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On the design and characterisation of low-stiffness auxetic yarns and fabrics

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Abstract

An auxetic material is one which exhibits a negative Poisson's ratio; it expands laterally when stretched longitudinally and contracts laterally when compressed longitudinally. The helical auxetic yarn is a novel fibre structure with a diverse range of potential applications. The unusual mechanical properties of the yarn can be determined by particular combinations of geometry and component material properties. This paper reports on the development of low-stiffness auxetic yarns and fabrics which offer a range of applications such as medical devices, particularly bandages, compression hosiery and support garments and fashion apparel. The mechanical performance of the yarns and fabrics is elucidated, with emphasis on the ability to exploit significant changes through a prescribed strain range. A yarn Poisson's ratio as low as -1.5 is demonstrated, and fabrics with in-plane and out-of-plane negative Poisson's ratios are illustrated. Stiffness is shown to be highly dependent upon yarn geometry.

Keywords

Weaving, fibre, yarn, fabric formation, measurement, performance, properties, testing

Introduction

An auxetic material is one which exhibits a negative Poisson's ratio.[1] This is a counterintuitive property which offers numerous interesting applications. Many auxetic examples, both synthetic and naturally occurring, have been investigated during the last 20 years including polymeric foams;[2,3] honeycomb structures;[4] microstructural changes in polyethylene induced by sintering;[5] skin;[6] rotation of molecular bonds in zeolites;[7] and single crystal arsenic.[8]

One of the most promising auxetic mechanisms for practical exploitation is the helical auxetic yarn (HAY).[9] This yarn has applications in braided, flat and tubular fabrics, and offers potential benefits in healthcare applications.

The HAY is a novel fibre structure comprised of two components; a relatively compliant *core* around which is helically wound a stiffer, *wrap,* fibre (Figure 1a). Under tension the wrap tends to straighten, thereby causing the core to displace laterally in a helical manner (Figure 1b). If the wrap fibre is much stiffer and of a lower diameter than the core this behaviour can result in a net increase in the effective diameter of the composite yarn – a negative Poisson's ratio. Such behaviour opens up a number of possible technology benefits based around exploiting the ability to cause pores to open in a fabric (Figure 1c),[9] including controlling filtration;[10] drug delivery, transfer/removal of, for example, wound exudate or visual indication by exposure of a substrate to effect colour change.[11,12]

Figure 2 shows one complete cycle length of the HAY. We define the nominal wrap angle θ as the angle subtended by the axis of the core and the axis of the wrap at zero strain. The longitudinal distance for one complete cycle is termed the pitch, λ. The pitch may be determined more readily than the wrap angle, although the latter is intuitively preferred as

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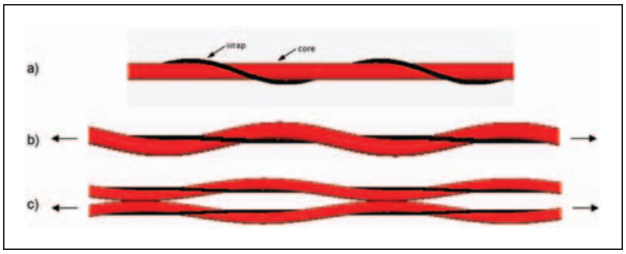

Figure 1. a) Components of the helical auxetic yarn (HAY); b) auxetic behaviour under tension; c) fabric application – pores open under tension in a complementary pair of HAYs.

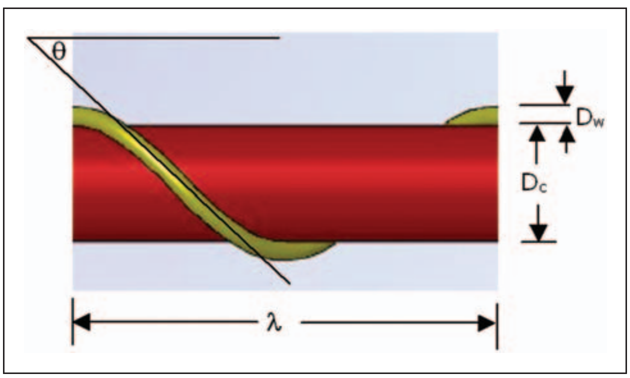

Figure 2. Geometry of the helical auxetic yarn.

Table 1. Summary of auxetic yarns and fabrics used in the experiments

Yarn	Fabric
A – 2 mm dia. covered rubber core, 6/110/34 textured nylon wrap, nominal angle 45°	*no fabric*
B – 1 mm dia. covered rubber core, 16/1 ringspun PET wrap, nominal angle 45°	B – yarn B warp, PET weft
C – 0.18 mm dia. covered rubber core, 2/110/34 textured nylon wrap, nominal angle 45°	C – yarn C warp, PET weft

a defining parameter of the yarn. The diameters of the unstrained core and wrap are D_c and D_w respectively.

We define the *effective diameter,* D_e, of the HAY as the diameter of a cylinder which would precisely contain the yarn at any given strain; this is the dimension which will usually be exploited in practical applications of the technology. Then the Poisson's ratio, ν, of the HAY, the ratio of lateral contractile strain to longitudinal tensile strain, is given by

$$\nu = \frac{-(D_e - D_{eo})/D_{eo}}{(L - L_o)/L_o} \quad (1)$$

where D_{eo} is the effective diameter of the HAY at zero strain ($= D_c + 2D_w$, where D_c is the diameter of the core and D_w the diameter of the wrap); L is the length of the HAY at any given strain; L_o is the length of the HAY at zero strain.

