessed to measure surface friction and a range of techniques have been used covering hardness, tensile and flexural properties to investigate the mechanical response of the materials. These methods are presented in more detail in section 3. These data will be compared with results obtained by a sensory panel evaluation of the same materials and used to predict the ‘feel’ of, for example, over-mouldings, to be presented in subsequent reports.

2 MATERIALS

The styrene-ethylene-butylene-styrene, (SEBS) thermoplastic elastomer copolymers (TPEs) (Multiflex, Pan Polymers) can be used to produce a range of soft-touch compounds that span the Shore hardness scale by adding additives such as carbon black, Table 1. These materials have been selected for the purposes of this investigation as having properties that are representative of a broader range of TPEs.

Specimens 150 mm by 150 mm were injection moulded according to the conditions listed in Table 2, either 2.6 mm or 3.9 mm thick, using a purpose built edge-gated mould design that has been described in detail elsewhere (Rides et al, 1996). Briefly the mould cavity was developed to provide a uniform flow field for molten material as it fills the mould. This is achieved by creating a domed structure between the sprue and weir-edge gate.

Trade name	Sample code	Nominal Shore hardness
Multiflex G90A 520 N0200 12615 Black	AAAT F001	90A
Multiflex G75A 520 205/09 10779 Black	AAAT F002	75A
Multiflex G45A21 B 72487 N0033 Black	AAAT F003	45A
Multiflex G60A 21 BT Z3519 N0104 Black	AAAT F004	60A
Multiflex G45A11 BZ 1743 Natural	AAAT F005	20A

Table 1: Sample details

Material	Melt temp. (°C)	Mould temp. (°C)	Cycle time (s)	Injection time (s)	Hold pressure (bar)	Hold time (s)	Cooling Time (s)
AAAT F001	180	50	77	0.80	20	20	50
AAAT F002	180	50	77	0.80	20	20	50
AAAT F003	180	50	90	0.76	30	20	60
AAAT F004	180	30	95	0.72	30	20	60
AAAT F005	180	30	150	0.76	24	20	40

Table 2: The injection moulding conditions for thick plates.

Care was taken to keep the materials clean during both the moulding process and cooling after ejection from the mould. Moulded samples were individually placed on paper on a wooden table and allowed to cool naturally at room temperature. The sprue was removed by cutting immediately after ejection from the mould tool. The samples were packaged in packs of five, each sample being separated by a sheet of paper and stored in re-sealable plastic bags.

3 METHODS FOR DETERMINING SURFACE TEXTURE

Surface texture is a particularly notable characteristic of natural materials such as leather, snake-skin and mother-of-pearl, moulded or embossed plastics. The ‘finish’ may be an essential element of a synthetic copy of a natural material or be used as a decorative effect to mask minor imperfections in moulded surfaces. Soft-touch materials, including paints and thermoplastic elastomer copolymers are used to give a very tactile, comforting feel, to an object i.e. a mobile phone case or to improve its functionality i.e. a screwdriver handle. In all cases the addition of a soft-touch finish has associations with quality, product differentiation and improved performance that adds value to a product.

Surface texture represents the deviations from a nominal surface that forms a three-dimensional surface topography. Such deviations can be repetitive or random. Typically surfaces are characterised using the 2-D profile formed by the intersection of a plane perpendicular to it. The orientation of this perpendicular plane is chosen to maximise the contours of the profile. Surface textures can also be assessed in 3-D but to date these methods are not supported by standards that are in the public domain. A variety of methods including atomic force microscopes, laser profilometers and white light interferometers can be used to measure surface profiles on length scales ranging from nanometres to micrometres. Ideally the length scale over which data are required is that which directly relates to touch; there is little merit in measuring on a length scale that exceeds to the sensitivity envelope of the cutaneous or kinaesthetic transducers. These data can be described in terms of roughness parameters that quantify, for example, the deviation of the profile from the mean, or record the magnitude of the highest peak and deepest valley.

3.1 LASER PROFILOMETERY

Laser profilometers are used to map surface profiles in both 2 and 3 dimensions. Such devices work by maintaining a point focus during a surface scan. This is achieved by moving the objective up or down which provides a direct measure of the surface profile, Figure 1. This type of non-contacting technique is well suited to measuring the profile of soft, easily deformed, surfaces. The technique does have its limitations. The instrument relies on the sample having a certain amount of reflectivity and although this is quite low at approximately 4%, it can pose problems for transparent or semi-transparent materials. A second practical difficulty is encountered in samples that have features with sharp drop-offs or undercuts due to loss of focus as a result of the often limited working range of laser profilometers and lack of light penetration respectively. Absorption of light by pigments can also add to the practical challenges of this type of measurement. The resolution of laser profilometers depends on the sensor used and typically ranges from 1 μm to 10 μm , noting that any increase in scan resolution will result in longer scan times, a factor that increases significantly for area scans.

A laser profilometer (UBM) was used to scan 5 mm² area of samples. The sampling frequency was set to 100 points per millimetre and the profile was acquired at a scan speed of 50 points per second. The resulting profile was filtered and analysed using Mountains Universal® software.

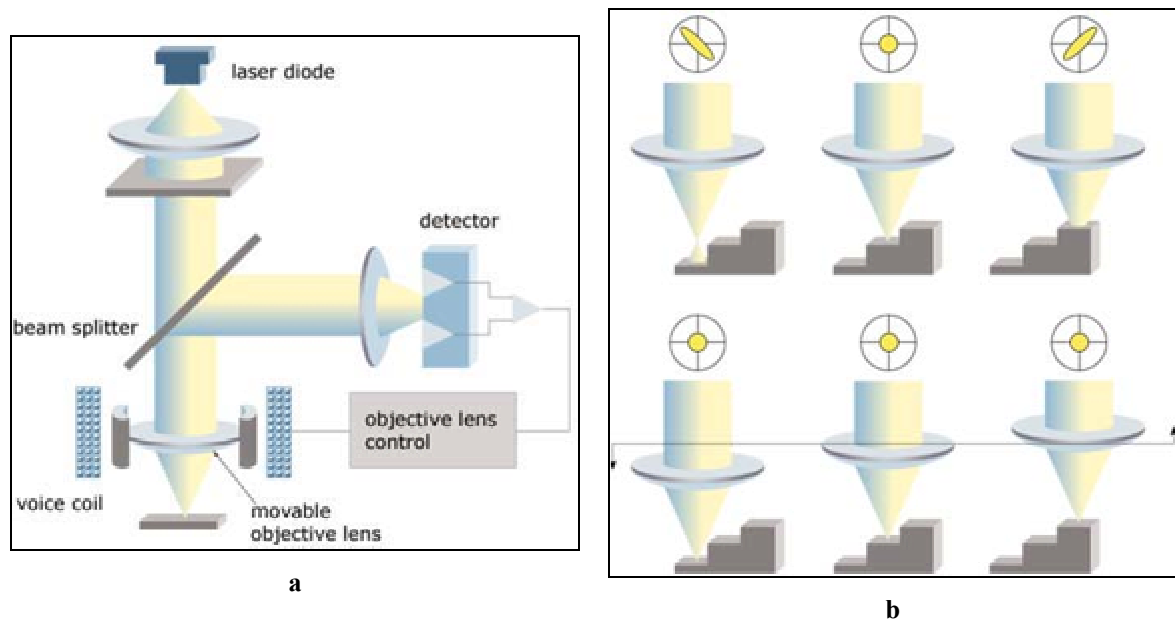


Figure 1 – Schematic construction of a laser diode auto-focus sensor (a) and its mode of operation (b)¹ Solarius Development Inc

3.2 SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy, (SEM), can be used to visualise surfaces which can be invaluable in interpreting data obtained from other surface texture measurement techniques. Non-conductive samples require a conductive, conformal coating to prevent electric charge accumulation. 1 cm² section sample from the laser scanned area was gold coated for two minutes. Orientation was preserved by a small cut made in the bottom right corner. Samples were mounted in a Hitachi FEGSEM and tilted at 45° to improve contrast, images were captured using KS400 digital image processing software. SEM images per se do not provide quantifiable surface texture data although stereo images can be used for this purpose (Gee et al,2004).

3.3 GLOSS

Changes in the texture of a surface affect its appearance by reducing the mirror or specular reflectivity measured at fixed and identical angles of incidence and reflection, typically 20°, 60° and 85°. Gloss is usually expressed as a percentage, and defined as the ratio of the luminous flux reflected from an object in the specular direction for a specified source and receptor angle to the luminous flux reflected from a highly polished black glass reference. The refractive index of the black glass standard is 1.567 in the specular direction and the angle used for measurements is 60° if the procedure described in ASTM standards D2457-3 and D523-89 is followed.

Specular gloss is usually used as a comparative measure of surface properties since it usually varies with surface smoothness and flatness. The amount of light reflected from a surface also depends on the concentration and type of pigments that may be present which limits the usefulness of gloss measurements in comparing differently coloured materials.

A Sheen Instruments Microgloss meter 60 was used to measure the gloss of the samples at 60° according to the standard ASTM D523-89.

4 MEASUREMENT OF SURFACE FRICTION

Friction between the skin and a material plays a significant role in our perception of the ‘feel’ of an object. Artefacts can feel dry, grippy, greasy, smooth, rough or slippery depending on the frictional force that develops during handling. The magnitude of this frictional force depends on contributions from adhesion and deformation. Adhesion between a probe, i.e. a finger, and test surface will increase the frictional load. Deformation of either the probe or test material will have the same effect. Friction can be quantified by defining a friction coefficient as

$$C_f = \frac{F_f}{F_v} \quad (1)$$

where F_f is the in-plane frictional force and F_v the vertical force as shown in Figure 2.

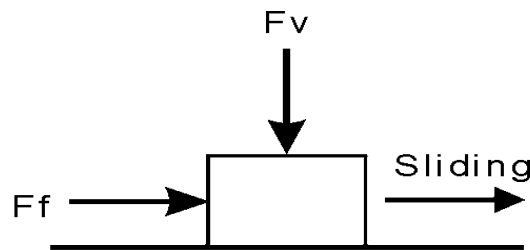


Figure 2: The frictional force, F_f is equivalent to the friction coefficient, C_f multiplied by the applied vertical force, F_v .

Two different friction coefficients can generally be defined. The static friction coefficient is defined as the peak in friction when the two surfaces just start moving over one another (Figure 3a). Before this occurs, the friction trace moves up a diagonal line as the force stored in elastically in the contact increases. The slope of this line becomes steeper as the compliance of the contact is reduced. The samples start moving relatively when the force generated by deformation of the “spring” of the contact increases to exceed the static frictional force. The dynamic friction is defined as the friction coefficient that occurs when the two surfaces are moving freely over one another.

Large differences in friction coefficient or high contact compliance can lead to the phenomenon of stick-slip where a repeated sequence of the two samples stopping and moving occurs (Figure 3b).

A friction system specially designed to quantify the frictional feel of materials (Gee et al, 2005a and b) uses strain gauged flexure elements to detect in-plane forces in both X and Y and the applied normal force in Z. This instrument is schematically shown in Figure 4. Testpieces up to 150 mm by 150 mm can be attached to the test-bed platen. Stroking the sample with one or more fingertips produces directionally dependent frictional forces and a normal force that can be used to monitor the position of the finger. These data are captured and analysed using Labview® software to produce values for the normal load, frictional load, friction coefficient, X-Y position and X and Y speed.

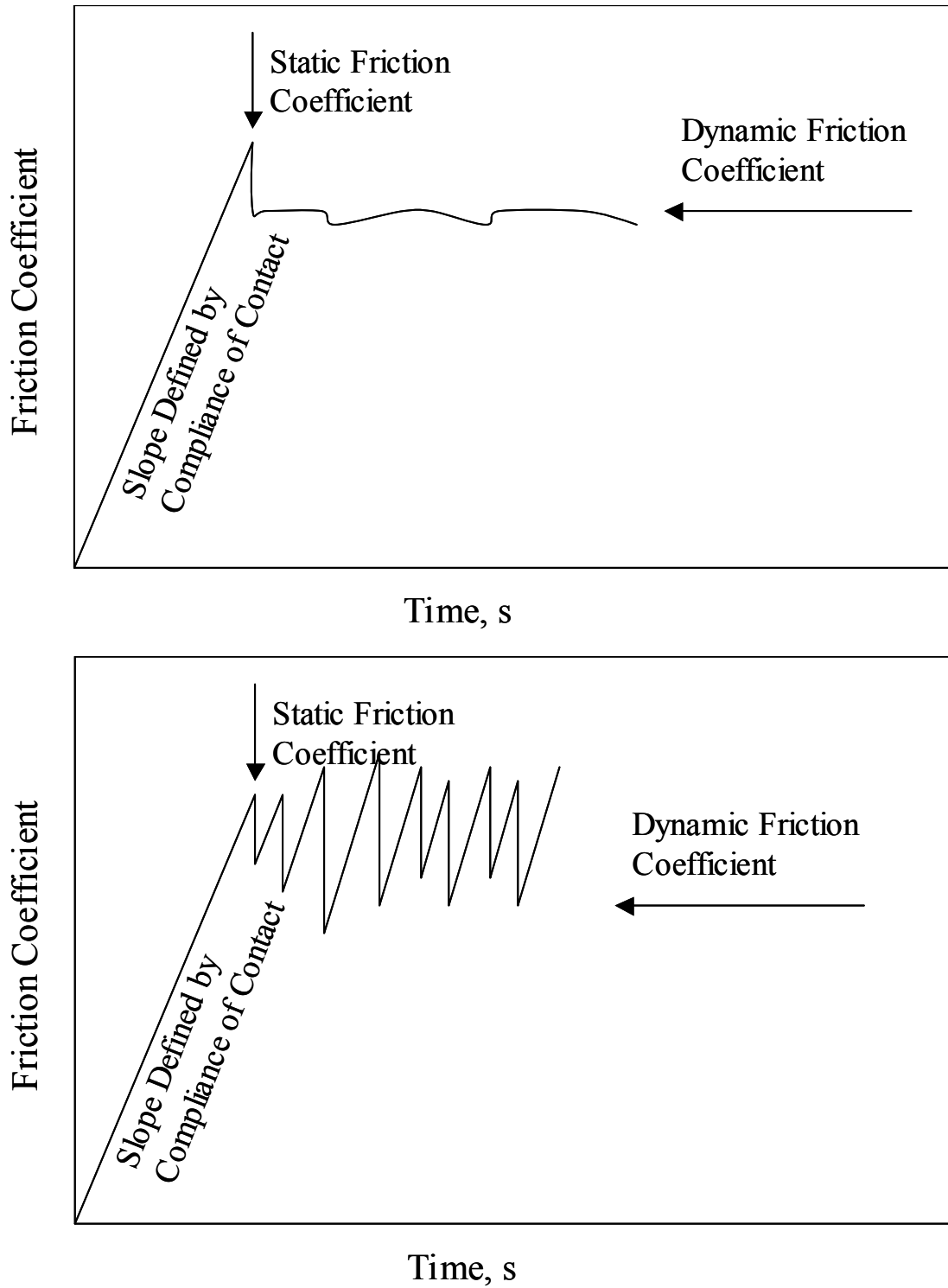


Figure 3, Schematic diagram of friction behaviour, a) static friction coefficient larger than dynamic friction coefficient, b) where large difference in static and dynamic friction coefficient or high compliance contact leads to stick-slip behaviour

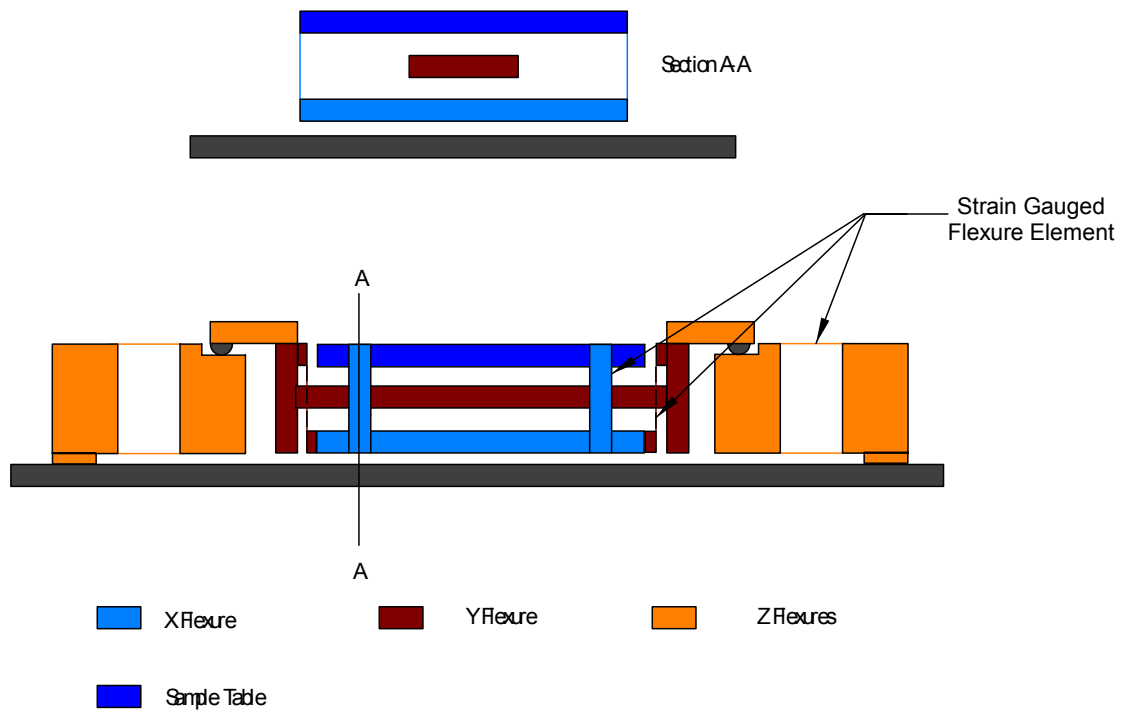


Figure 4. Schematic diagram of soft metrology friction test system

The procedure employed in this investigation was to use the right index finger as a 'probe'. The sliding velocity was approximately 0.08 m/s and the sliding distance was approximately 8 cm in the +X or -X directions (Figure 5). The contact angle was approximately 30° and contact was maintained only when the finger was moving over the surface. The normal load was subjectively kept 'constant'.

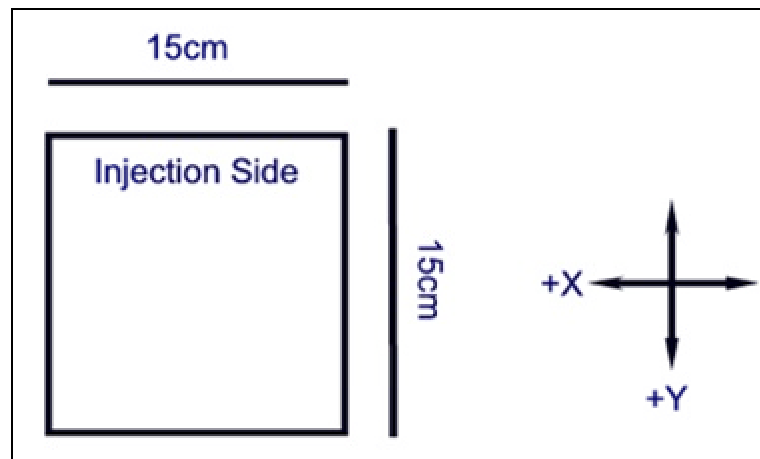


Figure 5. Schematic of sample orientation, and definition of directions. The injection side defines the entry point of the melt during manufacture.

Each measurement was conducted on an area of material that had not previously been used and lasted approximately 1s. Friction measurements were also made using hardened steel and rubber ball probes.

5 DETERMINATION OF THERMAL DIFFUSIVITY

Some materials feel cool to touch whilst others feel warm. This perception depends, in part, on the thermal properties of the material i.e. its temperature, thermal conductivity and heat capacity. At room temperature materials with large heat capacities and thermal conductivities such as copper will initially feel cool to touch since they will rapidly wick heat away from the skin. Materials with opposite properties e.g. expanded polystyrene foam will feel warm to the touch. The thermal diffusivity, α of a material is a measure of the rate at which thermal energy is dissipated and is defined as

$$\alpha = \frac{\lambda}{\rho * C_p} \quad (2)$$

where λ is the thermal conductivity, ρ is the density and C_p the heat capacity of the material.

5.1 MEASUREMENT OF THERMAL CONDUCTIVITY

Thermal conductivity measurements were made using the line source probe method (Dawson et al, 2005) using commercial apparatus, the pVT 100 (SWO Polymertechnik GmbH). A diagram of the instrument is shown in Figure 6. The sample (diameter 9.8 mm, length approximately 50 mm) is contained within a heated chamber, sealed at the top and bottom by PTFE seals. The measurement cycle consists of inserting a probe that contains both a heating element and a thermocouple into the sample maintained at constant temperature. A known voltage is then applied to the heater element in the probe for 30 s. Any change in temperature is recorded by the probes thermocouple. The heating element and thermocouple are vertically parallel to each other and separated by a distance of 0.5 mm

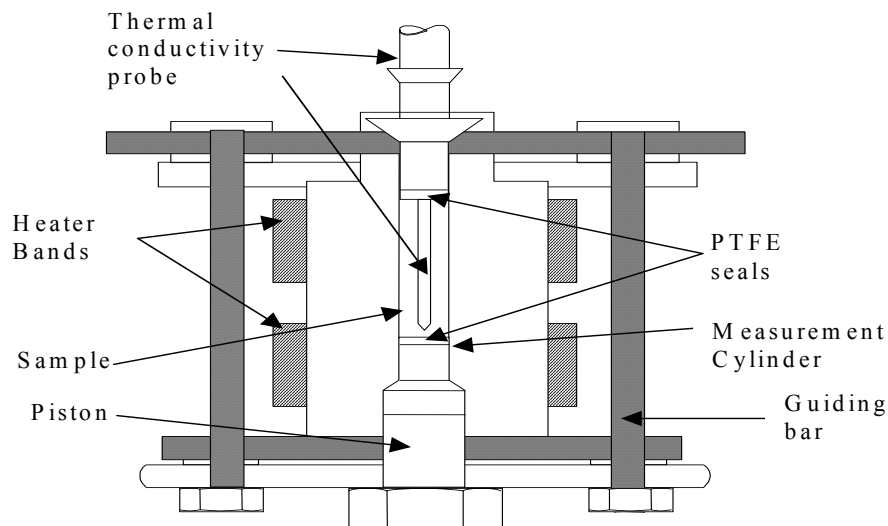


Figure 6. Schematic of the thermal conductivity apparatus

The thermal conductivity of the material can be obtained from a plot of sample temperature versus $\ln(\text{time})$ as schematically shown in Figure 7. Figure 7 shows three distinct regions. At short times the temperature rise is dominated by the initial heating of the probe. At long times the probe temperature is affected by radial heat losses from the

sample (heat loss through the wall of the sample chamber begins to dominate). Between these two extremes there is a linear region that is characteristic of the sample's properties.

It can be shown (Oemke and Wiegmann, 1994) that the temperature rise ΔT from temperature T_1 to T_2 produced within the probe, over the time interval from t_1 to t_2 is given by

$$\Delta T = T_1 - T_2 = \frac{Q}{4\pi\lambda} \ln\left(\frac{t_1}{t_2}\right) \cdot B \quad (3)$$

Where Q is the input heat and λ , the thermal conductivity.

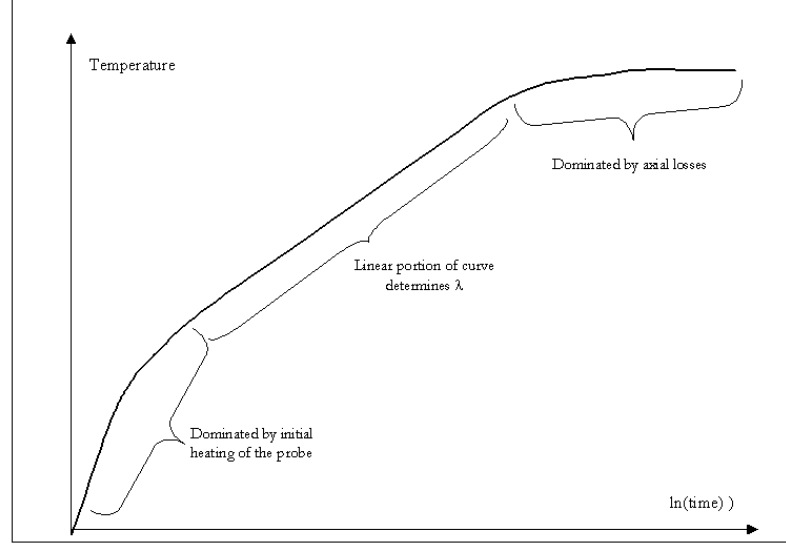


Figure 8. A schematic temperature-time profile for thermal conductivity measurements.

5.2 DETERMINATION OF SPECIFIC HEAT CAPACITY

Specific heat capacity measurements were performed on a Perkin Elmer power compensated DSC7. The basis of DSC measurements is that a sample of known weight is placed in a holder and the amount of energy, provided by an electrical heater, required to increase the temperature of the sample per degree is measured (ISO 11357-1). The test is carried out at a constant heating rate during which the heater power is continuously and automatically adjusted to compensate for heat absorbed or evolved by the sample to ensure that the sample holder temperature is identical to that of the reference holder. The energy input to the electrical heater is measured. The DSC is calibrated with a certified reference material (sapphire). Sealed aluminium pans are used to contain the samples during measurement. The sample size is 10 mg – 15 mg. Specific heat capacity measurements were made over the range -25 °C to 100 °C at a heating rate of 10 °C/min.

Based on the DSC principle (ISO 11357-1) and the definition of the specific heat capacity it can be shown that the specific heat of the specimen, c_p^{sp} can be obtained using equation

4

$$c_p^{sp} = c_p^{cal} \cdot \frac{m^{cal} (P_{specimen\ run} - P_{blank\ run})}{m^{sp} (P_{calibration\ run} - P_{blank\ run})} \quad (4)$$

where m^{sp} and m^{cal} are the masses of the specimen and sapphire calibrant respectively, P is the heat flow rate (dQ/dt) for tests on the empty pan ($P_{\text{blank run}}$) and pans containing the specimen ($P_{\text{specimen run}}$) and calibrant ($P_{\text{calibration run}}$), and C_p^{cal} is the specific heat of the sapphire calibrant. Further details of the derivation of this function and the experimental procedure are to be found in ISO 11357-1 and ISO 11357-4.

5.3 MEASUREMENT OF DENSITY

The density of the material was determined simply by measuring the dimensions of strips used for mechanical testing and weighing them. The typical dimensions of each strip used were 20 mm by 145 mm and either 2.6 mm or 3.9 mm thick.

6 MECHANICAL PROPERTIES – ‘COMPRESSIBILITY’

Squeezing an object or prodding it using one or more fingers is commonly used to ‘assess’ the ‘softness’ of a material unless ‘stretchiness’ is an important consideration. This type of assessment involves the application of essentially a shear stress in rubbery materials since the shear modulus is so much smaller than the bulk modulus. In practical terms, measurement of the material performance in shear or compression is generally more difficult than measurements made in tension. This is in part due to the difficulty in measuring the very small strains that are typically present. For many materials, where there is a significant linear relationship (Section 6.2.2) between stress and strain, the mechanical behaviour under other stress states can be calculated providing Poisson's ratio¹ is known. However this may not be true for materials such as carbon-filled rubbers where the relationship between stress and strain is usually significantly non-linear (Section 6.2.3).

6.1 SHORE HARDNESS

Soft-touch materials are typically assessed by compression during prodding, stroking or gripping. This approach is similar to measuring the indentation of a probe. Most manufacturers of elastomers or soft-touch materials measure indentation or ‘hardness’ using the Shore (or Durometer) scale. During the test, a small round end indenter with known dimensions is pushed into the material under a controlled load for a specified time period. The time delay is to allow for the strain relaxation behaviour of the elastomer. The standard test, ASTM D2240-04, specifies a minimum thickness for the material and areas where measurements cannot be made. This eliminates any contributions to the measurement from the underlying substrate from edge effects. At the end of the time period, the remaining depth of the indenter is measured and a value from 0 (full protrusion) to 100 (no protrusion) is quoted.

The indenter geometry shown for the commonly used Shore A scale (Figure 8), is selected on the basis of the nominal hardness of the material and the results are then quoted with respect to the scale used. Materials that register more than 90 on the A scale should be measured on the Shore D scale and softer materials below 20 Shore A need to be assessed using the Shore O scale. Although this type of measurement is low cost and rapid to make, the data generated are *not* regarded as a material property due to the

¹ Poissons ratio is defined as the ratio of the longitudinal to lateral strain and is usually close to 0.5 for rubbery material

complex stress state that arises during indentation. Shore hardness data are therefore used for comparative purposes.