In the unstrained condition, $D_e = D_{eo}$

We describe the strain at which Poisson's ratio first becomes negative as the *activation strain* of the HAY.

A detailed parametric analysis of the design envelope has been conducted by Wright et al.[13] Numerical methods were used to investigate the effects of material properties and geometry upon the tensile performance of the HAY. Strain-dependent auxetic 'phases' were identified and reported, in addition to the analysis of the effects of component design upon Poisson's ratio of the HAY. Sloan et al.[14] report the mechanical characterisation of the HAY, describing the equipment and methodology for obtaining practical yarns, with a focus on stiffer yarns for higher-modulus applications such as composites and blast mitigation.

Previous work in the field of auxetic textiles includes the knitting of auxetic polypropylene fibres;[15] these fibres are auxetic at microstrains. Other work has been reported on the knitting of auxetic fabrics from non-auxetic yarns.[16–18] The HAY is auxetic in real-world strain regimes and is particularly well suited to woven fabrics, although knitting is also feasible.

This paper reports work on the design and characterisation of various yarns and fabrics having low stiffness or tensile modulus, and therefore being particularly suited for healthcare and fashion applications. We study the effects of wrap angle on HAY performance and the pore-opening behaviour of fabrics in which the HAYs are incorporated.

Methods

Three HAYs were fabricated for evaluation and two were subsequently chosen for incorporation into 'bandage-like' fabrics, readily strained to above 20% by a human. These yarns and fabrics are summarised in Table 1. Yarn A consisted of a UK Sewing Services[19] 2 mm diameter black covered rubber 'shock cord' core, wrapped with 6/110/34 textured nylon over a range of wrap angles. Yarn B consisted of a UK Sewing Services EL/M128 1 mm diameter covered rubber core, with a Rex H Perkins[20] ringspun PET 16/1 (630dtex equivalent) wrap, at a nominal wrap angle

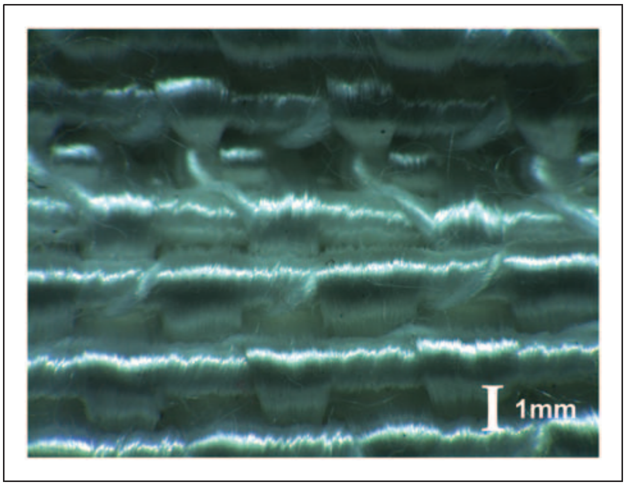

Figure 3. Fabric B comprising helical auxetic yarn B as warp fibres (horizontal).

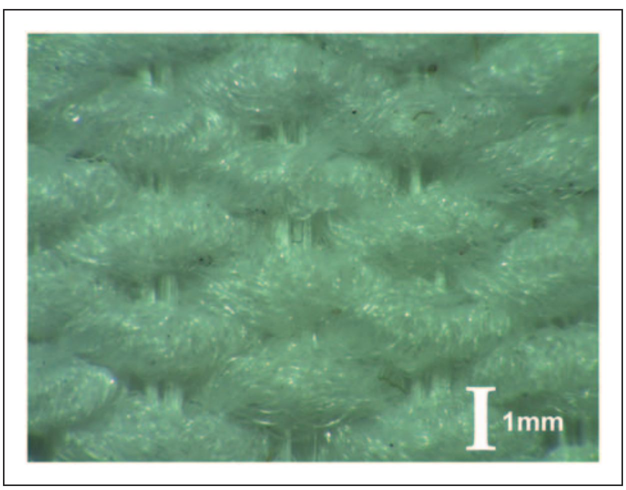

Figure 4. Fabric C comprising helical auxetic yarn C as warp fibres (horizontal). (The fibrous nature of the textured nylon wrap obscures the HAY structure.).

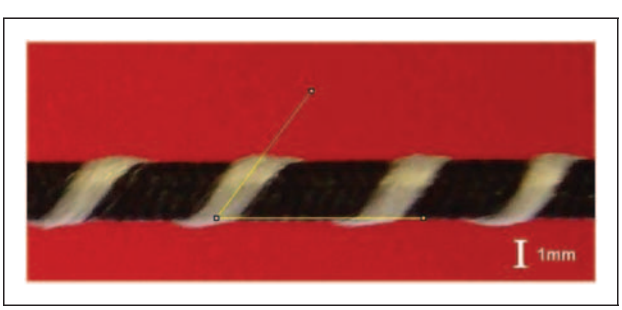

Figure 5. High-resolution image of helical auxetic yarn A during tensile test and subsequent measurement of wrap angle.

of 45 degrees. This yarn was incorporated into Fabric B (Figure 3) – a plain weave narrow fabric, 20 mm wide, 2-ply fabric consisting of 26 warp ends, 13 's' and 13 'z', inserted at 1end/dent. Weft ends were 1100dtex natural, multifilament PET, inserted at 14picks/inch (5.6picks/cm).