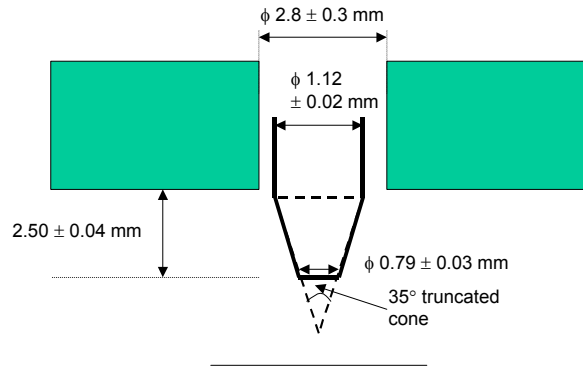


Figure 8: A schematic representation of the indenter used to measure hardness on the Shore A scale (redrawn from ASTM D 2240-04)

Measurements of Shore hardness using the A scale were made using a Ray-Ran digital durometer (model WS777) following the procedures described in ASTM D2240-04. Hardness measurements were made using two stacked 3.9 mm thick sheets to comply with the requirements of the standard that specifies a minimum sample thickness of 6 mm. A type A indenter was used and the indentation load was controlled at 1 kg. Each test was carried out at least 12 mm from any edge and the dwell time was set to 15 s.

6.2 TENSILE PROPERTIES

The act of squeezing or stroking rubber essentially involves applying a shear stress to the material. Experimentally the very small strains that are produced by these shear stresses are difficult to measure, hence it is common practice to measure properties in tension and convert them to shear using Poisson's ratio.

Rubbers are viscoelastic materials i.e. their mechanical properties depend on the timescale of the measurement. This time-dependent sensitivity increases as the measurement temperature approaches that of the glass-to-rubber transition temperature. The mechanical properties of viscoelastic materials are commonly determined using stress relaxation or creep experiments. In a stress relaxation test, a constant strain ϵ_s is applied and the time varying stress $\sigma(t)$ is measured. If a uniaxial tensile strain is applied, then a tensile stress relaxation function can be determined using the equation

$$E(t) = \sigma(t)/\epsilon_s \quad (5)$$

The quantity $E(t)$ can then be considered as a time-dependent Young's modulus. This behaviour is linear viscoelastic if $E(t)$ is independent of the magnitude of ϵ_s . For the small strains (<5%) measured for the materials studied in this investigation the cross-sectional area can be considered invariant with strain, and engineering and true stresses are approximately equal.

6.2.1 Stress relaxation measurements

Stress relaxation measurements were made in tension using a Dynamic Mechanical Analyser (TA2980). This machine was also used for dynamic property measurements (see section 6.2.2.). The specimen length between clamps was about 15 mm for each specimen tested. Cross-section dimensions were typically 5 mm by 4 mm. The applied strain, held constant in these tests, was determined as the ratio of the clamp displacement to the original clamp separation. The value for the strain determined this way is susceptible to a small error arising from the compliance of the apparatus and movement of the specimen within the clamps. Although the magnitude of these errors has not been evaluated, they are expected to be small because of the low stiffness of the specimens. Measurements of stress $\sigma(t)$ with time under strain were made at selected strains ϵ_s starting at the lowest strain and then moving progressively to higher values. A time interval between tests of at least the duration of the previous test was imposed to allow the specimen to recover from the applied strain before the next measurement began. Values for stress relaxation modulus have been derived using equation (5) and are plotted against time under the applied strain.

6.2.2 Dynamic mechanical properties

Mechanical properties can also be conveniently determined using dynamic mechanical tests in which a sinusoidal, time-varying strain is applied and the time-varying stress is measured. For a viscoelastic material, the stress and strain waveforms are out of phase. If the stress and strain waveforms are tensile and have amplitudes σ_0 and ϵ_0 respectively, and the phase difference is δ , then a dynamic tensile modulus E' can be determined using the equation

$$E' = \frac{\sigma_0 \cos \delta}{\epsilon_0} \quad (6)$$

This dynamic modulus (also referred to as storage modulus) depends on the measurement frequency and can be correlated with the stress relaxation modulus in equation (5) through expressions that relate the frequency to an effective time in a stress relaxation test.

Measurements of dynamic mechanical properties were made on the same TA Instruments machine used for the stress relaxation tests. The same specimen and inter-clamp length were also used in both tests to facilitate correlations of results from the two test methods. Dynamic mechanical tests are commonly used to determine the variation of the dynamic modulus with temperature and explore the dependence of modulus on the dynamic strain amplitude.

A test under a constant deformation rate is commonly used to determine the mechanical properties of elastic materials. A plot of stress against strain is a straight line at small strains where the behaviour is linear. With viscoelastic materials, the stress/strain plot is a curve, even when behaviour is linear viscoelastic. The shape of the curve varies with strain rate. The gradient of a stress/strain curve therefore depends both upon strain and strain rate. These phenomena are a direct consequence of the variation of deformation behaviour with time under load, and consequently, this method has limited value for determining properties such as modulus.

6.2.3 Non-linear behaviour

Rubbers are often loaded with carbon black to improve their mechanical properties or to reduce material costs. The presence of carbon particles increases properties such as $E(t)$ and E' in equations (5) and (6) and makes them strain dependent. Doubling the strain in a measurement of this type of material does not lead to a doubling of stress, and the deformation behaviour is therefore referred to as non-linear. In the case of carbon particle reinforcement, the non-linear behaviour is significant at small strains (in the region of 1% and less) and is attributed to a breakdown of the particle structure with increasing strain level. The breakdown is recoverable, but the recovery is not immediate and can take hours depending on the type of carbon black and the maximum strain sustained in a test.

6.2.4 Flexural droop testing

The flexural droop test is a simple and inexpensive method for determining a measure of the modulus of low stiffness materials. The principle of the method is to measure the deflection of the free end of a cantilever of material rigidly clamped at the opposite end, Figure 9. The deflection arises solely due to the weight of the specimen, rather than there being an imposed load. Simple beam theory (Appendix 1) can be used to interpret the deflection of the end of the beam in terms of modulus given the dimensions of the specimen and its density, provided the ratio of the end deflection to beam length is small. For low stiffness materials this may not be the case and thus the assumptions made in the beam theory analysis may not be valid resulting in erroneous modulus values being determined. However, the method may still be considered to be suitable for qualitatively ranking of materials. This method has been evaluated here for its applicability for testing elastomeric materials.

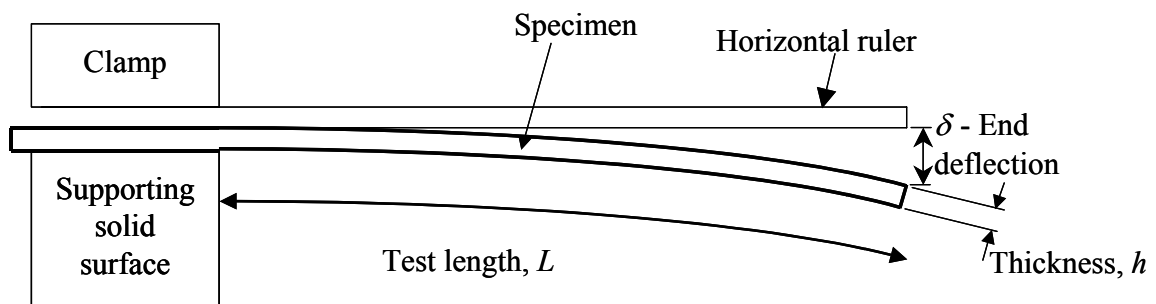


Figure 9. Schematic of flexural droop testing

For comparison reasons each of the specimens was set with the same amount of length of material (L) overhanging and thus free to droop. The vertical height of the upper surface of the specimen at the clamp from a reference plane (base plate) was determined using a vernier gauge. The vertical height of the free end of the specimen when allowed to droop was then determined using the vernier gauge from the same reference plane. The difference between these two values was taken as the deflection of the specimen due to its weight. This process was repeated with the specimen turned over to take into account any non-straightness (distortion) of the specimen that may have occurred due, for example, to the moulding process. The average of these two deflection values was taken as the true deflection value that was then used in the calculation of modulus.

7 RESULTS

7.1 ASSESSMENT OF SURFACE TEXTURE

7.1.1 Laser Profilometry

Figure 10 shows a contour map of a 5 mm by 5 mm region of sample F004 (Shore hardness 62A). The map has an incline from the bottom left to the top right of gradient approximately 20 $\mu\text{m}/\text{mm}$ due to slight sample misalignment that is subsequently removed by computation.

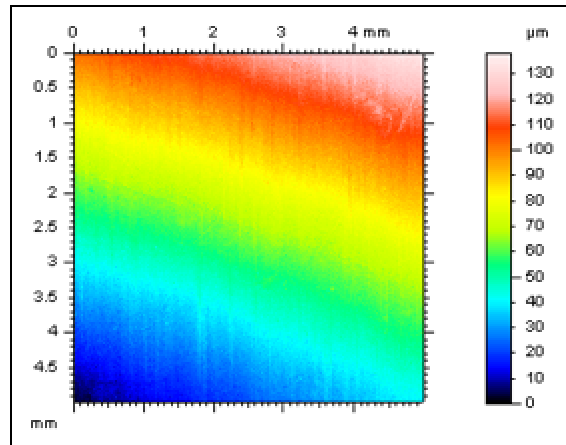


Figure 10. Contour map for as-processed TPE type F004.

These data were ‘levelled’ by applying a phase correct Gaussian filter with a cut-off wavelength $\lambda_{co} = 0.8 \text{ mm}$ (Leach, 2001). Long wavelengths ‘waviness’ (the slope) were discarded, and outliers in the remaining short wave ‘roughness’ data were removed by applying a threshold at 0.1 % - 99.9 %. A photo-simulation of the resulting processed areal data shown in Figure 11a and is compared with an SEM image, obtained at a similar magnification, Figure 11b. The SEM image was obtained at a tilt angle of 45° in order to improve the contrast of the small linear surface features.

The images show comparable features present including regular vertical striations every 0.1 mm - 0.5 mm, occasional scratches, and protrusions or particles approximately 0.1 mm - 0.2 mm in diameter

7.1.2. Gloss

Figures 12 and 13 show the mean gloss values measured at 60° for thick and thin TPE samples respectively. Each data point represents a mean and standard deviation of at least 10 measurements. From these figures it is evident that there is a difference in the finish of the samples, the upper surface being shinier than the lower surface, an effect that is more noticeable for the higher Shore hardness materials. There are also indications of a difference in the finish between thick and thin specimens, which is to be expected given that there are differences in the moulding conditions and the spacers used in the mould cavity. The variation in gloss for samples of comparable thickness is relatively minor, especially for the thick specimens where the variation between different materials is within experimental error. Stronger indications of material dependence on gloss are shown in Figure 13 for thinner specimens, the gloss decreasing with increasing Shore hardness, noting that the softest TPE, sample F005 (Shore hardness 23A), doesn’t contain carbon black.

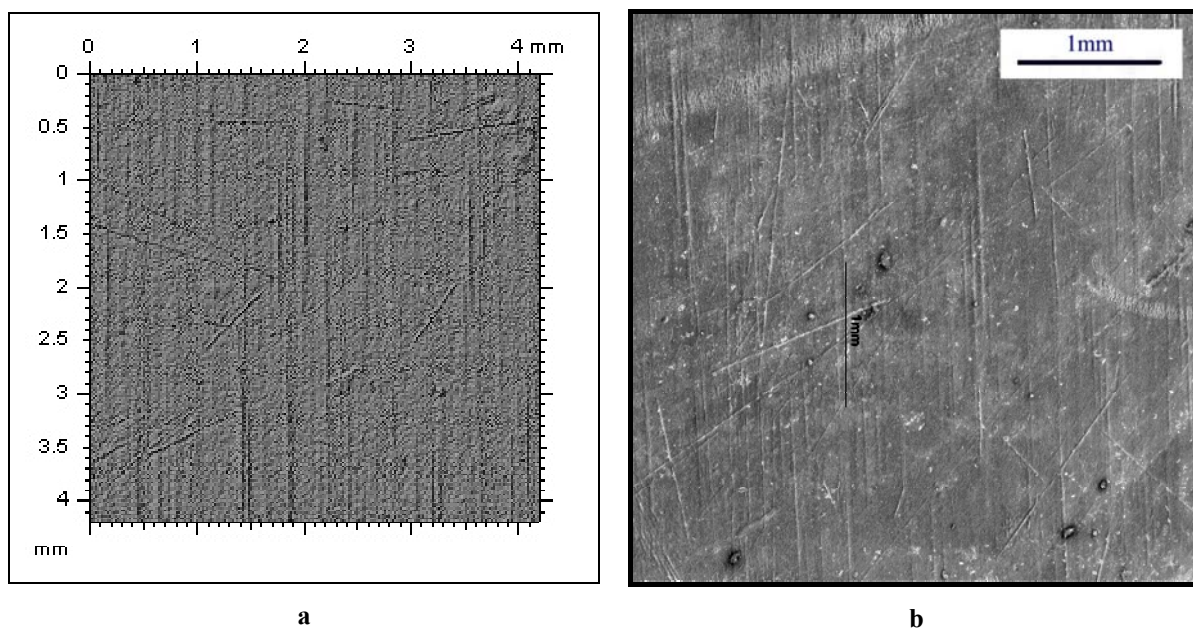


Figure 11. Photo-simulation of surface areal data and (a), Scanning electron micrograph of TPE type F004 surface (b)

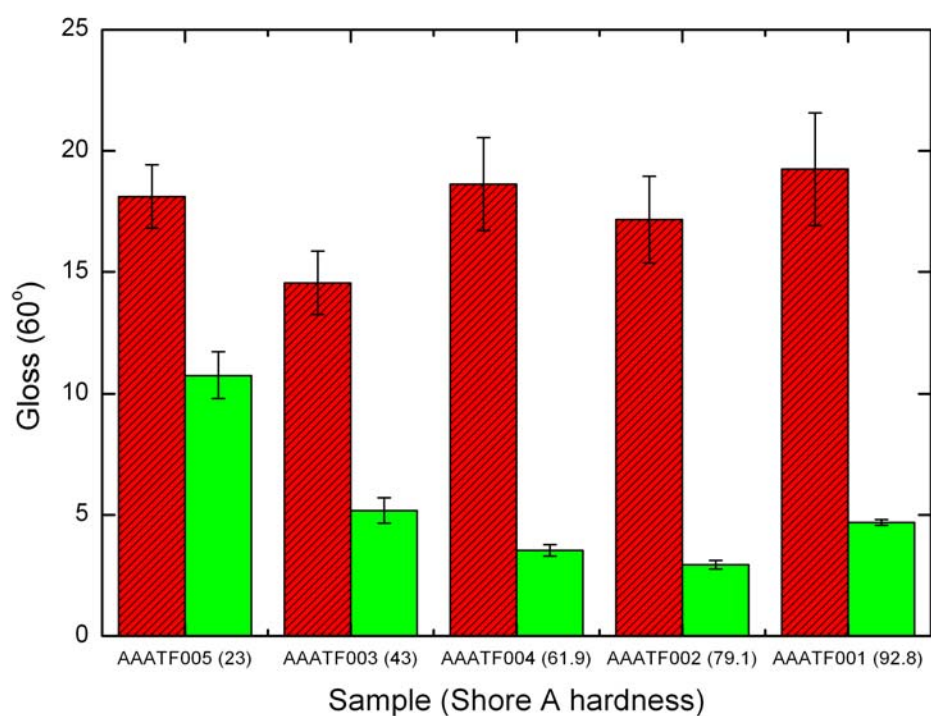


Figure 12: Differences in gloss (60) between side 1 (red) and side 2 (green) for thick samples, Shore hardness values are given in brackets. Sample F005 does not contain carbon black.

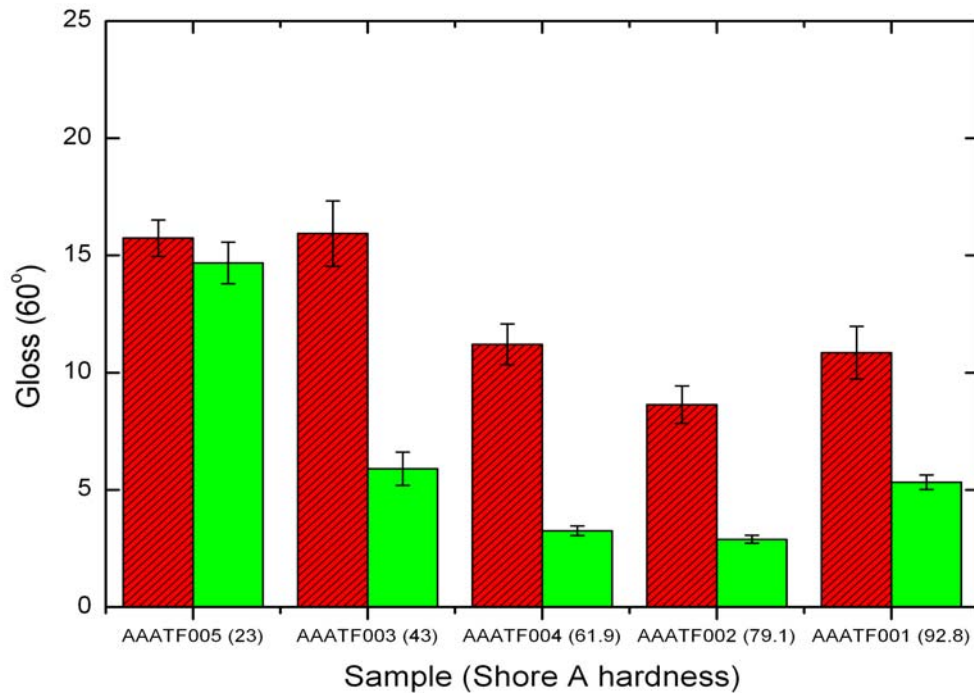


Figure 13: Differences in gloss between side 1 (red) and side 2 (green) for thin samples. Shore hardness values are given in brackets. Sample F005 does not contain carbon black.

7.1.3 The effect of wear on gloss

It became apparent during this study that the surface appearance of some of the materials changed markedly as a result of handling i.e. by the basic action of sliding a fingertip across the ‘hardest’ and ‘softest’ materials reducing the gloss.

To further investigate this phenomenon materials F001 and F005 were subjected to controlled ‘wear’ tests to simulate the effects of handling. Figure 14 schematically shows the surface of a sample divided into four sectors.

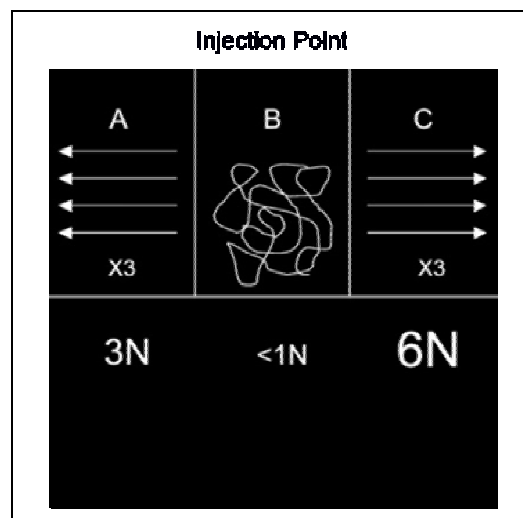


Figure 14. Schematic of TPE sample sections used for different fingertip wear tests, and directions/forces applied during wear testing

Before ‘wear’ tests were performed, the gloss (60°) of sectors A, B and C were measured. Two sets of gloss data were obtained, one parallel to the injection (X) direction and one perpendicular to it (Y direction).

‘Wear’ tests were performed on the materials by moving a fingertip over section A in the +X direction four times, with a nominal contact force $\approx 3\text{N}$, continuously monitored via force platform. The spacing between each track was approximately 1cm. Section C was subject to a similar test in the $-X$ direction, but with a nominal contact force of $\approx 6\text{N}$. As a control, section B was subject to random probing with nominal contact force $<1\text{N}$. Figures 14 and 15 show the effects of ‘wear’ on the measured gloss values.

Values displayed are the mean and standard deviations of three trials. Data labels “A” “B” and “C” indicate the region tested (Figure 14) and labels “3N” “R” and “6N” refer to the applied normal contact force.

Gloss measurements of the as-processed materials were consistently greater when sampled along the Y axis (Defined in Figure 5) compared with X measurements by 30% and 7% for F001 (Shore hardness 90A) and F005 (Shore hardness 22A) respectively. Gloss values for F001 (Shore hardness 90A) were at least 40% greater than equivalent values for F005 (Shore hardness 22A).

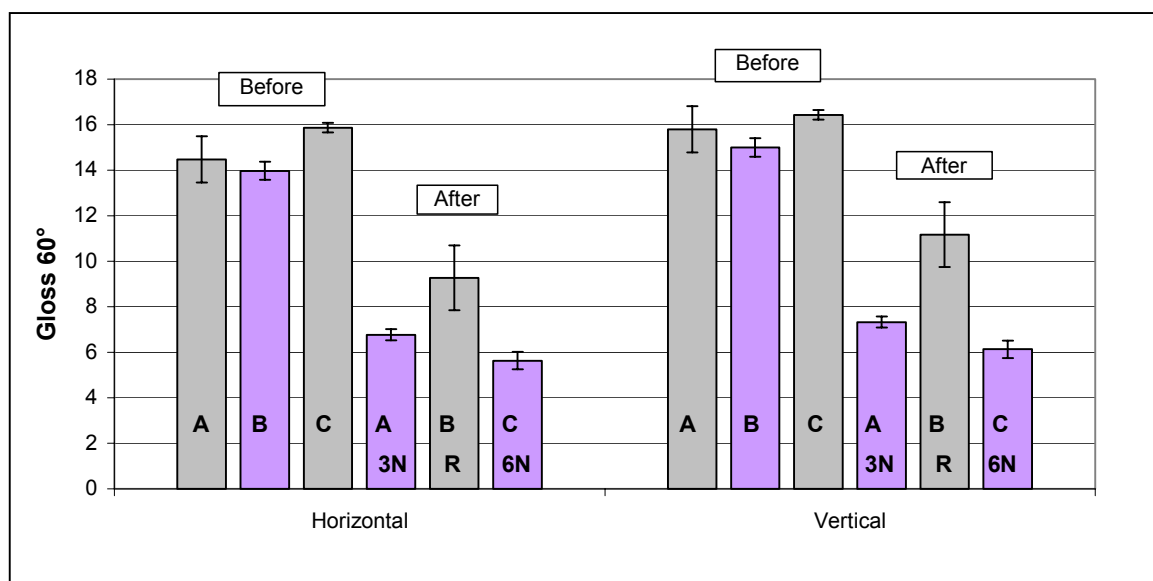


Figure 15. Variation in Gloss (60°) with sampling direction and applied normal contact force, for the ‘softest’ TPE, material F005.

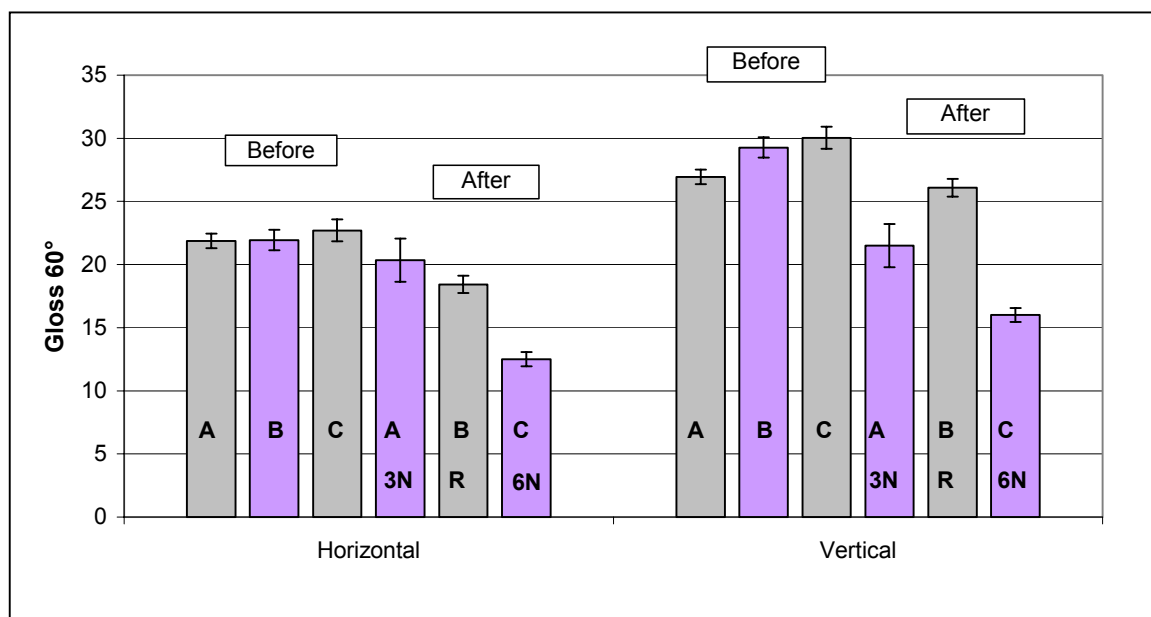


Figure 16. Variation in Gloss (60°) with sampling direction and applied normal contact force, for the ‘hardest’ TPE, material F001.

7.1.4 Surface texture evaluation following ‘wear’ tests

The surface of each TPE that had been subject to fingertip wear tests was examined using the UBM auto-focus profilometer and the Hitachi FEGSEM. Sections (1cm² in area) were cut from area C, (Figure 14) and the remaining as-processed area, using a scalpel. Tactile wear tests caused a decrease in all gloss values, which increased with normal contact force. Both controlled and random force/direction ‘wear’ test on the samples resulted in similar changes in gloss along both horizontal and vertical axes although there appears to be a significant disparity for the 3N applied load, material F001. The effect of wear had a more profound effect on the gloss of the softer material F005 which was reduced by an additional 20-25% compared with the harder material F001.

		<i>Material</i>					
		<i>F001</i>			<i>F005</i>		
		<i>Fingertip Force (N)</i>					
		3	Random	6	3	Random	6
Reduction in gloss (%)	Horizontal	20	16	45	54	35	64
	Vertical	6	11	47	54	29	64

Table 3. Summary of the percentage decrease in gloss of samples F001 and F005 following tactile wear tests.

The SEM images of material F005 contained unidentified rectangular deposits approximately 10 µm by 45 µm when viewed from above, some of which appeared embedded in the surface (Figure 17).

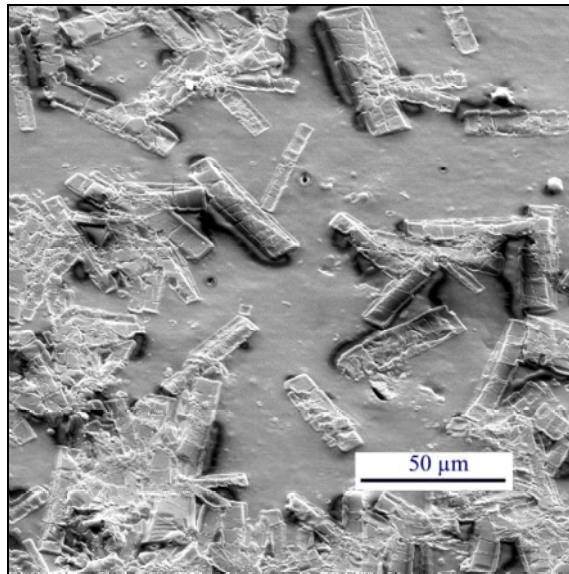


Figure 17. Scanning electron micrograph of the surface of TPE type F005 has surface features that appear to be paper fibres.

Figures 18a, b are the results of a subsequent study with an optical microscope. Almost all of the surface is contaminated with the rectangular deposits (a), which are of a similar morphology to the fibres that constitute the tissue in which samples were stored (b). No further surface assessments were made using this material.