Yarn C was produced using a Stretchline[21] covered rubber 3-end (2 wrap, 1 core) 0.18 mm core, with a 2/110/34 (2 ends of 34 filaments, 110dtex) textured nylon wrap, at a nominal wrap angle of 45 degrees. This was incorporated as 48 warp ends into Fabric C (Figure 4) – a 25 mm wide, 12picks/inch (4.7picks/cm) single-ply plain-weave narrow fabric with 550dtex PET weft in order to produce fabrics which gave a drape and handle more commensurate with conventional bandages.

Tensile measurements were performed using a Lloyd Instruments' EZ20 materials testing machine with flat-faced clamps and a 500 N load cell for yarn A and the fabrics, and a 50 N load cell for yarns B and C. Load rates were 5 mm/min. except for yarn A, which was 1 mm/min. Yarn preloads were 0.2 N. Gauge lengths were 150 mm for yarn A and 100 mm for yarns B and C. Fabric gauges were 50 mm, marked on the fabrics. Stiffness, being the ratio of load to extension, was obtained from the gradient of the load-extension curve measured directly by the tensile test.

Wrap angles and strains were determined using images captured at synchronised time intervals using a high-resolution CMOS camera (Edmund Optics EO-5012C, 4.9M pixel) and ImageJ public domain image processing software.[22] The procedure was described in detail by Sloan et al.[14] Figure 5 shows a raw image and angle measurement. The subjective error (which far exceeds any systematic error) in this procedure is estimated at less than 3%.

Figure 6 shows a typical image of an activated HAY. By producing a negative binary image the effective diameter at any given strain can be established using the ImageJ *Line Width* variable in conjunction with a calibrated pixel count (Figure 7), and thereby the Poisson's ratio of the HAY (or fabric) can be evaluated.

To measure the pore-opening effect, images were analysed to determine the open area of the fabric for a range of strains. A series of images were loaded into ImageJ and converted to 32-bit greyscale. The *Image/Threshold* facility was used to identify and mark the open areas and the *Measure* facility used to report the percentage of open area (Figure 8).

A constant pixel window (450×200) equidistant between gauge markers was maintained for each measurement. In order to reduce the subjective error an average was taken of two threshold settings, one from a positive threshold slider sweep (starting with no area masked and stopping when the open area was judged to

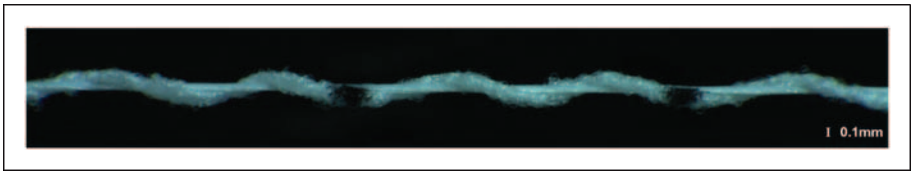

Figure 6. Yarn C activated under tension.

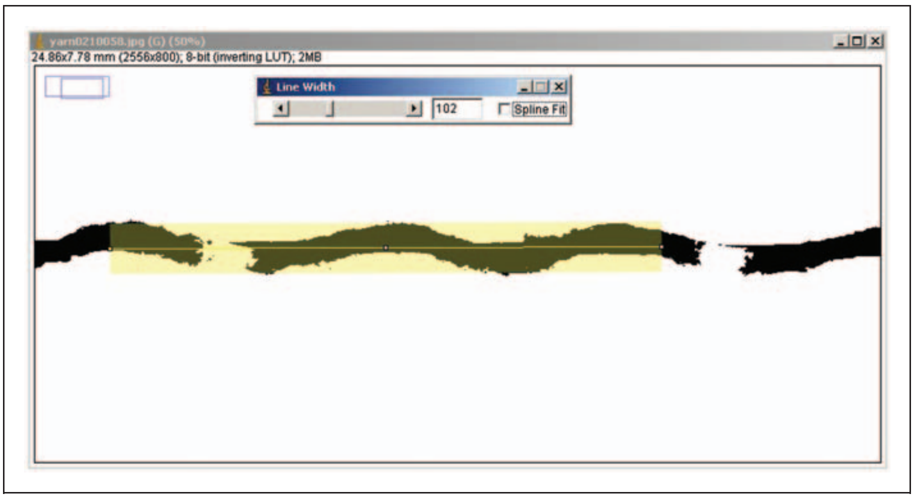

Figure 7. Measuring effective diameter of a helical auxetic yarn.

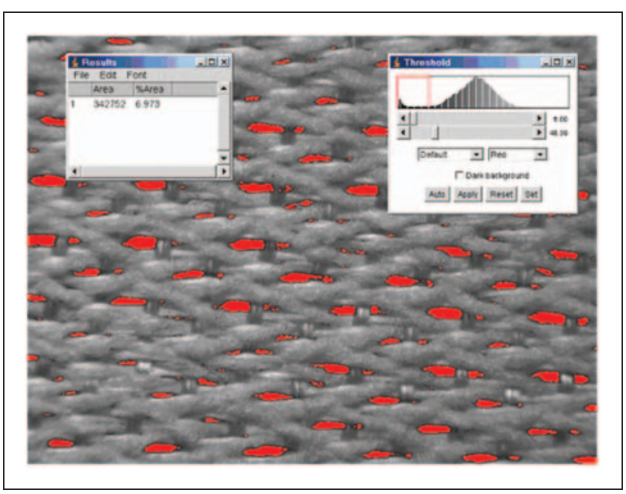

Figure 8. Measuring the proportion of open area of fabric at a given strain. The *Threshold* slider is adjusted until the open area is judged to be precisely represented by the red mask. Then the area is measured (indicated in the *Results* window).

be precisely masked) and one from a negative threshold slider sweep (starting with all area masked as open and gradually reducing the level of masking until the open area was judged to be precisely masked).

Results and discussion

Yarns

Each yarn illustrates different aspects of performance as a function of design variables. With yarn A, we show the effect of wrap angle upon stiffness; yarn B illustrates wrap angle measurement and manufacturing consistency; yarn C demonstrates dependence of Poisson's ratio upon strain.

Yarn A. Figure 9 shows the tensile load/strain behaviour of yarn A components, and Figure 10 the load/strain behaviour for a range of measured initial wrap angles.

The HAY exhibits an initially low stiffness (approximately 50 N/m), effectively governed by the stiffness of the core, with a rapid transition to a much higher stiffness (200 N/m) as the wrap straightens. Because the wrap is initially only lightly strained in the yarn (because it begins as a helix) it will effectively operate over a greater fabric strain range than it would if used separately.

By varying the initial wrap angle in manufacture we obtain an additional design freedom – to vary the strain dependence of this behaviour. The lower the wrap angle, the lower the strain at which the auxetic

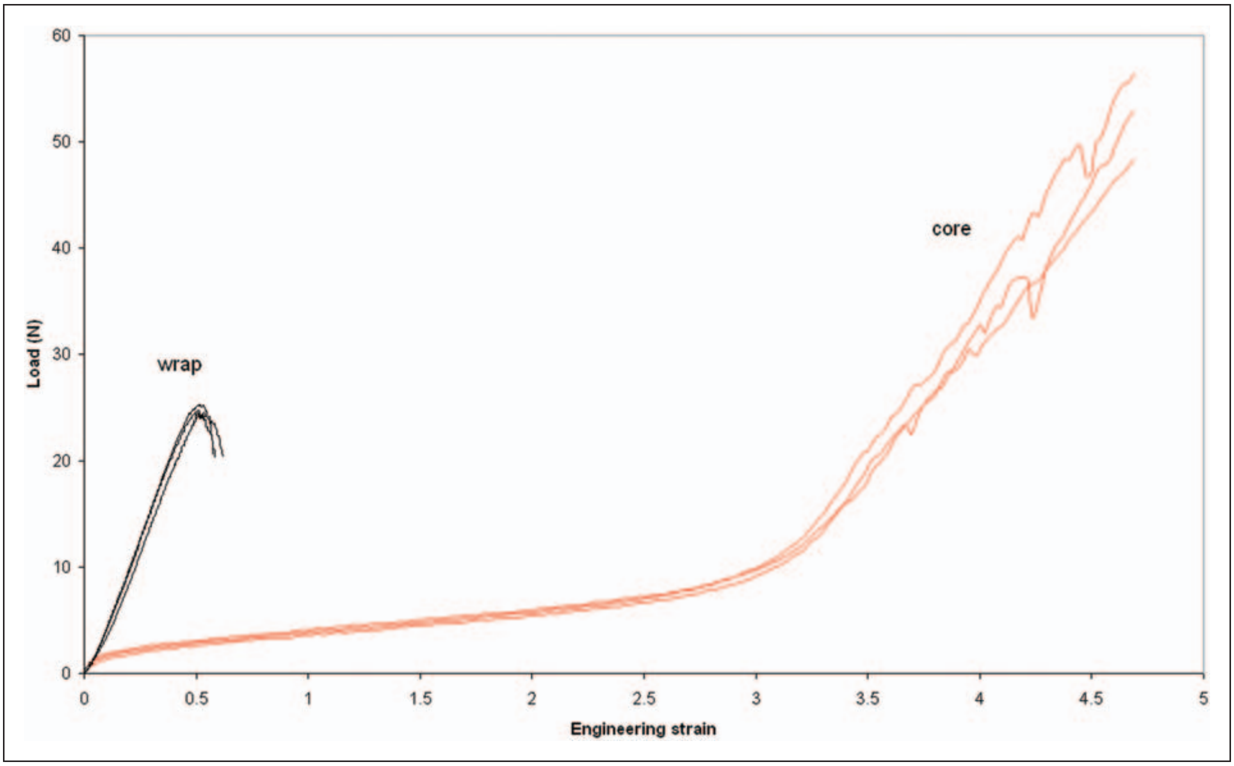

Figure 9. Load-strain data for three samples each of yarn A core and wrap components.