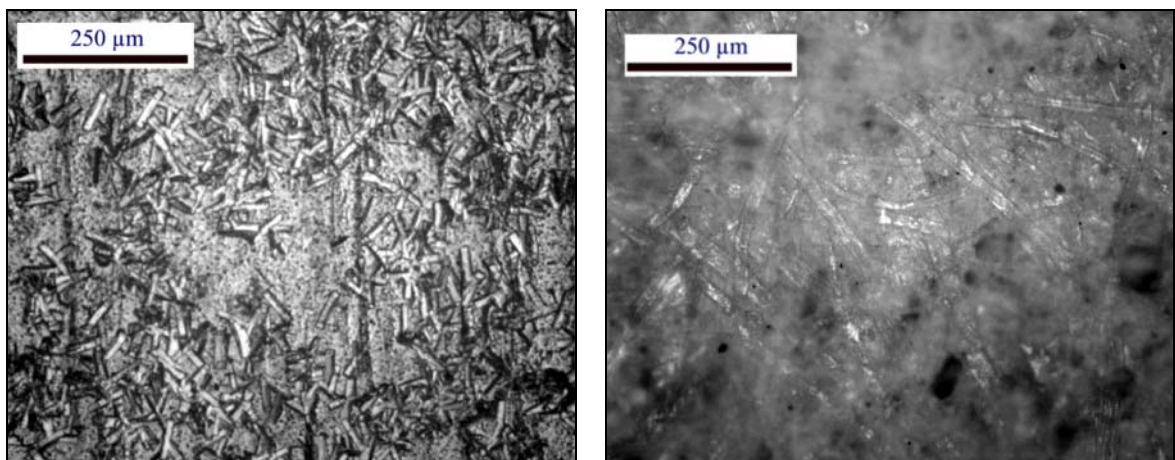


Figure 18. 10X optical micrographs showing a comparison of the surface features of sample (a) and the tissue used as an interleaf to keep samples apart during storage (b)

Figure 19 shows SEM images of an as processed sample F001 and one that has been mildly abraded due to handling. A difference in surface topography is apparent suggesting that the act of handling removes a fragile surface bloom revealing an underlying texture that is rough over the scale 1- 2 μm .

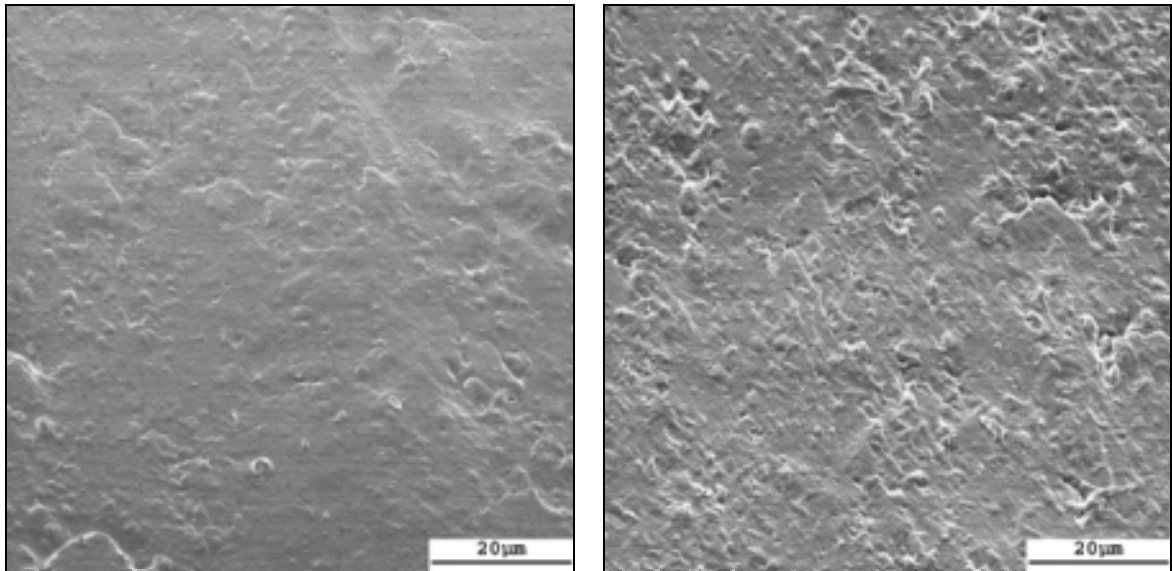


Figure 19. SEM images of F001. (a) As-processed and (b) after being subjected to a 6N tactile ‘wear’ test (b)

Figures 20 and 22 are axonometric² surface profiles of the as processed sample F001 and Figures 21 and 23 are of the surface after the 6N tactile wear test. The differences between Figures 20 and 22 and 21 and 23 are in the cut-off frequency of the Gaussian filter as described in the captions (Leach, 2001). The area scanned was 0.25mm² at a scanning rate of 1000 points/mm.

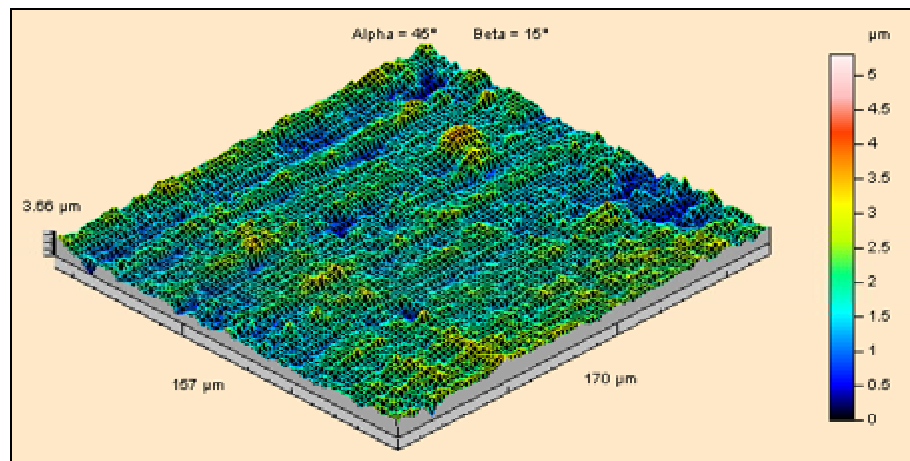


Figure 20. Axonometric surface profile for as-processed TPE type 001, Gaussian Filter 0.08mm, Threshold 0.1% - 99.9%

² Axonometric projections are plans typically viewed at 45° with the depth added vertically. All lengths are drawn as their true lengths

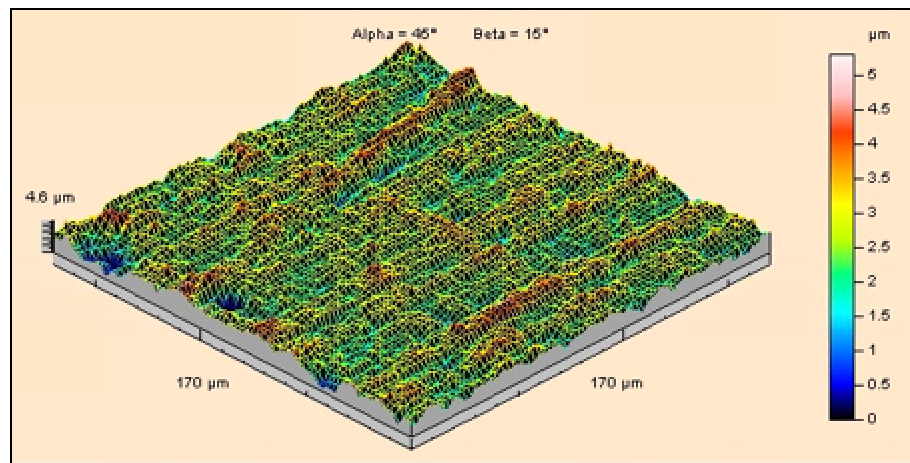


Figure 21. Axonometric surface profile of TPE type 001 following 6N tactile wear test, Gaussian Filter 0.08mm, Threshold 0.1% - 99.9%

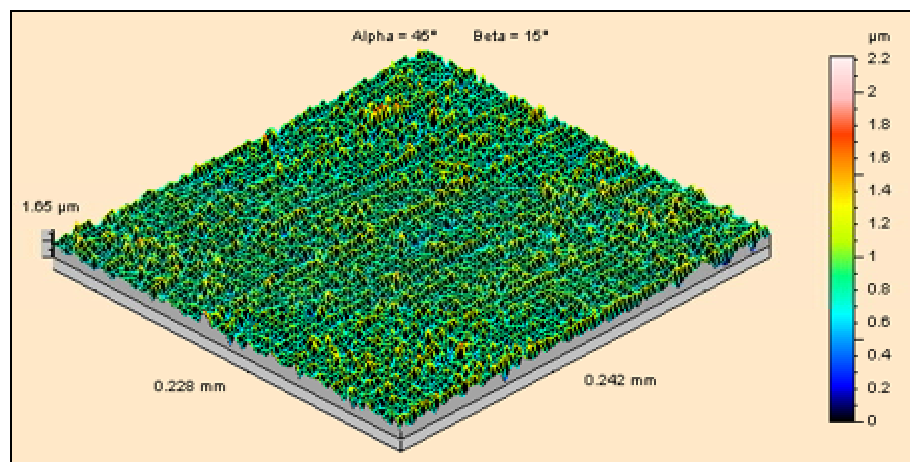


Figure 22. Axonometric surface profile of as-processed TPE type 001, Gaussian Filter 0.008mm, Threshold 0.1% - 99.9%

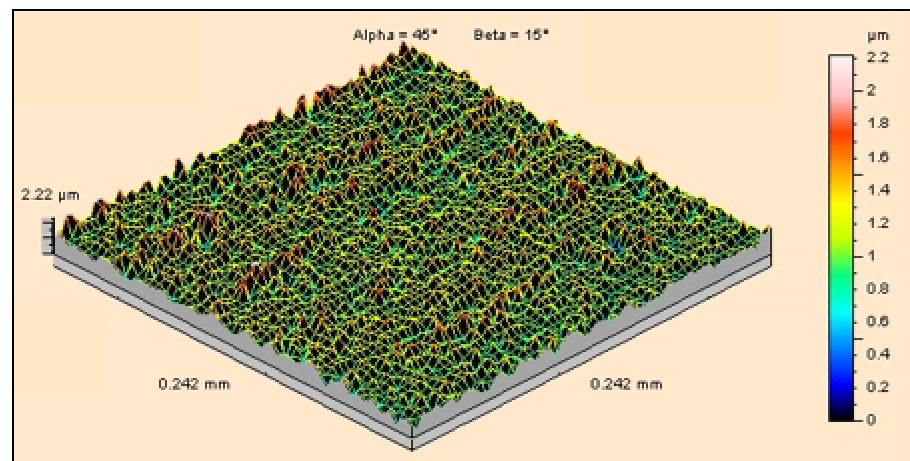


Figure 23. Axonometric surface profile of TPE type Ff001 following a '6N tactile wear test', Gaussian Filter 0.008mm, Threshold 0.1% - 99.9%

The surface on this scale is not very homogeneous as shown in Figure 20. In Figures 22 and 23 the larger scale features present in Figures 20 and 21 are excluded as waviness and only features $< 8\mu\text{m}$ in size remain. This information is used to generate the parameters that characterise the surface. The surface representations are much more homogeneous, with less irregularity and the 6N sample (Figure 23) exhibits a greater level of height variance on this scale, over the as-processed material (Figure 22).

Sq values³ of the profiles were calculated using Mountains software. Each profile was sectioned into four quarters and Sq parameters were determined for each area. The standard deviation of the sectioned Sq parameters is a measure of homogeneity and is treated as the error. Figures 24 and 25 illustrate the change in Sq with surface treatment for data filtered using cut-offs of 0.08 mm and 0.008 mm respectively. The variation in Sq across the each sample was much greater with a filter cut-off of 0.08, than with a filter cut-off of 0.008 mm. For dimensions smaller than 0.008 mm, Sq increases with nominal contact force used in the tactile wear test.

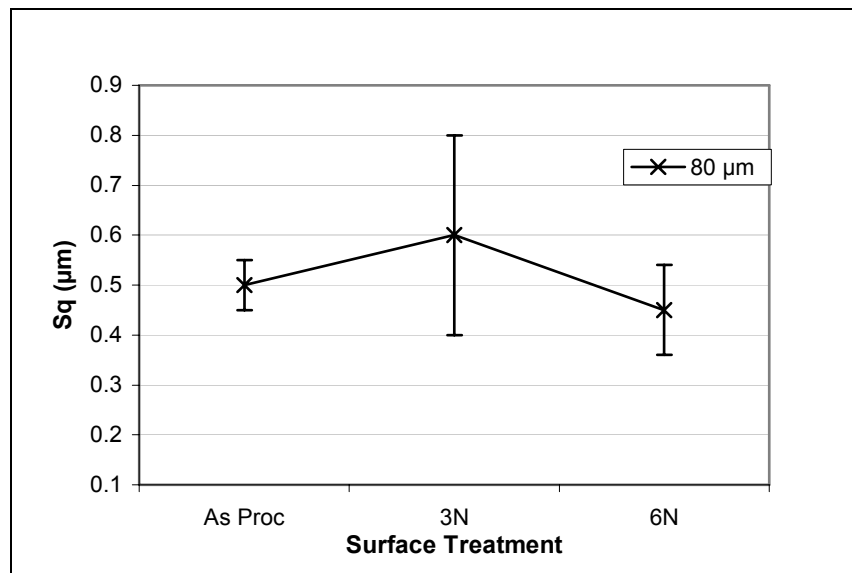


Figure 24. Variation in Sq with wear state, processed using a filter cut-off of 0.08mm

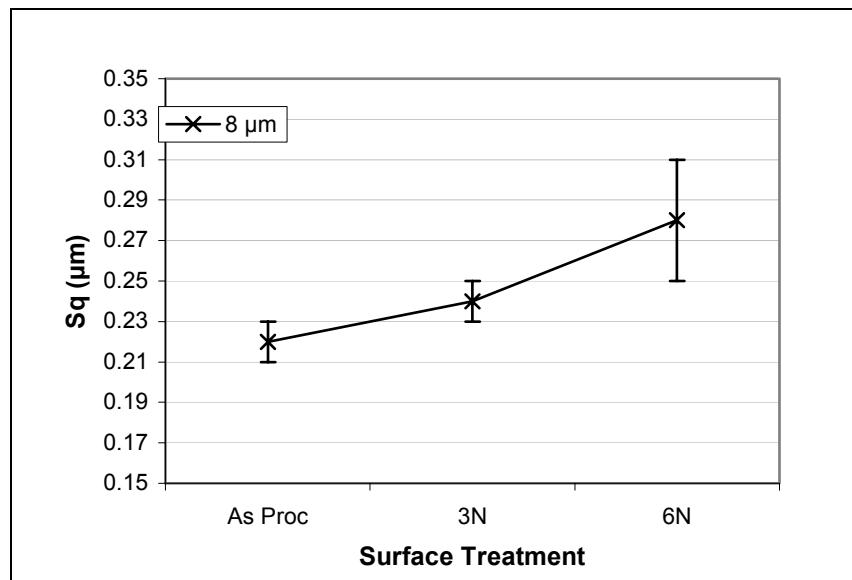


Figure 25. Variation in Sq with wear state, processed using a filter cut-off of 0.008mm

³ Sq is the root mean squared deviation of the surface heights from a midline (Tomlins et al, 2005)

For completeness, Figure 26 shows how the mean Gloss (60°) value varies with Sq ($\lambda_{co}=8\mu\text{m}$) for the F001 type TPE. Although the associated errors are large, the gloss generally decreases with increasing Sq. The random-force test sample was included on the basis of its measured Sq, and its gloss is slightly higher than the trend suggests

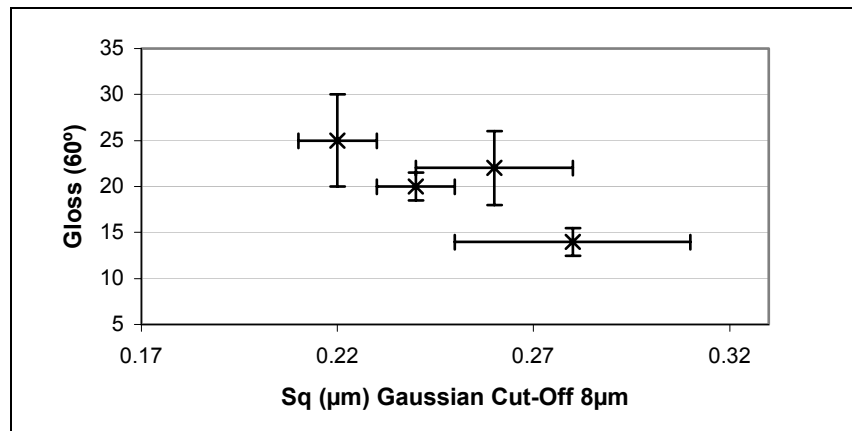


Figure 26. Variation in gloss with Sq of 0.25mm^2 surfaces filtered using a 0.008mm cut-off

7.2 SURFACE FRICTION

Measurements of skin-surface friction were obtained using the right index finger from a 23 year old male. It was found that the average normal force applied during ‘natural’ tactile exploration was 1N - 4N. Friction between samples and a fingertip was sensitive to test conditions and subject to noise. Stick-slip was frequently observed, especially when a large normal force was applied.

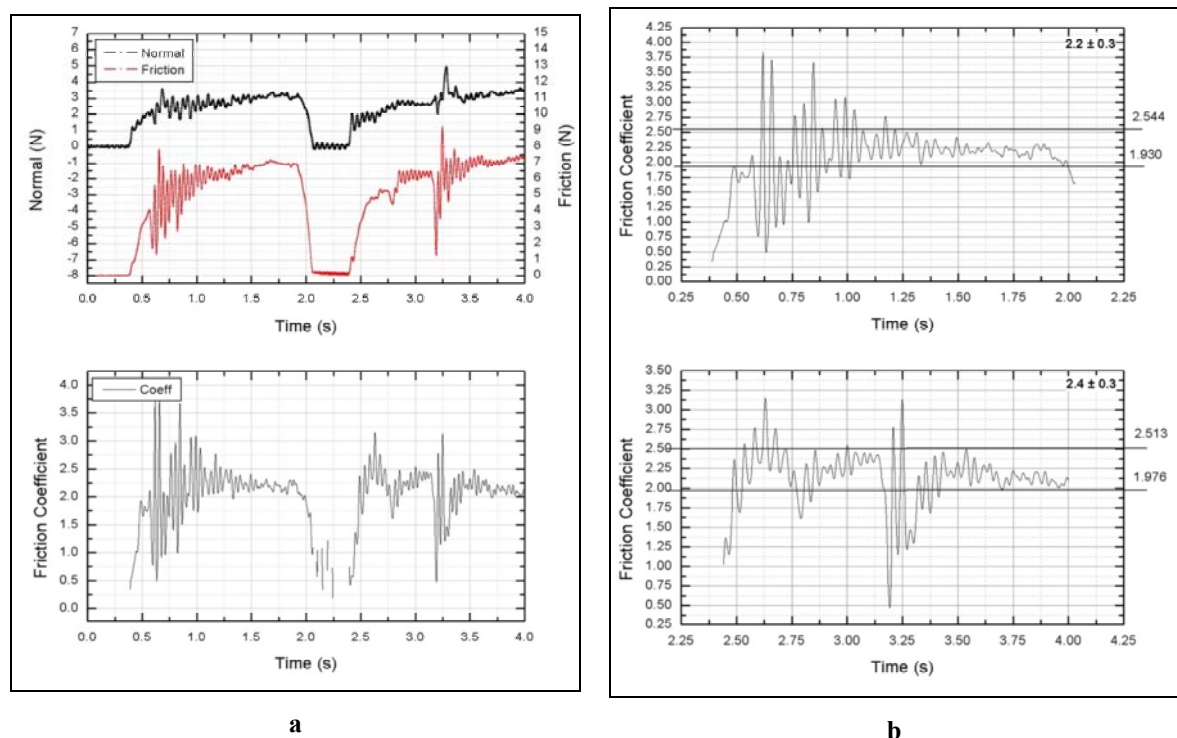


Figure 27. Typical tactile friction data for material F002 All data (a) upper and lower bounds of the friction coefficient (b).

Figure 27a shows a plot of the frictional force and normal load produced by two successive sweeps of a finger over material F002. The friction coefficient generated according to equation 1 is shown in Figure 27b with upper and lower bounds estimated by eye. Comparative measurements were also made using both a steel ball and rubber ball probes. These tended to produce more reproducible data than a fingertip as shown in Figures 28a and 28b. Figure 29 shows a comparison of the friction coefficient measured by three different probes. These results suggest that there is little difference in the skin-rubber friction coefficients for these materials. There is a reasonable agreement between the finger, metal ball and rubber ball friction coefficients for materials F003 and F004 that implies that the friction coefficient is not particularly sensitive to the nature of the 'probe'. This is apparently not the case for materials F001 and F002 where the skin-rubber friction coefficient is significantly higher than that measured for the rubber ball and metal ball probes. These differences in frictional behaviour may reflect higher levels of adhesion between a fingertip and these harder materials due to deformation.

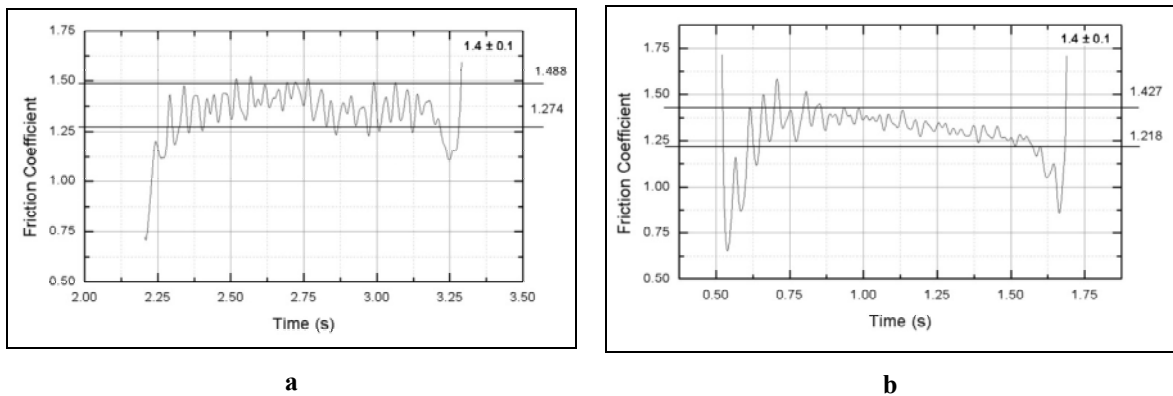


Figure 28. Typical friction data for trials with the spherical steel probe on TPE 002.

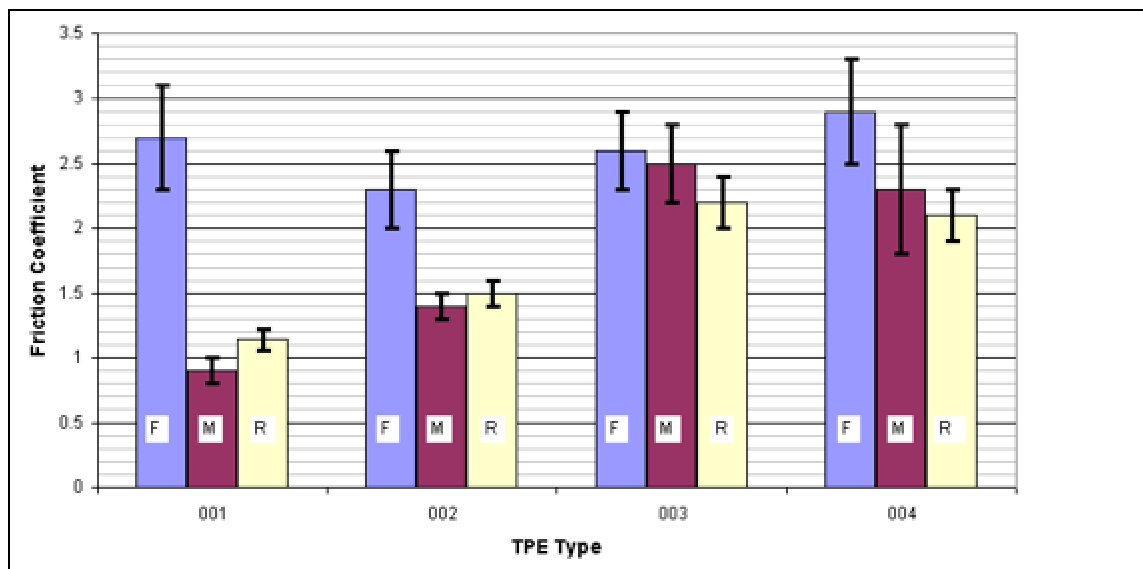


Figure 29. The dependence of the mean friction coefficient on different materials and probe types (F=finger, M=metal ball, R=rubber ball).

7.3 THERMAL PROPERTIES

7.3.1 Thermal conductivity

Figure 30 shows the temperature dependence of the thermal conductivity of materials F001 to F005 measured at atmospheric pressure. The thermal conductivity of all samples increases with increasing temperature across the temperature range 20 °C to 180 °C, Figure 30 and Table 4. One sample, AAATF003, was tested three times to determine the repeatability of the measurements. The results indicate that there are significant differences between the materials at lower temperatures, except that AAATF001 and F004 which are similar. As temperature increases the differences between the materials decrease to a negligible amount.

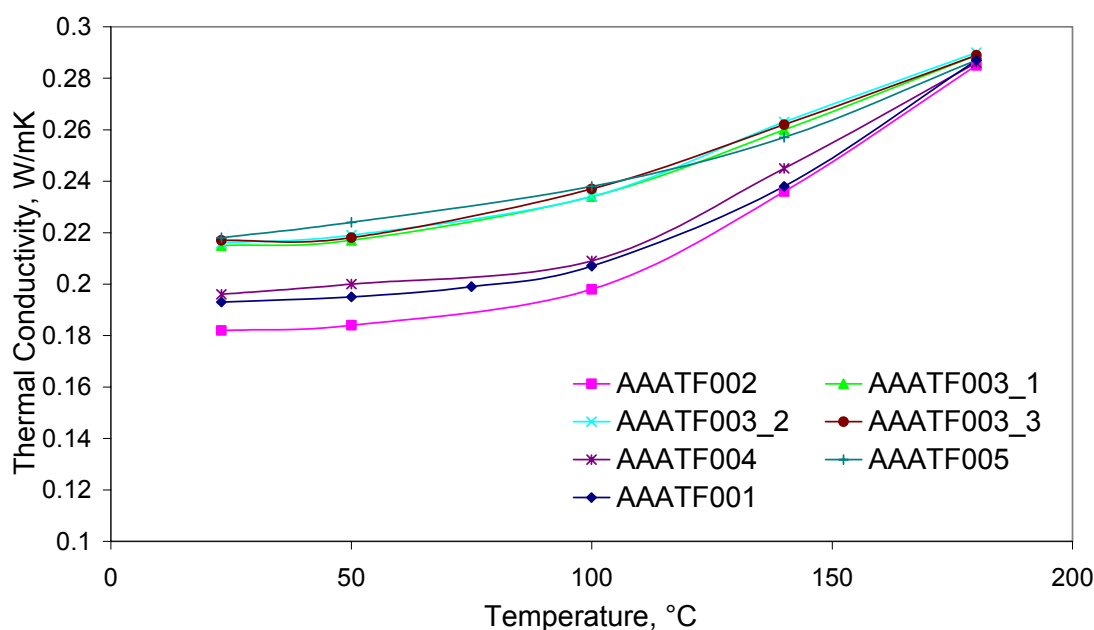


Figure 30. Thermal conductivity of TPE samples over the range 23 °C to 180 °C, at atmospheric pressure.

7.3.2 Heat capacity

The variation of specific heat capacity, calculated according to equation 4, with temperature is shown for all materials in Figure 31. All of the samples appear to show a minimum in C_p at approximately 20 °C although samples F001 and F004 do not show the pronounced minima seen with the other materials.

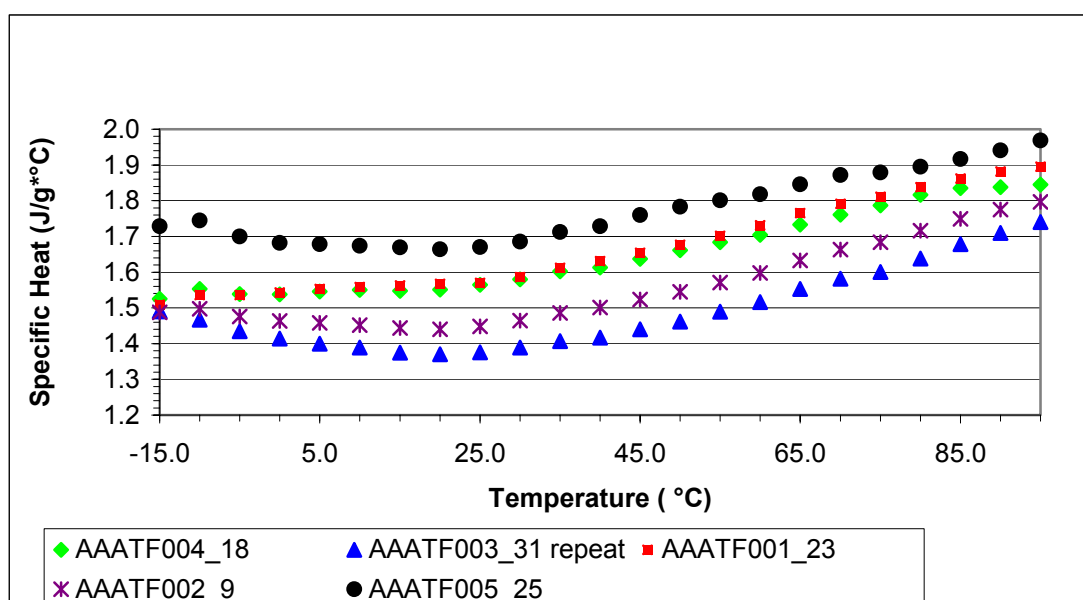


Figure 31: The variation of specific heat with temperature for samples 1 to 5. Note that samples F001 and F004 show identical behaviour.