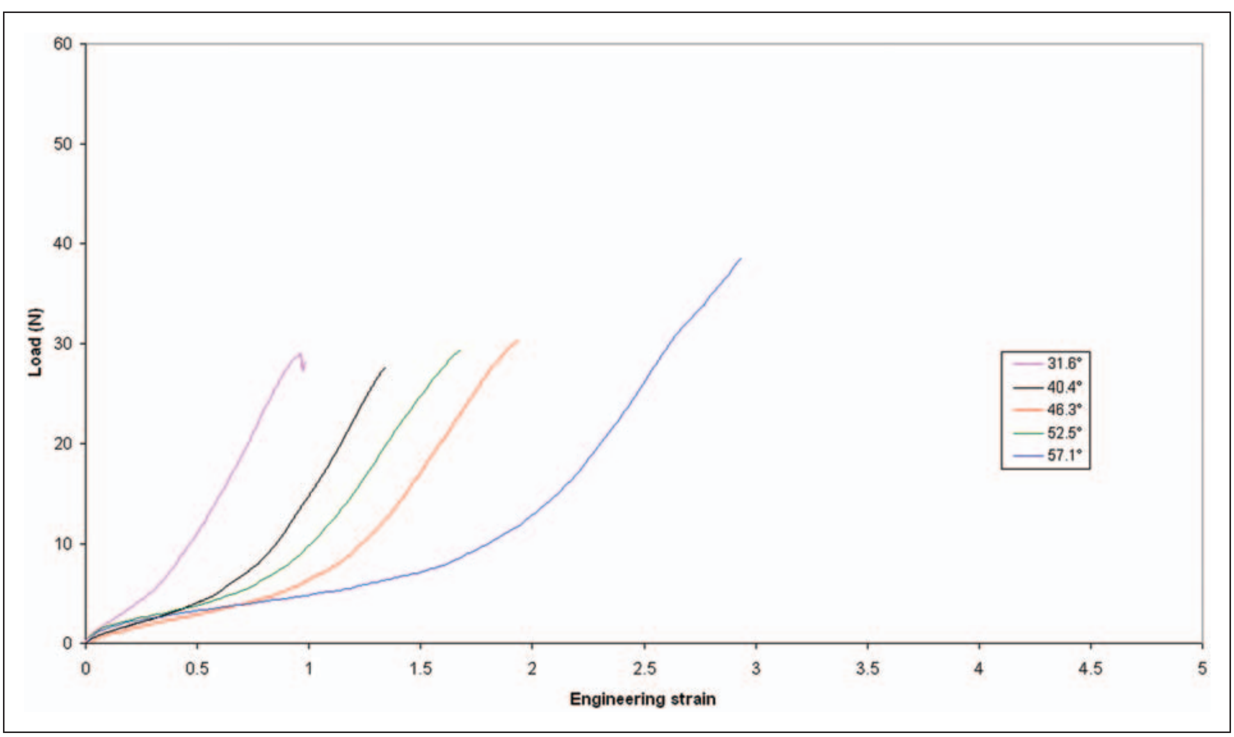

Figure 10. Measurements of the effect of initial wrap angle on strain-dependent behaviour of yarn A.

Table 2. Measurements of wrap angles in two samples of yarn B

wrap cycle	1	2	3	4	5	6	7	8	9	10	AVG	STDEV
sample #1	47.41	46.50	46.36	49.94	46.67	46.02	46.36	46.38	44.38	49.40	46.94	1.63
sample #2	46.52	47.57	46.06	47.99	47.16	48.37	46.01	44.05	42.61	43.38	45.97	1.99

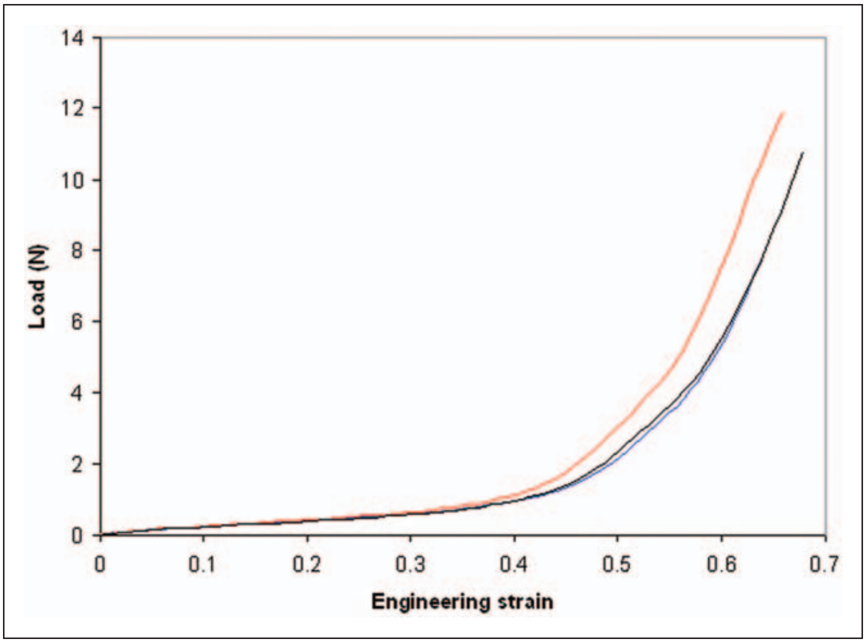

Figure 11. Variation of tensile load with strain for three samples of yarn B.

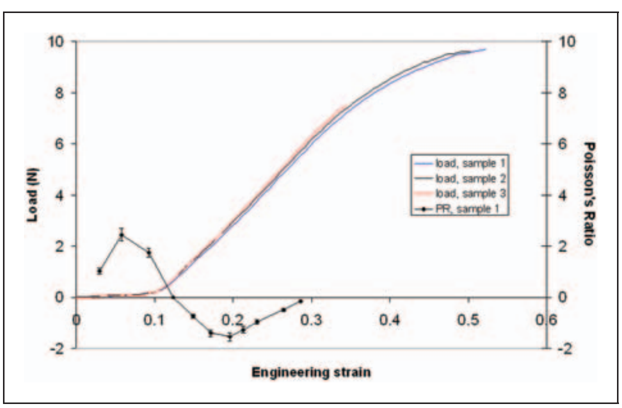

Figure 12. Variation of tensile load with strain for three samples of yarn C, overlaid with Poisson's ratio of one sample.

mechanism activates – this is due to the earlier onset of stress in the wrap.[12] As the wrap straightens (and the core becomes helical) the stiffness of the wrap gradually dominates that of the structure.

Yarn B. Table 2 lists the measurements of 10 different initial (unstrained) wrap angles in each of two samples of yarn B, together with the means (AVG) and standard deviations (STDEV). The standard deviations are less than 2 in 46 degrees, or approximately 4%, indicating that the manufacturing process is well-controlled and repeatable for this particular yarn: depending upon material properties and the design of the wrap (e.g. monofilament v multifilament), conformance of wrap to core during manufacture can vary significantly.

Figure 11 shows the variation of load with strain for three samples of yarn B. Stiffness varies from 25 N/m to over 150 N/m.

Yarn C. Figure 12 shows the variation of load with strain for three samples of yarn C, overlaid with the Poisson's ratio of one of the samples. For this yarn, stiffness varies from 50 N/m to over 800 N/m.

The variation of Poisson's ratio with strain is consistent with that predicted by numerical models:[13] at very low strains the HAY Poisson's ratio becomes increasingly positive as the components decrease in diameter due to their positive Poisson's ratios; as the wrap begins to straighten the core is displaced laterally causing a decrease in

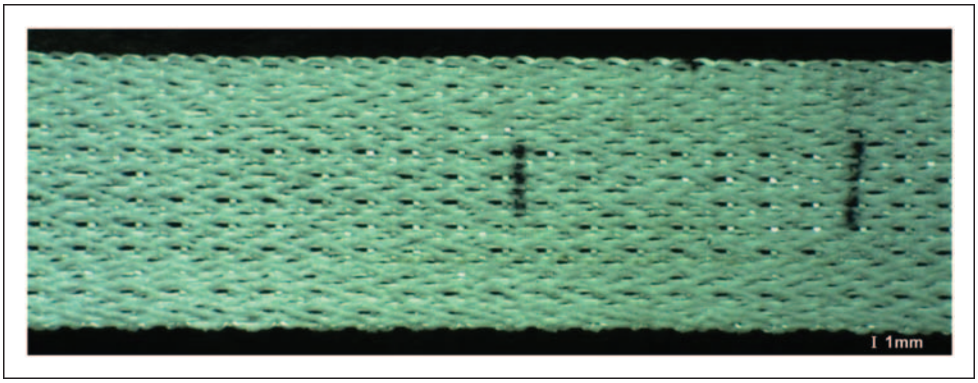

Figure 13. Fabric C at approximately 30% strain, showing open pores and gauge markers.

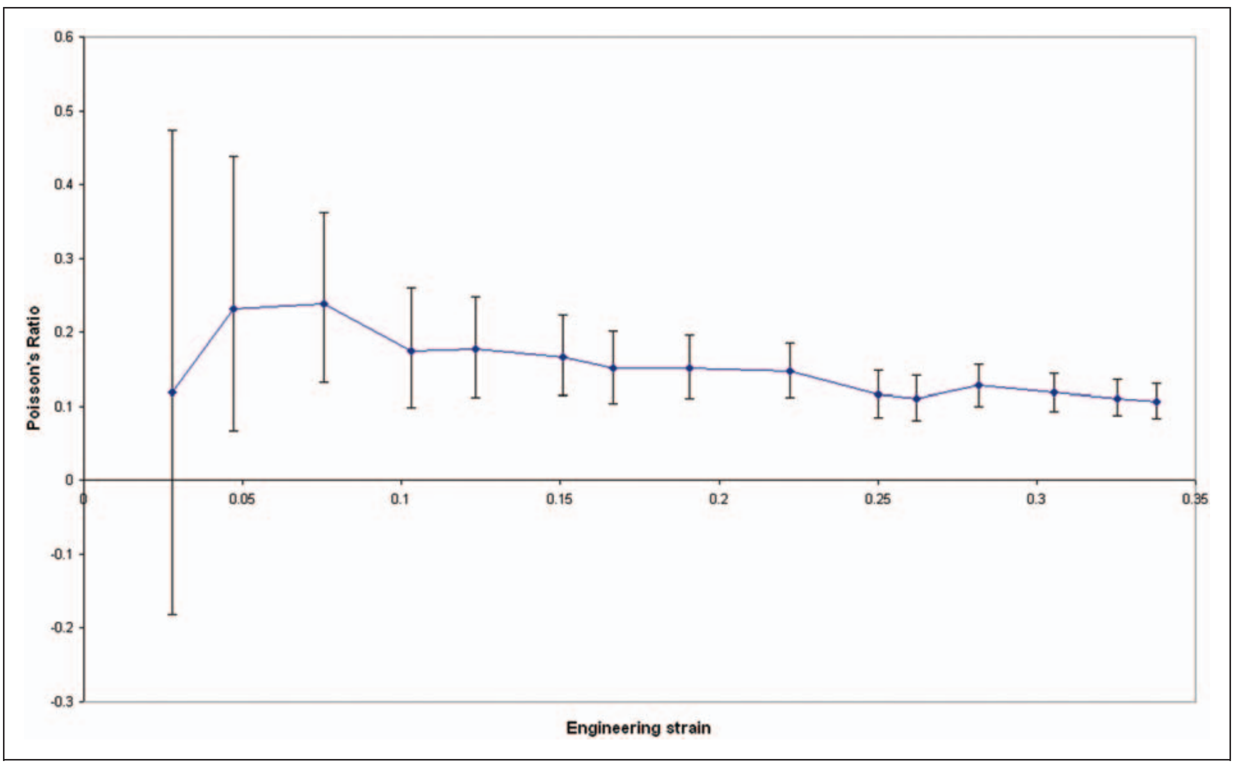

Figure 14. Variation of Poisson's ratio with longitudinal strain for fabric C.