7.3.3 Thermal diffusivity

Values of thermal diffusivity calculated from thermal conductivity, heat capacity and density measurements following equation 2 are shown in Table 4. These values are consistent with similar rubber-like materials that have been reported elsewhere (Bafnec et al, 1999).

Sample	Shore hardness (A scale)	Heat capacity J/(g °C)	Density kg/m ³	Thermal Conductivity W/(m K)	Thermal Diffusivity *10 ⁻⁵ m ² s ⁻¹
AATF001	92.8 (0.6)	1.570	1.136	0.193	0.108
AATF002	79.1 (1.9)	1.448	1.155	0.182	0.109
AATF003	43.0 (0.9)	1.376	1.194	0.217	0.132
AATF004	61.9 (0.4)	1.565	1.121	0.196	0.112
AATF005	23.0 (0.9)	1.670	1.047	0.218	0.125

Table 4: Calculated thermal diffusivity at 23°C

7.4 MECHANICAL PROPERTIES

7.4.1 Shore hardness

Measurements of Shore hardness (A scale) are shown in Table 5. Two samples of each material were tested, and at least ten measurements were made per sample. Specimens were stacked to ensure a minimum thickness of 6 mm according to the requirements of ASTM 2240-04. These data indicate that there are no significant differences in stiffness between stacks constructed from two thick specimens or three thin specimens.

Sample	Shore hardness (A scale)	
	Thick sample	Thin sample
F001	92.8 (0.6)	91.4 (0.8)
F002	79.1 (1.9)	79.5 (0.8)
F003	43.0 (0.9)	43.1 (1.2)
F004	61.9 (0.4)	62.2 (0.9)
F005	23.0 (0.9)	25.6 (0.6)

Table 5: The mean and standard deviations of Shore A hardness data (average of 10 measurements per sample).

7.4.2 Non-linear tensile behaviour

7.4.2.1 Stress relaxation

Figures 32 to 35 show stress relaxation results for each of the samples, F001, F005 and F004. For each material, the stress relaxation modulus is seen to decrease with increasing time and applied strain. The dependence of modulus on strain is greatest for the material where the reinforcing effect of the carbon is greatest.

7.4.2.2 Dynamic mechanical properties

Figure 35 shows the dependence of dynamic modulus on dynamic strain amplitude for the material F004 (Shore hardness 62A) at a frequency of 1 Hz. At the end of each test, specimens were allowed to recover for a period of 1 hour before the start of the next test to allow the carbon structure to reassemble prior to testing again at the lower strains. No attempt has been made, however, to monitor recovery to establish whether this time period is sufficient.

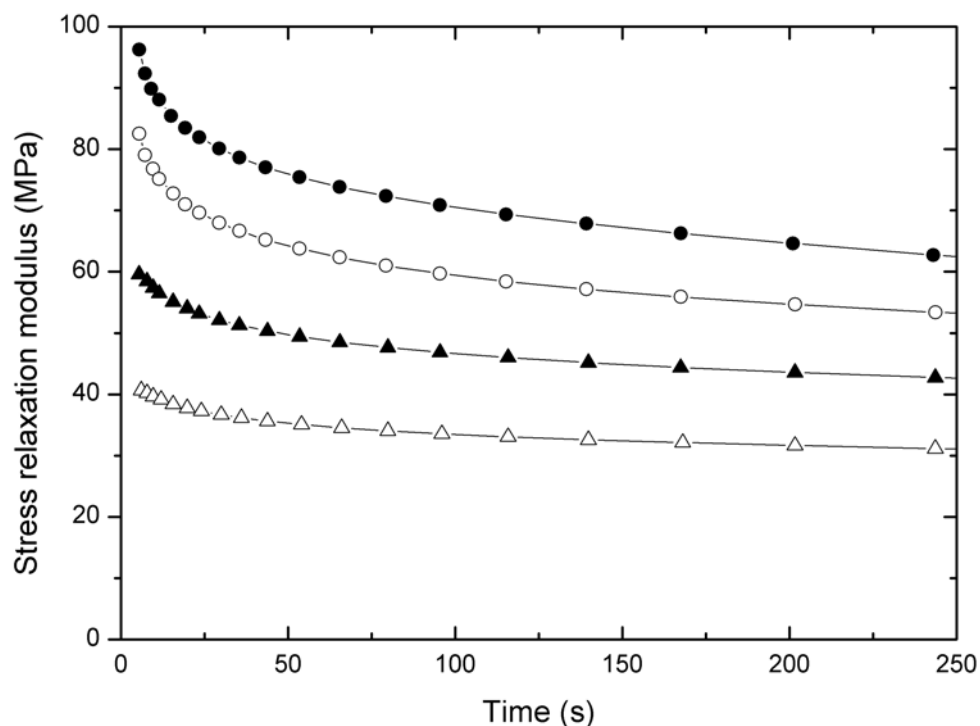


Figure 32. Stress relaxation results for material F001 at different strain levels (● = 0.2%, ○ = 0.5%, ▲ = 1%, △ = 2%)

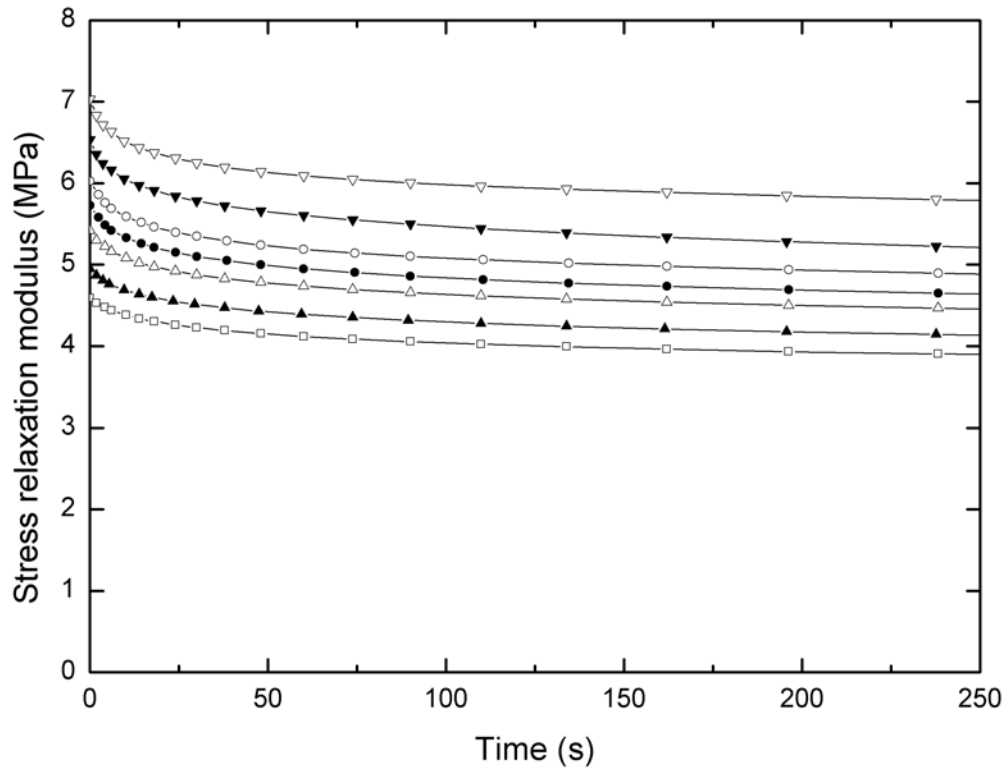


Figure 33. Stress relaxation results for material F004 at different strain levels (∇ = 0.2%, $\blacktriangledown$ = 0.5%, $\circ$ = 1%, $\bullet$ = 1.5%, Δ = 2%, $\blacktriangle$ = 3%, $\square$ = 4%)

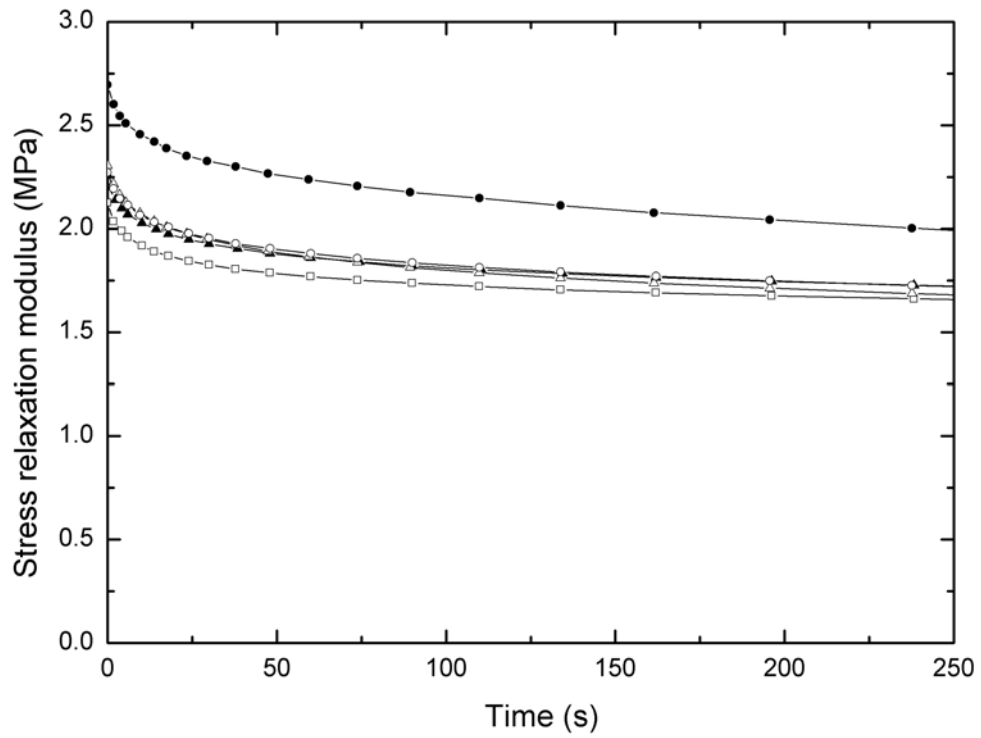


Figure 34. Stress relaxation results for material F003 at different strain levels ($\bullet$ = 0.2%, $\circ$ = 0.5%, Δ = 1%, $\blacktriangle$ = 1.5%, $\square$ = 3%)

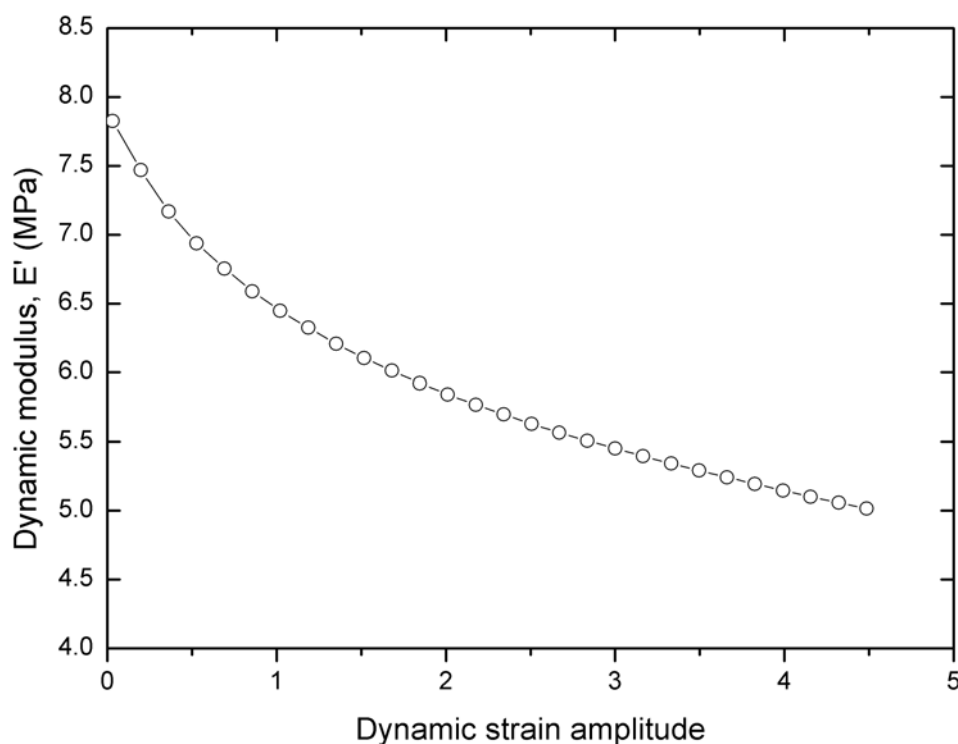


Figure 35: The dependence of the dynamic storage modulus E' on dynamic strain amplitude for material F003.

7.4.2.3 Droop testing

Flexural tests were performed on the five elastomers using specimens that were approximately 19 mm in width (b), 2.6 mm in thickness (h) and 145 mm of overhanging length (L) at room temperature. The specimens were cut from the plaque mouldings in the direction of flow. End deflection and modulus values for the materials were obtained as presented in Table 7.

For comparison, data obtained from tensile testing have also been presented (Figure 36). Tensile modulus values were determined based on the change in true stresses and strains over the true strain range 10% to 50% as this provided reasonably small scatter in data. They were also determined from the tensile tests at the same strains as were occurring in the droop tests for each material. However, the latter data are considered to be more unreliable due to the data being determined at strains that are very low for the tensile testing set-up used. These data show qualitative agreement in that the flexural droop method ranks the materials in the same order as the tensile test. Furthermore, the flexural droop testing also shows the same ranking as Shore A hardness values.

For the high stiffness materials the quantitative agreement of the flexural modulus values with the tensile modulus values obtained using data from 10% to 50% is poor as the strains in the droop test are significantly lower in comparison and the results exhibit significant strain dependence at low strains. However, comparing flexural modulus values with tensile modulus values at strains equivalent to that in the flexural droop tests indicates significantly better agreement, although the accuracy of the tensile data at such low levels of strain is questionable. The level of quantitative agreement between tensile and flexural modulus results becomes worse with decreasing stiffness and indicates that the flexural droop method over-predicts the modulus of lower stiffness materials. This is considered to be due to the theory not taking into account the effects of such large

deflections occurring, as indicated in Table 6. The use of various lengths for the overhanging specimen to obtain a similar maximum strain in all tests was assessed. However, for the lowest hardness materials the lengths and deflections become small and the errors in the measurement start to grow significantly.