Poisson's ratio. Eventually the lateral displacement of the core exceeds D_{eo}, giving rise to a negative Poisson's ratio. The Poisson's ratio reaches a maximum negative value when the wrap becomes completely straight and then tends towards a positive value as component diameters continue to decrease. For yarn C, Poisson's ratio becomes negative at 12.3% engineering strain and reaches a maximum negative value of -1.55 at 19.5% strain. It ceases to be auxetic at approximately 30% strain.

Fabrics

Pore opening. Figure 13 shows the pore-opening effect in Fabric C at approximately 30% strain. Lateral strain is measured at the edges of the sample, longitudinal strain by gauge markers shown in the figure. In this fabric the Poisson's ratio of the fabric remains positive for all strains (Figure 14). This is largely a function of the choice of weft material and weave geometry, allowing warp yarns to overlap, thereby causing a thickening

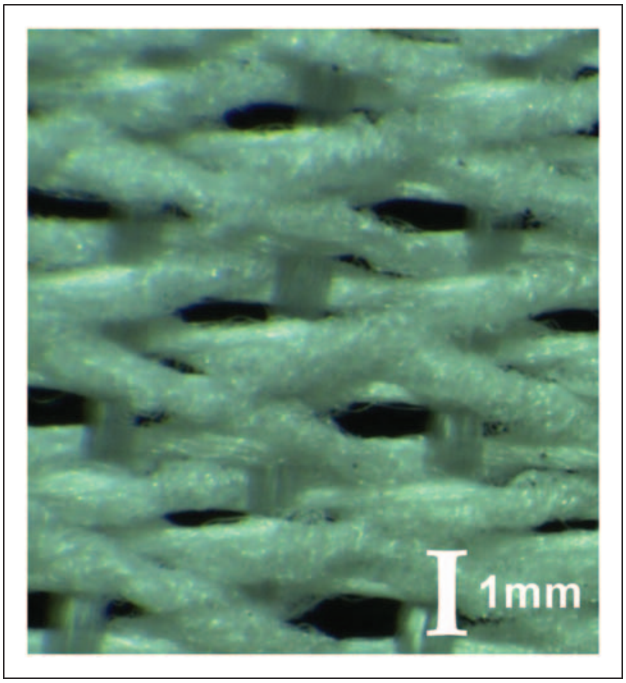

Figure 15. Fibres overlap, giving rise to negative Poisson's ratio out-of-plane and a consequent reduction in in-plane negative Poisson's ratio.

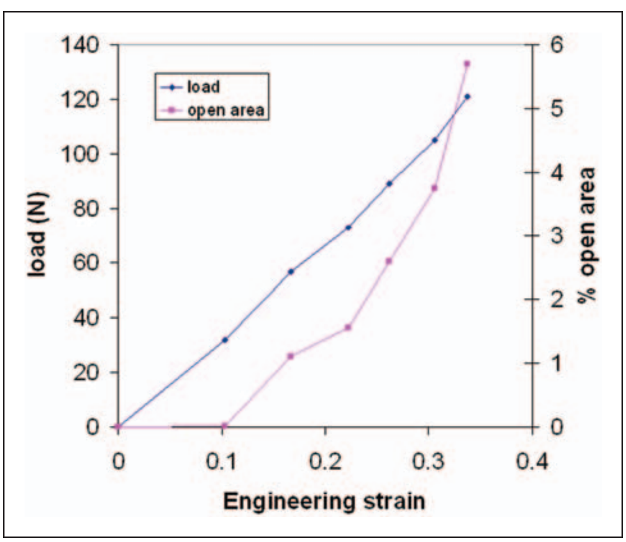

Figure 16. Variation of fabric percentage open area and load with strain for fabric C.

of the fabric and thus an *out-of-plane* negative Poisson's ratio. This effect is illustrated in close-up in Figure 15. A more elasticated weft or higher weft crimp would be expected to give rise to a negative in-plane Poisson's ratio for the fabric. We also observe an inhomogeneous distribution of the pores with greater opening in the centre of the fabric. This is probably due to the manufacturing process, whereby there is a greater density of yarns near the edges.

Figure 16 compares open area with load v strain for the fabric. The trends are different, indicating that there is not a direct correlation between load and open area. It is likely that this is due to a variety of factors, including the out-of-plane (thickening) effects, crimp of warp and weft, warp tension, location of weft yarns and (lack of) homogeneity of the fabric.

Colour change. It is also possible to exploit the pore-opening effect to generate a colour change for indicative or aesthetic purposes, for example by inserting a substrate of a different colour beneath an exterior auxetic layer. Figure 17 shows a variant of Fabric B (binder removed, creating a tubular fabric), containing red filler yarns, under 0 N and 80 N tension, the latter exposing the red colour of the filler through the open pores of the fabric.

Auxetic behaviour. Figure 18 shows the strain-dependency of Poisson's ratio of Fabric B. This fabric exhibits a negative in-plane Poisson's ratio in the strain range 15–40%, reaching a maximum negative value of –0.1 at approximately 32% strain.

Conclusions

The aim of this work was to manufacture and characterise low-stiffness HAYs, and fabrics therefrom, and to quantify their auxetic behaviour for potential medical and fashion applications.

Auxetic yarns have been produced with a negative Poisson's ratio as low as −1.5 and auxetic fabrics exhibiting negative Poisson's ratio to −0.1. Increased auxetic behaviour in fabrics is possible by attending to 3D effects and weft performance at the design stage.

Yarn stiffness was found to vary by factors of 4–16 over strain ranges typically 10–70%.

Performance may be designed to be application-specific by means of appropriate selection of yarn geometry, with additional design freedom conferred by variation of wrap angle.