	AAATF001	AAATF002	AAATF004	AAATF003	AAATF005
Shore A hardness	92.8	79.1	61.9	43	23
Density, g/cm ³	1.14	1.16	1.12	1.19	1.05
End deflection, mm	3.9	9.3	22.9	60.1	95.9
Flexural droop modulus, MPa	99.4	47.9	23.3	8.2	5.2
Tensile modulus, MPa (determined @ 10% to 50% strain)	10.6	7.0	5.6	2.8	1.6
Estimate of tensile modulus at similar strains to droop test, MPa	84	35	14	4	1.2
Maximum strain in droop test	0.2%	0.4%	0.8%	2.3%	3.5%
Deflection/length ration (δ/L)	0.03	0.08	0.20	0.52	0.83

Table 6: Modulus values determined from flexural droop testing

In conclusion, the simple, quick and inexpensive method has demonstrated its suitability for ranking materials and yields correct order-of-magnitude values for modulus. Through careful selection of test geometry the accuracy of the method can be improved, but care is required to ensure correct comparison of data as such data are strain dependant.

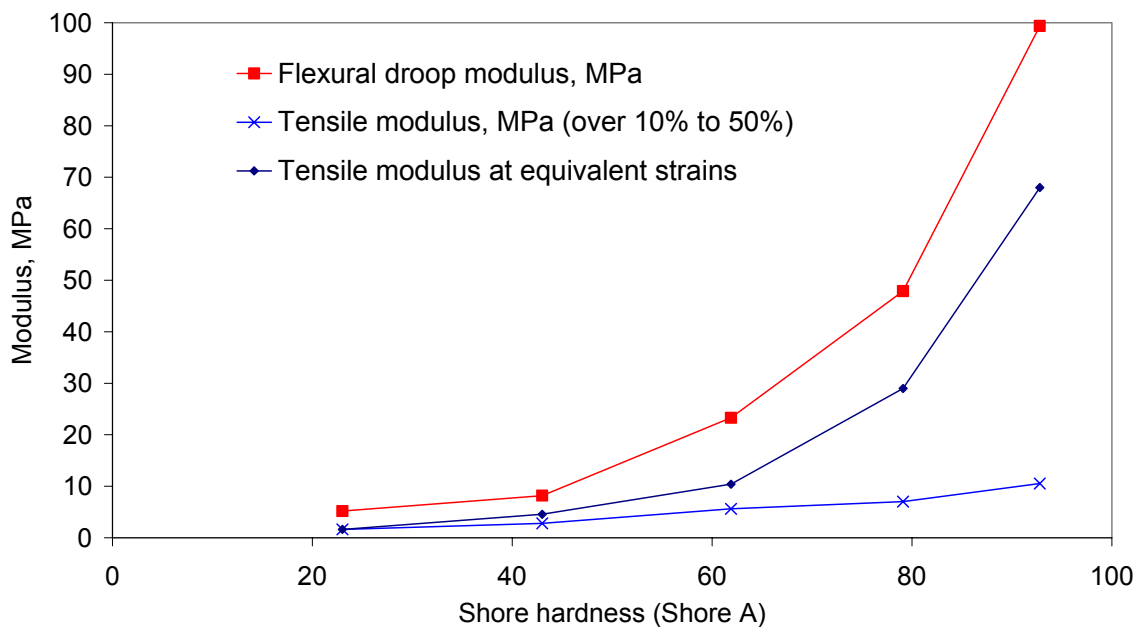


Figure 36: Comparison of modulus values from flexural droop and tensile testing for a range of material Shore hardnesses

8 DISCUSSION

This report describes methods for measuring physical properties of rubbery materials that are believed to play a key role in perception i.e.

- Surface texture

- Surface friction
- Thermal diffusivity, a combination of thermal conductivity and heat capacity
- ‘Compressibility’ – a measure of the materials response to prodding or squeezing

These data will be used to:

- Develop models for predicting the materials response to indentation by probes when used as a thin over-moulding, a common application for soft-touch materials.
- Assess potential links between sensory perception of a material and its physical characteristics.

The materials chosen for this study are thermoplastic elastomers based on styrene-ethylene-butylene-styrene copolymers. These materials can like other soft-touch compounds be formulated to produce a product range that spans the Shore A hardness scale through the addition of additives including carbon black. Square mouldings (150 mm by 150 mm) are suitable for a wide variety of physical tests.

Surface texture: Gloss measurements offer a low cost, rapid method for comparing surface finishes of materials that can identify differences between surfaces. Some care needs to be exercised when comparing materials of different colours due to the presence of pigments. It should be noted that the surface gloss of rubbery materials can easily be reduced by as much as 50% through the simple act of handling the material. This sensitivity raises concerns over the value of this parameter for un-treated samples. Changes in the measured gloss data can be correlated with quantifiable changes in surface texture based on data collected by laser profilometry or white light interferometry. These latter techniques can be used to obtain 2D profiles or 3D areal textures that can be analysed to provide measures of roughness such as Ra (2D) or Sq (3D). The surface of soft rubbery materials can be unduly tacky which can make it difficult to keep it clean for measurement purposes attracting fibres and other particles that may not be easily observable by the naked eye. This susceptibility to contamination again raises concerns over how the sample should be handled in order to produce realistic data.

Assessment of surface texture can be used to identify and quantify patterns in the surface that reflect the finish of the mould tool which may impart an anisotropic feel to samples.

Surface friction: Fingertip – material friction coefficients can easily be determined from measurements of normal force and frictional load via a force platform instrument. Such measurements when compared with the industry standard probes, a rubber ball and steel ball can reveal differences in the friction coefficient, especially for ‘harder’ materials. This disparity is probably due to an additional adhesion component linked with the fingers deformability. Stick – slip type behaviour is often observed during movement of a fingertip over rubbery materials.

Thermal diffusivity: The thermal conductivity, heat capacity and density of a material need to be measured before its thermal diffusivity can be calculated. The thermal diffusivities of the SEBS materials studied here tend to decrease with increasing Shore hardness which may reflect changes in the concentration or type of carbon black or other additives that have been used to adjust the properties of the materials.

Mechanical properties: Measurement of Shore hardness (A scale) can be used to differentiate between different materials using a low cost, rapid measurement method although it should be recognised that this parameter is not recognised as a material property. This limitation is due to the complexity of the stresses induced in the sample

during indentation. The stress-strain relationship within rubbery materials is complicated by the dependence of modulus on both time and strain that for the materials studied here increases with increasing carbon content during a stress relaxation test. Similarly for small strain dynamic mechanical tests the storage modulus is dependent on both frequency and dynamic strain amplitude.

9 ACKNOWLEDGEMENTS

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APPENDIX 1: ANALYSIS OF FLEXURAL DROOP TEST DATA

The analysis assumes that the beam is uniformly loaded over its length with a total load of W (Newtons) due solely to its mass. The load W is thus given by

$$W = Lhb\rho \quad (1.1)$$

where L is the beam length, h its thickness (in the direction of bending), b its width (transverse to the direction of bending) and ρ its density.

The end deflection δ is given by

$$\delta = \frac{WL^3}{8EI} \quad (1.2)$$

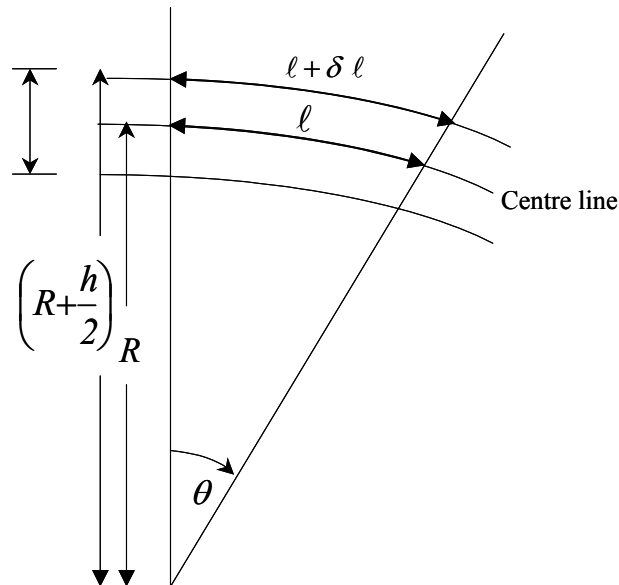
where I is the moment of inertia of the beam given by

$$I = \frac{h^3b}{12} \quad (1.3)$$

Thus the modulus E is given by

$$E = \frac{12WL^3}{8\delta h^3b} \quad (1.4)$$

The maximum strain in a beam which is located at the beam's surface can be determined from the curvature of the beam schematically shown below, where R is the radius of curvature of the beam, h is the thickness of the beam and ℓ is a length of a segment of the beam.



From simple geometry considerations

$$\ell = R\theta \quad [1.5]$$

and

$$\ell + \delta \ell = \left(R + \frac{h}{2} \right) \theta \quad [1.6]$$

thus

$$\delta \ell = \frac{h\theta}{2} \quad [1.7]$$

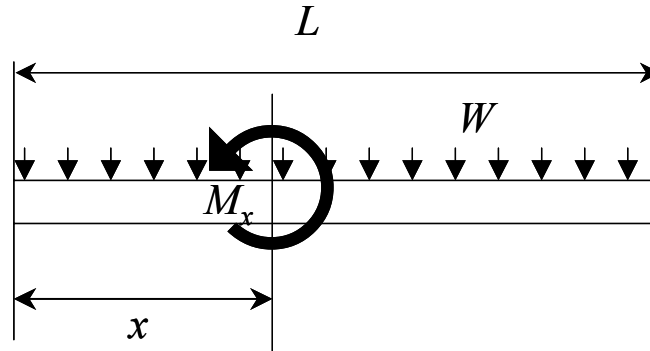
Thus the maximum strain ϵ_{max} in the beam is given by

$$\epsilon_{max} = \frac{\delta \ell}{\ell} = \frac{h}{2R} \quad [1.8]$$

The radius of curvature, R , given by the relation

$$\frac{1}{R} = \frac{M}{EI} \quad [1.9]$$

where M is the bending moment in the beam and I is the moment of inertia of the beam.



The bending moment varies with position along the length of the beam, it being a maximum at the clamped end.

The moment M_x at position x is given as follows

$$\begin{aligned} M_x &= \frac{W(L-x)}{L} \left(\frac{L-x}{2} \right) \\ &= \frac{W(L-x)^2}{2L} \end{aligned} \quad [1.10]$$

At $x = 0$ the bending moment is a maximum and equals

$$M_{x=0} = \frac{WL}{2} \quad [1.11]$$

The maximum radius of curvature $R_{x=0}$ is given by

$$\frac{1}{R_{x=0}} = \frac{M_{x=0}}{EI} \quad [1.12]$$

Thus by substitution into D.4 the maximum strain in the beam is given as

$$\frac{\delta \ell}{\ell} = \frac{2h\delta}{L^2} \quad [1.13]$$

APPENDIX 2: THERMAL CONDUCTIVITIES AND SPECIFIC HEAT CAPACITIES FOR A RANGE OF TPE'S

<i>Material</i>	<i>Temperature, °C</i>	<i>Thermal Conductivity, W/mK</i>	
		<i>Thermal Conductivity</i>	<i>Standard Deviation</i>
AAATF001	23	0.193	0.0014
	50	0.195	0.0041
	75	0.199	0.003
	100	0.207	0.0106
	140	0.238	0.0052
	180	0.287	0.0076
AAATF002	23	0.182	0.0027
	50	0.184	0.006
	100	0.198	0.0036
	140	0.236	0.0109
	180	0.285	0.0038
AAATF003 Test1	23	0.215	0.0083
	50	0.217	0.0027
	100	0.234	0.002
	140	0.26	0.0038
	180	0.289	0.0069
AAATF003 Test2	23	0.216	0.0063
	50	0.219	0.0065
	100	0.234	0.0016
	140	0.263	0.0178
	180	0.29	0.0057
AAATF003 Test3	23	0.217	0.0015
	50	0.218	0.0039
	100	0.237	0.0014
	140	0.262	0.0053
	180	0.289	0.0023
AAATF004	23	0.196	0.0062
	50	0.2	0.0044
	100	0.209	0.0019
	140	0.245	0.0074
	180	0.286	0.0239
AAATF005	23	0.218	0.0109
	50	0.224	0.0099
	100	0.238	0.0069
	140	0.257	0.0032
	180	0.287	0.0057

Table A2.1. Thermal conductivities of SEBS thermoplastic elastomers over the range 23°C to 180°C

Temperature (°C)	Specific Heat (J/g*°C)				
	AAATF004_18	AAATF003_31 repeat	AAATF001_23	AAATF002_9	AAATF005_25
-20.0	1.211	1.251	1.241	1.112	1.278
-15.0	1.525	1.490	1.509	1.488	1.729
-10.0	1.553	1.467	1.536	1.497	1.745
-5.0	1.539	1.435	1.536	1.476	1.700
0.0	1.538	1.414	1.543	1.463	1.682
5.0	1.546	1.400	1.553	1.458	1.678
10.0	1.550	1.389	1.558	1.452	1.674
15.0	1.548	1.375	1.563	1.444	1.669
20.0	1.551	1.370	1.567	1.440	1.664
25.0	1.565	1.376	1.570	1.448	1.670
30.0	1.580	1.389	1.586	1.464	1.686
35.0	1.602	1.407	1.612	1.486	1.712
40.0	1.613	1.417	1.631	1.501	1.729
45.0	1.637	1.440	1.654	1.523	1.760
50.0	1.661	1.462	1.677	1.545	1.783
55.0	1.684	1.489	1.702	1.571	1.801
60.0	1.704	1.516	1.731	1.598	1.818
65.0	1.733	1.553	1.765	1.633	1.846
70.0	1.761	1.582	1.791	1.663	1.872
75.0	1.787	1.600	1.811	1.684	1.879
80.0	1.816	1.638	1.838	1.716	1.895
85.0	1.835	1.678	1.862	1.749	1.917
90.0	1.838	1.710	1.882	1.775	1.941
95.0	1.845	1.740	1.895	1.797	1.969

Table A2.2. Specific Heat Capacities of Elastomeric Samples From –20 °C to 95 °C