Auxetic yarns and fabrics have applications as indicators – by virtue of various forms of colour change. This has potential in fashion, compression bandaging and other fields where accurate indication of the appropriate tension (or indeed excess or inadequate tension) is required.

By exploiting the ability to open pores in the fabric structure there are possible applications in filtration and fluid transfer, such as drug delivery or exudate removal.

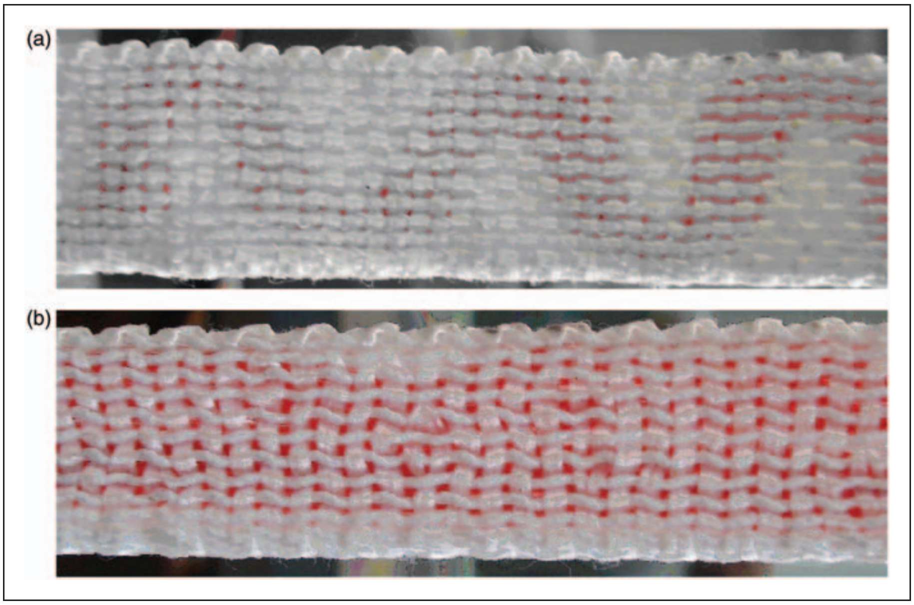

Figure 17. Prototype colour-change fabric B; a) 0 N tension, b) 80 N.

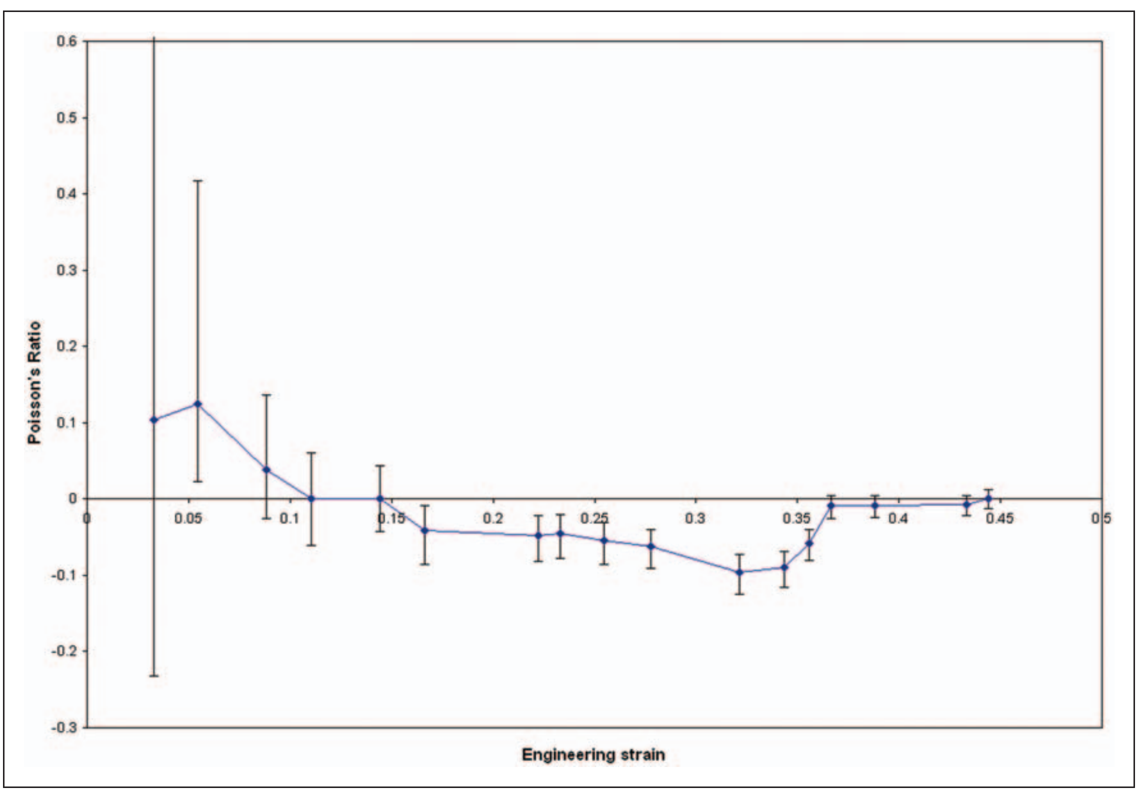

Figure 18. Variation of Poisson's ratio with longitudinal strain for fabric B.

In choosing appropriate materials and geometry for the core and wrap components of the HAY and for the fabric construction, it is possible to design a system which shows strain-dependent variation in tensile modulus and negative Poisson's ratio. This offers possibilities for dynamic stiffness support garments and bandages.

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